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

WATER QUALITY OF THE DELAWARE AND RARITAN CANAL, NEW JERSEY, 1998-99

Water-Resources Investigations Report 01-4072

Prepared in cooperation with the

NEW JERSEY WATER SUPPLY AUTHORITY

USGS
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By Jacob Gibs, Bonnie Gray, Donald E. Rice, Steven Tessler, and Thomas H. Barringer

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West Trenton, New Jersey

2001

U.S. DEPARTMENT OF THE INTERIOR

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U.S. GEOLOGICAL SURVEY

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Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
acre	4,047	square meter
acre	0.4047	hectare
square foot (ft^2)	929.0	square centimeter
square foot (ft^2)	0.09294	square meter
square mile (mi^2)	259.0	hectare
square mile (mi^2)	2.590	square kilometer
	Volume	
gallon (gal)	3.785	liter
gallon (gal)	0.003785	cubic meter
cubic foot (ft^3)	0.02832	cubic meter
	Flow	
foot per second (ft/s)	0.3048	meter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per minute (ft^3/min)	0.02832	cubic meter per minute (m^3/min)
mile per hour (mi/h)	1.609	kilometer per hour
gallon per minute (gal/min)	0.06308	liter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second
	Temperature	
degree Fahrenheit (°F)	°C = 5/9 x (°F-32)	degree Celsius (°C)

CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS--Continued

Vertical datum: In this report “sea level” refers to the National Geodetic Vertical Datum 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.

Water-quality abbreviations:

µg -micrograms
mg -milligrams
mg/L -milligrams per liter
µg/L -micrograms per liter
µS/cm -microsiemens per centimeter at 25 degrees Celsius

DOC -dissolved organic carbon
SOC -suspended organic carbon
POC -purgeable organic compound
TOC -total organic carbon
VOC -volatile organic compound

Water Quality of the Delaware and Raritan Canal, New Jersey, 1998-1999

By Jacob Gibs, Bonnie Gray, Donald E. Rice, Steven Tessler,
and Thomas H. Barringer

ABSTRACT

Since 1934, the Delaware and Raritan Canal has been used to transfer water from the Delaware River Basin to the Raritan River Basin. The water transported by the Delaware and Raritan Canal in New Jersey is used primarily for public supply after it has been treated at drinking-water treatment plants located in the Raritan River Basin. Recently (1999), the raw water taken from the canal during storms has required increased amounts of chemical treatments for removal of suspended solids, and the costs of removing the additional sludge or residuals generated during water treatment have increased. At present, action to control algae is unnecessary.

The water quality of the Delaware and Raritan Canal was studied for approximately 16.5 months from mid-January 1998 through May 1999 to determine whether changes in water quality along the length of the canal are associated with storms. Nine water-quality constituents, and field measured specific conductance and turbidity were statistically tested.

Instantaneous or grab samples of water were collected from the Delaware and Raritan Canal after five storms and during four nonstorm events. Median values of water-quality constituents in samples collected immediately after storms and during nonstorm conditions when statistically compared by sampling location were not significantly different. Therefore, the data were combined or aggregated to eliminate one of the two explanatory variables, either individual sampling sites or the two types of sampling events, in order to generate a sample population large enough to show statistically significant differences. After combining sampling events, only the median concentration of suspended organic carbon, and field measured specific conductance and turbidity, were significantly different among sampling sites. Median concentrations of total and filtered ammonia plus organic nitrogen, total phosphorous, turbidity, ultraviolet absorbance at 254 nanometers, and dissolved organic carbon in samples collected after storms were significantly greater than in samples collected during nonstorm conditions, when the sampling locations were aggregated in the statistical analysis. Methyl *tert*-butyl ether, the most frequently detected volatile organic compound (VOC), was detected in 55 of 80 samples. The highest concentration of methyl *tert*-butyl ether, 3.2 micrograms per liter, was measured in a sample collected during nonstorm conditions.

The median of the continuously monitored specific conductance during nonstorm conditions at Port Mercer, N.J., increased by approximately 3 to 4 µS/cm (microsiemens per centimeter) (1.5 to 2 percent of the median specific conductance) relative to that at the nearest upstream site, at Lower Ferry Road. The land use in the influent basins for this reach of the Delaware and Raritan Canal is primarily urban. One possible source of water with high specific conductance is either domestic or industrial wastewater that continuously discharges into pipes, then empties into the canal. Another possible source is ground water from an area within this reach where the elevation of the water table is higher than that of the water surface of the Delaware and Raritan Canal.

The median continuously monitored specific conductance measured during nonstorm conditions at the Route 18 Spillway site increased relative to that of the nearest upstream site, Ten Mile Lock, by approximately 3 to 4 µS/cm. The mean net change in continuously monitored specific conductance for this reach during storms also increased. Land use in the two largest influent

basins within this reach, the Borough of South Bound Brook and Als Brook, is predominantly urban.

The mean and median of continuously monitored turbidity varied along the length of the canal. In the reach between Raven Rock and Lower Ferry Road, the mean and median for continuously monitored turbidity during the study period increased by 7.2 and 6.2 NTU (nephelometric turbidity units), respectively. The mean of continuously monitored turbidity decreased downstream from Lower Ferry Road to Ten Mile Lock. Turbidity could increase locally downstream from influent streams or outfalls, but because the average velocity of water in the canal is low, particles that cause turbidity are not transported appreciable distances. In the reach between Ten Mile Lock and the Route 18 Spillway, the mean and median of the continuously monitored turbidity changed less than 0.5 NTU during the period of record. The small change in turbidity in this reach is not consistent with an average velocity for the reach; the average velocity in this reach was the lowest in all of the reaches studied. The expected decrease in turbidity due to settling of suspended solids is likely offset by turbid water entering the canal from influent streams or discharges from storm drains. Field observation of a sand bar immediately downstream from the confluence of Als Brook and the canal confirmed that the Als Brook drainage basin has contributed stormwater-generated sediment to the canal that could reach the monitor located at the Route 18 Spillway and the raw water intakes for two drinking-water treatment plants.

INTRODUCTION

The Delaware and Raritan Canal, which was put into operation in 1834, was originally constructed as a barge canal. In 1934, the State of New Jersey acquired the canal, and it is currently operated by the New Jersey Water Supply Authority (NJWSA). Since 1934, the canal has been used for interbasin transfer of water from the Delaware River Basin to the Raritan River Basin. Water purveyors, who are customers of the NJWSA, use the canal as a source of raw water that will be treated and distributed as public drinking water.

Since 1997, several water purveyors have noticed that the raw water withdrawn from the canal during precipitation events has required increased amounts of chemicals for the removal of suspended solids which, in turn, generates increased amounts of sludge or residuals. The increased use of chemicals in treating the water and removing additional sludge or residuals contributes to the increased cost of producing drinking water that meets the desired chemical quality and regulatory standards. Drinking-water purveyors are concerned that this worsening of water quality during storms could be part of a long-term trend of declining water quality and want to determine the possible sources or causes. To address these concerns, the U.S. Geological Survey (USGS), in cooperation with the New Jersey Water Supply Authority, conducted a study from mid-Janury 1998 through May 1999 to determine whether the water quality in the canal is affected by stormwater runoff from basins influent to the canal, and if so, to identify which of the canal reaches are the largest sources of the poorer water quality that the drinking-water-treatment plants are treating during storms. In order to effectively manage the logistics of conducting sampling along the 58-mile long canal during a storm, the collection of surface-water samples and analysis of water-quality data were divided into two projects. The first project, a reconnaissance of the entire length of the canal is designed to evaluate changes, statistically and qualitatively, in the quality of water at the ends of reaches of 10 miles or longer. The second project, which has not been conducted as of the publication of this report, will consist of collecting and analyzing samples from individual influent streams or pipes that discharge into the canal in those reaches of the canal where significant changes in water quality have occurred.

Purpose and Scope

This report describes the first project in a two-part study and characterizes the water quality of the Delaware and Raritan Canal over a period of approximately 16.5 months (mid-January 1998 through May 1999). Water samples were collected and analyzed to determine changes in the water quality of the canal associated with storms, and to compare the water quality related to storms to that of periods when no precipitation occurred, along the length of the canal.

Six continuous water-quality monitors were used to collect data along almost the entire length of the canal. Specific conductance, temperature, and turbidity were the water-quality characteristics that were continuously monitored.

Instantaneous water samples were collected at seven locations after the start of five storms and four times when there was no precipitation. The instantaneous water-quality samples were analyzed for nitrogen species (nitrite, nitrite plus nitrate, ammonia, and ammonia plus organic nitrogen in filtered samples, and ammonia plus organic nitrogen in whole water samples), phosphorous in filtered and unfiltered samples, total suspended solids, suspended organic carbon, dissolved organic carbon, ultraviolet absorbtion at 254 nanometers (UV 254), and 29 volatile organic compounds (VOCs). Specific conductance and turbidity were measured in the field. Results of these analyses and measurements are presented in tables and figures.

In addition, water-quality data obtained during the study were organized and formatted into a relational database. Geographic information system (GIS) files were created to represent the canal and cultural features associated with the canal, and land uses of the drainage basins influent to the canal.

Approach

The changes in the water quality along the length of the canal caused by stormwater runoff and continuous discharges to the canal from unknown sources, and the biological, chemical, and physical processes that occur in the canal, were evaluated by measuring constituents in instantaneous water samples collected at seven locations along the canal where width- and depth-integrated samples could be obtained. Instantaneous water-quality samples were collected after the start of five storms (after 0.5 inch of precipitation had fallen) and on four occasions when there had been no precipitation for the previous ten days (hereafter called a nonstorm event or condition). Continuous measurements of temperature, specific conductance, and turbidity were collected at six sites, at five of which instantaneous water samples also were collected. This arrangement of continuous water-quality monitoring locations divided the length of the canal into five reaches. The change in water quality along the length of the canal was determined by sampling at each instantaneous water-quality sampling site and subsequent analysis of the samples at the USGS National Water Quality Laboratory (NWQL) or the USGS New Jersey District laboratory, or by continuously measuring the changes in water quality in each reach at the continuous water-quality monitoring sites and subsequent evaluation of that data.

Previous Studies

The hydrology of watersheds flowing into and under the canal has been studied by Ebasco Services, Inc. (1988). Watersheds and watershed divides adjacent to the feeder part of the canal, which extends from the canal inlet on the Delaware River to Southard Street in the City of Trenton, N.J., are described in the report, and the watersheds that drain into or under the feeder part of the canal are identified. Maps containing information on influent basins to the feeder part of the canal were incorporated into geographic information system coverages generated in this study.

The plans and goals for the establishment and maintenance of a state park encompassing the canal and for a natural-resource inventory of the state park are contained in a report by the Delaware and Raritan Canal Commission (1977). Streams that flow into or under the canal, the drainage basins of those streams that flow into or under the canal, and areas of local runoff or overland flow that reach the canal were identified in the natural-resource inventory of the report.

Rutgers University (1980) conducted a study of the hydrologic, hydraulic, water-quality, and operational characteristics of the canal. The discussion of water quality is a snapshot of the water quality for 1974 through 1977. The Rutgers University report also contains a list of structures and their locations on canal property. This list was incorporated into geographic information system coverages generated for the present study.

Camp, Dresser, and McKee, Inc.(1986) evaluated seven ways to divert stormwater that flows into the U.S. Route 1 conduit of the canal to the Assunpink Creek. The diversion of stormwater to the Assunpink Creek would reduce the cost of repeated dredging to maintain the flow capacity of the conduit. The proposed alternatives were not adopted (Steven Nieswand, U.S. Geological Survey, oral commun., 1999). Camp, Dresser, and McKee, Inc. (1986) delineated the drainage areas from which stormwater originates, then flows into the canal and the U.S. Route 1 conduit. The spatial information on stormwater drainage basins that discharge into the conduit was incorporated into geographic information system coverages generated in the present study. Results of chemical analyses of sediment collected from seven storm drains that empty into the conduit for trace elements, polychlorinated biphenyls, and chlorinated pesticides also are reported.

NJWSA has no historical documentation or reports that conclude water-quality degradation associated with excessive algal growth occurred in canal water, and none of the water purveyors has complained to the NJWSA about the taste or odor of treated drinking water that might be attributable to algae in canal water (Edward Buss, New Jersey Water Supply Authority, written and oral commun., 1999).

Hickman and Barringer (1999) and Hay and Campbell (1990) discuss water-quality changes at the Delaware River at Lumberville, Pa. (USGS surface water-quality station 01461000) during 1986-95 and 1976-86, respectively. The Delaware River at Lumberville drains an area of 6,598 mi^2; water quality at this station can be used to represent the water quality at the intake of the canal on the Delaware River because this station is located approximately 0.7 miles downstream from the intake. Within the 0.7 miles, there is a negligible increase in the drainage area of the Delaware River. Thus, very little change in the water quality would be expected to occur within this reach. Hay and Campbell (1990) evaluated 22 constituents for trends at the Delaware River at Lumberville, Pa. The results of their analysis (at a statistical confidence level of 95 percent or greater) indicated that concentrations of total organic carbon decreased and pH increased during 1975-86, and that concentrations of sulfate decreased during 1979-86. Hickman and Barringer (1999) evaluated trends for 23 water-quality constituents. The results of their analyses (at a statistical confidence level of 95 percent or greater) indicated that biochemical oxygen demand increased, and total nitrogen, total ammonia nitrogen, organic plus ammonia nitrogen, total organic carbon, and fecal coliform (MPN) decreased during 1986-95.

Acknowledgments

The authors thank John Petersen, John Gallucci, Paul Luhrman, Michael Anderson, and Leonard Navarro of the NJWSA for collecting all the instantaneous water samples during storms. The authors also thank the NJWSA personnel, in particular Edward Buss and Joseph Sheppard, for providing reports and information about canal operations and design, which helped make this project report possible.

DESCRIPTION OF STUDY AREA

The study area consists of the Delaware and Raritan Canal and all drainage basins influent to the canal (fig. 1). The study area lies almost wholly within the Piedmont Physiographic Province in New Jersey. A small part of the area, part of the Duck Pond Run influent drainage basin, is in the Coastal Plain Physiographic Province.

Average annual precipitation in the study area ranges from 42 to 46 inches. The average annual runoff ranges from 21 to 23 inches (Schopp and Bauersfeld, 1985).

Delaware and Raritan Canal

The Delaware and Raritan Canal is approximately 58 miles long from the water intake on the Delaware River, 0.7 miles upstream from Raven Rock, to the end of the canal at the Route 18 Spillway, which empties canal water into the Raritan River at New Brunswick (fig. 1). The canal is entirely within the Piedmont Physiographic Province in New Jersey (Otto S. Zapecza, U.S. Geological Survey, oral commun., 1999).

The canal is roughly parallel to the Delaware River from the inlet on the Delaware River to Calhoun Street in Trenton, a distance of 21.8 miles. At Calhoun Street, the canal turns to the northeast, away from the Delaware River, and is roughly parallel to the Fall Line, the dividing line between the Piedmont and Coastal Plain Physiographic Provinces. Near Southard Street in Trenton, the canal goes underneath U.S. Route 1 in two identical 13 feet by 8 feet reinforced concrete rectangular conduits that extend approximately 1.15 miles to Mulberry Street in Trenton (Camp, Dresser, and McKee, Inc., 1986). The canal becomes an open channel again downstream from Mulberry Street and runs approximately parallel to U.S. Route 1 from Trenton City to the aqueduct over the Millstone River. After crossing the Millstone River, the canal follows the right bank (in the downstream direction) of the Millstone River until it reaches the confluence of the Millstone and Raritan Rivers. The canal then follows the Raritan River along the right bank and ends at the Route 18 Spillway in New Brunswick.

In 2000, there are eight historically certified locks on the Canal. These eight locks have been modified; the lock gates have been replaced with weirs and sluice gates that control the water level or, in the case of the Raven Rock lock, with a set of sluice gates only. Supplemental overflow weirs have been installed at five locks--Griggstown, Ten Mile, South Bound Brook, Five Mile (Rutgers University, 1980) and Kingston (John Petersen, New Jersey Water Supply Authority, oral commun., 1999).

The aqueduct that carries canal water over the Millstone River has a series of sluice gates to allow diversion of Millstone River water into the canal during periods of flooding in the Millstone River to maintain the structural stability of the aqueduct (Rutgers University, 1980) or to provide additional water to the canal during droughts in the Delaware River Basin.

Drainage Basins Influent to the Delaware and Raritan Canal

The total area of basins draining into the canal (hereafter called influent drainage basins) is 53,860 acres. The four largest influent drainage basins, which account for 76.2 percent of the total area of all the influent drainage basins, in descending order of drainage area, are Wickecheoke Creek (16,987 acres), Lockatong Creek (14,815 acres), Duck Pond Run (3,904 acres), and Als Brook (2,411acres), (Delaware and Raritan Canal Commission, 1977). Duck Pond Run flows into the canal between Port Mercer and Griggstown (fig. 1). Land use in the Duck Pond Run Basin is undergoing rapid change from agricultural to urban (fig. 2). The Als Brook Basin drains into the canal between Ten Mile Lock and Landing Lane Bridge about 1.5 miles from the Route 18 Spillway (fig. 3). The Als Run drainage basin contains a mixture of land uses, (urban, 48.1 percent; agriculture, 3 percent; and undeveloped, 48 percent) which was determined from the 1986 integrated terrain land use (ITU) coverage, (New Jersey Department of Environmental Protection, 1996). The Wickecheoke Creek and the Lockatong Creek Basins drain into the feeder part of the canal between the Raven Rock feed gates and Brookville (fig. 4). The predominant land use in the Wickecheoke Creek and the Lockatong Creek Basins is agricultural (60 percent of the total area of the two basins) (fig. 4).

METHODS OF INVESTIGATION

Eight sites were selected at locations along the canal, from the inlet on the Delaware River at Bull’s Island, N.J. (fig. 4), to the outlet at the Raritan River near

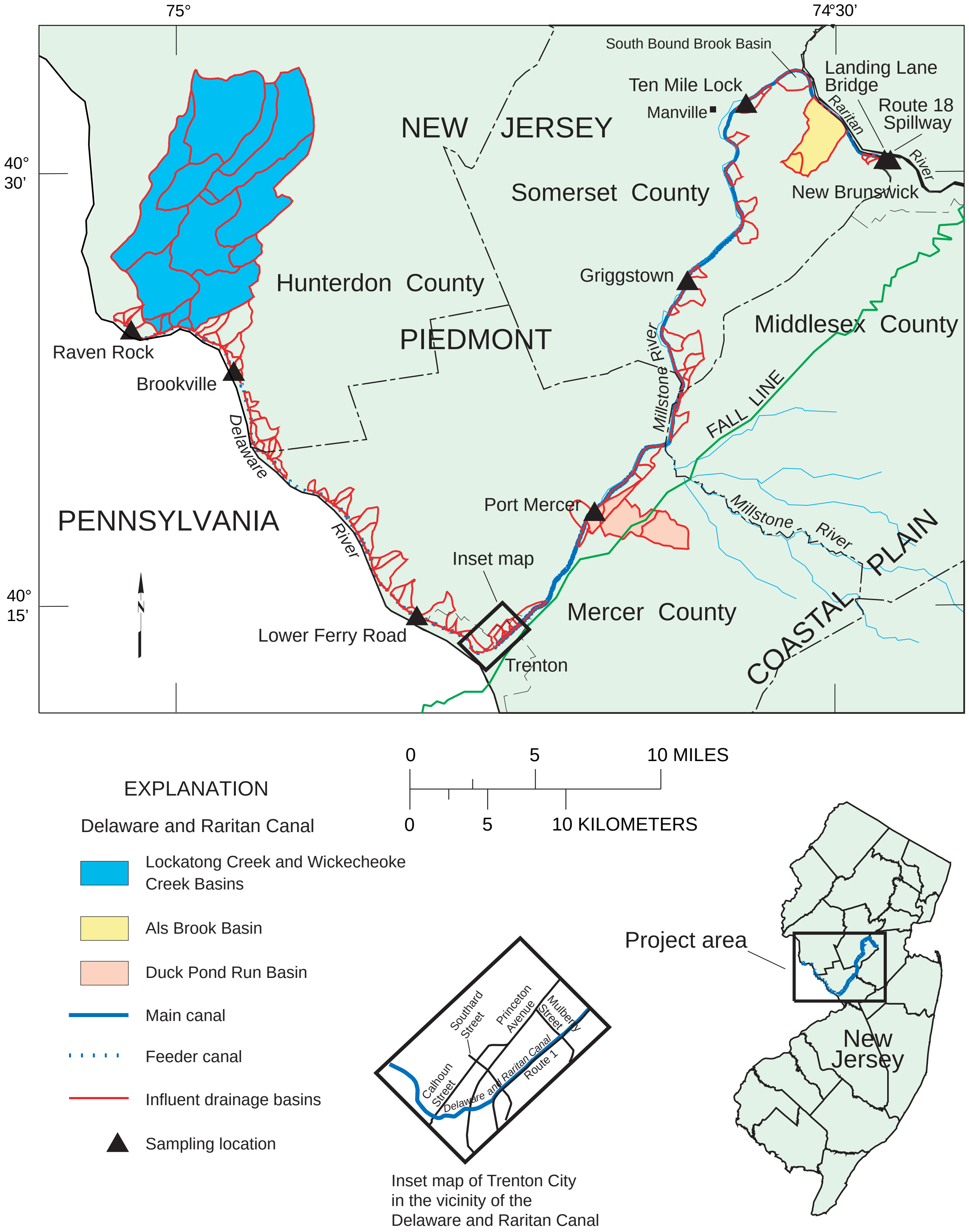


Figure 1. Locations of water-quality sampling sites and influent drainage basins along the Delaware and Raritan Canal, New Jersey.

