Occurrence of Fecal-Indicator Bacteria and Protocols for Identification of Fecal-Contamination Sources in Selected Reaches of the West Branch Brandywine Creek, Chester County, Pennsylvania

by Peter J. Cinotto

In cooperation with the
Chester County Water Resources Authority and the
Chester County Health Department

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Contents

Contents—Continued

Figures

Figures—Continued

Table

Appendix 1 - Site Descriptions

Appendix 2 - Coatesville Study Reach Data Tables

Appendix 2 - Coatesville Study Reach Data Tables—Continued

Appendix 3 - Wagontown Study Reach Data Tables

Appendix 4 - Sandbag and Optical-Brightener Data Table

Appendix 5 - 2003 Streamflow-Gaging Station 01480617 Data Table

Conversion Factors and Datum

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
gallon (gal)	3.785	liter (L)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
Flow rate		
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
Mass		
pound, avoirdupois (lb)	0.4536	kilogram (kg)
Specific capacity		
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter [(L/s/m]
Hydraulic conductivity		
foot per day (ft/d)	0.3048	meter per day (m/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1988 (NAD 88).

Altitude, as used in this report, refers to distance above the vertical datum.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Concentrations of bacteria in water are given in colonies per 100 milliliters (col/100 mL), and concentrations in sediment are given in colonies per gram (col/g).

Abbreviations used in report:

<, less than
>, greater than
mL, milliliter
g, gram

Occurrence of Fecal-Indicator Bacteria and Protocols for Identification of Fecal-Contamination Sources in Selected Reaches of the West Branch Brandywine Creek, Chester County, Pennsylvania

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Abstract

The presence of fecal-indicator bacteria indicates the potential presence of pathogens originating from the fecal matter of warm-blooded animals. These pathogens are responsible for numerous human diseases ranging from common diarrhea to meningitis and polio. The detection of fecal-indicator bacteria and interpretation of the resultant data are, therefore, of great importance to water-resource managers. Current (2005) techniques used to assess fecal contamination within the fluvial environment primarily assess samples collected from the water column, either as grab samples or as depth- and (or) width-integrated samples. However, current research indicates approximately 99 percent of all bacteria within nature exist as attached, or sessile, bacteria. Because of this condition, most current techniques for the detection of fecal contamination, which utilize bacteria, assess only about 1 percent of the total bacteria within the fluvial system and are, therefore, problematic. Evaluation of the environmental factors affecting the occurrence and distribution of bacteria within the fluvial system, as well as the evaluation and modification of alternative approaches that effectively quantify the larger population of sessile bacteria within fluvial sediments, will present water-resource managers with more effective tools to assess, prevent, and (or) eliminate sources of fecal contamination within pristine and impaired watersheds.

Two stream reaches on the West Branch Brandywine Creek in the Coatesville, Pa., region were studied between September 2002 and August 2003. The effects of sediment particle size, climatic conditions, aquatic growth, environmental chemistry, impervious surfaces, sediment and soil filtration, and dams on observed bacteria concentrations were evaluated. Alternative approaches were assessed to better detect geographic sources of fecal contamination including the use of turbidity as a surrogate for bacteria, the modification and implementation of sandbag bacteria samplers, and the use of optical brighteners. For the purposes of this report, sources of bacteria were defined as geographic locations where elevated concentrations of bacteria are observed within, or expected to enter, the main branch of the West Branch Brandywine Creek. Biologic sources (for example, waterfowl) were noted where applicable; however, no specific study of biologic sources (such as bacterial source tracking) was conducted.

Data indicated that specific bacterial populations within fluvial sediments could be related to specific particle-size ranges. This relation is likely the result of the reduced porosity and permeability associated with finer sediments and the ability of specific bacteria to tolerate particular environments. *Escherichia coli* (*E. coli*) showed a higher median concentration (2,160 colonies per gram of saturated sediment) in the 0.125 to 0.5-millimeter size range of natural sediments than in other ranges, and enterococcus bacteria showed a higher median concentration (61,830 colonies per gram of saturated sediment) in the 0.062 to 0.25-millimeter size range of natural sediments than in other ranges. There were insufficient data to assess the particle-size relation to fecal coliform bacteria and (or) fecal streptococcus bacteria.

Climatic conditions were shown to affect bacteria concentrations in both the water column and fluvial sediments. Drought conditions in 2002 resulted in lower overall bacteria concentrations than the more typically wet year of 2003. *E. coli* concentrations in fluvial sediment along the Coatesville study reach in 2002 had a median concentration of 92 colonies per gram of saturated sediment; in 2003, the median concentration had risen to 4,752 colonies per gram of saturated sediment.

Symbiotic relations between bacteria and aquatic growth were likely responsible for increased bacteria concentrations observed within an impoundment area on the Coatesville study reach. This reach showed evidence of elevated aquatic growth and sharp increases in *E. coli* concentrations from upstream to downstream through the impoundment area in both 2002 and 2003. In 2003, *E. coli* concentrations within the waters column increased from 940 colonies per 100 milliliters upstream to 6,000 colonies per 100 milliliters at the dam crest. Given that these bacteria likely resulted from natural bacterial regrowth, the use of *E. coli* as an indicator of fecal contamination was severely impaired.

Variable environmental conditions along the West Branch Brandywine Creek made the common field-chemical parameters of specific conductance, temperature, pH, and dissolved oxygen ineffective and (or) impossible to use for the determination of inputs of fecal contamination. Extreme variations in

chemical gradients commonly were related to the urban/industrial signature of the watershed. For example, during base-flow sampling in 2002, specific-conductance values exceeding 1,000 microsiemens per centimeter observed in effluent from a local steel mill. This effluent raised the specific conductance within the West Branch Brandywine from just above 200 microsiemens per centimeter upstream from the outfall to just below 500 microsiemens per centimeter downstream from the outfall. These chemical gradients also, likely, had an effect on the initial colonization of bacteria, the formation of biofilms, and the persistence of certain types of bacteria along the study reach.

Data collected in 2003 indicated that nutrients increased during both base-flow and stormflow conditions along the Coatesville study reach. For example, during base-flow sampling in 2003, 20 pounds of phosphorus was shown to enter the West Branch Brandywine Creek along the Coatesville study reach. The largest contributors to this base-flow nutrient load were likely two wastewater-treatment facilities adjacent to the study reach. During stormflow sampling in 2003, 480 pounds of phosphorus was shown to enter the West Branch Brandywine Creek along the Coatesville study reach. Data, along with other research, indicated the largest contributor to this stormflow nutrient load was likely remobilized sediment originating from a large dam impoundment. These elevated nutrient concentrations were considered sufficient to promote accelerated aquatic growth along the reach.

Data collected in 2003 showed that wastewater constituents entered the West Branch Brandywine Creek largely from urban storm-sewer systems. Samples from the primary storm sewer for the city of Coatesville had detections for 20 of 69 wastewater constituents. These constituents included both strong and weak indicators of fecal contamination and generally indicated the storm-sewer system along the Coatesville study reach was a likely source of fecal-indicator bacteria and fecal contamination under base-flow conditions. By comparison, 5 constituents were detected in samples from the upstream end of the reach, and 10 constituents were detected in samples from the downstream end of the reach. During stormflow, numbers of detections were similar along the entire length of the study reach—five in samples from the upstream end, eight in samples from the center of the reach, and seven in samples from the downstream end of the reach. These data indicate that point sources (such as culverts and pipes, septic systems, and wastewater-treatment facilities) are not likely the origin of bacteria contamination during stormflow. The bacteria concentrations observed during stormflow events probably result from remobilized sessile bacteria stored within fluvial sediments. In this case, these bacteria should not be considered indicators of current fecal contamination.

Impervious surfaces were found to increase bacteria concentrations along the West Branch Brandywine Creek because contaminated runoff from impervious areas generally flows into, and is concentrated within, the confines of the local storm-sewer system. During 2002, storm-sewer outfalls draining impervious areas were associated with all major locations of elevated bacterial concentrations (greater than 1,200 colonies per gram of saturated sediment) in fluvial sediments. During 2003, wetter conditions and overall bacteria concentrations higher than in 2002 resulted in point sources of bacterial contamination becoming less pronounced; however, the storm-sewer system, draining adjacent impervious areas, was still observed to be the primary source of bacteria along the reach. Where stormwater and (or) other runoff from these areas was allowed to infiltrate and (or) flow through wetland and riparian buffers, bacteria concentrations were not observed to be elevated above background levels commonly observed throughout similar areas of the same reach.