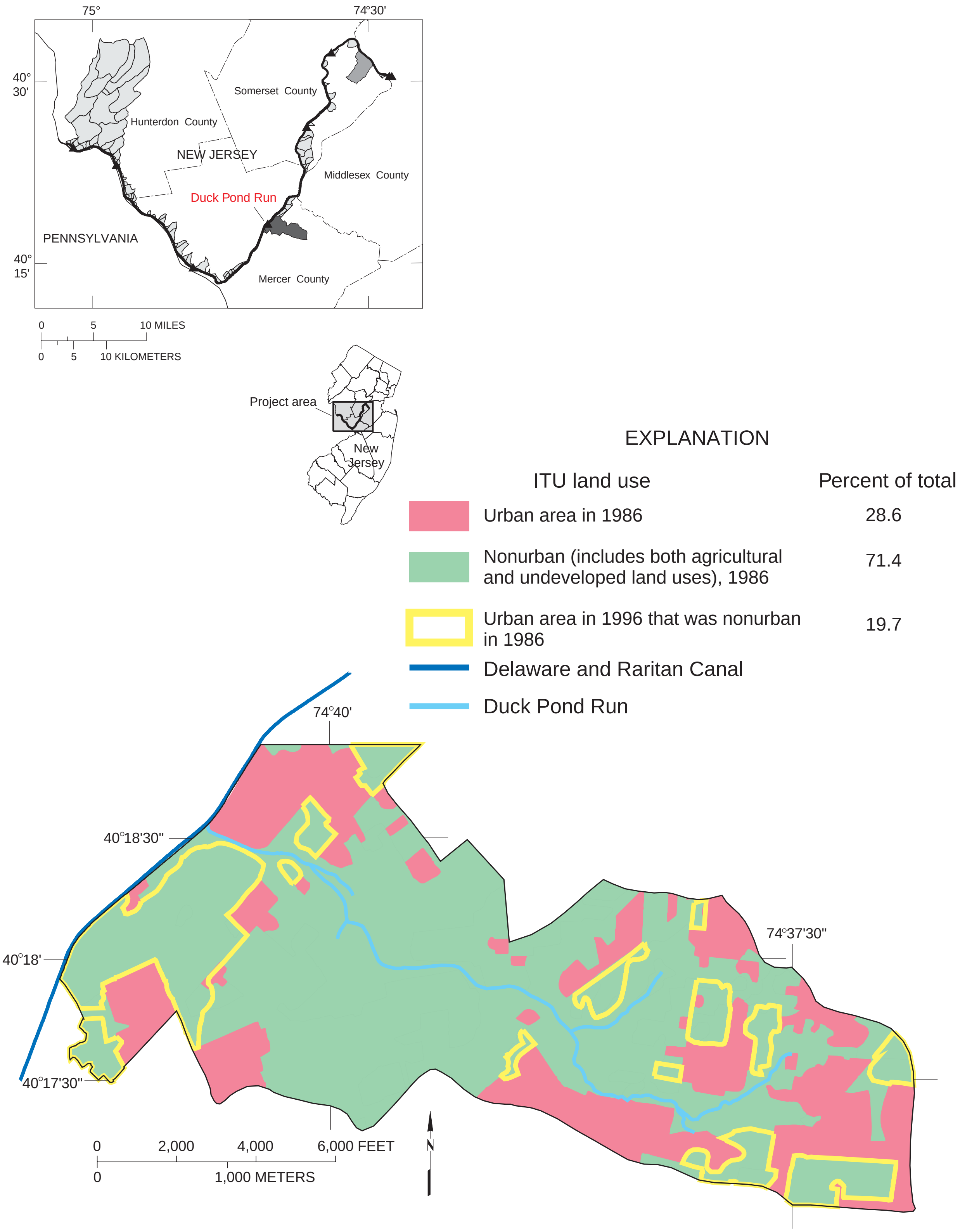
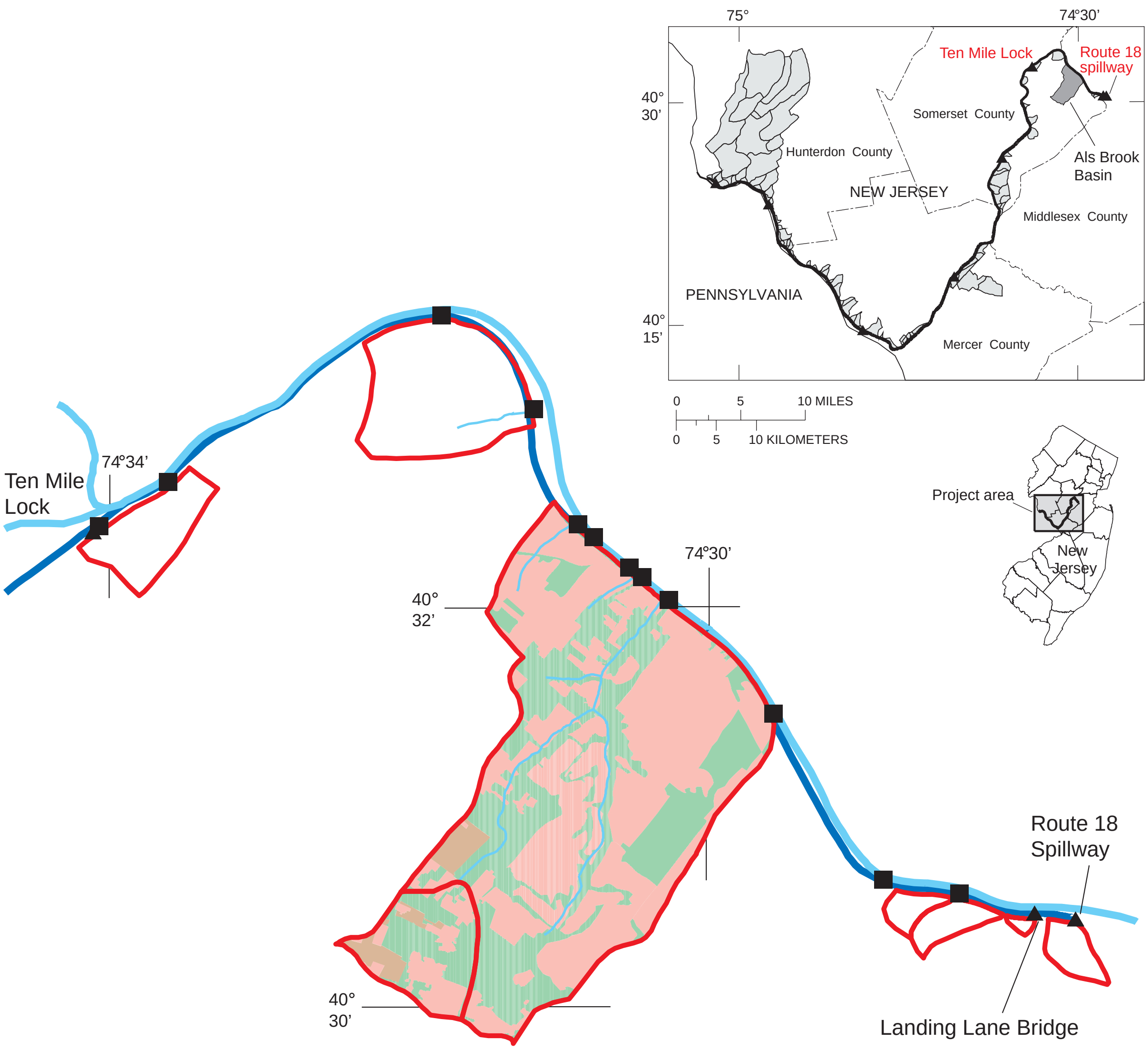


Figure 2. Land use in the Duck Pond Run drainage basin, New Jersey, in 1986 and 1996, based on Integrated terrain land use (ITU), as interpreted from U.S. Geological Survey 1996 digital infrared orthophoto.



EXPLANATION

Digital orthophoto quadrangle land use, Als Brook Basin, 1986

		Percent of total
🟥	Urban	48.1
🟫	Agricultural	3.9
🟩	Undeveloped	48

- Influent stream
- Delaware and Raritan Canal
- River
- Influent drainage basin

▲ Sampling location

■ Infalls, field verified

Figure 3. Land use within the Als Brook drainage basin and hydrologic infalls to the Delaware and Raritan Canal, Somerset County, New Jersey.

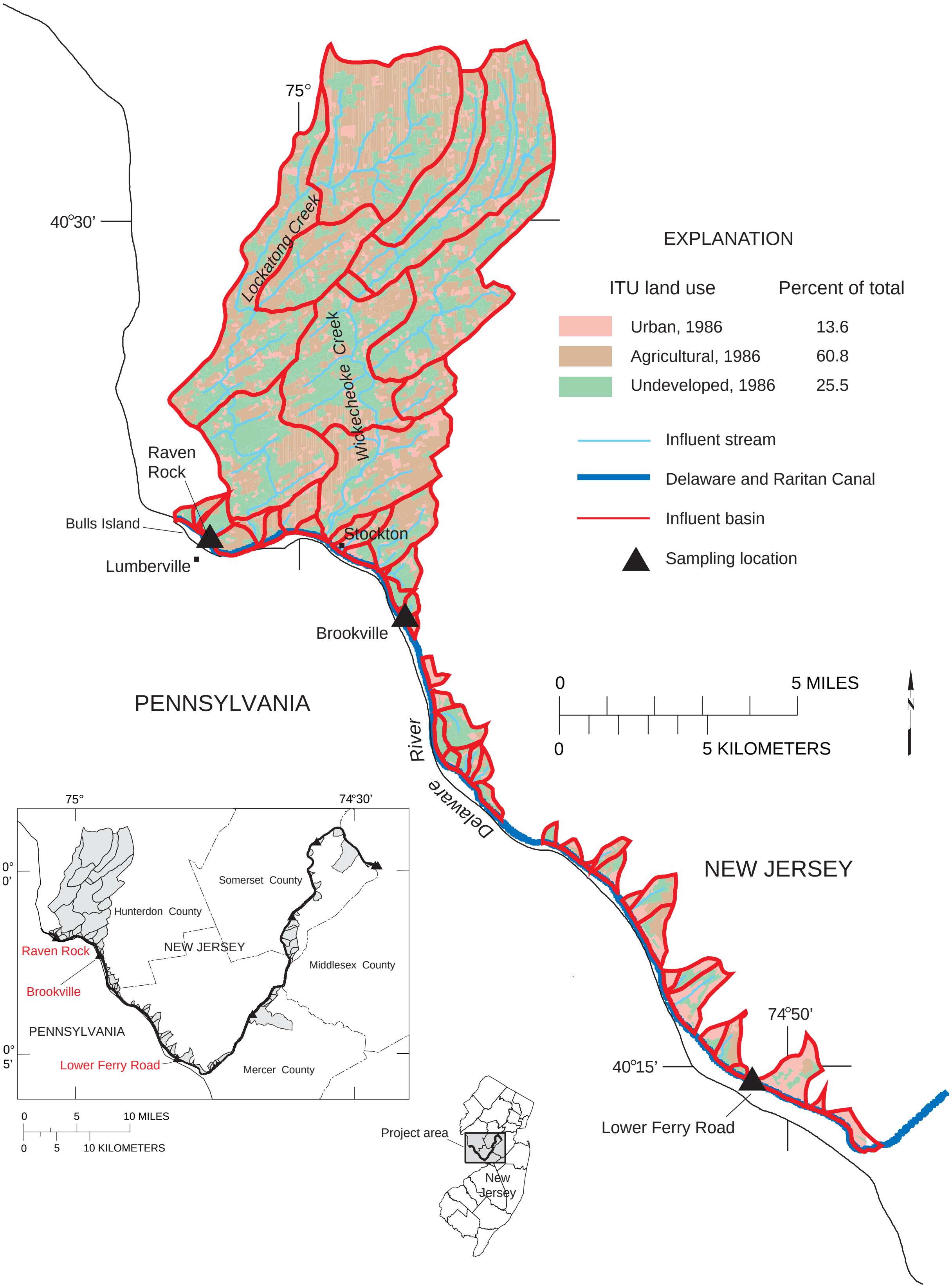


Figure 4. Drainage basins influent to the feeder section of the Delaware and Raritan Canal and 1986 integrated terrain land use (ITU), Hunterdon and Mercer Counties, New Jersey.

New Brunswick. Of the eight sites, six were equipped with continuous water-quality-monitoring equipment. Instantaneous water-quality samples also were collected at five of these sites. The other two sites were used to collect only instantaneous water-quality samples. One site was used only to continuously monitor water quality. Instantaneous samples were collected after more than a 0.5 inch of precipitation fell in the study area. Nonstorm samples were collected after a 10-day period with precipitation no greater than 0.5 inch falling in the study area. Water quality during storms and nonstorm conditions was compared to determine the changes caused by stormwater runoff that entered the canal.

Site Selection

The sites selected for the study are points along the canal that could be affected by runoff from influent basins upstream and the two points used to define the most upstream and downstream locations of the study area of the canal (fig. 1). The eight sites are described below in downstream order.

The Raven Rock site is in Hunterdon County (fig.1). It is 0.75 miles downstream from the Bulls Island inlet (fig. 4), which diverts water from the Delaware River into the canal. It is also the location of the feeder sluice gates that regulate the flow to the canal. The water quality at this site was considered to be an indicator of the quality of the water entering the canal from the Delaware River.

The Brookville site is also in Hunterdon County. It is 5.1 miles downstream from the feeder gates at Raven Rock at a bridge over the canal and is 1.8 miles south of Stockton (fig. 4). The spillway from the Wickecheoke Creek is located 2.3 miles upstream, and the Lockatong Creek spillway is located 3.9 miles upstream (fig.4). These are the two largest influent basins that drain into the canal. Their combined drainage area is 34,827 acres. A quarry, which is near the site, contributes stormwater runoff that enters the canal at a point just upstream from the site.

The Lower Ferry Road site is just upstream from Trenton City, Mercer County, at Lower Ferry Road at the bridge that crosses over the canal (fig. 4). It is 12.9 miles downstream from Brookville and 18 miles downstream from Raven Rock. Many spillways and culverts are located between the Brookville and Lower Ferry Road sites, approximately 10.9 miles downstream from the Lambertville feed gates. Land use in the influent basins between this site and the Raven Rock site is 13.6 percent urban, 60.8 percent agricultural, and 25.5 percent undeveloped (fig. 4).

The Port Mercer site is at Port Mercer in Mercer County at the Province Line (Quaker Bridge) Road bridge that crosses over the canal. It is 4.7 miles downstream from Trenton and 10.7 miles downstream from Lower Ferry Road. A small part of the canal runs through a culvert underneath U.S. Route 1, a major highway, for approximately 1.16 miles. This site is at the end of a reach that is surrounded by an urban area (Trenton) and at the beginning of a reach surrounded by land that was originally agricultural, but is rapidly becoming urban.

The Griggstown site is at the Griggstown causeway in Somerset County, where the causeway bridge crosses the canal. It is 11.3 miles downstream from Port Mercer (fig. 1). At this point, the canal extends in the northeastern direction parallel to the Millstone River. Some storm drains that carry water from a large quarry 3.7 miles upstream from this site empty directly into the canal. The land use in the influent basins downstream from the site and upstream from the next monitoring site is about 16 percent urban and 61 percent agricultural, as determined from the 1986 ITU land-use coverage.

The Ten Mile Lock site is in Somerset County. It is 8.9 miles downstream from Griggstown and 2 miles downstream from Millstone Borough across the canal and the Millstone River from Manville. This site is 0.3 miles upstream from the intake for one of the water purveyors. Land in the influent drainage basins downstream from this site is heavily urbanized.

The Landing Lane Bridge site is in New Brunswick, Middlesex County, approximately 7.5 miles downstream from Ten Mile Lock and 6.4 miles downstream from the town of South Bound Brook. The bridge at this site is the last one before the canal ends at the Route 18 Spillway, approximately 0.22 miles downstream. The drainage basin at the town of South Bound Brook (5.2 mi upstream from Landing Lane Bridge) consists primarily of road storm drains that discharge into the canal. The canal makes another sharp turn to the southeast and parallels the Raritan River. Als Brook Basin (fig.1) drains 2,411 acres and is the largest influent drainage basin located along the reach between Ten Mile Lock and Landing Lane Bridge.

The Route 18 Spillway site is at New Brunswick, Middlesex County. This continuous water-quality monitoring site is on the bank opposite the Route 18 Spillway; at this point on the left bank looking downstream, the canal empties into the Raritan River. The intakes of several water purveyors are on the canal just downstream from this site. One small influent basin with an area of 53 acres drains into the canal between Landing Lane Bridge and the Route 18 Spillway.

Continuous-Monitoring Sites

All sites except Brookville and Landing Lane Bridge were used for continuous monitoring. Brookville was not used because of the proximity of Raven Rock. The Landing Lane Bridge site was not used because of the difficulty of mounting the continuous water-quality monitor on the steel bridge. The continuous water-quality-monitoring sensors at all six sites were placed approximately 2 feet below the average surface elevation of the canal water. The depth of the sensors is about one-third of the average depth of water (approximately 6 feet) in the canal. The actual location of the continuous water-quality monitor differed in some cases from that of the instantaneous water-quality sampling site because the monitors measure water quality at a point, whereas the instantaneous water samples are depth- and width-integrated. For example, at Raven Rock the monitor was mounted on the left retaining wall of the canal 200 feet downstream from the feed gates so that the gates would protect the monitor from large debris such as tree limbs. At the Lower Ferry Road, Port Mercer, and Griggstown sites, the monitors were positioned near the midpoint of the canal on the downstream side of each bridge to protect the monitors from large debris. At the Ten Mile Lock site, the monitor was attached to the right retaining wall, 20 feet upstream from the weir. At the Route 18 Spillway site, the monitor is on the right retaining wall just upstream from the end of the canal, near the raw water intakes for two water-treatment plants.

Instantaneous Water-Quality Sample-Collection Sites

The water column in the canal was sampled at seven of the eight study sites. The Route 18 Spillway site could not be used for instantaneous water-quality sampling because flow was not uniform at this site. Also, water was almost always flowing at the Route 18 Spillway on the left bank, which promoted algal growth on the spillway during the study. Therefore, a good cross-section sample of water flowing over the Route 18 Spillway could not be obtained safely because algal growth made the surface of the spillway slippery.

Samples were collected at the centroid of flow upstream from the weir at Ten Mile Lock to avoid collecting a nonrepresentative, aerated sample. At Raven Rock, samples were collected from the upstream side of the bridge, upstream from the feed gates, also to avoid collecting a nonrepresentative, aerated sample. At both of these sampling sites, the canal narrows before water flows through gates or over a weir, which creates excellent stream mixing. At four of the five remaining sites, the samples were collected on the upstream side of the bridge; at the Port Mercer site, the samples were collected on the downstream side of the bridge because no walkway is present on the upstream side.

Water-Quality Sampling

A total of 63 samples were collected at all sites except the Route 18 Spillway during nine sampling rounds--five storms and four nonstorm events. The instantaneous water samples were analyzed for nitrogen species (nitrite, nitrite plus nitrate, ammonia, and ammonia plus organic nitrogen in filtered samples, and ammonia plus organic nitrogen in whole water samples), phosphorous in filtered and unfiltered samples, total suspended solids, suspended organic carbon, dissolved organic carbon, UV 254nm, and 29 VOCs; specific conductance and turbidity were measured in the field. Samples analyzed for VOCs were collected during four storms and four nonstorm events. Three additional sampling rounds were conducted during nonstorm conditions. These samples were analyzed for total suspended solids. Specific conductance, temperature, and turbidity were measured in the field when the three additional nonstorm samples were collected.

Storm condition samples were collected whenever there was sufficient precipitation to cause appreciable runoff into the canal. This criterion was met when more than 0.5 in. of precipitation fell in a 24-hour period over the entire study area. Storm sampling commenced toward the end of the precipitation, and all samples were collected at seven locations in less than 8 hours. The five storm-sampling rounds were conducted on September 8 and October 8, 1998, and on February 2, May 19, and May 25, 1999. Nonstorm sampling rounds were conducted on March 30, June 29, November 12, and December 21, 1998.

All sampling rounds, whether storm or nonstorm, were conducted at least 10 days apart to make each round independent of the others. The 10-day waiting period was not observed for the May 25, 1999, storm-sampling round because of a lack of precipitation during the study time period and the precipitation that occurred on May 19, 1999, was slightly greater than 0.5 inches. The approximate time needed for water to travel the length of the canal is 8 to 10 days.

Water-Quality Monitoring

The water-quality constituents selected for analysis in this study are those that are most likely to be affected by stormwater runoff and that could also affect drinking-water treatment. Maximum Contaminant Levels (MCLs) in drinking water have been issued by the State of New Jersey for nitrate, nitrite, and turbidity. MCLs also have been issued by the State for many of the VOCs analyzed for in canal water during this study (Shelton and Lance, 1999).

Specific conductance also is strongly influenced by precipitation and runoff from snowmelt and road deicing (Hem, 1992). Ammonia, organic nitrogen, suspended organic carbon, and total suspended solids affect drinking-water treatment. Dissolved organic carbon, UV254, and methyl *tert*-butyl ether (MTBE) (one of the 29 VOCs analyzed for) affect the color, taste, and odor of drinking water, which are aesthetic concerns of drinking-water treatment regulated by the State of New Jersey Secondary Maximum Contaminant Levels (Shelton and Lance, 1999). Phosphorous, both dissolved and whole water, is an essential nutrient for plants (Hem, 1992) and can enter the canal from the Delaware River and from precipitation runoff from influent basins. Excessive growth of algae can affect drinking-water taste and odor. Also, excessive growth of rooted plants can reduce the flow of water in the canal (Rutgers University, 1981).

Continuous On-Site Measurements

Turbidity, specific conductance, and temperature were measured by using a multi-parameter water-quality monitor (Yellow Springs Incorporated (YSI) 6000 UPG) with an internal battery source and data logging capability. Each water-quality monitor was programmed to record at 30-minute intervals for the first 3 months of the study period (mid-January 1998 through mid-April 1998), then at 15-minute intervals for the remainder of the study period. The continuous water-quality data were plotted, reviewed, and edited to correct erroneous values. After this review, the data were entered into the USGS

Automated Data Processing System (ADAPS) database, which is part of the USGS National Water Information System (NWIS).

Turbidity.--Turbidity is the measurement of suspended solids in a liquid. The unit of measurement is the nephelometric turbidity unit (NTU), which is determined by focusing a beam of light on the sample water, and then measuring the light that is scattered off the particles. The light source recommended for use by the International Standards Organization is a light emitting diode with a wavelength between 830 and 890 nanometers. The light is detected by a highly sensitive photodiode at a 90^o angle from the beam of light (Yellow Springs Incorporated, 1996).

The optical measurements are very susceptible to fouling. For this reason, the turbidity probe on the YSI 6000 UPG comes equipped with a mechanical wiper that rotates on the probe face. This discourages the build up of biological debris and the formation of bubbles from outgassing. The values are calculated from an average of eight readings taken at 4-second intervals (Yellow Springs Incorporated, 1996).

Specific Conductance.--Specific conductance is the ability of a substance to conduct an electrical current. It is the reciprocal of resistivity. The presence of charged ions allows a solution to conduct an electrical current. As the ion concentration increases, the conductance of the solution increases. For this reason conductance provides an indication of ionic strength (Hem, 1992).

The YSI 6000 UPG incorporates a cell with four pure nickel electrodes. Two of the electrodes are current driven, and two are used to measure the voltage drop. The voltage drop is then converted into a conductance value in millisiemens and multiplied by the cell constant to arrive at a value in microsiemens per centimeter (µS/cm) (Yellow Springs Incorporated, 1996).

Temperature.--The YSI 6000 UPG contains a thermistor of sintered metallic oxide which changes predictably in resistance with temperature variations. An algorithm is built into the YSI 6000 UPG software that converts the resistance to temperature in degrees Celsius, Kelvin, or Fahrenheit (Yellow Springs Incorporated, 1996).

Calibration Procedures

All continuous water-quality monitors were calibrated in the New Jersey District field laboratory a few hours prior to deployment in the field to ensure accurate measurements. Once the calibrated monitors were installed at a measurement site, the monitor readings were checked against calibrated portable field meter readings prior to unattended operation. Approximately every 2 weeks, the water-quality readings from the monitors were checked against portable field meter readings, then the monitors were replaced with newly calibrated monitors. This cycle was repeated for the duration of the project. If the difference between readings from the monitor and the field meter was not within acceptable limits, the difference was recorded and a correction or deletion was made to the continuous water-quality records after analysis of the data in the New Jersey District office.

Turbidity.--A two-point calibration, at 0 and 100 NTU, was performed just prior to deployment of the monitor. In most cases, this calibration range is sufficient because the majority of readings occur in this range and the calibration of the sensor is linear between 100 and 1000 NTU (Yellow Springs Incorporated, 1996). The standards were freshly prepared at the time of calibration. Filtered, de-ionized water was used for the 0 NTU standard, and the 4,000 NTU formazin was diluted to prepare the 100 NTU standard. Calibration was performed in the New Jersey District field laboratory, and not in the field, because turbidity is not temperature compensated and formazin turbidity standards change with temperature. The standards provided a means of determining whether adjustments were needed for the previously collected data as a result of calibration drift.

Specific Conductance.--The conductivity of solutions of ionic species is highly dependent on temperature. For this reason, the YSI 6000 UPG monitor uses temperature and raw conductivity values to generate a specific conductance value compensated to 25^{o} C (Yellow Springs Incorporated, 1996). A two-point calibration that bracketed the expected field values was performed in the New Jersey District field laboratory just prior to deployment of the monitor. The field laboratory provided a controlled environment for the monitor and the standards.

Temperature.--No calibration or maintenance of the temperature sensor is required (Yellow Springs Incorporated, 1996). Before initial deployment, a three-point thermistor check of the sensor was performed by using a National Institute for Science and Technology (NIST) traceable thermometer.

Instantaneous Water-Column Water-Quality Sampling

The four nonstorm sampling rounds were conducted by USGS personnel. The five storm sampling rounds were conducted by NJWSA. Employees of the NJWSA, who collected all storm samples, used the methods of collection and field measurements also used by the USGS. USGS personnel performed all sample processing. Both collection and processing were performed following the guidelines set forth in the USGS National Field Manual for the Collection of Water-Quality Data (Wilde and others, 1998). Analyses were performed at the USGS National Water Quality Laboratory (NWQL) in Lakewood, Colorado, with the exception of the analysis for UV254, which was performed at the USGS New Jersey District laboratory (NJWRDL). All water-quality data for the Delaware River at Lumberville, Pa., and at Trenton, N.J., were obtained as part of the USGS-New Jersey Department of Environmental Protection Cooperative Surface Water Quality Ambient Network and were used for comparisons with the water quality in the canal.

Sample collection.--Samples were collected using a weighted bottle sampler equipped with a 1-liter polyethylene bottle and suspended from a polyethylene rope. Samples were collected at equal increments across the canal using depth integration to produce a representative sample. At the Raven Rock and Ten Mile Lock sites, the samples were collected at the centroid of flow, upstream from either the sluice gates or the weir, respectively.

During nonstorm sampling, the sample water was collected at five increments across the canal, composited into a clean 10-liter churn splitter previously rinsed with canal water and taken back to the van for processing on site. During storms, the water was collected in field-rinsed, 1-liter polyethylene bottles and placed on ice to be processed the next day. The samples for organic carbon analysis were collected in baked, amber glass bottles at the centroid of flow about 1-foot below the water surface and placed on ice until processed. The samples for VOCs also were collected at the centroid of flow by using a vendor-certified precleaned disposable teflon bailer and immediately dispensed into baked, amber vials.The vials were examined to be certain that no air was present in the vials after filling; vials were then placed into an ice filled cooler.

Sample processing.--Samples were churned at a uniform rate of about 9 inches per second with care being taken not to break the surface of the water. The baffled piston of the churn was moved up and down a minimum of ten times to ensure proper mixing, and the sample was dispensed into polyethylene bottles that were pre-rinsed twice with de-ionized water (DI) and once with canal water prior to filling for analysis of unfiltered nutrient constituents. The unfiltered nutrient samples were preserved with sulfuric acid (H_2SO_4) to a pH of <2 and immediately chilled.

The sample water was then filtered through a 0.45-µm pore-size disposable Gelman filter pre-conditioned with 1 liter of DI water. The sample bottles also were rinsed twice with DI water and once with filtered canal water prior to filling. These samples were analyzed for dissolved (filtered) constituents. The filtered samples to be analyzed for nutrients were treated with sulfuric acid (H_2SO_4) to a pH of <2. The samples were then chilled.

The samples for analysis of organic carbon and UV254 were filtered in a stainless steel Gelman filter using a 0.45-µm pore-size silver filter. The sample water that passed through the silver filter was collected in baked glass amber bottles, then analyzed for dissolved organic carbon (DOC) and UV254. The suspended organic carbon (SOC) particles were retained on the silver filter, which was placed into a covered petri dish and chilled prior to analysis.

Samples collected during storms and nonstorm conditions were processed in the same manner; however, the storm samples were processed the next day at the USGS field laboratory. The processed samples were shipped overnight to the USGS NWQL. The analysis for UV254 was performed at the NJWRDL.

Laboratory and Field Analyses

Total suspended solids.--Total suspended solids are that part of total solids retained by a filter after drying. A well-mixed sample is filtered through a weighted standard glass-fiber filter, and the residue retained on the filter is dried to a constant weight in an oven at 103 to 105 ^{o}Celsius. The increase in weight of the filter represents the total suspended solids (Eaton and others, 1998).

Whole water and filtered nitrogen species.--The nitrogen species in the analyses included dissolved nitrite (NO_2) as N, dissolved nitrite plus nitrate ($NO_2 + NO_3$) as N, dissolved ammonia (NH_3) as N, and total and dissolved ammonia nitrogen plus organic nitrogen, also called Kjeldahl nitrogen. The whole water represents the total nitrogen species, and the dissolved species are that which pass through a 0.45-µm pore-diameter filter.

Whole water and filtered phosphorous.--Phosphorous is a rather common element in igneous rock and is fairly abundant in sediments. It is a component of sewage and is always present in animal metabolic waste (Hem, 1992). It is present in natural waters and in wastewaters almost solely as phosphate (Eaton and others, 1998). The whole-water sample represents the total phosphorous, and the dissolved phosphorous is that which passes through a 0.45 µm-pore-diameter filter.

Dissolved and suspended organic carbon.--Organic carbon is composed of a variety of organic compounds in various oxidation states (Eaton and others, 1998). Dissolved organic carbon (DOC) is the fraction of total non-volatile organic carbon (TOC) that passes through a 0.45-µm-pore diameter silver filter; suspended organic carbon (SOC) is the fraction of TOC that is retained by the filter.

The method used to measure the DOC is the ultraviolet-promoted persulfate oxidation method. The principle behind this method is that organic carbon is oxidized to carbon dioxide (CO_2) by persulfate in the presence of ultraviolet light. The CO_2 is purged from the sample, dried, and transferred with a carrier gas to a nondispersive infrared spectrometer for measurement (Eaton and others, 1998).

The SOC is detected by the wet-oxidation method. In this method, the sample is acidified, purged to remove inorganic carbon, and oxidized with persulfate in an autoclave to temperatures from 116 to 130 ^{o}C. The resultant CO_2 is then measured by a nondispersive infrared spectrometer (Burkhardt and others, 1997).

Specific conductance.--Specific conductance is the ability of an aqueous solution to conduct an electric current (conductance) of a body of unit length and unit cross-section at a specified temperature (Hem, 1992). The specific conductance measurements were performed both at the USGS NWQL and in the field. The standard temperature for laboratory measurement is 25 ^{o}C. All field measurements were made by using temperature compensated meters.

Ultraviolet absorbance at 254 nanometers.--Some dissolved organic compounds commonly found in water and wastewater strongly absorb ultraviolet (UV) radiation. Ultraviolet radiation is light that has a wavelength of between 100 and 400 nanometers. UV-absorbing organic constituents in a sample absorb UV light in proportion to their concentration. UV absorption is measured at 253.7 nanometers (UV254). Although UV absorption can be used to detect certain individual organic contaminants, UV254 is intended to be used to provide an indication of the aggregate concentration of UV-absorbing organic constituents in filtered sample water (Eaton and others, 1998).

Volatile organic compounds.--The method of analysis used for VOCs is purge and trap gas chromatography/mass spectrometry (GC/MS). This technique involves the transfer of the VOCs from an aqueous phase to a gaseous phase by bubbling an inert gas (such as helium) through a water sample contained in a purging chamber. The vapor is swept through a trap that adsorbs the target compounds or constituents. The trap is then heated and backflushed with the same inert gas to desorb the compounds onto a gas chromatographic column. The gas chromatograph is temperature-programmed to separate the compounds, which are then detected by a mass spectrometer (Connor and others, 1998). During this study, 29 target compounds or constituents were analyzed for in canal water. The analysis used for this project has 29 target compounds for which concentrations were reported and stored in NWIS.

Turbidity.--Turbidity measurements were performed in the field. Turbidity in water is caused by suspended and colloidal matter such as clay, silt, finely divided organic and inorganic matter, and plankton and other microscopic organisms. Turbidity is an expression of the optical property that causes light to be scattered and absorbed rather than transmitted with no change in direction or flux level through the sample. The nephelometric method was used during his study; thus the unit of measurement is the nephelometric turbidity unit (NTU). This method consists of using a beam of light to illuminate the sample and a photoelectric detector to indicate the intensity of light scattered at 90^{o} to the path of the incident light (Eaton and others, 1998).

Data Analysis

Continuous Water-Quality Data

All continuously monitored water-quality data collected during this study that met the data-quality objectives of the study are presented in Deluca and others (2000).

Data Preparation.--Continuously monitored turbidity and specific conductance data for the study period (mid-January 1998 to mid-April 1999) were retrieved from the USGS NWIS water-quality database (QWDATA). Initially, the data were electronically recorded at 30-minute intervals. After 3 months, the data were reviewed, and the data-recording interval was reduced to 15 minutes because of rapid changes in turbidity during storms. To make the data for the project compatible for the entire study period, every second value was eliminated from the 15-minute interval data for each site so that the data set would consist of values recorded at 30-minute intervals. Then the retained values were merged with the 30-minute interval data recorded during the first 3 months of the study. The data for all six continuous monitoring sites were then merged into one file to facilitate the analysis for the five stream reaches.

The data had two limitations. First, the continuous water-quality monitoring instruments were subject to failure from time to time, resulting in periods of lost observations throughout the period of this study. Second, a drought emergency was declared by the Delaware River Basin Commission from December 14, 1998, to February 2, 1999 (William E. Harkness, U.S. Geological Survey, written commun., 1998 and 1999), resulting in mandated flow reductions in two steps. Mandated flow was 85 million gallons per day beginning on December 14, 1998, and 70 million gallons per day beginning on December 23, 1998.

Normal flow resumed on February 2, 1999. The reductions in flow during the drought emergency increased the time of travel.

The first data limitation resulted in lost records of net change in a reach defined by upstream and downstream continuous monitoring sites because of instrument failure, which was random and rarely occurred for the same parcel of water passing each site. The upstream data were lagged in time so that the same parcel of water was measured by both the upstream and downstream water-quality monitors. The second limitation required the computation of time-lag values for the periods of unreduced flow, the period after the first flow reduction, and the period after the second flow reduction.

Analysis of the Change in Water Quality in a Reach.--The objective of the analysis of the continuously monitored water-quality data was to determine the mean and median net change in turbidity and specific conductance. A peak in the outflow at the downstream station of a reach was matched with the corresponding peak at the upstream station of a reach to determine the mean travel time in the reach; this travel time was used as the lag time to calculate the difference or net change in turbidity and specific conductance. This process was repeated for each reach for the periods of normal flow and for the period following the second flow reduction (70 percent of normal flow). This approach to interpreting continuously monitored data is possible because the flow rate in the canal is actively controlled to maintain a fairly constant rate within ± 10 percent over long periods of time (months), and relatively few data gaps break the continuous data record. During the drought emergency, the lag time for the short period of the first flow reduction was estimated by averaging the lag time of the normal flow and the lag time of the second flow reduction for each reach.

The mean and median[1] were computed for the series of values of net change for each reach. An estimate of the systematic value is the mean or median (Helsel and Hirsch, 1992). If the estimate of the time of travel is reasonably accurate, the systematic value of the net change in turbidity or specific conductance in a reach represents water quality in the canal altered by water from influent drainage basins, and the biological, chemical, and physical processes that occurred in a reach over long periods (months). The mean of net changes is more likely to be affected by extremely large values, either positive or negative, than is the median.

Instantaneous Water-Quality Data

All instantaneous water-quality data were reviewed for sample consistency among related constituents. For example, the total phosphorous concentration should not be less than the filtered phosphorous concentration within a tolerance based on the laboratory analytical precision. All instantaneous water-quality data that passed this data review step were published in Deluca and others (2000) and were included in the statistical evaluation. The data are presented in box plots (Helsel and Hirsch, 1992) as a function of sampling location, water-quality constituent, and storm or nonstorm sample.

The hypothesis tested is that the quality of water in the canal was not affected by the sampling location along the length of the canal, or by storms or nonstorm events. All statistical hypotheses were tested by using nonparametric statistics at a significance level (α) of 0.05. Two types of nonparametric statistical tests were used, both using rank-transformed data--a two-way analysis of variance (ANOVA) (Helsel and Hirsch, 1992) and the Kruskal-Wallis nonparametric test of medians for three or more independent samples (Daniel, 1990). The Tukey multiple comparison test was used to determine whether the median concentration of a constituent at a particular sampling site and during either a storm or nonstorm event was significantly different from the median for another site, storm or nonstorm event when using either the ANOVA or the Kruskal-Wallis tests. First, the hypothesis was tested on the median value for a water-quality constituent by using a two-way ANOVA. The

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[1] The median is the value of the fiftieth percentile when the data are arranged in ascending magnitude.

relatively small number of data values from a sampling site for storm or nonstorm event, a maximum of five values, meant that it was likely that for either sampling site or event type the null hypothesis that the medians are statistically the same would be accepted. If the null hypothesis was accepted, the nonsignificant effect was aggregated, and a Kruskal-Wallis nonparametric test was performed, followed by another Tukey multiple-comparison test. Only data that are statistically different are presented in box plots in this report.

Relational Database

For this study, water-quality data were reorganized and formatted into a relational database. Procedures were developed to export data from the NWIS into a fully normalized relational database (hereafter called CanalDB). This section describes the database structure and briefly summarizes the kinds of data it contains.

The water-quality database was structured around a data model that reflects the associations and relations among the various pieces of information that need to be stored and retrieved. The data model was then used to generate the physical database. The data model was designed using the CASE software package, ERwin (version 3.5.2, Platinum Technologies Inc.). Once the model was completed, ERwin was used to generate the physical database in Microsoft Access 97 format.

The CanalDB data model is described in appendix A. All table definitions, and field properties and definitions of the CanalDB, are listed in a data dictionary, which is the primary reference for tables and fields. An entity-relation diagram, which shows how data elements are linked, also is presented in Appendix A (fig. A1). Together, the model diagram and the data dictionary serve as the basic documentation for CanalDB.

Geographical Information System

A geographic information system (GIS) was used to examine the relations between water quality in the canal and drainage basins influent to the Delaware and Raritan Canal. Ellis and Price (1995) delineate drainage basins in New Jersey and identify those basins that are influent to the canal. Their information was augmented with information provided by Camp, Dresser & McKee (1986) and Ebasco (1988) for the feeder section of the canal. Site visits were made with NJWSA personnel to the main canal to verify that all the influent basins for that part of the canal were included in the GIS. The land use within the influent basins also was incorporated into the GIS. New Jersey Department of Environmental Protection (1996) integrated terrain unit (ITU) 1986 land use was used. Additionally, land use was directly interpreted from USGS digital infrared orthophoto quarter quads (DOQs) (U.S. Geological Survey, 2000) for the Als Brook and Duck Pond Run influent basins. For Duck Pond Run Basin, the DOQ source image dates were 1995 (Princeton-southwest and Hightstown-northwest) and 1997 (Princeton-northeast). For Als Brook basin the DOQ source image date was 1995 (Bound Brook-southeast and Plainfield-southwest).

WATER QUALITY OF THE DELAWARE AND RARITAN CANAL

The determination of which reaches of the canal were affected by stormwater runoff is based primarily on the analysis of continuous water-quality monitoring data and field trip observations because the results of the statistical tests were not significant at $\alpha \leq 0.05$.

Samples Collected During Storm and Nonstorm Events

Ammonia and nitrite concentrations in filtered samples from the canal were not compared statistically by using the Kruskal-Wallis nonparametric test for ranked data for the effect of location or storms because the concentrations were censored at the USGS

NWQL method reporting levels of 0.02 and 0.01 mg/L, respectively, for 25 of 62 and 20 of 62 sample analyses. The range of concentrations and median values of nitrite and ammonia for all the sampling sites on the canal during storm and nonstorm events are shown in table 1.

The hypothesis that the quality of water in the canal was not affected by sampling location, or by storms or nonstorm events, was tested for all constituents except ammonia and nitrite by using rank-transformed data in a two-way ANOVA. The two explanatory variables (treatments) were type of sampling event and sampling location. No statistically significant difference was indicated for the median of any constituent in a two-way ANOVA. A relatively small number of replicates in each cell of the ANOVA, a maximum of five values, resulted in a statistically significant difference for only one of the explanatory variables because of the relatively large range in concentrations. Therefore, the values of the nonsignificant explanatory variable with the largest significance level were aggregated, and the Kruskal-Wallis test (equivalent to a one-way ANOVA) was performed for each constituent except ammonia and nitrite.

Suspended organic carbon (SOC) was the only constituent for which the median concentration at each sampling site differed significantly ($\alpha \leq 0.05$) from that at the other six sites (fig.5). The median concentrations of SOC at the three sampling locations on the feeder part of the canal (Raven Rock, Brookville, and Lower Ferry Road) were significantly greater than that at Ten Mile Lock, which is on the main part of the canal. The median concentrations of SOC in samples collected at Port Mercer, Griggstown, and Landing Lane Bridge were not significantly different ($a > 0.05$) from those at the three sites on the feeder part of the canal or at Ten Mile Lock.