Two run-of-the-river dams along the Coatesville study reach were evaluated for their effects on observed bacterial concentrations. These dams were shown to have greater or lesser effects on bacterial concentrations depending on the size of the structure and the capacity of the structure to impede flows. The smaller upstream dam had an approximate height of 3 feet and showed little observed effect on measured turbidity values; these data indicated that the dam did not effectively impede the flow of water or sediment within the West Branch Brandywine Creek. Consequently, this small dam did not show any observed effect on bacterial concentrations either upstream or downstream of the structure. The larger dam, near the middle of the reach, had an approximate height of 20 feet and showed greater effects on both turbidity and bacteria concentrations. The capacity of the larger dam to impede flows, combined with nutrients entering the reach, resulted in increased biologic activity throughout the impoundment area. Within this larger impoundment, enterococcus bacteria populations were observed to decrease sharply and *E. coli* bacteria populations were observed to increase sharply as flow approached the dam crest. All bacteria levels were then observed to drop to background levels, in both the water column and fluvial sediment, immediately downstream from the dam crest. Additional study is required to determine the cause for this rapid die off.

Turbidity was assessed as a potential surrogate for *E. coli* bacteria. Regression analysis indicated higher turbidity levels usually can indicate higher concentrations of bacteria (R^2 = 0.67), but the relation was too sporadic on the West Branch Brandywine Creek to use turbidity as a surrogate for estimated bacteria concentrations. Evaluation of data from individual base-flow and stormflow events resulted in variable and generally poor statistical relations between *E. coli* bacteria and turbidity (R^2 values ranged from 0.02 to 0.94).

Sandbag samplers were used in 2003 to determine their suitability for the assessment of fecal contamination. Sandbag samplers rely on the ability of bacteria to attach to surfaces and use the larger sessile bacteria populations instead of the more commonly used planktonic bacteria populations. *E. coli* bacteria concentrations observed in the sandbag samplers, after 1 week in place, were similar to those found within natural sediments collected concurrently. Enterococcus bacteria concentrations within the same sandbag samplers were not similar, and were generally lower, than those observed within the natural sediments. This discrepancy was likely because sand within the

samplers was sieved to a size that was likely too coarse for enterococcus bacteria to persist.

Optical-brightener samplers were installed along with each sandbag sampler. Optical brighteners are additives used in common household detergents; therefore, detection of optical brighteners, along with elevated fecal-indicator bacteria concentrations, strongly indicates a link to humans. Positive results for optical brighteners were detected only at the outfalls of two sewage-treatment facilities; because of treatment of the effluent from these facilities, these samples did not have elevated bacteria concentrations. The lack of additional positive results was largely because this method is not sensitive to low concentrations of optical brighteners.

Introduction

The presence of fecal-indicator bacteria indicates the potential presence of pathogens originating from the fecal matter of warm-blooded animals. These pathogens are responsible for numerous human diseases ranging from common diarrhea to meningitis and polio. Water contaminated with elevated levels of pathogens affects not only human health but also the economy of the surrounding region as fisheries, beaches, aesthetics, and water supplies are degraded. The detection of fecal-indicator bacteria and interpretation of the resultant data are, therefore, of great importance to water-resource managers.

Current (2005) methods used to assess fecal contamination within the **fluvial**[1] environment primarily analyze samples collected from the water column, either as grab samples or as depth- and (or) width-integrated samples. Two problems are present within this methodology. First, in nature approximately 99 percent of all bacteria are **sessile** or attached to surfaces within the environment (Potera, 1998); consequently, these bacteria are not well represented in samples from the water column that target primarily **planktonic** or free-floating bacteria. Second, direct fecal input into the fluvial system cannot explain widespread and consistent occurrences of bacteria within a watershed (Byappanahalli and others, 2003). Because of these problems, identification of sources of fecal contamination becomes problematic, and according to Nix and Merry (1990), current methods limit the ability to accurately and cost effectively assess the extent of fecal contamination in the fluvial environment.

All bacteria, such as *Escherichia coli* (*E. coli*) and (or) enterococci, possess the ability to attach to inorganic and organic surfaces such as rocks, pipes, fish, and (or) other surfaces. Bacteria detect the surface of an object by contact and disturbance of the cell envelope; this disturbance causes a genetic change or expression that allows the cell to attach to an object by means of polymeric fibers that anchor it to a surface (Geesey and others, 2003). These sessile bacteria are genetically different from planktonic bacteria because of the adhesion-induced genetic changes (Otto and Silhavy, 2002). Bacterial species also have been shown to preferentially attach within different environments and with specific partners (Costerton and others, 1999). This condition means the attachment process is not completely random, and natural sessile bacterial populations are not expected to be equally distributed throughout a watershed. Sediment particle size, available nutrients, predation, and other factors all may be important in the attachment of bacteria.

Subsequent to attachment, sessile bacteria excrete a slime coating and create what is known as a protective biofilm. The physical structure of a biofilm generally is described as patchy with many interstitial voids and channels that act as a circulatory system for the biofilm; water flows through these voids and channels delivering nutrients and exchanging metabolic products among the organisms within the biofilm (Davey and O'Toole, 2000). Bacteria and (or) other organisms within these protective biofilms have been shown by Davey and O'Toole (2000) and Costerton and others (1999) to function as a cooperative consortium, in a complex and coordinated manner, and to exhibit different patterns of gene expression within different regions of the biofilm. Simplified, this result means bacteria within biofilms can coordinate functions with other bacteria and (or) organisms in a symbiotic relation in which each organism is of benefit to the entire biofilm community. Biofilms commonly occur in nature; for example, Carol Potera (1998) stated, "In nature, 99 percent of all bacteria aggregate as biofilms—complex colonies composed of billions of bacteria that pool their resources to resist being killed by antimicrobial agents." Notable examples of biofilms are the slime coating on fish, the slippery film on rocks in streams, and the plaque that builds up on teeth. Biofilms also can pose a major health risk; the Center for Disease Control estimates that 65 percent of human bacterial infections involve biofilms (Potera, 1999). William Costerton found that because of the protective nature of biofilms, approximately 1,500 times more of an antimicrobial agent is needed to kill bacteria within biofilm than planktonic bacteria (in Potera, 1998).

As part of a cooperative program between the Chester County Water Resources Authority, Chester County Health Department, and the U.S. Geological Survey (USGS), a study was proposed in 2001 to identify potential sources of fecal-indicator bacteria within the West Branch Brandywine Creek, gain a better understanding of bacteria occurrence and distribution within the fluvial system, and develop protocols to assist water-resource managers in the detection of point and nonpoint sources of fecal contamination within the fluvial system. The initial scientific basis of this study was ongoing research conducted by Francy and Gifford (2002) that showed beach sand could have higher concentrations of bacteria than the adjacent lake water. Thus, the decision was made to focus the study on the relation of bacteria to fluvial sediment and, to a lesser

[1] Words that are in **bold** are found in the Glossary section at the back of this report.

extent, the water column. Initially, samples were collected during the summer of 2002. A determination was made, on the basis of those findings, to extend the study into 2003 with the goal of increasing the general understanding of bacterial response within the fluvial environment as well as developing updated fecal-indicator bacteria sampling and processing protocols. The second year of data collection was completed in the summer of 2003.

Purpose and Scope

This report describes the human and environmental factors affecting the occurrence and distribution of bacteria, identifies potential sources of fecal contamination, and presents modified sampling protocols for the detection of fecal-indicator bacteria in selected reaches of the West Branch Brandywine Creek. Sources of bacteria, for the purposes of this report, are defined as geographic locations where elevated concentrations of bacteria are observed within, or expected to enter, the main branch of the West Branch Brandywine Creek. The origins of bacteria from these sources are described to the fullest extent data will allow, for example, when analysis of wastewater constituents indicates an anthropogenic (human) source of fecal-indicator bacteria.

This study encompasses two reaches of the West Branch Brandywine Creek; one approximately 15,000-ft reach that flows through the city of Coatesville, Pa., and one approximately 2,500-ft reach that flows near Wagontown, Pa., approximately 1 mi upstream from the Coatesville reach. Samples were collected at various times from each of these two study reaches from September 2002 to August 2003 (summer and fall only). Samples were processed for a wide variety of constituents including *E. coli*, enterococcus, fecal coliform, and fecal-streptococcus bacteria; the field-chemical characteristics of specific conductance, pH, temperature, dissolved oxygen, and turbidity; and water-quality constituents including wastewater constituents and nutrients. In addition, in-stream samplers were modified from previous designs described by Nix and Merry (1990), installed throughout the Coatesville study reach, and processed for *E. coli*, enterococci, and optical brighteners. Streamflow was measured at two long-term (greater than 30 years) USGS streamflow-gaging stations along the Coatesville study reach and at additional sampling sites as required. Even though individual sections of this report may only discuss certain data, all collected data are presented in the report appendixes.

Description of Study Area

The West Branch Brandywine Creek in Chester County, Pa., is utilized heavily for water supply (potable, industrial, and livestock), irrigation, aesthetics, boating and fishing, wildlife water supply, and stocking of trout and other fish (warm-water, cold-water, and migratory) (Pennsylvania Department of Environmental Protection, 1999, p. 62). On the basis of these uses, as well as the potential for varied bacterial response to these uses, two stream reaches were selected for study on the West Branch Brandywine Creek (fig. 1). The primary study reach flows through a predominantly urban / industrial region in and below the city of Coatesville, Pa. The secondary study reach (less intensively sampled) is approximately 1 mi upstream from the Coatesville study reach; this reach flows through a predominantly forested region near Wagontown, Pa. For the purposes of this report, these reaches are termed the Coatesville study reach and the Wagontown study reach, respectively.

Coatesville Study Reach

The Coatesville study reach is on the West Branch Brandywine Creek as it flows through the city of Coatesville, the Borough of South Coatesville, and the Borough of Modena, in Chester County, Pa. (fig. 1). This reach drains approximately 55 mi^2 and is characterized by a largely urban or industrial land use/land cover adjacent to the study reach; however, areas of light to moderate residential and forested land use /land cover are present through the reach. Sewer systems in this region are not combined, and separate sanitary- and storm-sewer systems are present; however, the system is old (built in the 1930s) and signs of interconnection were observed. The Coatesville study reach is dominated by a steel mill that can be readily observed within the stream valley that has been heavily altered by historical industrial use and urban development. Evidence of channel relocation and flood-plain filling exists throughout the reach. For example, a major tributary that flows through the city of Coatesville, Pa. (Gibbons Run) was completely buried sometime between 1929 and 1946 and now serves as the main storm-sewer for the city of Coatesville, Pa. (fig. 2). These types of stream-channel relocation, burial, and modification were common practices throughout the industrial regions of Pennsylvania during the industrial revolution of the late 1800s and early 1900s.

Figure 1. Study area on West Branch Brandywine Creek, Chester County, Pennsylvania.

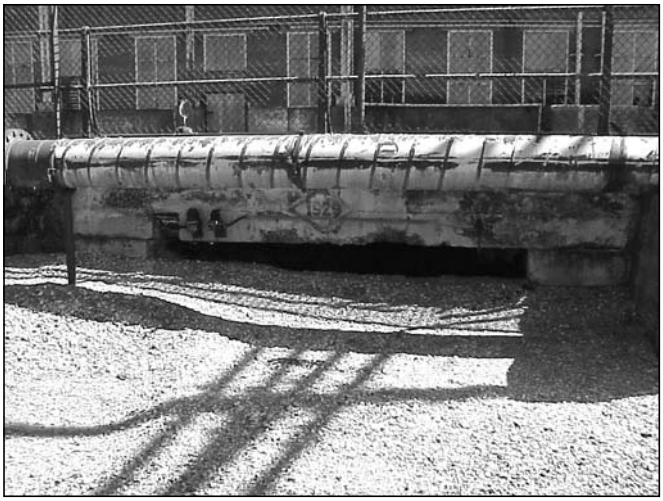


Figure 2. Headwall of 1929 bridge that previously spanned Gibbons Run, Coatesville study reach, West Branch Brandywine Creek, Chester County, Pennsylvania. (photograph by P.J. Cinotto, USGS)

Sixty-four base-flow sampling sites (fig. 3), 15 stormflow sampling sites (fig. 4), and 15 sandbag sampling sites (fig. 5) were located throughout the approximately 15,000-ft length of the Coatesville study reach (for precise locations of each site, station numbers, descriptions, and downstream order of these stations are presented in appendixes 1 and 4). Base-flow sampling sites were located throughout the main channel of the West Branch Brandywine Creek and at the confluences of all tributaries, at all major outfalls, and at various springs. Stormflow sampling sites and sandbag sites were at similar locations but with much less density. All sites were assigned a project identification number (in the order they were located), a location (latitude and longitude), and a station stream distance (distance along the stream channel from the upstream end of the study reach in feet). All sites also were assigned USGS site identification numbers and all data were entered into the USGS National Water Information System database (NWIS) as required by USGS protocol. Comprehensive site data describing all sampling locations within the Coatesville study reach are presented in appendixes 1 and 4, and all data collected are presented within appendixes 2, 4, and 5.

Wagontown Study Reach

The Wagontown study reach is on the West Branch Brandywine Creek as it flows near the town of Wagontown, in Chester County, Pa. (fig. 1). This reach drains approximately 37 mi^2 and is characterized by largely forested land cover adjacent to the reach with areas of light to moderate industrial and residential land use. In contrast to the Coatesville study reach, the Wagontown study reach has not been heavily altered (with the minor exception of various roadway construction projects such as the U.S. Route 30 bypass). Two regions, described as wetlands for the purposes of this report, are at the upstream and downstream ends of the Wagontown study reach. These areas were observed to be saturated with adjacent springs discharging through the streambanks into the West Branch Brandywine Creek. Both wetland areas are present in what appear to be abandoned (and partially filled in) channels resulting from the migration of the West Branch Brandywine Creek; no further wetland classification was completed within these areas. A light industrial facility that is a known historical source of untreated sewage entering the West Branch Brandywine Creek (D. Town, Chester County Health Department, oral commun., 2002) is adjacent to the Wagontown study reach. According to the Chester County Health Department, untreated sewage from this facility was discharged directly over the streambank and into the West Branch Brandywine Creek at irregular intervals, prior to about 2001, from an on-lot septic system.

Ten base-flow sampling sites were located throughout the approximately 2,500-ft Wagontown study reach (fig. 6); no storm samples were collected from this reach and no sandbag samplers were installed (precise locations of each site, station numbers, descriptions, and downstream order of these stations are presented in appendix 1). These sites were within the main channel of the West Branch Brandywine Creek and at various springs. All sites were assigned a USGS site identification number, a project identification number (in the order they were located), a location (latitude and longitude), and a station stream distance (distance along the stream channel from the upstream end of the study reach in feet). All data were entered into the USGS National Water Information System database (NWIS). Comprehensive site data for all sampling locations within the Wagontown study reach are presented in appendix 1, and all data collected are presented in appendix 3.

Previous Studies

Various studies previously collected data and (or) conducted research on fecal-indicator bacteria within the West Branch Brandywine Creek. An ongoing, biweekly data-collection program conducted jointly by the Chester County Health Department, Chester County Water Resources Authority, and the USGS (during warm-weather months from 1981 to the present) initially identified concentrations of fecal-indicator bacteria within the West Branch Brandywine Creek that exceeded the maximum acceptable concentration (200 col/100 mL) established by the Pennsylvania Department of Environmental Protection (1999). Subsequent to this detection by the biweekly program, an additional study was completed by Town (2001) that further defined stream reaches with elevated concentrations of fecal-indicator bacteria (greater than 200 col/100 mL) and, consequently, potential fecal contamination. The Coatesville study reach, as described in this report, was one of the stream reaches identified by Town as containing elevated concentrations of fecal-indicator bacteria.