The interquartile range (the value at the 75th percentile less the value at the 25th percentile, shown as the upper and lower ends of the box in the box plot) of SOC for samples collected at the three sites on the feeder part of the canal is larger than the interquartile range for samples from the other sites on the main part of the canal, except for Landing Lane Bridge (fig. 5). The lowest average velocity, 0.22 ft/s, of the six reaches defined by continuous water-quality monitor sites was measured between Ten Mile Lock and the Route 18 Spillway. Therefore, the large

Table 1. Maximum, median, and minimum concentrations of nitrite and ammonia in storm and nonstorm samples from all sampling sites on the Delaware and Raritan Canal, N.J.

Constituent	Data summary descriptor	Concentration during event (mg/L)	
		Storm	Nonstorm
Nitrite as N	Maximum	0.028	0.023
	Median	.011	.0135
	Minimum	[1]<.01	[1]<.01
Ammonia as N	Maximum	.16	.093
	Median	.0375	.02
	Minimum	[1]<.02	[1]<.02

[1] Laboratory reporting level

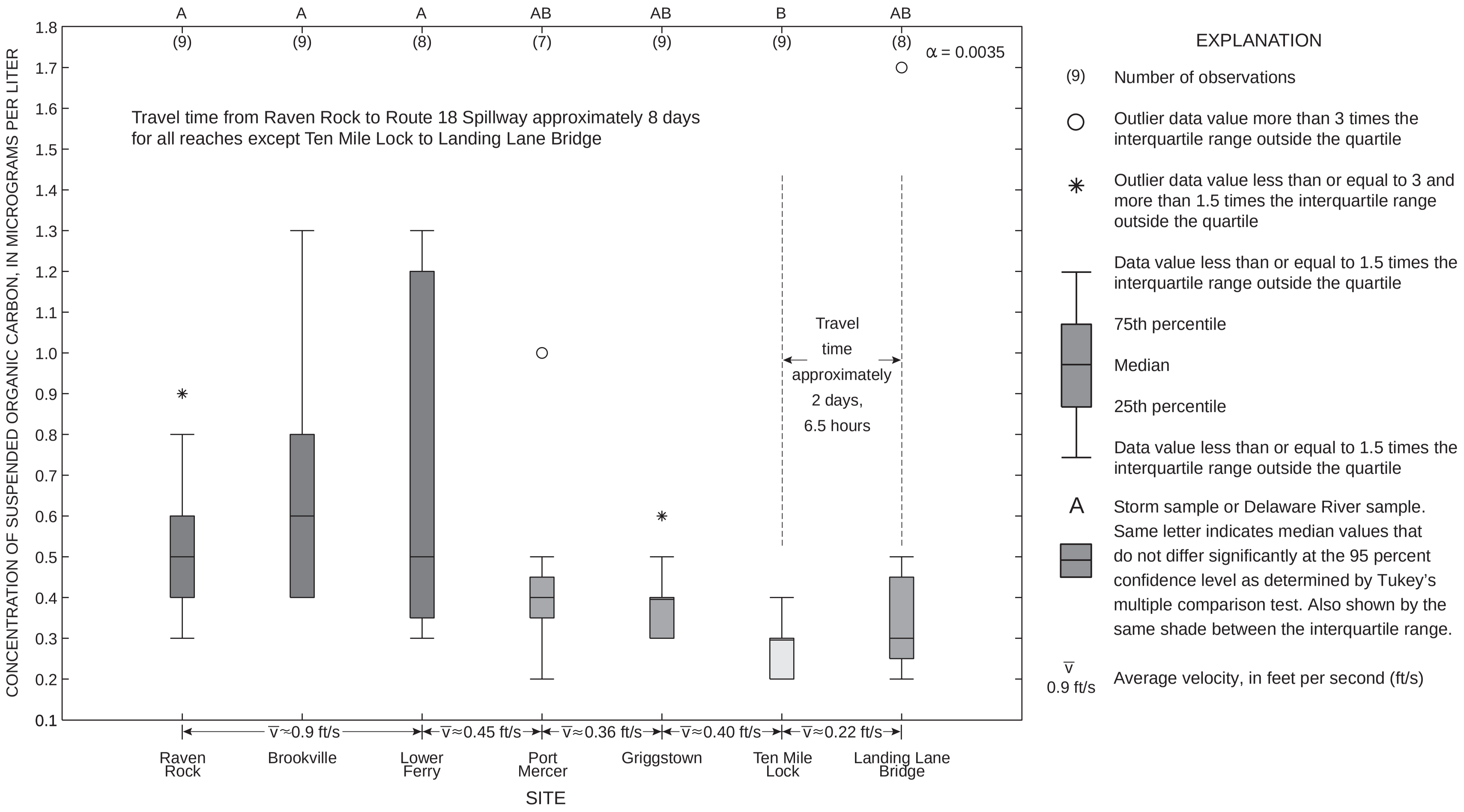

Figure 5. Distributions of concentrations of suspended organic carbon in samples collected during storms and nonstorm conditions at sites on the Delaware and Raritan Canal, N.J., 1998-99.

interquartile range for SOC in samples collected at Landing Lane Bridge would not be caused by inflows to the canal upstream from Ten Mile Lock because the particles that are larger than clay particles and that have a density greater than that of water would tend to settle and not be transported to Landing Lane Bridge in the approximately 2.27 days needed for canal water to go from Ten Mile Lock to Landing Lane Bridge, which is approximately 0.22 miles upstream from the Route 18 Spillway.

When compared statistically by using the Kruskal-Wallis test (Daniel, 1990), stormwater that entered the canal significantly ($\alpha < 0.05$) changed the median value of ammonia plus organic nitrogen (fig. 6), organic carbon (fig. 7), and UV254 (fig. 8; table 2) in filtered water samples collected during storms from that collected during nonstorm sampling. Median concentrations of nitrite plus nitrate (fig.9) and phosphorus (fig. 10; table 2) in filtered samples collected during storms were not significantly different ($\alpha > 0.05$) from those in filtered samples collected during nonstorm conditions.

The following water-quality constituents analyzed for in whole-water samples collected from the canal during storms had medians that were significantly larger ($a \leq 0.05$) than the medians of nonstorm samples: phosphorus (fig. 11), turbidity (fig.12), ammonia plus organic nitrogen (fig. 13) (table 2). The following constituents analyzed for in whole water or unfiltered samples collected during storms did not have medians that were significantly larger ($a > 0.05$) than the medians for samples collected during nonstorm events: specific conductance (fig. 14), suspended organic carbon (fig. 15), MTBE (fig. 16), and total suspended solids (figure 17; table 2).

Storms that produced runoff to the canal were shown to significantly affect the median concentrations of 6 of the 12 water-quality constituents that were statistically evaluated (table 2). Median concentrations of total and dissolved ammonia plus organic nitrogen increased during storms. Because concentrations of ammonia are relatively small, ammonia plus organic nitrogen is important to the quality of stormwater that enters the canal. The median concentration of total phosphorous increased during storms, and the median concentration of dissolved phosphorous did not (dissolved phosphorous concentrations were small). Thus, particulate phosphorous is an important factor in the quality of stormwater that enters the canal. The median concentration of total suspended solids did not increase during storms; however, the median concentration of turbidity did increase during storms. This seeming inconsistency in the results was probably caused by the poorer precision in measuring total suspended solids than in measuring turbidity. Total suspended solids are reported to one significant figure, and turbidity is reported to two significant figures.

A comparison was made of aggregated water-quality data from all sampling sites on the canal and data from the Delaware River near the intake of the canal, by constituent. The sampling site on the Delaware River at Lumberville, Pa., which is 0.7 miles downstream from the intake, is the site with water-quality data that is closest to the intake. Water-quality data for this site are available for all constituents studied, except for VOCs and field measured tubidity. The sampling site on the Delaware River, nearest the intake, with data on VOCs is the Delaware River at Trenton, N.J., which is approximately 20 miles downstream from the intake. Field measured turbidity data for the Delaware River were not available for comparison with the turbidity data for the canal.

Median values of all constituents except ammonia, nitrite, and dissolved phosphorous in nonstorm samples from the canal were not significantly different ($\alpha > 0.05$) from that in samples collected from the Delaware River at Lumberville, Pa., during a 5-year period (water years 1995 through 1999) during storms and nonstorm events. Storms with precipitation of more than 0.5 inches in one day are relatively rare and occurred at Trenton, N.J., for about 7 percent of the storms during the period of record for this rain gage, 1913-81 (R.D. Schopp, U.S. Geological Survey, written commun., 1999). Concentrations of ammonia, nitrite, and dissolved phosphorous in filtered water from

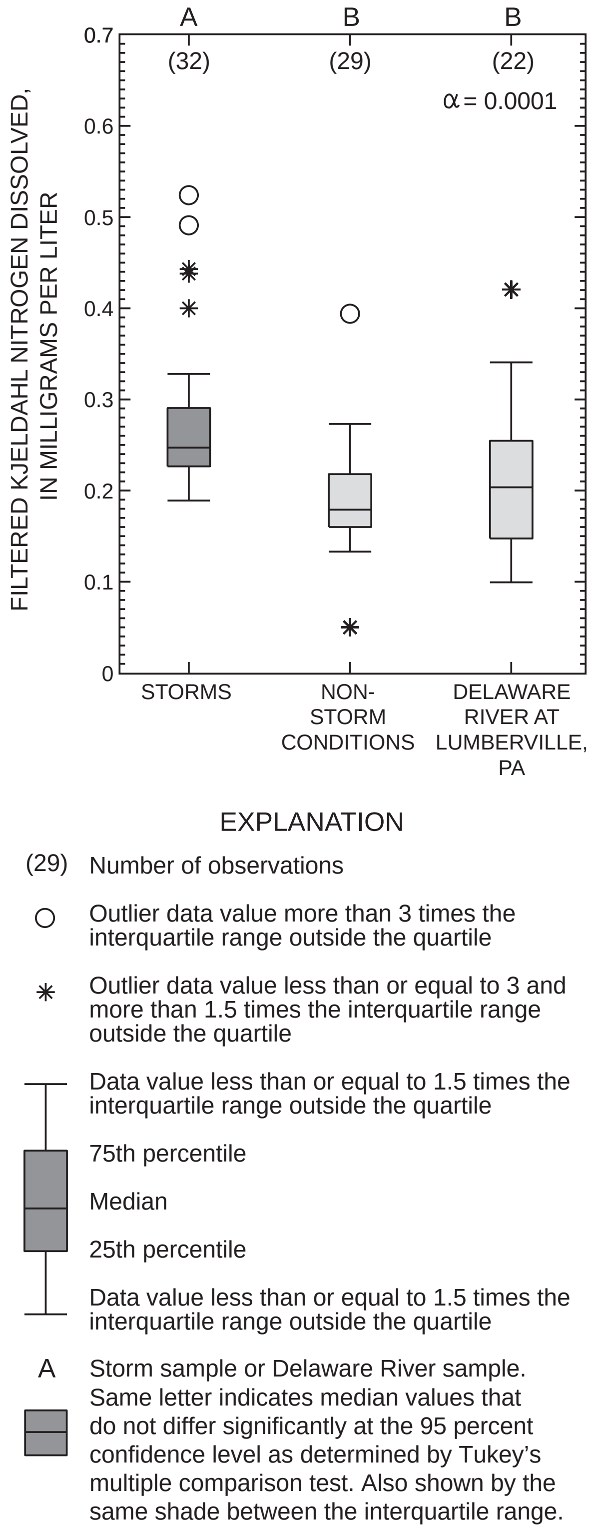

Figure 6. Distribution of concentrations of ammonia plus organic nitrogen in filtered samples collected during storms and nonstorm conditions from the Delaware and Raritan Canal, N.J., and the Delaware River at Lumberville, Pa.

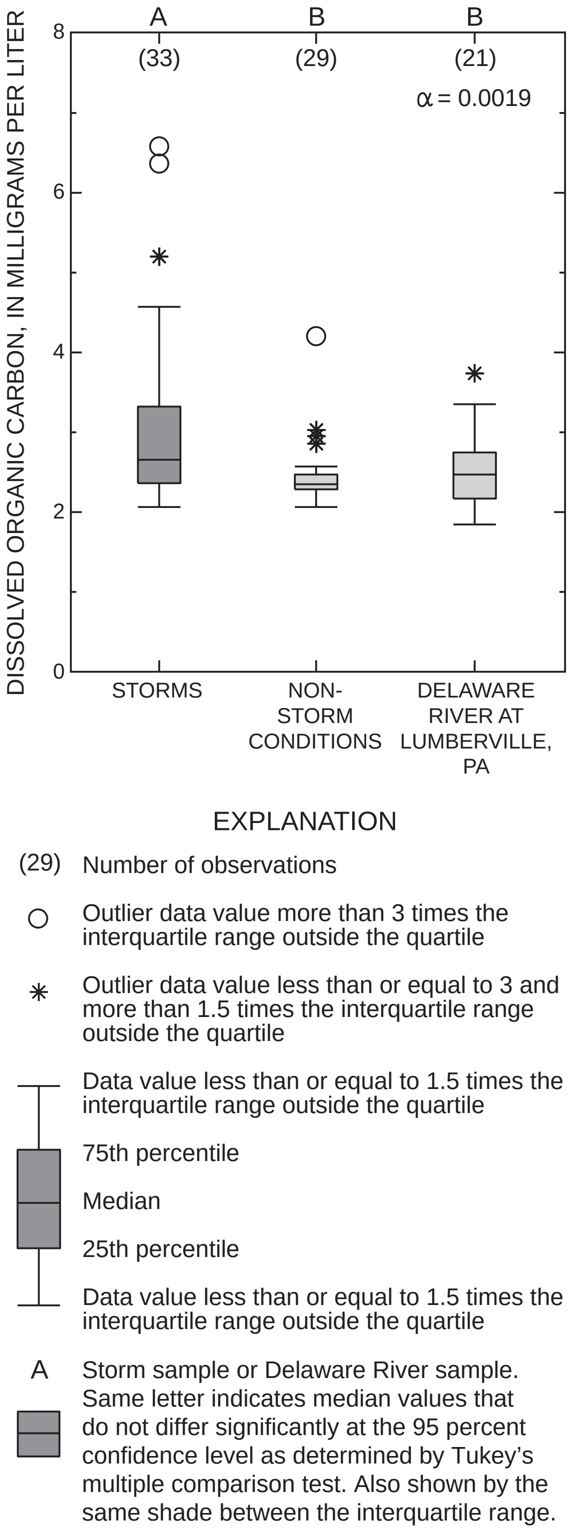

Figure 7. Distribution of concentrations of dissolved organic carbon in samples collected during storms and nonstorm conditions from the Delaware and Raritan Canal, N.J., and the Delaware River at Lumberville, Pa.

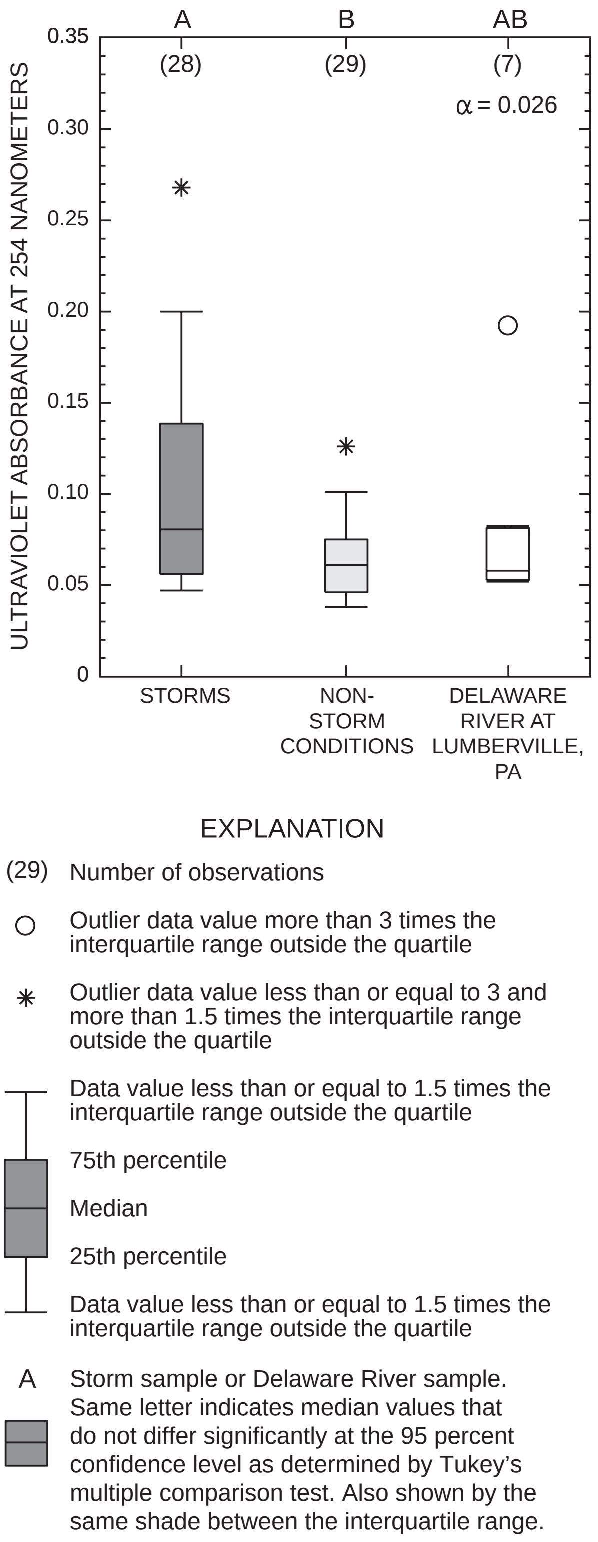

Figure 8. Distribution of ultraviolet absorbance at 254 nanometers in filtered samples collected during storms and nonstorm conditions from the Delaware and Raritan Canal, N.J., and the Delaware River at Lumberville, Pa.

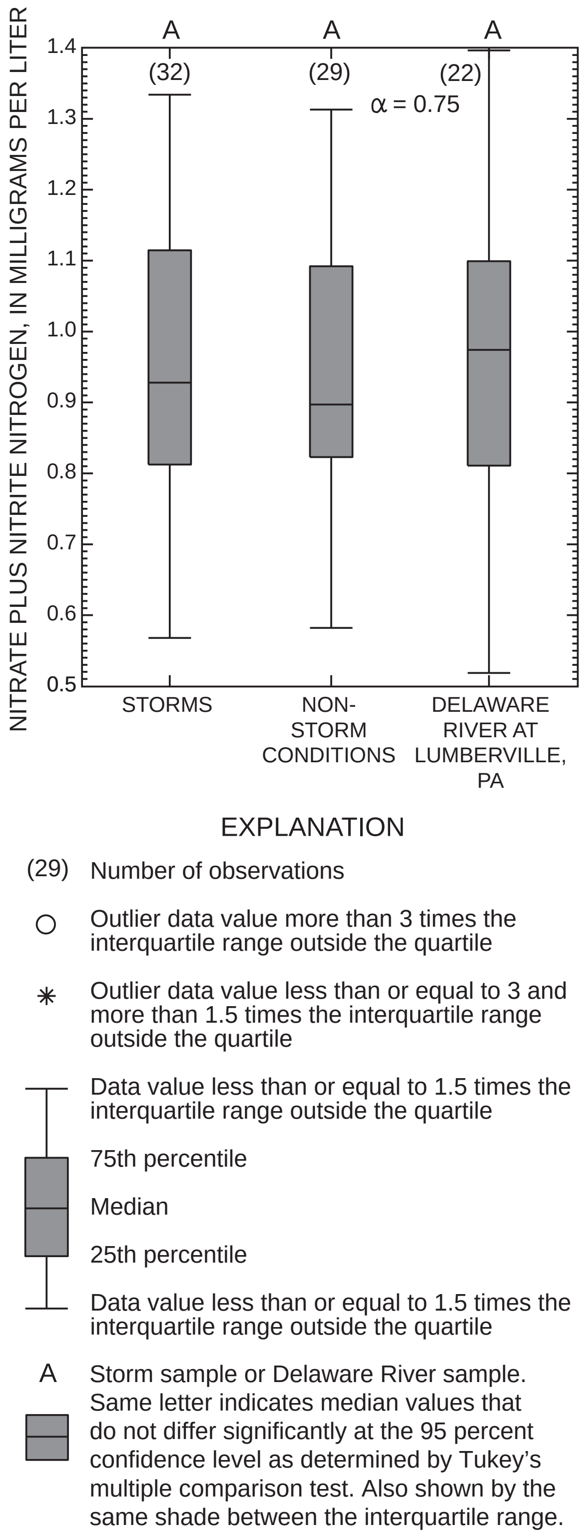

Figure 9. Distribution of concentrations of nitrate plus nitrite nitrogen in filtered samples collected during storms and nonstorm conditions from the Delaware and Raritan Canal, N.J., and the Delaware River at Lumberville, Pa.