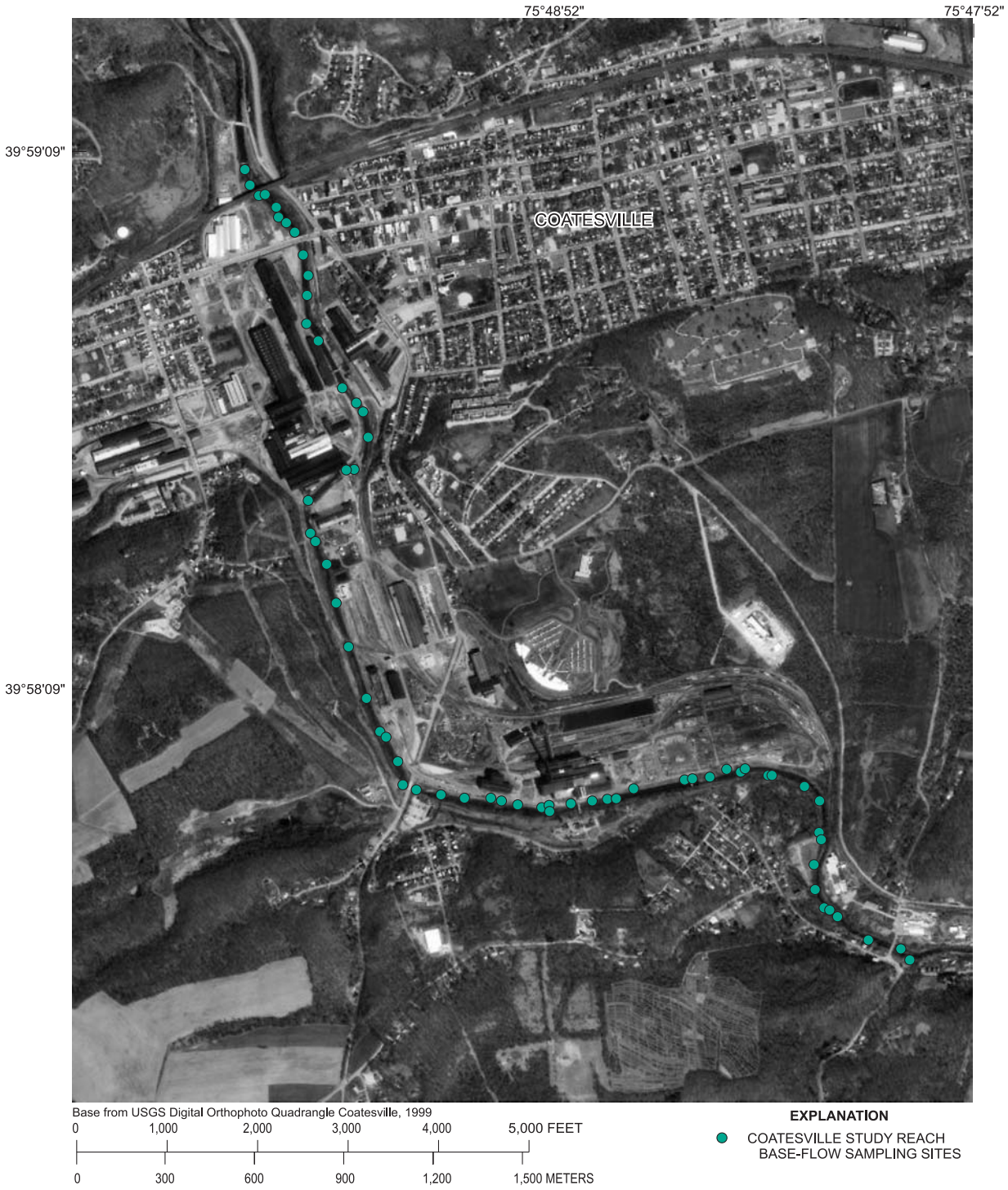


Figure 3. Base-flow sampling sites on the Coatesville study reach, West Branch Brandywine Creek, Chester County, Pennsylvania.

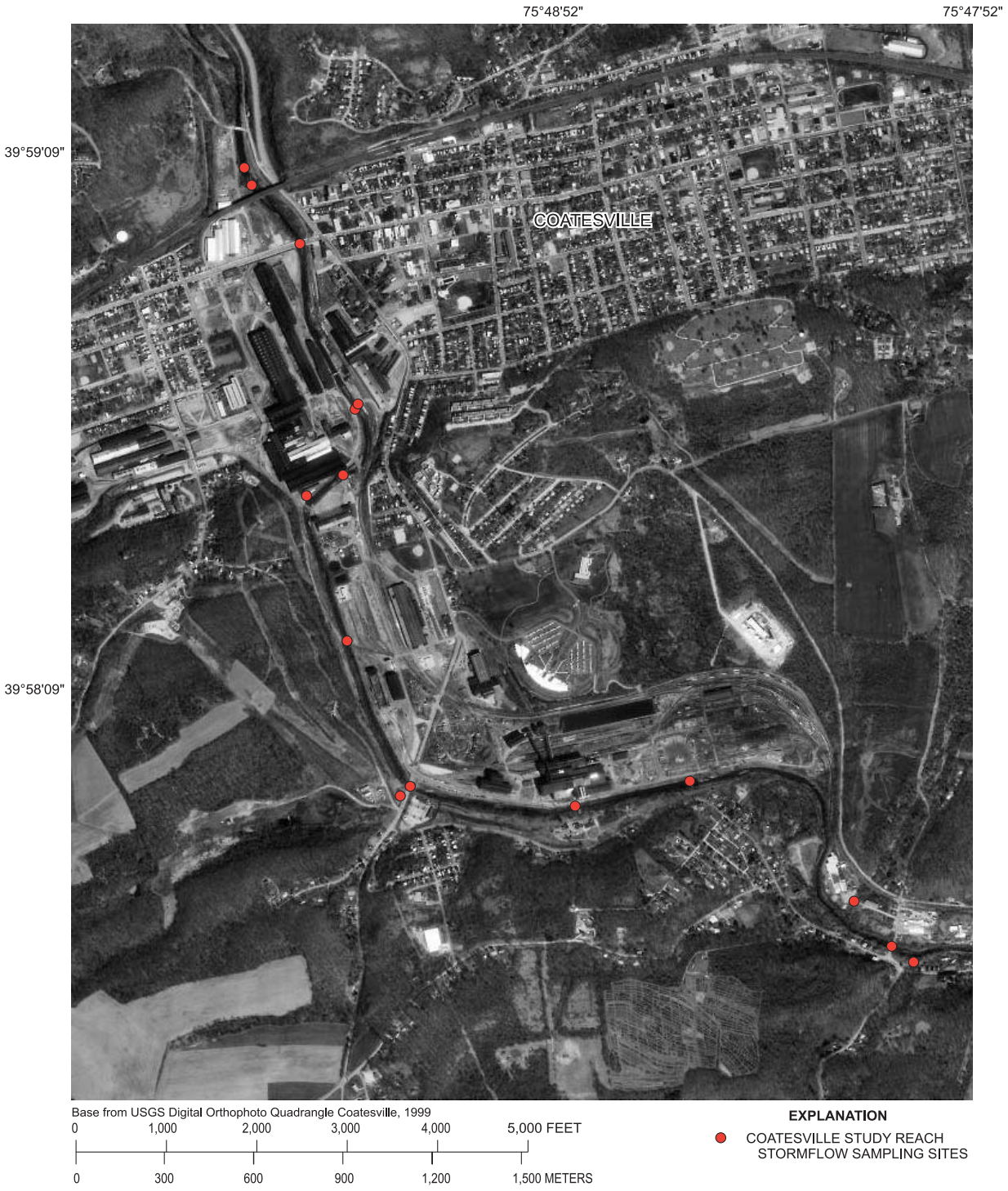


Figure 4. Stormflow sampling sites on the Coatesville study reach, West Branch Brandywine Creek, Chester County, Pennsylvania.

Figure 5. Sandbag sampling sites on the Coatesville study reach, West Branch Brandywine Creek, Chester County, Pennsylvania.

Figure 6. Base-flow sampling sites on the Wagontown study reach, West Branch Brandywine Creek, Chester County, Pennsylvania.

Methods of Sample Collection and Analysis

Samples were collected and processed for various bacteria in natural fluvial sediments, artificial sediments in samplers (sandbags), and the water column. Field chemistry including temperature, dissolved oxygen, pH, turbidity, and specific conductance was determined at each sampling location. Water-quality samples were collected from six sites along the Coatesville study reach and analyzed for wastewater constituents and nutrients. All samples were collected and processed according to USGS standard techniques, presented or cited below, unless alternative methods were developed; all alternative methods are described in detail.

Collection and Analysis of Bacteria Within the Water Column

Samples collected from the water column were analyzed for *E. coli*, enterococcus, fecal coliform, and fecal streptococcus bacteria using membrane filtration methods described in Myers and Wilde (1997) (table 1). Water samples were collected as a single-point grab sample with sterile 250-mL whirl-closure type plastic bags. The bag was submerged in the **thalweg** of the stream, opened, allowed to fill, quickly sealed, and placed on ice (fig. 7). Samples were transported within 6 hours to the Chester County Health Department Laboratory for filtration and analysis; all samples were incubated immediately after filtration. Results for all bacterial analyses are presented in the appendixes at the end of this report.

Collection and Analysis of Bacteria Within Fluvial and Artificial Sediments

Samples collected from fluvial sediments were analyzed for *E. coli*, enterococcus, fecal coliform, and fecal streptococcus bacteria using membrane filtration methods described above. Sediment samples were collected as single-point grab samples from wet, fluvial sediments exposed to flow from the potential fecal-contamination source in question; for example, from the bank or bed of a natural stream channel (fig. 8) or from within or near the mouth of a culvert. Sampling equipment consisted of a stainless-steel garden trowel rinsed in stream water before and after the collection of each sample. These samples were immediately placed in sterile 250-mL bags and transported on ice to the Chester County Health Department Laboratory along with samples collected from the water column.

No approved method for processing sediments for bacterial analyses is available; the method was, therefore, developed on the basis of discussions with numerous researchers while also considering the limitations of available laboratory equipment and personnel. Bacteria attach to sediments and must be mechanically removed. To accomplish this removal, the original sample was collected from wet sediments while attempting to minimize the amount of residual water transferred into the sterile sample bag with the sediment. This technique minimized the bacterial component associated with planktonic bacteria in the water column and focused on sessile bacteria attached to the sediments. Upon delivery to the Chester County Health Department Laboratory, the sediment sample was allowed to settle for approximately 30 minutes. After all fine sediments had settled out, the remaining water was decanted and discarded. Twenty grams of the remaining wet sediments were then added to a 100-mL volumetric flask and sterile de-ionized water was added until 100 mL of total volume was reached; note that project limitations did not allow for the utilization of standard

Table 1. Sample-processing protocols (from Myers and Wilde, 1997) for collected bacteria samples from the West Branch Brandywine Creek, Chester County, Pennsylvania.

[m-TEC, *Escherichia coli* media; m-E and EIA, enterococci media; m-FC, fecal coliform bacteria media; KF media, fecal-streptococcus bacteria media; °C, degrees Celsius]

Fecal-indicator bacteria (and media type)	Filter size (microns)	Ideal count range (colonies per filter)	Holding time	Incubation time and temperature
Escherichia coli (m-TEC)	0.45	20-80	6 hours	2 hours at 35.0°C and then 22 to 24 hours at 44.5°C (filter then transferred to urea substrate broth for 15 to 20 minutes before counting)
Enterococci (m-E and EIA)	.45	20-60	6 hours	48 to 50 hours at 41.5°C on m-E media. Transfer filter to EIA media for 20 minutes at 41.0°C before counting.
Fecal coliform bacteria (m-FC)	.65	20-60	6 hours	22 to 26 hours at 44.5°C
Fecal streptococcus bacteria (KF media)	.45	20-100	6 hours	48 to 50 hours at 35.5° +/– 0.5°C

Figure 7. U.S. Geological Survey personnel collecting bacteria sample from the water column in the West Branch Brandywine Creek, Chester County, Pennsylvania. (Photograph by P.J. Cinotto, USGS)

Figure 8. U.S. Geological Survey personnel collecting bacteria sample from fluvial sediments in the West Branch Brandywine Creek, Chester County, Pennsylvania. (Photograph by P.J. Cinotto, USGS)

buffering solutions for this dilution step; however, buffering solutions should be used for future analysis. This diluted mixture was shaken by hand for 45 seconds and then allowed to settle for 30 seconds; note that consistency could likely be improved in future analyses by implementing a wrist-action shaker (or equivalent) with a standardized rate of shaking. The resultant solution was analyzed by membrane-filtration methods, as would a water-column sample. Results for all bacterial analyses are presented in the appendixes at the end of the report.

The initial dilution factor for the solution created from the combination of natural, fluvial sediment and sterile de-ionized water (as noted above) was computed on the basis of the submerged specific weight (γ_S) of fluvial sediment (commonly used in sediment transport and geomorphic analyses). This dilution factor was required because, given laboratory limitations and the large number of samples to be processed, determining dilution factors by weight was impractical. Specific weight is defined as the weight of a material divided by the weight of the water it displaces; therefore, submerged specific weight of fluvial sediment is simply defined as the specific weight of quartz (2.65) minus the specific weight of water (1.00), or 1.65. Quartz is commonly used in this type of equation because it is the most common mineral found in fluvial sediments. On the basis of this submerged specific weight, the initial dilution factor was established as shown in the example below (note that the ~ symbol, called a tilde, means the value is approximate). Subsequent dilutions were simple dilutions based on the volume of water analyzed by routine membrane-filtration techniques (filtering more or less water through each filter).

20 g of fluvial sediment / 1.65 =
~12.12 mL of fluvial-sediment volume

100 mL of total volume - 12.12 mL fluvial sediment volume =
~87.88 mL of water volume or ~87.88 g

20 g of fluvial sediment /107.88 g total weight (20+87.88) =
0.185 = fraction of sample that is sediment 1.0/0.185 = 5.405 =
dilution factor

With proper significant figures, this calculation yields an approximate dilution factor of 5.4 for natural, fluvial sediments.

As a check of the computed dilution factor above, a sample of sieved, general-purpose construction sand (0.5 - 1.0 mm) was saturated and allowed to drain by gravity. Ten replicates of this saturated, sieved sand were prepared, whereby 20 g were added to a volumetric flask and then diluted to 100 mL with sterile, de-ionized water (as would occur during normal laboratory analysis). During this process, all weights and volumes were closely measured. On the basis of these measurements, the volume of 20 g of saturated, sieved sand was determined to yield approximately 10.62 mL in volume with a standard deviation of 0.17 mL. Using this value in the above dilution-factor equation yields a dilution factor of 5.469 (or 5.5 with proper significant figures) for the sieved, saturated sand. Given that some level of inherent error is in this technique, this slight difference was considered reasonable and expected.

Even though the method described above of processing natural, fluvial-sediment samples is reasonably accurate, the method for calculating the dilution factor potentially reduces precision and, likely, introduces some error into the final reported value of colonies of bacteria per gram of saturated sediment. The primary problem is that fluvial sediments in the Coatesville, Pa., region generally are not composed of a pure, homogeneous sand; less dense organic matter, other mineral types of various specific weights, and irregular particle sizes can and do affect the overall dilution factor. Although some precision was undoubtedly sacrificed by this method, the overall accuracy of the analysis for detection of fecal-indicator bacteria is still reliable. Because of the natural lack of homogeneity in bacterial populations within the environment, all bacterial anal-

yses have an inherent lack of precision. In an attempt to increase the precision of the analysis and simplify sampling techniques, a solution was derived on the basis of the work of Nix and Merry (1990). In this method, fine-mesh nylon bags (made of nylon stockings) were filled with steam-sterilized, sieved sand and placed in the flow of the water column to be analyzed. This method will be described in detail later; however, the homogeneity (both size and composition) of the sieved sand generally assists in increasing the precision of the analysis.

Field Chemistry

Chemical measurements were made for temperature, dissolved oxygen, pH, turbidity, and specific conductance at all sites where bacteria samples were collected. Field-chemical measurements were made using a YSI water-quality sonde (fig. 9). The water-quality sonde was calibrated daily according to manufacturer's instructions and checked against standards before and after each calibration; all measurements with the water-quality sonde were recorded only after readings had stabilized. Where possible, multiple measurements were made from a cross section perpendicular to streamflow; however, where flow was limited, as from a small outfall, a single-point measurement was made. Multiple results from a cross section for temperature, turbidity, and specific conductance were averaged; the median value was used for dissolved oxygen and pH. Results for all field-chemical measurements are presented in the appendixes at the end of the report.

Water-Quality Samples

Water samples from selected sites on the Coatesville study reach were analyzed during the 2003 field season to detect potential wastewater constituents and (or) nutrients. Samples from five sites were collected during base flow, and samples from three sites were collected during a storm event. One blank sample was sent to the laboratory with base-flow samples to detect potential "false positive" results caused by contamination during the sampling process. Collection and transport of these samples was completed following guidelines established in USGS Techniques of Water-Resources Investigations Reports (TWRI) (U.S. Geological Survey, various years) and USGS National Water-Quality Laboratory documentation (U.S. Geological Survey, 2003). Results for all water-quality samples are presented in the appendixes at the end of the report.

Figure 9. U.S. Geological Survey personnel recording field-chemical measurements in Coatesville study reach, 2002, West Branch Brandywine Creek, Chester County, Pennsylvania. (Photograph by P.J. Cinotto, USGS)

Quality Assurance / Quality Control

Quality-assurance and quality-control techniques were applied to the collection of bacteria samples from the water column and sediments, field chemical measurements, and water-quality samples following, as possible, published USGS guidelines (U.S. Geological Survey, various years), and USGS National Water-Quality Laboratory documentation (U.S. Geological Survey, 2003). Some sampling procedures were created as part of this study and, consequently, quality-assurance and quality-control procedures were developed as required. Bacteria grab samples from the water column were collected utilizing sealed, sterile whirl-closure bags that were opened below the water surface; these bags were then immediately stored on ice. Fluvial-sediment samples were collected using a stainless steel trowel to scoop the fluvial-sediment samples and place them in the whirl-closure bags. This trowel was thoroughly washed in the streamwater adjacent to each site prior to sample collection; however, the trowel was not sterilized with bleach. Field chemistry was measured with a multi-parameter YSI water-quality sonde calibrated daily according to manufacturer's specifications. Data from the sonde also were compared to a present water-quality monitor at USGS streamflow-gaging station 01480617 (West Branch Brandywine Creek at Modena, Pa.) when samples were collected adjacent to this station. Water-quality samples were collected and sent to the USGS National Water-Quality Laboratory per guidelines noted above. An additional field blank sample was sent with samples from the base-flow sampling event to detect and prevent false-positive results. Data for the field blank sample are presented in appendix 2 along with other sample data. Laboratory surrogates (samples with a known concentration of a specific analyte) also were analyzed along with wastewater samples from the West Branch Brandywine Creek. These recoveries (presented in percentages) are listed along with sample values in appendix 2 and give an indication of the accuracy and precision of the analysis. Other quality-assurance and quality-control techniques were performed at the National Water-Quality Laboratory as part of routine analysis. Data from these processes are available upon request from the National Water-Quality Laboratory; however, any sample data determined to be outside of established National Water-Quality Laboratory quality-control limits are not released from the National Water-Quality Laboratory without specific disclaimers that are noted, as applicable, throughout the text.