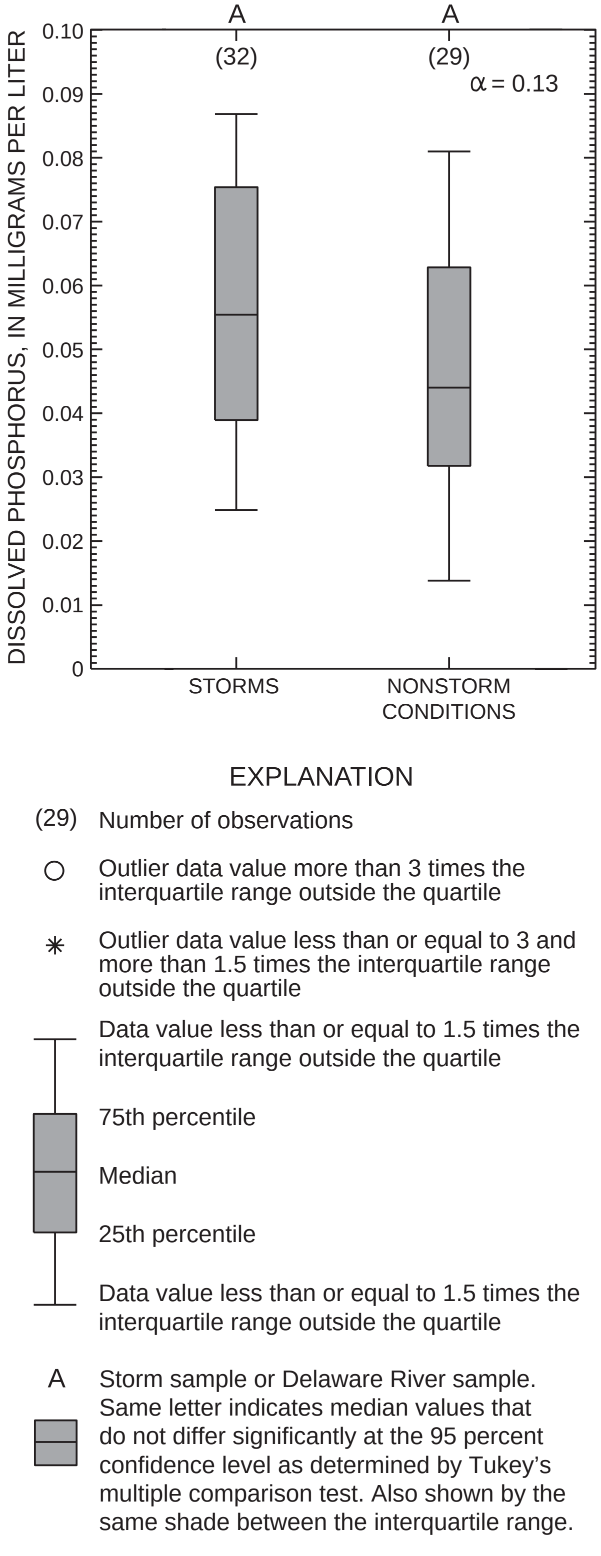

Figure 10. Distribution of concentrations of phosphorus in filtered samples collected during storms and nonstorm conditions from the Delaware and Raritan Canal, N.J.

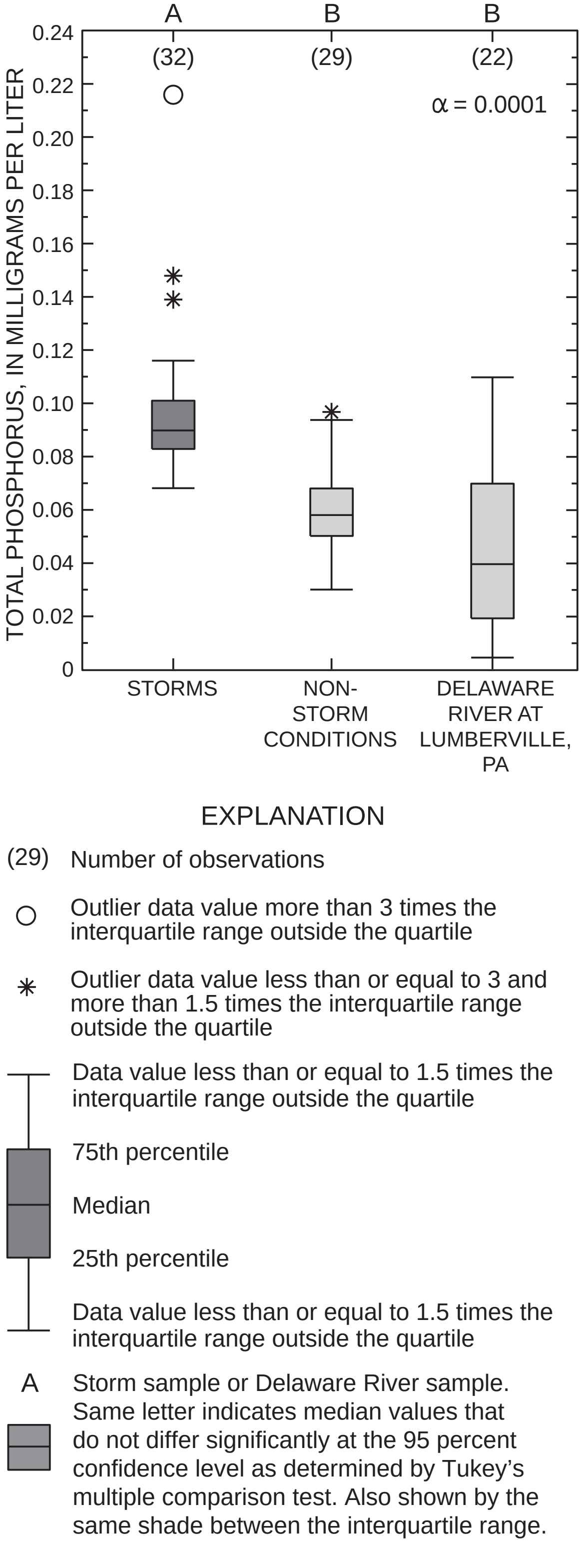

Figure 11. Distribution of concentrations of total phosphorus in samples collected during storms and nonstorm conditions from the Delaware and Raritan Canal, N.J., and the Delaware River at Lumberville, Pa.

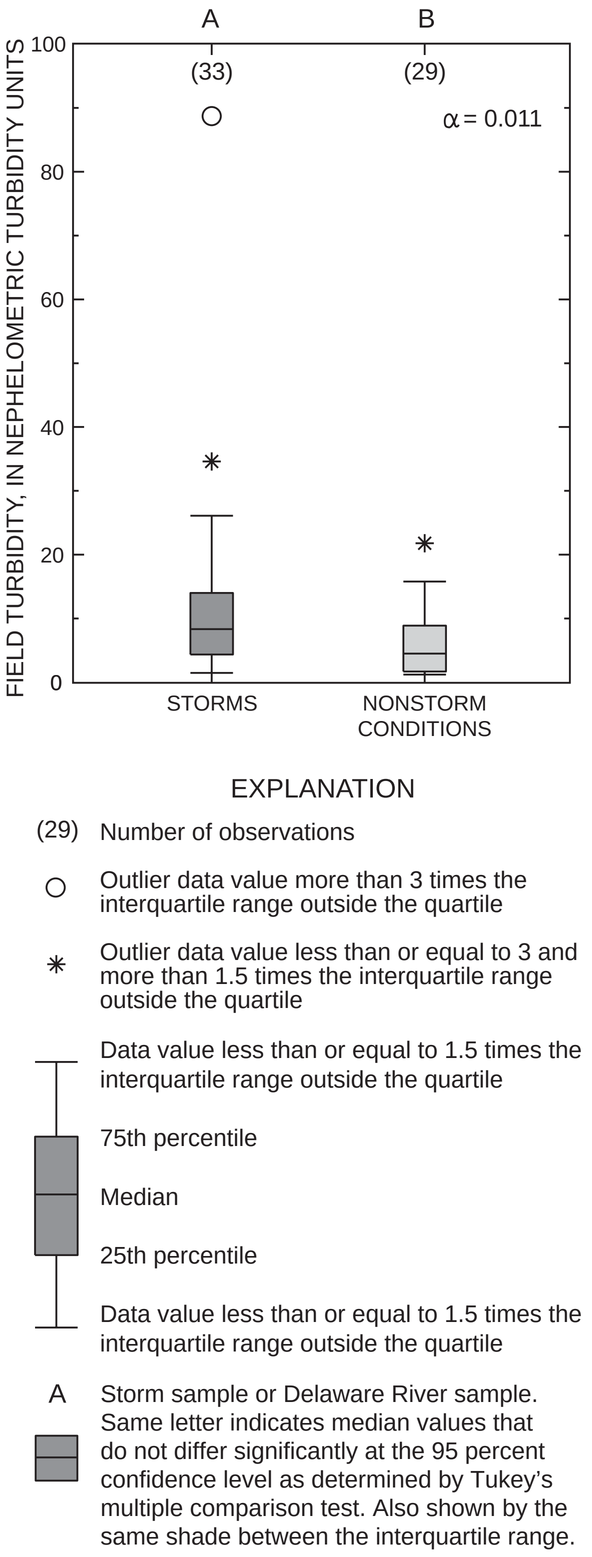

Figure 12. Distribution of field turbidity in samples collected during storms and nonstorm conditions from the Delaware and Raritan Canal, N.J.

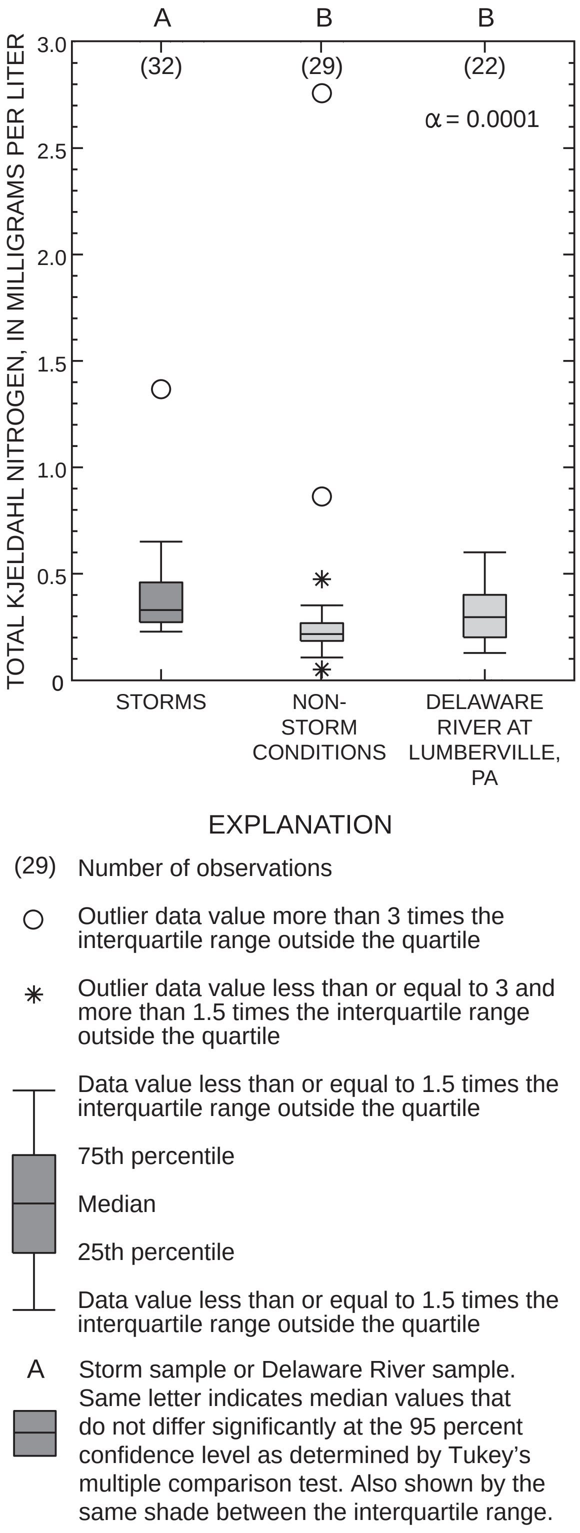

Figure 13. Distribution of concentrations of total ammonia plus organic nitrogen in samples collected during storms and nonstorm conditions from the Delaware and Raritan Canal, N.J., and the Delaware River at Lumberville, Pa.

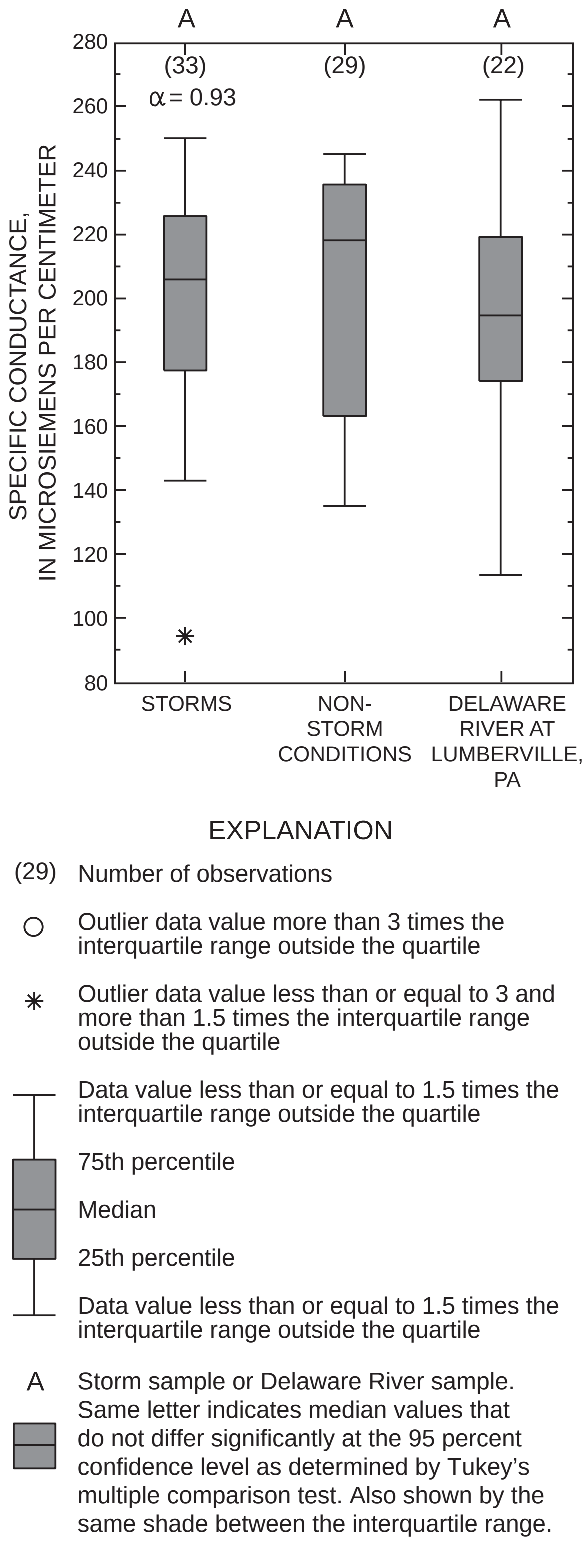

Figure 14. Distribution of specific conductance in samples collected during storms and nonstorm conditions from the Delaware and Raritan Canal, N.J., and the Delaware River at Lumberville, Pa.

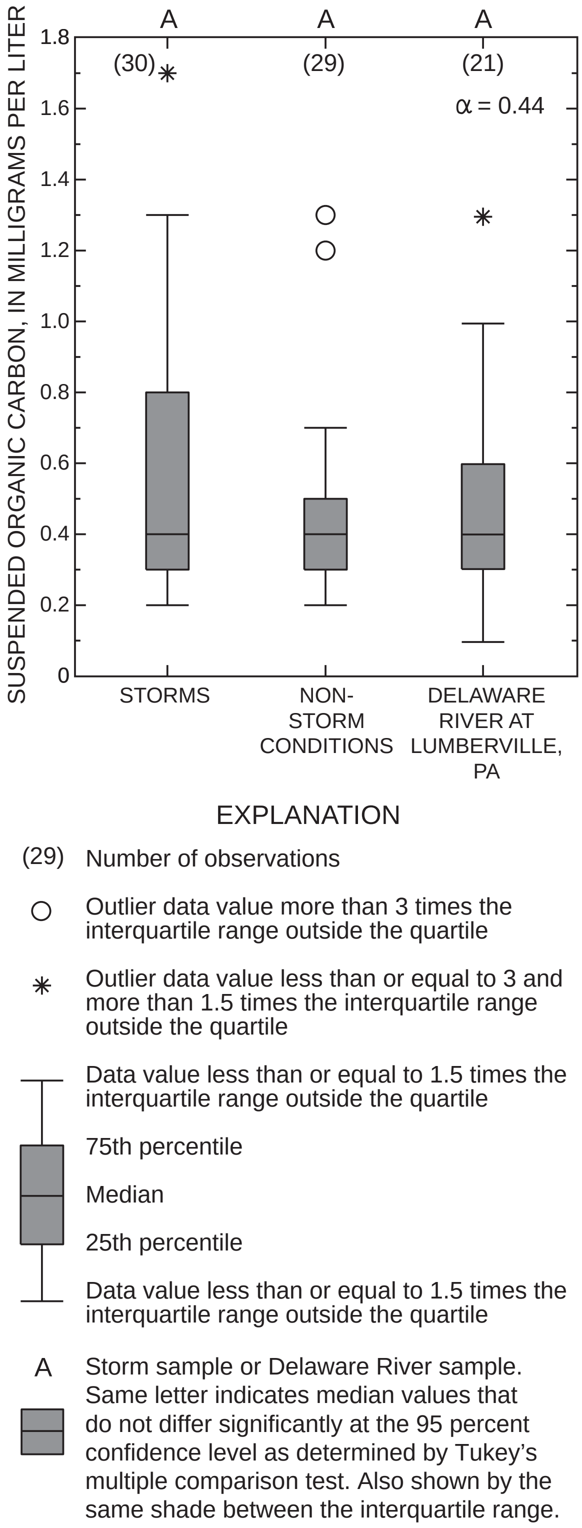

Figure 15. Distribution of concentrations of suspended organic carbon in samples collected during storms and nonstorm conditions from the Delaware and Raritan Canal, N.J., and the Delaware River at Lumberville, Pa.

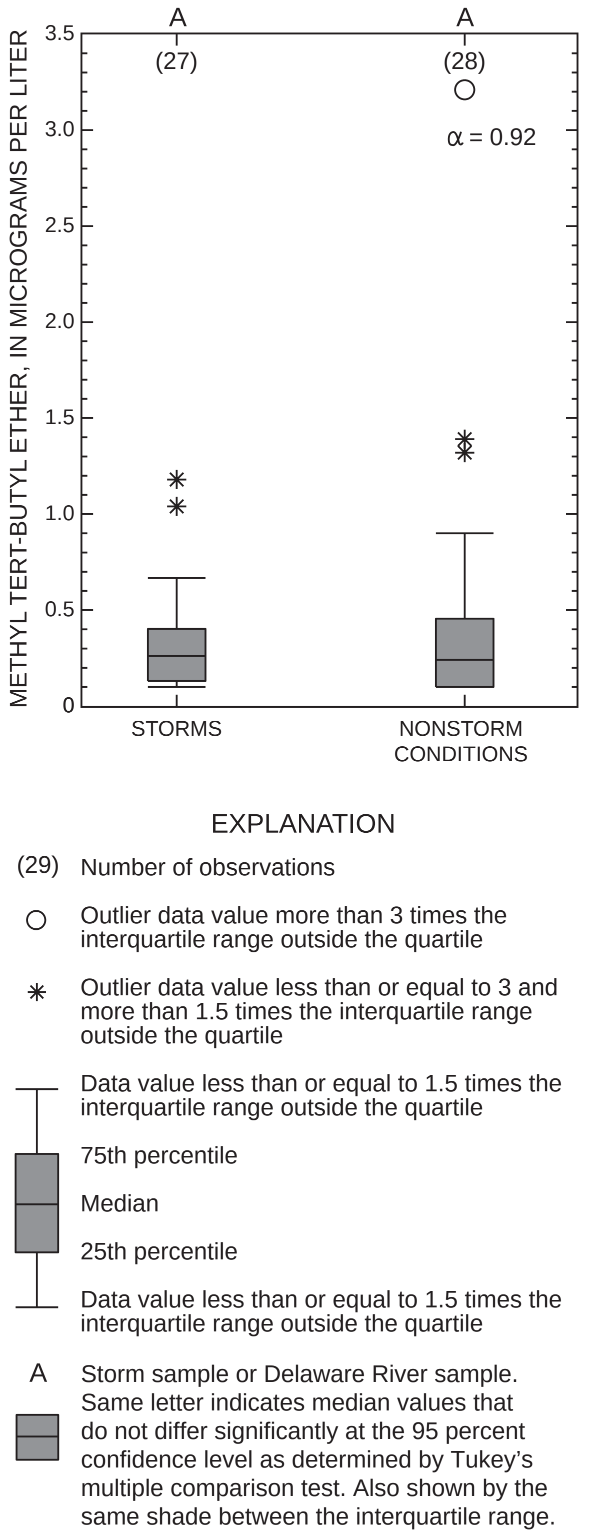

Figure 16. Distribution of concentrations of methyl tert-butyl ether in samples collected during storms and nonstorm conditions from the Delaware and Raritan Canal, N.J.