Relation of Bacteria to the Fluvial Environment in the West Branch Brandywine Creek and Its Tributaries

Human and Environmental Factors Potentially Affecting Concentrations of Bacteria in the West Branch Brandywine Creek and Its Tributaries

The West Branch Brandywine Creek, as stated above, is diverse; adjacent land use, chemical composition of stream water, geology, and (or) geomorphology all vary dramatically throughout the watershed. Data collected during 2002 and 2003, as well as data from other research, indicated that particle distribution (grain size and sorting), moisture, symbiotic relations with other organisms, water chemistry, land cover, sediment and soil filtration, stream gradient (dams), and (or) competition for available resources all are important factors in bacterial contamination and the persistence of those bacteria within the water column and sediments of the fluvial system. These factors, as well as applicable data and citations, are described in detail below.

The use of specific bacteria as an indicator of fecal contamination is totally dependent on the idea that these bacteria are only found in the presence of fecal contamination; however, data presented below indicate that these bacteria may be present within the environment independent from fecal contamination. Therefore, interpretation of this, or any, bacteria data must be tempered with knowledge of the origin, or potential origin, of those bacteria before they should be considered "fecal indicators."

In effect, bacteria within the fluvial system may be strongly related to fecal contamination, only slightly related to fecal contamination (as in remobilized bacteria), or not related to fecal contamination at all (as in bacterial regrowth). Interpretations of any bacteria data attempting to determine fecal contamination must be based on assessment of the specific environment. For example, high bacteria concentrations with another indication of fecal contamination (such as a positive test for certain wastewater constituents) are likely fecal sources; if the inferred source is sediment resuspension, then there is less confidence because the fecal source may be no longer present or the source could be bacterial regrowth; and if there is an inferred biotic response (regrowth), then there is likely no relation to fecal contamination.

Particle Distribution of Sediments

Fluvial sediment samples were collected in 2002 and 2003 throughout the Coatesville and Wagontown study reaches (specific details are presented in appendix 2 and 3, respectively); these sediments were analyzed by membrane-filtration methods for bacteria including *E. coli*, enterococcus, fecal coliform, and fecal streptococcus bacteria. The dominant particle size was visually estimated for each sample by use of a commercially available sand-gauge card (fig. 10). Sand-gauge cards commonly are used in geomorphic and sediment-transport studies and generally provide a reliable estimation of particle size; however, it should be noted that the precision and accuracy of these determinations is less than would be obtained by sieve analysis. Of all fluvial-sediment samples collected, 116 were analyzed for *E. coli*, 55 were analyzed for enterococci, 10 were analyzed for fecal coliform bacteria, and 10 were analyzed for fecal streptococcus bacteria. Sample populations were too small to make conclusions about fecal coliform bacteria and fecal streptococcus bacteria concentrations within specific particle-size ranges; however, *E. coli* bacteria had higher median concentrations in the particle-size range of 0.125 to 0.5 mm (fine to medium sand) than in other particle-size classes (fig. 11), and enterococcus bacteria had higher median concentrations in the particle-size range of 0.062 to 0.25 mm (silt and clay to fine sand) than in other particle-size classes (fig. 12).

It must be noted that the sample populations within certain particle-size ranges were small (as noted by the number of observations presented in figures 11 and 12, respectively) and, therefore, statistically limited; for example, only 1 *E. coli* sample fell within the 2-4 mm particle size range. These small sample populations were largely because the natural particle distribution within the fluvial environment is driven by the energy available to transport the particles; therefore, different streams will have different sediment characteristics as will different reaches along the same stream. For example, if a stream is steep and fast, and generally capable of washing away all the fine sediment, one would expect to find few fine sediments in any of the samples. Further data are, therefore, required from other fluvial environments to refine the present data sets and also determine if a broad comparison between fluvial systems is possible or if these data are valid only for the West Branch Brandywine Creek. Also of note is that whereas the quartile distributions for the *E. coli* data set were visually similar; the quartile distributions for the enterococci data set were visually varied. This type of quartile variation (as observed by comparing the enterococci data presented in figure 12 to the *E. coli* data presented in figure 11) generally indicates a less significant relation among the means of each particle-size range and, therefore, these data should be interpreted with caution; however, no specific statistical tests were performed to validate this. Whereas a larger, future enterococci data set may reduce this problem, the variation observed within these data sets indicates that enterococci species may simply have more natural variation in the environments they prefer to colonize than do *E. coli*. Due in part to these small populations, variable data, and lack of statistical analyses, comparisons of particle-size classes, for example, comparing *E. coli* and enterococci concentrations within the 0.125 to 0.5 mm particle-size range, must be considered in absolute terms and used with great caution.

Data collected during this study indicate that particle distribution (grain size) is a potential factor affecting bacteria concentrations within fluvial sediments; other studies also have suggested similar conclusions. Studies such as Alm and others (2003) and Whitman and Nevers (2003) have suggested varia-

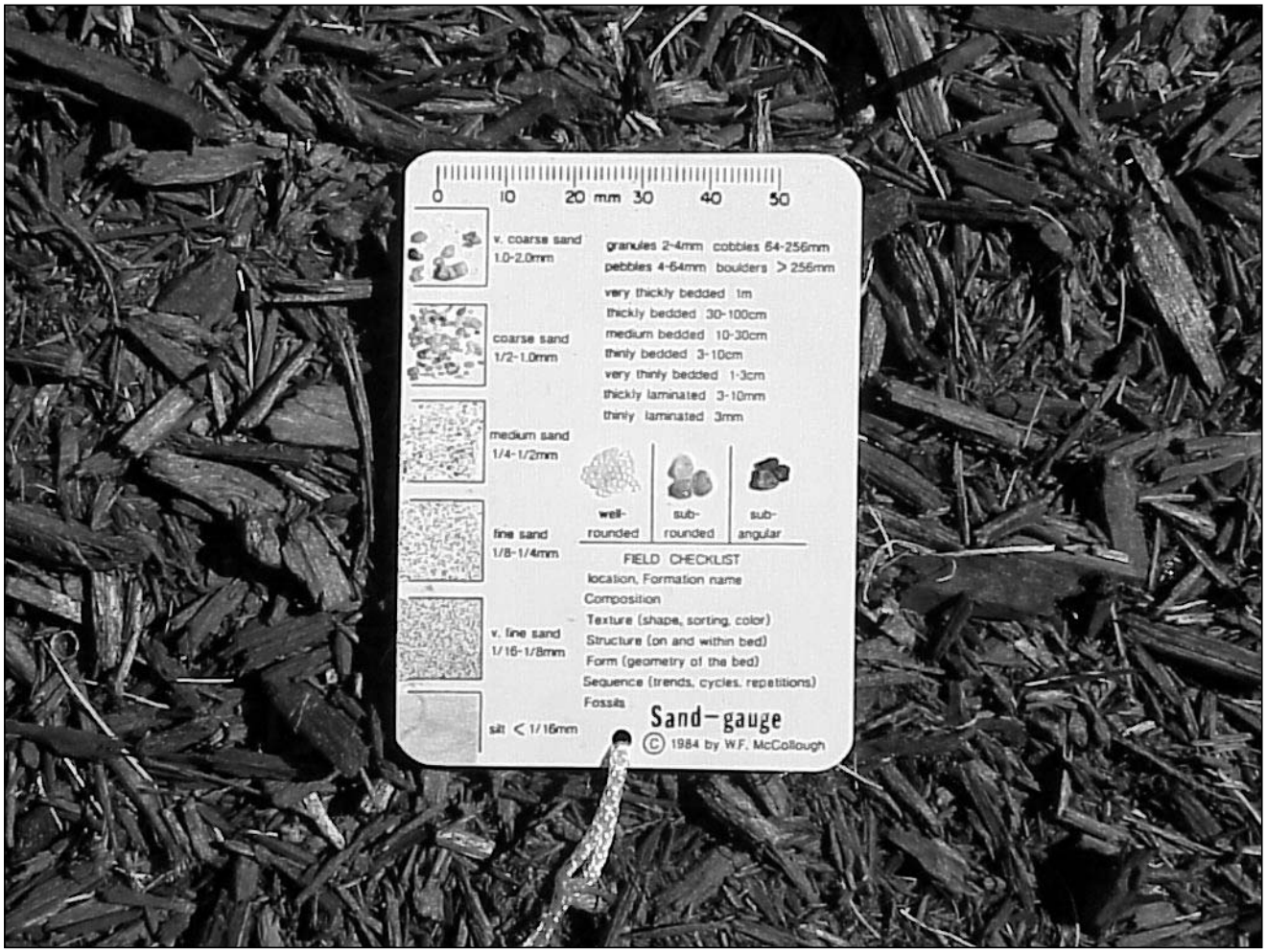
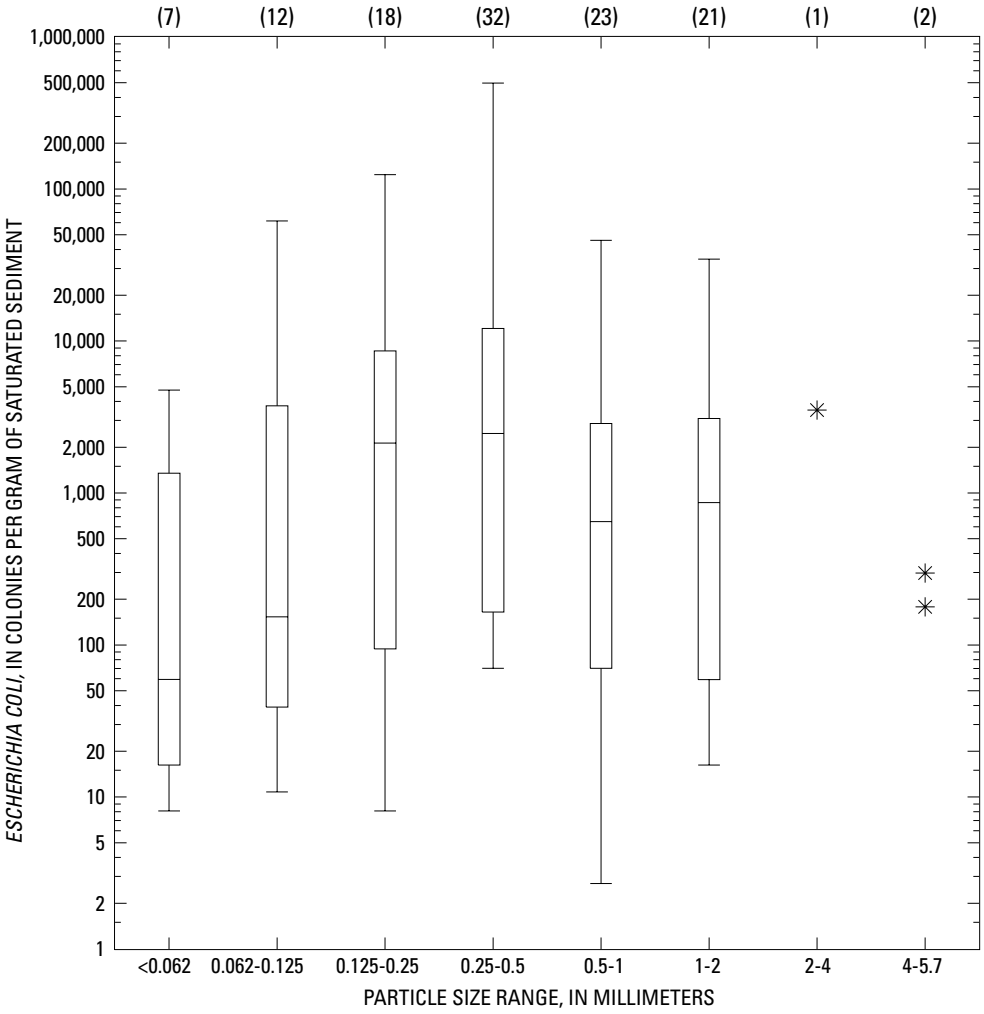


Figure 10. Sand-gauge card used for visual estimation of sediment particle size. (Photograph by P.J. Cinotto, USGS)

tions between bacteria concentrations may be present among different particle-size ranges (commonly between coarse beach sand and finer, deep-water, **lacustrine** sediments). These findings also would seem to support the findings of Davey and O'Toole (2000) that showed biofilms require water to flow through interstitial voids in order to supply nutrients and remove waste; any such flow would be severely impaired by the reduction in porosity and permeability associated with finer sediments. Conversely, very coarse sediments may not provide sufficient protection from the environment to allow the persistence of a substantial concentration of bacteria; for example, with too much exposure, bacteria may be subject to the effects of sunlight inactivation, protozoan grazing, and (or) other effects (Alm and others, 2003).

Climatic Conditions

Rainfall and the subsequent streamflows during 2002 were at all-time lows for much of the northeastern United States including Chester County, Pa. The West Branch Brandywine Creek had the lowest flows on record during the summer of 2002. Comparison of the streamflows during base-flow sampling in 2002 to the $Q_{7\text{-}10}$ statistic (7-day, 10-year low-flow statistic or the average minimum streamflow expected for 7 consecutive days once every 10 years) illustrated the conditions under which the samples were collected. The $Q_{7\text{-}10}$ for USGS streamflow-gaging station 01480500 (West Branch Brandywine Creek at Coatesville, Pa.) was 7.7 ft^3/s as of October 2003; the streamflows during base-flow sampling in 2002 ranged from only 4.4 ft^3/s on September 12, 2002, to 6.5 ft^3/s on September 18, 2002. Base-flow sampling in 2003 took place during a more typical year with streamflows ranging from 40 to 71 ft^3/s along the same reach of stream.



EXPLANATION

ESCHERICHIA COLI DISTRIBUTION

(7) NUMBER OF OBSERVATIONS

✳ OUTLIER DATA VALUE LESS THAN OR EQUAL TO 3 AND MORE THAN 1.5 TIMES THE INTERQUARTILE RANGE OUTSIDE THE QUARTILE

DATA VALUE LESS THAN OR EQUAL TO 1.5 TIMES THE INTERQUARTILE RANGE OUTSIDE THE QUARTILE

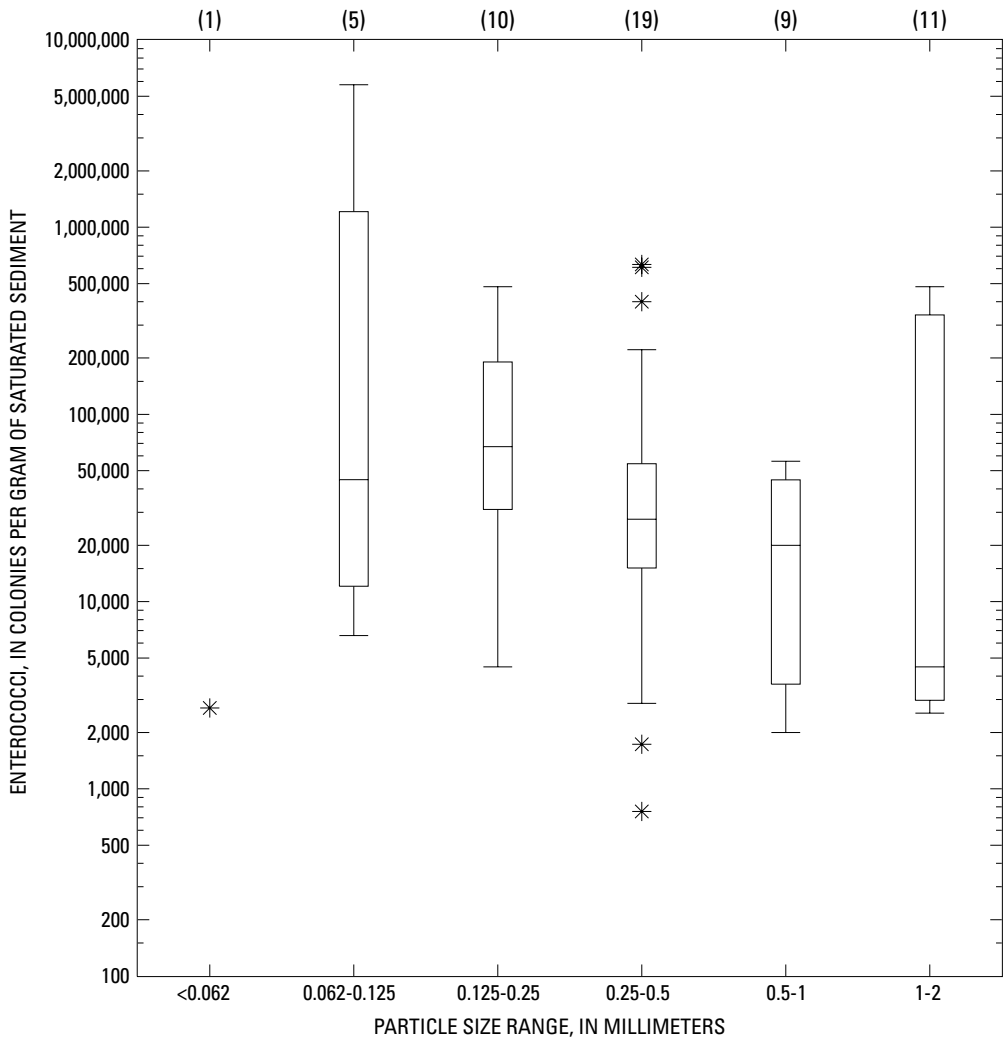
75TH PERCENTILE

MEDIAN

25TH PERCENTILE

< LESS THAN

Figure 11. Distribution of *Escherichia coli* in fluvial sediment, by particle-size range, West Branch Brandywine Creek, Chester County, Pennsylvania.