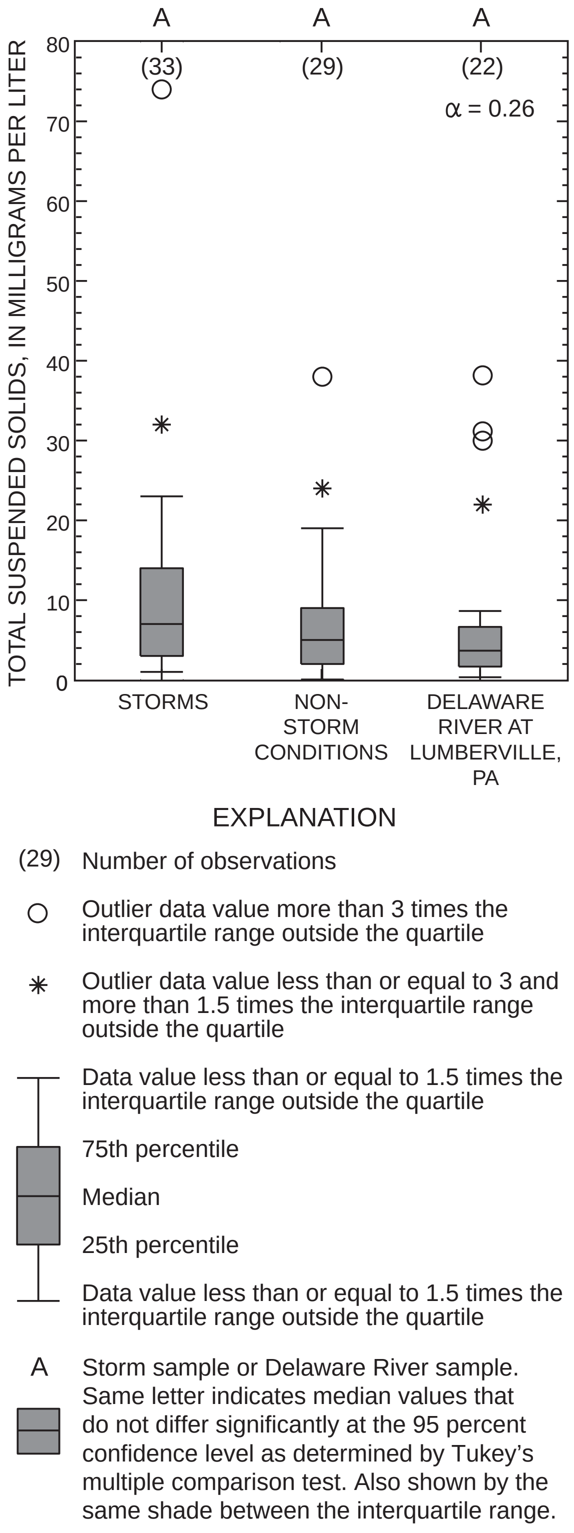

Figure 17. Distribution of concentrations of total suspended solids in samples collected during storms and nonstorm conditions from the Delaware and Raritan Canal, N.J., and the Delaware River at Lumberville, Pa.

Table 2. Results of the Kruskal-Wallis test on median values of constituents in storm and nonstorm samples from all sampling sites on the Delaware and Raritan Canal, N. J.
[--, no data; nm, nanometers]

Constituents in filtered water	Statistically significant difference in median values (storm median value was greater than nonstorm median value)	Kruskal-Wallis test, alpha value	Constituents in unfiltered or whole water	Statistically significant difference in median values (storm median value was greater than nonstorm median value)	Kruskal-Wallis test, alpha value
Ammonia	No statistical test	--	Ammonia plus organic nitrogen	Yes	.0001
Ammonia plus organic nitrogen	Yes	.0001	Methyl tert-butyl ether (MTBE)	No	.92
Nitrite	No statistical test	--	Phosphorus	Yes	.0001
Nitrite plus nitrate	No	.75	Specific conductance	No	.93
Organic carbon	Yes	.0019	Suspended organic carbon	No	.44
Phosphorus	No	.13	Total suspended solids	No	.26
Ultraviolet absorbance at 254 nm	Yes	.026	Turbidity	Yes	.011

the canal were not compared to that from the Delaware River at Lumberville because either the data were highly censored or the laboratory reporting levels were changed. Phosphorus in filtered-water samples was not statistically evaluated because the laboratory lower reporting level was increased from 0.01 to 0.05 mg/L on October 1, 1998 (the beginning of water year 1999) (U.S. Geological Survey, 1998). The percentage of censored values of phosphorous in filtered water to the total number of analyses of phosphorous in filtered-water samples collected from the Delaware River at Lumberville during water years 1995-99 is 4 percent. The change in laboratory reporting level resulted in an increase in the percentage of censored values of phosphorous analyzed for in filtered-water samples from the canal during 1998-99 to 8 percent.

Only 6 of 29 VOCs were detected in 55 samples of canal water by using purge and trap GC/MS analysis with a method reporting level of 0.2 µg/L. MTBE was detected in 43 samples; the highest concentration was 3.2 µg/L. Toluene was detected in five samples; the highest concentration was 0.7 µg/L. Chloroform was detected in four samples, and all the concentrations were approximately 0.1 µg/L. Methylene chloride, ortho-Xylene, and meta- plus para-Xylenes were detected once each at concentrations of 0.1, 0.2, and 0.5 µg/L, respectively. The highest concentration of MTBE and the greatest number of analytes were detected in a nonstorm sample collected at Brookville. None of the 55 samples contained a VOC concentration that exceeded U.S. Environmental Protection Agency or State of New Jersey Primary Drinking Water Maximum Contaminant Levels.

A statistical comparison was performed on concentrations of MTBE in samples from the canal and in samples from the Delaware River at Trenton collected during water years 1995-99 (fig. 18). Results of the statistical comparison of the medians of MTBE concentrations for the two sites indicated that they were not significantly different ($\alpha > 0.05$).

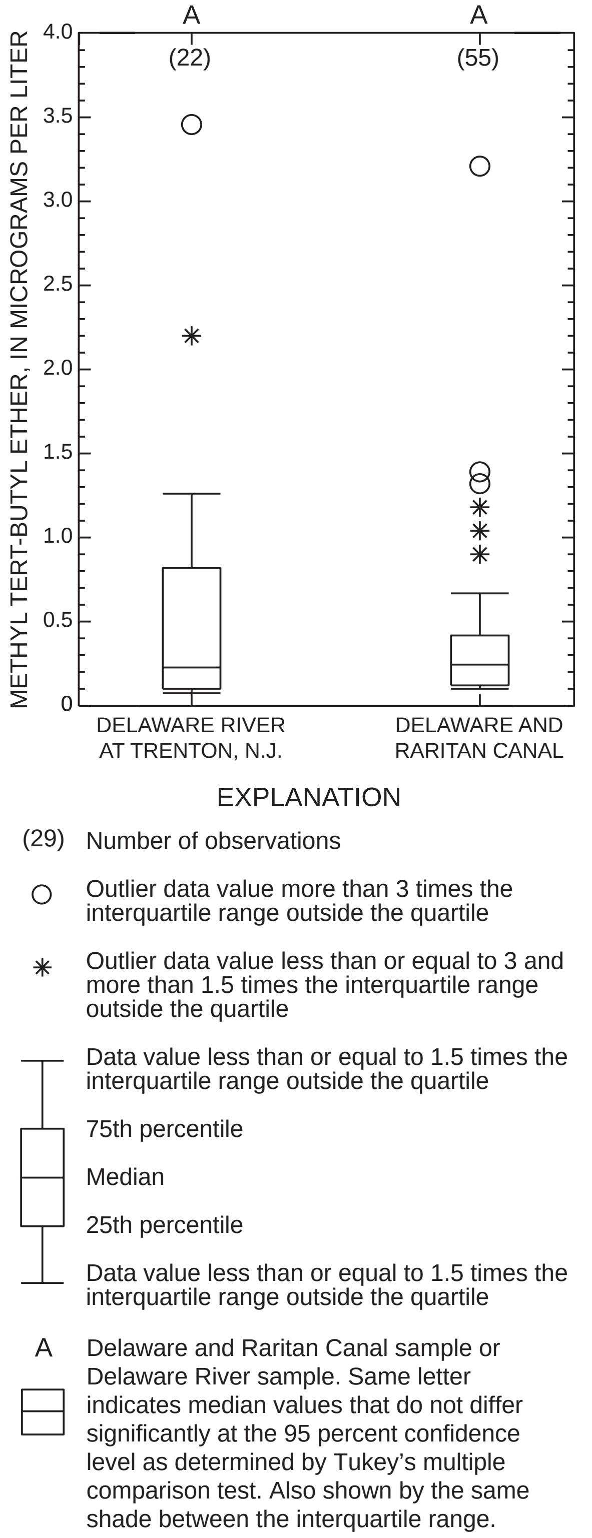

Figure 18. Distribution of concentrations of methyl tert-butyl ether in samples collected from the Delaware River at Trenton, N.J., during water years 1995-99 and the Delaware and Raritan Canal, N.J., during water years 1998-99.

The results of the nonparametric two-way ANOVA tests showed that the water quality at one sampling location was not more affected by stormwater runoff into the canal than at any of the other six sampling locations. The instantaneous water-quality data did not reveal a pattern of water-quality change that would narrow the focus of a future more detailed investigation into the effects of stormwater runoff on the water quality of a particular reach of the canal.

Continuous Water-Quality Monitoring

The six continuous water-quality monitoring locations divide the canal into five reaches that cover almost the entire length of the canal. Water temperature (T), specific conductance (SC), and turbidity were recorded every 30 minutes for approximately 1 year and 3 months, from February 1998 to May 1999. The data on SC are summarized in figure 19 and on turbidity in figure 20. Temperature was used solely to correct the specific conductance to the reference temperature of 25 ^{o}Celsius. Daily maximum, minimum, and mean of water temperatures are reported in Deluca and others (2000) and stored in CanalDB.

The data from an upstream location were lagged in time so that upstream and downstream sensors measured the same parcel of water. The upstream measurement value was subtracted from the downstream value to obtain the net change in turbidity or SC that occurred in each reach bounded by two continuous water-quality monitors. This approach to interpreting continuously monitored data is possible because the flow rate in the canal is actively controlled to maintain a fairly constant flow rate within ± 10 percent over long periods of time (weeks), and relatively few gaps break the continuous data record.

The population of net changes in turbidity or SC for the period of record of this study has a systematic value and plus or minus some amount of random variability. If the estimate of the time of travel is reasonably accurate, the systematic value represents turbidity or SC in a reach of the canal that has been altered by water from influent drainage

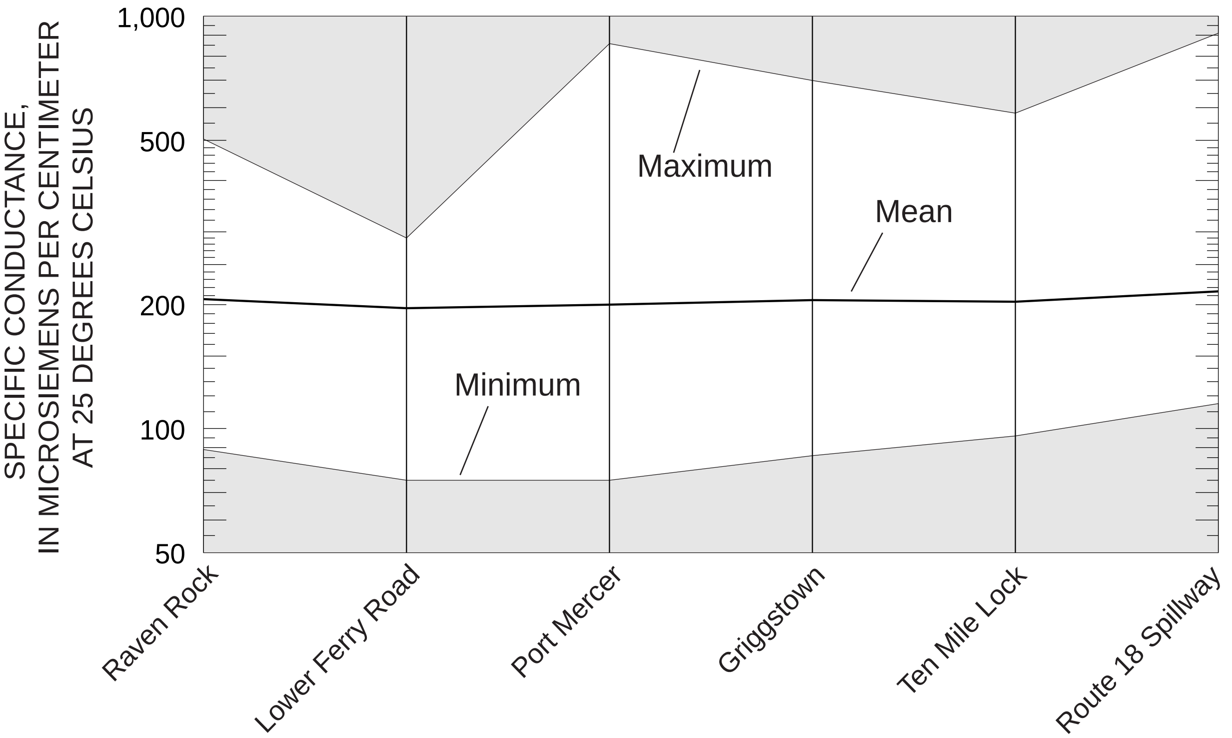

Figure 19. Minimum, maximum, and mean of continuously monitored specific conductance at six sampling locations along the length of the Delaware and Raritan Canal, N.J., February 1998 to May 1999.

basins, as well as the biological, chemical, and physical processes that occurred in a reach over long periods of time (months). The mean is more likely to be affected by extremely large values of net change than is the median.

A comparison of the mean and median of a population reveals information about the distribution of values of the population. If the mean and median values are not similar, then the population has a small percentage of extremely large or small values that affect the mean more than the median (Helsel and Hirsch, 1992). The relation between the mean and median of the population of net changes in turbidity or SC in a reach can be used to infer whether or not measurable effects of storms had occurred.

Specific Conductance

The range and mean of continuously monitored SC for the project period of record are shown in figure 19. The mean SC changed little along the length of the canal; during the period of record the mean ranged from 196 µS/cm at Lower Ferry Road to 215 µS/cm at the Route 18 Spillway. The minimum value of SC ranged from 75 µS/cm at Port Mercer to 115 µS/cm at Route 18 Spillway. The minimum values of SC for canal water can be compared to the SC of precipitation at Washington Crossing, N.J., which has a seasonal precipitation-weighted mean of 24 and 18 µS/cm for 1998 and 1999, respectively (National Atmospheric Deposition Program (NRSP-3)/National Trends Network 2000, 2000). Maximum SC is greater downstream from influent basins with a large percentage of urban land use, 858 µS/cm at Port Mercer and 991 µS/cm at Route 18 Spillway, than downstream from influent basins with a large percentage of non-urban land use, 290 µS/cm at Lower Ferry Road.

The mean and median of net changes in SC for the five reaches that constitute almost the entire length of the canal are shown

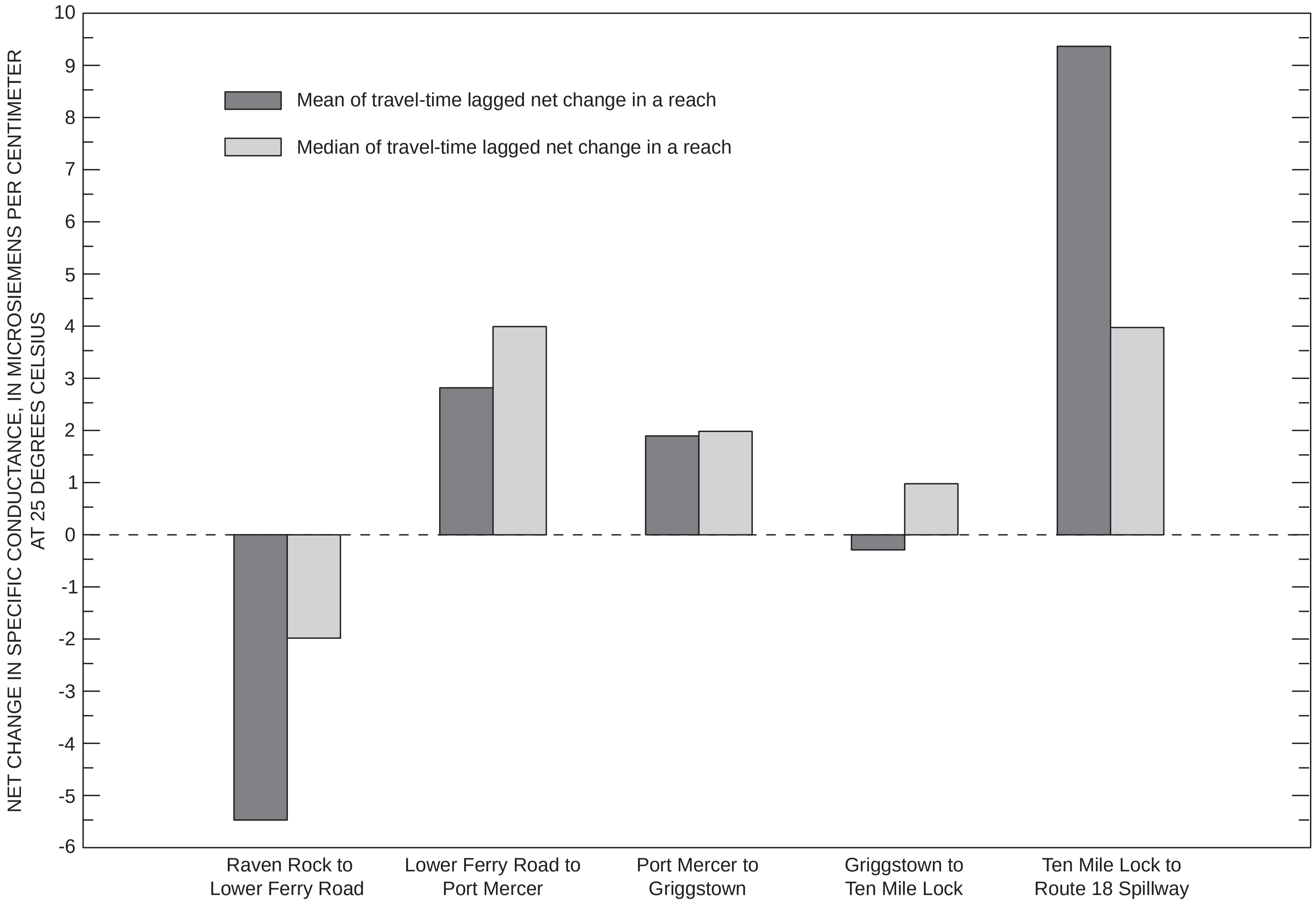

Figure 20. Mean and median of the travel-time lagged net changes in specific conductance in the five reaches of the Delaware and Raritan Canal, N.J., February 1998 to May 1999.

in figure 20. The change in SC in the reach between Raven Rock and Lower Ferry Road shows the effect of stormwater runoff from the influent basins of Lockatong and Wickecheoke Creeks. These two influent drainage basins with a combined drainage area of 31,802 acres compose the largest drainage area in the study area. When the water from the Lockatong and Wickecheoke Creeks that has a SC lower than the canal water enters the canal, the SC of canal water at Lower Ferry Road is reduced by approximately 5.5 μS/cm for the mean value and 2.5 μS/cm for the median value for the project period of record. The differing values of the mean and the median net change in SC in a reach indicate that a small number of extreme values of net change in SC have affected the mean more than the median; therefore, the decreases in SC are associated with storms and stormwater with a lower SC that enters this reach of the canal.

If a net change of 5 μS/cm were determined by a few field measurements, the net change would be within ± 3 percent of the reading, the accepted measurement accuracy for SC (Radtke and others, 1998). The mean net change in the reach between Raven Rock and Lower Ferry Road is significant because the mean is the central value of a population of tens of thousands of measurements. The continuous-monitoring mean SC is supported by the field measurements for SC at Brookville, which is immediately downstream from the confluence of the Wickecheoke Creek and the canal (fig. 4). The means of storm and nonstorm field measured SC values, which are based on five and four measurements, respectively, differed by approximately 15 μS/cm.

In the canal reach between Lower Ferry Road and Port Mercer, SC increased to a mean of 2.7 μS/cm and a median of 4μS/cm for the net changes. A review of the continuous data record of the lagged net changes showed that an increase in SC in this reach occurred mostly during nonstorm conditions. The net change in SC that occurred in this reach under nonstorm conditions can be deduced from the agreement between the mean and median values of the net change in SC (fig. 20). A possible source of high SC water in this reach is domestic or industrial wastewater that continuously discharges into pipes, which empty into the Delaware and Raritan Canal, and ground water that flows from areas within this reach where the water table is higher than the surface-water level of the Delaware and Raritan Canal.

The mean and median of the net change in SC between Port Mercer and Griggstown both increased about 1.9 μS/cm (fig. 20). Duck Pond Run is the largest influent drainage basin in this reach. During 1998-99, this basin was undergoing change from agricultural and forested land uses to urban land use.

Net changes in SC in the reach between Griggstown and Ten Mile Lock are small, -0.25 μS/cm for the mean and 0.9 μS/cm for the median. Only five small influent drainage basins with a total area of 1,038 acres drain into the canal in this reach.

The greatest net change in SC in the five reaches, an increase of 9.3 and 4.0 μS/cm for the mean and median values of the period of record of this project, respectively, occurred in the most downstream reach between the Ten Mile Lock and Route 18 Spillway. A mean value much larger than the median value of net change in SC indicates that the net change in SC is associated with precipitation runoff from the two largest influent basins in this reach, the Borough of South Bound Brook and Als Brook. The primary land use in the basins influent to this reach of the canal is urban, and many storm drains in this area empty road runoff into the canal. The fourth largest influent drainage basin, Als Brook, drains into the canal about 1.34 miles upstream from the Route 18 Spillway.

Turbidity

The maximum and minimum turbidity for the six continuous water-quality monitoring sites is 960 and 0.3 NTU, respectively (fig. 21). The mean value of the continuously monitored turbidity data for the duration of the study increased from

11.8 NTU at Raven Rock to 19.6 NTU at Lower Ferry Road, then gradually decreased downstream to 8.6 NTU at the Route 18 Spillway (fig. 21).

The mean and median of net changes in turbidity for the five reaches are shown in figure 22. The reach between Raven Rock and Lower Ferry Road shows the effect of the influent basins of Lockatong and Wickecheoke Creeks. When the water from the Lockatong and Wickecheoke Creeks with higher turbidity entered the canal, the turbidity at Lower Ferry Road increased over the turbidity at Raven Rock by approximately 7.3 NTU for the mean value and 6.1 NTU for the median value of the project period of record. The average velocity of the canal water in this reach was estimated to be 0.9 ft/s. This average velocity was less than the commonly accepted 1.5 ft/s needed to transport sand.

The canal water between Lower Ferry Road and Port Mercer underwent a net change in turbidity for the project period of record of -4 NTU for the mean and -3.4 NTU for the median. The average velocity of the canal water in this reach is estimated to be 0.45 ft/s. Significant attenuation of turbidity occurred in this reach. A new housing development was under construction near the canal about 0.25 miles upstream from the Port Mercer continuous water-quality monitor. After and during a storm, a plume of high-turbidity water was visible coming from a storm drain, which received overland flow from the construction site, and entering the canal on the right bank, then hugging the right bank. This source of turbid water will probably be

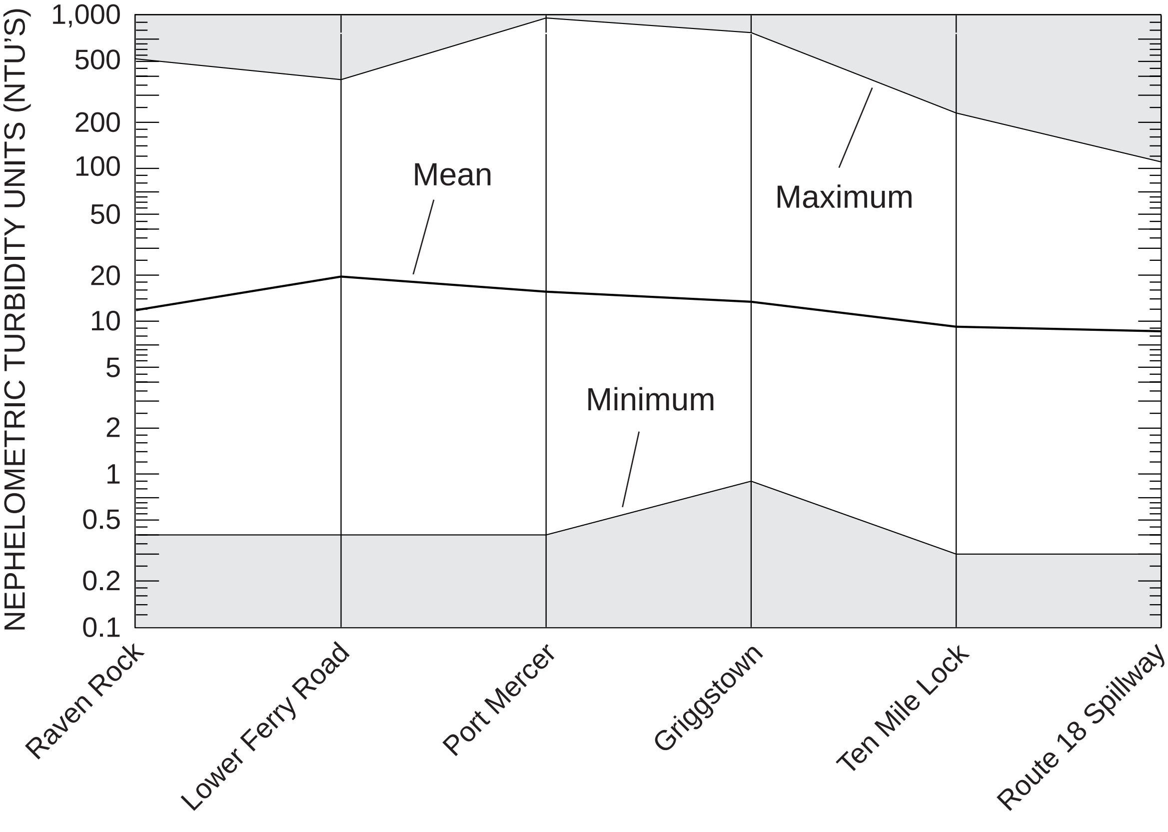

Figure 21. Minimum, maximum, and mean of continuously monitored turbidity at six sampling locations along the length of the Delaware and Raritan Canal, N.J., February 1998 to May 1999.

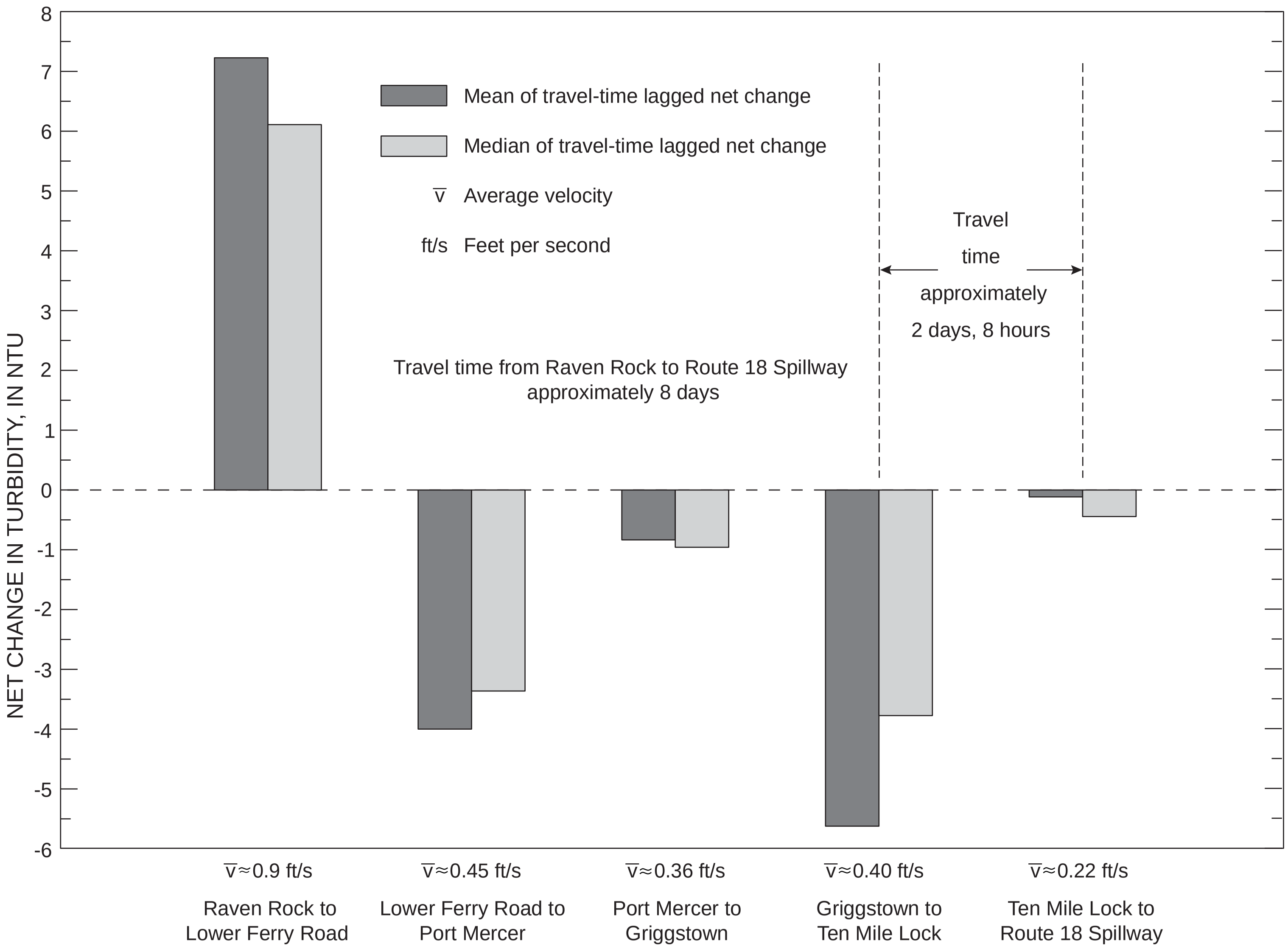

Figure 22. Mean and median of the travel-time lagged net changes in turbidity in the five reaches of the Delaware and Raritan Canal, N.J., February 1998 to May 1999.

eliminated once the housing development is completed. It is not apparent from a data review that the turbid water that entered the canal mixed sufficiently with the canal water in the 0.25 miles between the storm drain and the monitor to be detected by the continuous water-quality monitor located almost midway across the canal. The period of record mean values for turbidity at Lower Ferry Road and Port Mercer are 19.6 and 15.6 NTU, respectively (fig. 21).

The water in the reach between Port Mercer and Griggstown underwent a net change in turbidity for the project period of record of -0.8 NTU for the mean and -1.0NTU for the median between the start and end of the reach (fig. 22). Almost no change in turbidity occurred in this reach, which is an unexpected result, because the estimated average velocity of the canal water in this reach, 0.36 ft/s, was lower than the average velocity of the reach between Lower Ferry Road and Port Mercer.

The minimal reduction in turbidity in the reach between Port Mercer and Griggstown could have been caused by dredging of the canal in this reach during the project. A review of the turbidity values for the project period of record showed that the turbidity generated by the dredging was detected by the Griggstown continuous water-quality monitor. The Duck Pond Run Basin drains into the canal in this reach. Stormwater from this basin might increase turbidity in this reach. The confluence of Duck Pond Run and the canal is approximately 11.2 miles upstream from the Griggstown continuous water-quality monitor. Any settleable solids or turbidity that enters the canal from Duck Pond Run would settle in the canal during the 45.7 hours of travel time before being detected by the Griggstown continuous water-quality monitor. Only duck weed, which floats on the water surface, was observed in this reach during field trips to the study area. Algae were not observed in this reach.

The water in the reach between Griggstown and Ten Mile Lock underwent a net change in turbidity for the project period of record of -5.6 NTU for the mean and -3.8 NTU for the median (fig. 22). The average velocity of canal water in this reach was approximately 0.40 ft/s. Thus, the attenuation of the turbidity in this reach was caused by settling of the suspended particles because the velocity of the water was low.

The water in the reach between Ten Mile Lock and the Route 18 Spillway underwent a net change in turbidity for the project period of record of -0.1 NTU for the mean and -0.4 NTU for the median (fig. 22). The average velocity of the water in this reach was approximately 0.22 ft/s, which was the lowest average velocity of the six reaches, and the net change in turbidity was negligible. If little turbidity is added to the canal water from influent drainage basins, this reach would have measurably large decreases in turbidity similar to those in the reach between Ten Mile Lock and Griggstown because of the low velocity; however, water from Als Brook Basin, the fourth largest influent drainage basin, and the Borough of South Bound Brook drainage basin, which covers an area of 500 acres, enters the canal about 1.34 miles and 5.5 miles, respectively, upstream from the Route 18 Spillway. Because Als Brook is closer to the continuous water-quality monitor located at the Route 18 Spillway and has an area 5.8 times larger than the Borough of South Bound Brook Basin, it was more likely to be the source of a significant amount of stormwater runoff that carried turbidity into the canal. A deposit of sand and gravel is present at the confluence of Als Brook and the canal and extends almost one-third of the width of the canal. No sand and gravel deposits in the canal were observed near the Borough of South Bound Brook drainage basin.

SUMMARY

In general, the chemical composition of water in the Delaware and Raritan Canal in New Jersey during nonstorm conditions is not statistically different from that of the water near the intake of the canal, at the Delaware River at Lumberville, Pa. The results of statistical hypothesis testing of the instantaneous water-quality sampling data collected during the project period of record, mid-January 1998 to May 1999, did not identify specific locations along the canal at which statistically significant changes in median values of water-quality constituents were associated with storms. To determine statistically significant differences for all the water-quality constituents, one explanatory variable (either precipitation conditions or sampling locations) was removed by combining either storm and nonstorm data, or data from all sampling locations. Thus, the results of the analysis of the continuous water-quality monitoring data provided the information needed to identify water-quality changes related to storms in the five reaches of the canal.

The concentrations of ammonia and nitrite nitrogen were not statistically tested because about 40 and 32 percent, respectively, of the data values were less than the method reporting level. Concentrations of filtered phosphorous in water samples from the canal could not be statistically compared with concentrations in samples collected at the Delaware River at Lumberville, Pa., because of a change in the laboratory reporting level in 1999, from 0.01 to 0.05 milligrams per liter. The change in laboratory reporting level resulted in a greater percentage of censored data from the canal (8 percent) than from the Delaware River at Lumberville, Pa. (4 percent). The nonstorm median concentrations of nine water-quality constituents in canal water were not significantly different from the median concentrations in samples collected during water years 1994-99 at the Delaware River at Lumberville, Pa., nor was field measured specific conductance significantly different.

Only the median concentrations of suspended organic carbon differed significantly along the length of the canal after the storm and nonstorm data were aggregated. Median concentrations were significantly higher during and after storms than for nonstorm events for the following constituents: total and filtered ammonia plus organic nitrogen, total phosphorous, turbidity, ultraviolet absorbance at 254 nanometers, and dissolved organic carbon.

Only five volatile organic compounds (VOCs) were detected. Toluene was detected five times; the highest concentration was 0.7 µg/L (micrograms per liter). Chloroform was detected 4 times, and all the concentrations were approximately 0.1 µg/L (micrograms per liter). Methylene chloride, ortho-Xylene, and meta- plus para-Xylenes were detected once each at concentrations of 0.1, 0.2, and 0.5 µg/L, respectively. Methyl *tert*-butyl ether (MTBE) was the most frequently detected VOC. MTBE was detected in 55 of 80 samples. The median concentration of MTBE in canal water (0.25 µg/L) was not statistically different from that in water from the Delaware River at Trenton, N.J.

Stormwater runoff into the canal reach between Raven Rock and Lower Ferry Road reduced the continuously monitored specific conductance (SC) at Lower Ferry Road relative to that at Raven Rock during 1998-99. The largest basins that drain into the canal in this reach are the Wickecheoke Creek (16,987 acres) and Lockatong Creek (14,815 acres).

The median of the continuously monitored SC for the period of record during nonstorm conditions at Port Mercer increased by approximately 3 to 4 µS/cm (microsiemens per centimeter) (1.5 to 2 percent of the median specific conductance), relative to that of the nearest upstream site, Lower Ferry Road, during 1998-99. Land use in the influent basins for this reach of the canal is primarily urban.

The median continuously monitored SC for the project period of record during nonstorm conditions at the Route 18 Spillway site increased relative to that of the nearest upstream site, Ten Mile Lock, by approximately 3 to 4 µS/cm, during 1998-99. The mean of the net change for the period of record in continuously monitored specific conductance for this reach during storms also increased. Land use in the two largest influent basins, the Borough of Bound Brook and Als Brook, is predominantly urban.

Continuously monitored turbidity differed along the length of the canal. Between Raven Rock and Lower Ferry Road, the mean and median for continuously monitored turbidity increased by 7.2 and 6.2 NTU (nephelometric turbidity units), respectively, during 1998-99. The continuously monitored turbidity decreased downstream from Lower Ferry Road to Ten Mile Lock.

Turbidity increased locally downstream from influent streams or outfalls and was not transported appreciable distances because of the low average velocities of water in the canal reaches from Lower Ferry Road to the Route18 Spillway, which ranged from 0.45 to 0.22 ft/s. Turbidity that entered the feeder part of the canal from Raven Rock to Lower Ferry Road probably was transported greater distances than in the rest of the canal because the average velocity, 0.9 ft/s, was at least twice that in the rest of the canal.

In the reach between Ten Mile Lock and the Route 18 Spillway, little change was measured in the continuously monitored turbidity, which decreased less than 0.5 NTU for the mean and median during 1998-99. If no additional turbidity was introduced in the reach between Ten Mile Lock and the Route 18 Spillway, a reduction of approximately 4 NTU, which is similar to that in the reach between Griggstown and Ten Mile Lock, would be expected. The lack of a reduction in turbidity values for the reach between Ten Mile Lock and the Route 18 Spillway is not consistent with the average velocity for this reach, which is the lowest average velocity of all the reaches. Field observation of a sand bar immediately downstream from the confluence of Als Brook and the canal confirmed that the Als Brook drainage basin has contributed sediment carried by stormwater to the canal; the storm water and suspended solids could reach the monitor at the Route 18 Spillway and the raw water intakes for two drinking-water treatment plants.

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APPENDIX A. RELATIONAL DATABASE DESIGN

INTRODUCTION

The CanalDB data model is described in this section. A complete listing of all table definitions and field properties and definitions in the CanalDB database is presented in a Data Dictionary. The Data Dictionary is the primary reference for the tables and fields in the Access database. A entity-relationship diagram of the data model also is presented (fig. A1). Together, the diagram and the Data Dictionary serve as the documentation for the database.

The following statement summarizes the water-quality data model: Sites may have one or more Samples, and Samples may have one or more Results. The core tables in CanalDB are the three tables that physically represent that statement (figs. A1 and A2), and each has a prefix of tbl: tblSite, tblSample, and tblResult (tables A1, A2, A3, respectively). All other tables in the database are used to provide classification and qualification information to the core tables; these are referred to as domain tables because each supplies information about (or selection lists for) a particular subject domain (for example, method, equipment, or parameter). There are ten domain tables in CanalDB, and all have a prefix of tds. Seven of these tables serve the tblSample core table (tdsHydrologicEvent, tdsHydrologicCondition, tdsSampleMedium, tdsSamplingMethod, tdsSamplingEquipment, tdsSamplingIntervalGroup and tdsSampleType; tables A4-A10, respectively), two serve the tblResult core table (tdsParameter and tdsResultFlag; tables A11 and A12), and one (tdsAgency; table A13) serves both of those core tables by providing selections for sample collection and result-reporting agencies.

CORE ENTITIES IN THE DATABASE

Site

A Site is defined as the place or location where Samples were collected. For each Site, data can include the official USGS Station name, Station ID (STAID), latitude, longitude, New Jersey State Plane coordinates (NJSP83), watershed code (HUC), and a comment.

Sample

A Sample is generally considered to be either field data (for example, stage level or temperature) or material (water specimen) collected at a single Site on a particular date and time. Samples are explicitly defined within CanalDB as a unique combination of site, date/time, collection agency, sample medium, sampling method, sampling equipment, and sample type (for example, regular, spike, or replicate). Each Sample is also classified to a “sampling interval group” that informs the user about whether the Sample is part of a series, for example 15-minute-interval data from a continuous monitoring station. Sampling also is associated with (but not defined by) hydrologic events (for example, storm or hurricane) and hydrologic conditions (for example, rising stage of a storm event). Figures A1 and A2 illustrate how Samples and the associated domain tables fit into the model.

Result

A Result is the field measurement or laboratory analytical value pertaining to a single Parameter in a single Sample. In this appendix, Parameter refers to a characteristic or constituent. Each Sample can have many Results, but each Parameter can occur only once within a single Sample (for example, pH measured twice must be for different times or

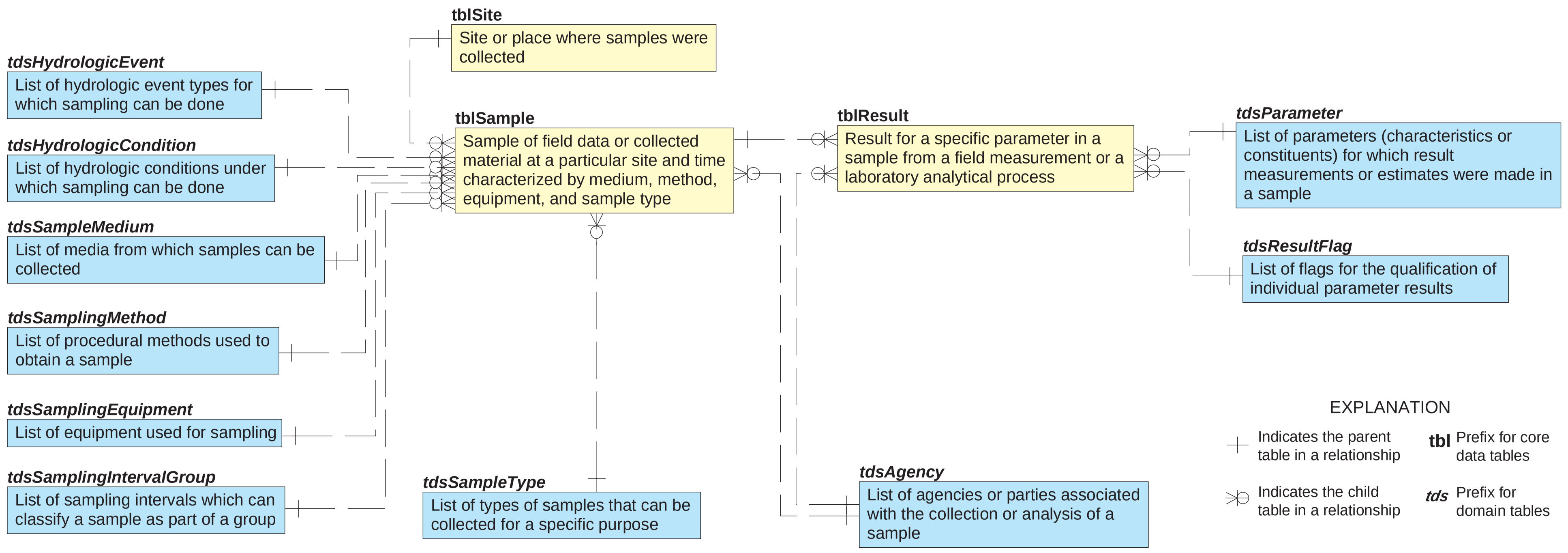

Figure A1. Data model for Delaware and Raritan Canal water-quality database (CanalDB) showing definitions for each table and their relationships.

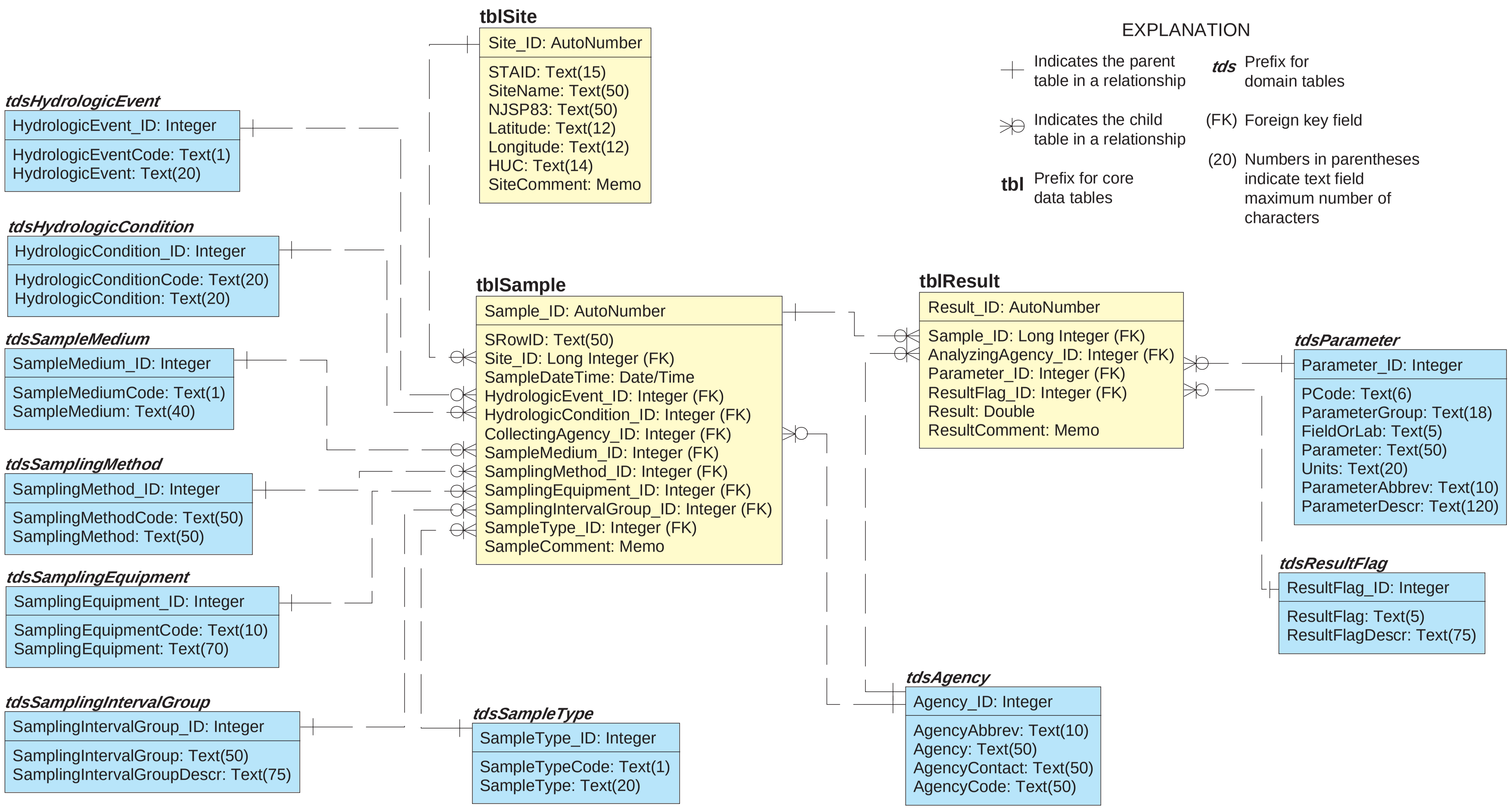

Figure A2. Structure of the Delaware and Raritan Canal water-quality database (CanalDB) showing fields in each table and selected properties (data type, text field size, foreign key designation (FK)).

sample types, collection agency, or method as defined for a different Sample). Results are further qualified by association with a Result Flag (for example, < or estimated) to aid in interpreting the integrity and accuracy of the reported value. Figures A1 and A2 illustrate how Results fit into the model.

Summary Table

At the writing of this report (March 2000), the CanalDB contains 10 Site records, 267,061 Sample records, and 766,711 Result records. Because most of the Samples/Results are 15-minute or 30-minute-interval continuous monitoring data, a new table, tblDailySummary (table A14) was created to summarize individual Parameters at a Site throughout a day. A total of 12,340 daily statistics (number of measurements (N), minimum, maximum, and mean) for individual parameters are stored in the table to allow efficient browsing. The reduction from 766,711 Result records to 12,340 summary records is due to compacting all 15-minute (N = 96 per day) and 30-minute (N = 48 per day) continuous monitoring data for each day. Measurements that are not part of a continuous series (instantaneous samples) are represented by a sample size (N) of 1.

The table tblDailySummary contains 17 identification/classification fields and 4 summary statistics fields (fig. A3). It is better suited to general browsing and queries of the data than is the individual Results table. It is also a more efficient link for Geographic Information Systems to display summarized values for spatial evaluation of parameters.

DATA DICTIONARY

The Data Dictionary is a listing of table and field properties for the CanalDB. Information about each table is shown in a heading area at the top of the table:

- Table Name is self explanatory.
- #Fields is the number of fields in the table.

tblDailySummary

Site_ID: Long Integer
STAID: Text
SiteName: Text
SampleDate: Date/Time
CollectingAgency: Text
HydrologicEvent: Text
HydrologicCondition: Text
SampleMedium: Text
SamplingMethod: Text
SamplingEquipment: Text
SamplingIntervalGroup: Text
SampleType: Text
AnalyzingAgency: Text
ParameterGroup: Text
FieldOrLab: Text
Parameter: Text
Units: Text
N: Long Integer
Minimum: Double
Maximum: Double
Mean: Double

Figure A3. Fields in the table tblDailySummary and their data types.

- #Recs is the current number of records at the time the dictionary was generated.
- Last Updated is the date of last update to the table at the time the dictionary was generated.
- Table Description is a description of the table contents or function.

Below the heading area, a numbered listing of each field in the table is accompanied by descriptive information:

- Field Name is self explanatory.
- PK is checked if the field is part of the primary key for the table.

- FK is checked if the field is a foreign key pointing to data in a “parent” table.

- Rqd is checked if the field is required to have a value for each record in the table; if unchecked the field is optional.

- Type is the data type of the field.

- Size is the size of the field (maximum number of characters for text fields; for other data types, it represents the number of bytes used for storage).

- Default is the default value for the field (usually refers to a foreign key value that represents a selection from a domain table).

- Description is a description of the field.

Table A-1. Characteristics of tblSite

Table Name	#Fields	#Recs	Last Updated:
tblSite	**8**	**10**	11/20/00 8:32:09 A

Table Description: **Site or place where samples were collected**

	Field Name	PK	FK	Rqd	Type	Size	Default	Description
1	Site_ID	☑	☐	☑	AutoNumber (Long)	4		Key that uniquely identifies a site (place) where sampling occurs
3	STAID	☐	☐	☐	Text	15		USGS site identification code
4	SiteName	☐	☐	☑	Text	50		Name by which site is known
5	NJSP83	☐	☐	☐	Text	50		New Jersey State Projection 1983 coordinate for site location
6	Latitude	☐	☐	☐	Text	12		Latitude in degrees-minutes-seconds format
7	Longitude	☐	☐	☐	Text	12		Longitude in degrees-minutes-seconds format
8	HUC	☐	☐	☐	Text	14		14-digit hydrologic unit code that identifies the watershed in which a site is located
9	SiteComment	☐	☐	☐	Memo	-		Comment about a site

Table A-2. Characteristics of tblSample

Table Name	#Fields	#Recs	Last Updated:
tblSample	**13**	**267061**	11/20/00 8:31:47 A

Table Description: **Sample of field data or collected material at a particular site and time characterized by medium, method, equipment, and sample type**

	Field Name	PK	FK	Rqd	Type	Size	Default	Description
1	Sample_ID	☑	☐	☑	AutoNumber (Long)	4		Key that uniquely identifies an individual sample of data or material
2	SRowID	☐	☐	☐	Text	50		Code representing the source and row number from the original USGS National Water Information System import file
3	Site_ID	☐	☑	☑	Number (Long)	4		Key that uniquely identifies a site (place) where sampling occurs
4	SampleDateTime	☐	☐	☑	Date/Time	8		Date and time at which a sample was collected, in the format yyyy-mm-dd hh:mm:ss
5	HydrologicEvent_ID	☐	☑	☑	Number (Integer)	2	0	Key that uniquely identifies a hydrologic event
6	HydrologicCondition_ID	☐	☑	☑	Number (Integer)	2	0	Key that uniquely identifies a hydrologic condition
7	CollectingAgency_ID	☐	☑	☑	Number (Integer)	2		Key that uniquely identifies an agency involved in collecting or analyzing samples
8	SampleMedium_ID	☐	☑	☑	Number (Integer)	2	9	Key that uniquely identifies a medium which is sampled

Table A-2. Characteristics of tblSample--continued

9	SamplingMethod_ID	☐	☑	☑	Number (Integer)	2		Key that uniquely identifies a sampling method used to collect a sample or make a measurement
10	SamplingEquipment_ID	☐	☑	☑	Number (Integer)	2		Key that uniquely identifies a type of equipment used for sampling
11	SamplingIntervalGroup_ID	☐	☑	☑	Number (Integer)	2		Key that uniquely identifies a sampling interval group
12	SampleType_ID	☐	☑	☑	Number (Integer)	2	9	Key that uniquely identifies a sample type
13	SampleComment	☐	☐	☐	Memo	-		Comment about a sample that assists with evaluating results

Table A-3. Characteristics of tblResult

Table Name	#Fields	#Recs	Last Updated:
tblResult	**7**	**766711**	11/20/00 9:36:52 A

Table Description: **Result for a specific parameter in a sample from a field measurement or a laboratory analytical process**

	Field Name	PK	FK	Rqd	Type	Size	Default	Description
1	Result_ID	☑	☐	☑	AutoNumber (Long)	4		Key that uniquely identifies a result of measurement or analysis for a single parameter from a sampling event
2	Sample_ID	☐	☑	☑	Number (Long)	4		Key that uniquely identifies an individual sample of data or material
3	AnalyzingAgency_ID	☐	☑	☑	Number (Integer)	2		Key that uniquely identifies an agency involved in collecting or analyzing samples
4	Parameter_ID	☐	☑	☑	Number (Integer)	2		Key that uniquely identifies a parameter (characteristic or constituent)
5	ResultFlag_ID	☐	☑	☑	Number (Integer)	2	0	Key that uniquely identifies a ResultFlag qualifying a result
6	Result	☐	☐	☐	Number (Double)	8		Result (value) for a parameter from a field measurement or laboratory analysis of a sample
7	ResultComment	☐	☐	☐	Memo	-		Comment for a result to provide information about a value not covered by other result qualifiers

Table A-4. Characteristics of tdsHydrologicEvent

Table Name	#Fields	#Recs	Last Updated:
tdsHydrologicEvent	**3**	**14**	11/20/00 9:05:31 A

Table Description: **List of hydrologic event types for which sampling can be done**

	Field Name	PK	FK	Rqd	Type	Size	Default	Description
1	HydrologicEvent_ID	☑	☐	☑	Number (Integer)	2		Key that uniquely identifies a hydrologic event
2	HydrologicEventCode	☐	☐	☑	Text	1		USGS code used to identify a hydrologic event
3	HydrologicEvent	☐	☐	☑	Text	20		Hydrologic event name

Table A-5. Characteristics of tdsHydrologicCondition

Table Name	#Fields	#Recs	Last Updated:
tdsHydrologicCondition	**3**	**7**	11/20/00 8:32:40 A

Table Description: **List of hydrologic conditions under which sampling can be done**

	Field Name	PK	FK	Rqd	Type	Size	Default	Description
1	HydrologicCondition_ID	☑	☐	☑	Number (Integer)	2		Key that uniquely identifies a hydrologic condition
2	HydrologicConditionCode	☐	☐	☑	Text	20		USGS code used to identify a hydrologic condition
3	HydrologicCondition	☐	☐	☑	Text	20		Description of a hydrologic condition

Table A-6. Characteristics of tdsSampleMedium

Table Name	#Fields	#Recs	Last Updated:
tdsSampleMedium	**3**	**35**	11/20/00 9:38:12 A

Table Description: **List of media from which samples can be collected**

	Field Name	PK	FK	Rqd	Type	Size	Default	Description
1	SampleMedium_ID	☑	☐	☑	Number (Integer)	2		Key that uniquely identifies a medium which is sampled
2	SampleMediumCode	☐	☐	☑	Text	1		USGS code used to identify a sample medium
3	SampleMedium	☐	☐	☑	Text	40		Sample medium name

Table A-7. Characteristics of tdsSamplingMethod

Table Name	#Fields	#Recs	Last Updated:
tdsSamplingMethod	**3**	**9**	11/20/00 8:35:17 A

Table Description: **List of procedural methods used to obtain a sample**

	Field Name	**PK**	**FK**	**Rqd**	**Type**	**Size**	**Default**	**Description**
1	SamplingMethod_ID	☑	☐	☑	Number (Integer)	2		Key that uniquely identifies a sampling method used to take a sample or make a measurement
2	SamplingMethodCode	☐	☐	☑	Text	50		USGS code used to identify a sampling method
3	SamplingMethod	☐	☐	☑	Text	50		Sampling method description

Table A-8. Characteristics of tdsSamplingEquipment

Table Name	#Fields	#Recs	Last Updated:
tdsSamplingEquipment	**3**	**114**	11/20/00 8:34:40 A

Table Description: **List of equipment used for sampling**

	Field Name	PK	FK	Rqd	Type	Size	Default	Description
1	SamplingEquipment_ID	☑	☐	☑	Number (Integer)	2		Key that uniquely identifies a type of equipment used for sampling
2	SamplingEquipmentCode	☐	☐	☑	Text	10		USGS code used to identify equipment used for sampling
3	SamplingEquipment	☐	☐	☑	Text	70		Equipment used for sampling

Table A-9. Characteristics of tdsSamplingIntervalGroup

Table Name	#Fields	#Recs	Last Updated:
tdsSamplingIntervalGroup	**3**	**4**	11/20/00 9:38:41 A

Table Description: **List of sampling intervals which can classify a sample as part of a group**

	Field Name	PK	FK	Rqd	Type	Size	Default	Description
1	SamplingIntervalGroup_ID	☑	☐	☑	Number (Integer)	2		Key that uniquely identifies a sampling interval group
2	SamplingIntervalGroup	☐	☐	☑	Text	50		Sampling interval group name
3	SamplingIntervalGroupDescr	☐	☐	☑	Text	75		Sampling interval group description

Table A-10. Characteristics of tdsSampleType

Table Name	#Fields	#Recs	Last Updated:
tdsSampleType	**3**	**12**	11/20/00 8:34:27 A

Table Description: **List of types of samples that can be collected for a specific purpose**

	Field Name	PK	FK	Rqd	Type	Size	Default	Description
1	SampleType_ID	☑	☐	☑	Number (Integer)	2		Key that uniquely identifies a sample type
2	SampleTypeCode	☐	☐	☑	Text	1		USGS code used to identify a sample type
3	SampleType	☐	☐	☑	Text	20		Sample type name

Table A-11. Characteristics of tdsParameter

Table Name	#Fields	#Recs	Last Updated:
tdsParameter	**8**	**61**	11/21/00 11:50:56

Table Description: **List of parameters (characteristics or constituents) for which result measurements or estimates were made in a sample**

	Field Name	PK	FK	Rqd	Type	Size	Default	Description
1	Parameter_ID	☑	☐	☑	Number (Integer)	2		Key that uniquely identifies a parameter (characteristic or constituent)
2	PCode	☐	☐	☑	Text	6		USGS code used to identify a specific parameter in the National Water Information System
3	ParameterGroup	☐	☐	☑	Text	18		Group to which a parameter belongs (such as nutrient)
4	FieldOrLab	☐	☐	☑	Text	5		Identifies whether a parameter value is determined in the field or in a laboratory
5	Parameter	☐	☐	☑	Text	50		Name of parameter
6	Units	☐	☐	☑	Text	20		Reporting units for a result of a parameter measurement or laboratory analysis
7	ParameterAbbrev	☐	☐	☑	Text	10		Parameter abbreviation
8	ParameterDescr	☐	☐	☑	Text	120		Parameter description

Table A-12. Characteristics of tdsResultFlag

Table Name	#Fields	#Recs	Last Updated:
tdsResultFlag	**3**	**10**	11/20/00 8:33:47 A

Table Description: **List of flags for the qualification of individual parameter results**

	Field Name	PK	FK	Rqd	Type	Size	Default	Description
1	ResultFlag_ID	☑	☐	☑	Number (Integer)	2		Key that uniquely identifies a ResultFlag qualifying a result
2	ResultFlag	☐	☐	☑	Text	5		Flag used to qualify a parameter result
3	ResultFlagDescr	☐	☐	☑	Text	75		Description of flag used to qualify a parameter result

Table A-13. Characteristics of tdsAgency

Table Name	#Fields	#Recs	Last Updated:
tdsAgency	**5**	**5**	11/20/00 8:29:30 A

Table Description: **List of agencies or parties associated with the collection or analysis of a sample**

	Field Name	PK	FK	Rqd	Type	Size	Default	Description
1	Agency_ID	☑	☐	☑	Number (Integer)	2		Key that uniquely identifies an agency involved in collecting or analyzing samples
2	AgencyAbbrev	☐	☐	☑	Text	10		Agency abbreviation or code
3	Agency	☐	☐	☑	Text	50		Agency name
4	AgencyContact	☐	☐	☐	Text	50		Agency contact information
5	AgencyCode	☐	☐	☐	Text	50		USGS numeric code for an agency in the National Water Information System

Table A-14. Characteristics of tblDailySummary

Table Name	#Fields	#Recs	Last Updated:
tblDailySummary	**21**	**12340**	11/21/00 11:50:56

Table Description: **Summary of daily values for each parameter at each site; this table is generated by a query and does not require integrity constraints which are already applied to the transactional database design**

	Field Name	PK	FK	Rqd	Type	Size	Default	Description
1	Site_ID	☐	☐	☐	Number (Long)	4		Key that uniquely identifies a site (place) where sampling occurs
2	STAID	☐	☐	☐	Text	15		USGS site identification code
3	SiteName	☐	☐	☐	Text	50		Name by which site is known
4	SampleDate	☐	☐	☐	Date/Time	8		Date on which samples were collected
5	CollectingAgency	☐	☐	☐	Text	10		Abbreviation or code of an agency involved in collecting or analyzing samples
6	HydrologicEvent	☐	☐	☐	Text	20		Hydrologic event name
7	HydrologicCondition	☐	☐	☐	Text	20		Description of a hydrologic condition
8	SampleMedium	☐	☐	☐	Text	40		Sample medium name
9	SamplingMethod	☐	☐	☐	Text	50		Sampling method description
10	SamplingEquipment	☐	☐	☐	Text	70		Equipment used for sampling
11	SamplingIntervalGroup	☐	☐	☐	Text	50		Sampling interval group name
12	SampleType	☐	☐	☐	Text	20		Sample type name
13	AnalyzingAgency	☐	☐	☐	Text	10		Abbreviation or code of an agency involved in collecting or analyzing samples

Table A-14. Characteristics of tblDailySummary--continued

14	ParameterGroup	☐ ☐ ☐	Text	18	Group to which a parameter belongs (such as nutrient)
15	FieldOrLab	☐ ☐ ☐	Text	5	Identifies whether a parameter value is determined in the field or in a laboratory
16	Parameter	☐ ☐ ☐	Text	50	Name of parameter
17	Units	☐ ☐ ☐	Text	20	Reporting units for a result of a parameter measurement or laboratory analysis
18	N	☐ ☐ ☐	Number (Long)	4	Number of measurements used in the daily summary statistics
19	Minimum	☐ ☐ ☐	Number (Double)	8	Minimum result value reported within the daily summary for a parameter
20	Maximum	☐ ☐ ☐	Number (Double)	8	Maximum result value reported within the daily summary for a parameter
21	Mean	☐ ☐ ☐	Number (Double)	8	Mean result value reported within the daily summary for a parameter