EXPLANATION

ENTEROCOCCI DISTRIBUTION

(1) NUMBER OF OBSERVATIONS

✳ OUTLIER DATA VALUE LESS THAN OR EQUAL TO 3 AND MORE THAN 1.5 TIMES THE INTERQUARTILE RANGE OUTSIDE THE QUARTILE

DATA VALUE LESS THAN OR EQUAL TO 1.5 TIMES THE INTERQUARTILE RANGE OUTSIDE THE QUARTILE

75TH PERCENTILE

MEDIAN

25TH PERCENTILE

< LESS THAN

Figure 12. Distribution of enterococci in fluvial sediment, by particle-size range, West Branch Brandywine Creek, Chester County, Pennsylvania.

Concentrations of *E. coli* within fluvial sediments of the Coatesville study reach were generally higher under base-flow conditions in 2003 (median concentration of 4,752 col/g of saturated sediment) than in 2002 (median concentration of 92 col/g of saturated sediment) (fig. 13). These findings are related to research conducted by Byappanahalli and others (2003) that showed a strong positive correlation between moisture content in sediment and bacteria concentrations. Whereas not substantiated by this study, the increased moisture (likely the increased duration of wetted periods) of the bank materials and overbank regions likely has some positive effect on bacteria concentrations within the localized region of the active stream channel.

Concentrations of bacteria in the water column also were substantially higher in the West Branch Brandywine Creek under base-flow conditions in 2003 than in 2002 (fig. 14). Numerous studies, such Gregory and Frick (2000), have indicated that wetter antecedent conditions (more rainfall) elevate

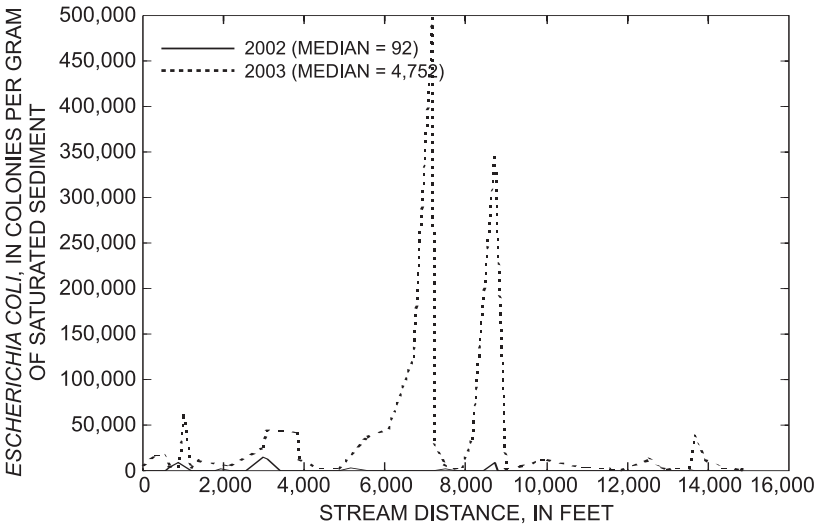


Figure 13. *Escherichia coli* in fluvial sediment, Coatesville study reach, 2002 and 2003, West Branch Brandywine Creek, Chester County, Pennsylvania.

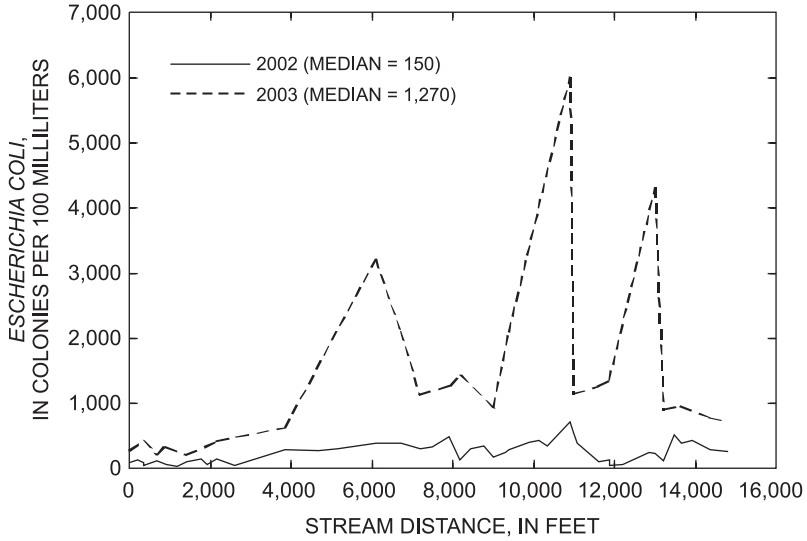


Figure 14. *Escherichia coli* in the water column, Coatesville study reach, 2002 and 2003, West Branch Brandywine Creek, Chester County, Pennsylvania.

bacteria concentrations within the fluvial system; although more data are required to substantiate these findings, wetter climatic conditions will also likely result in higher bacteria concentrations throughout the fluvial environment of the West Branch Brandywine Creek.

It should be noted that runoff patterns from the surrounding watershed undoubtedly affect bacteria concentrations within the water column under any given climatic condition; however, mobilization of stream sediments containing elevated bacteria concentrations likely adds to this bacteria load. Given this condition, storm events during wet periods can likely mobilize (erode) these more highly contaminated sediments from near-bank regions and, thus, cause wet-period storm samples from the water column to have higher concentrations of bacteria than would be expected during drier years. However, this may not occur consistently because, as was noted above, runoff patterns may vary from storm to storm.

Aquatic Growth in the Water Column and Sediments

As noted above, the West Branch Brandywine Creek was under severe drought conditions during 2002. These conditions had the effect of reducing the energy available within the stream to transport sediment; thus, turbidity resulting from the transport of sediment also was reduced. The normal, large sediment loads of the West Branch Brandywine Creek commonly mask subtle variations in turbidity that may be attributed to such factors as increased aquatic growth within dam impoundments (J.D. Newbold, Stroud Water Research Center, oral commun., 2003) and (or) various clear-water inputs from the numerous outfalls present along the reach.

During base-flow sampling in 2002 along the Coatesville study reach, a subtle increase in turbidity was clearly visible within the impoundment of a relatively large, **run-of-the-river dam** (locally known as Dam #4) (fig. 15). This subtle increase ranged from 3 NTU (nephelometric turbidity units) above the dam to 5 NTU at the dam crest. Along with the increased turbidity attributed to increased aquatic growth, a sharp increase in *E. coli* concentration also was measured (180 col/100 mL above the dam to 710 col/100 mL at the dam crest); however, no point sources of fecal-indicator bacteria, including appreciable populations of waterfowl, were found in or around the dam impoundment area. Data from the same impoundment the following year (2003) showed a more typical decrease in turbidity (11 NTU above the dam to 6 NTU at the dam crest) as sediment loads settled out in the quiescent water of the impoundment area. These data indicated that any increases in turbidity resulting from aquatic growth were masked by turbidity resulting from increased sediment loads. During 2003, however, the sharp increase in *E. coli* concentration was again observed through the impoundment area of Dam #4 although in a much higher concentration than the previous year (940 col/100 mL above the dam to 6,000 col/100 mL at the dam crest) (fig. 16). The repetition of the elevated concentration of *E. coli* within the dam impoundment indicated that similar processes were taking place in 2002 and 2003 regardless of variations in turbidity.

Research conducted by McFeters and others (1978) studied the causes of elevated bacteria concentrations in an unpolluted, pristine stream in Wyoming; their data showed populations of various coliform bacteria increased from 2 to 3 orders of magnitude at 13°C when grown in sterile algal supernatant (*Chlorella*). Similarly, research by Whitman and others (2003) showed *E. coli* and enterococci were ubiquitous in algal mats along Lake Michigan beaches, and these bacteria could survive over 6 months in sun-dried algal mats stored at 4°C. Each of these studies suggested algal growth may be related to an important natural source of bacteria and that the increased concentrations of *E. coli* observed within the impoundment area of Dam #4 may be simply because of an associated increase in algal growth and not fecal contamination. It should be noted that this theory is not widely accepted; some researchers (D.S. Francy, U.S. Geological Survey, oral commun., 2003) sug-

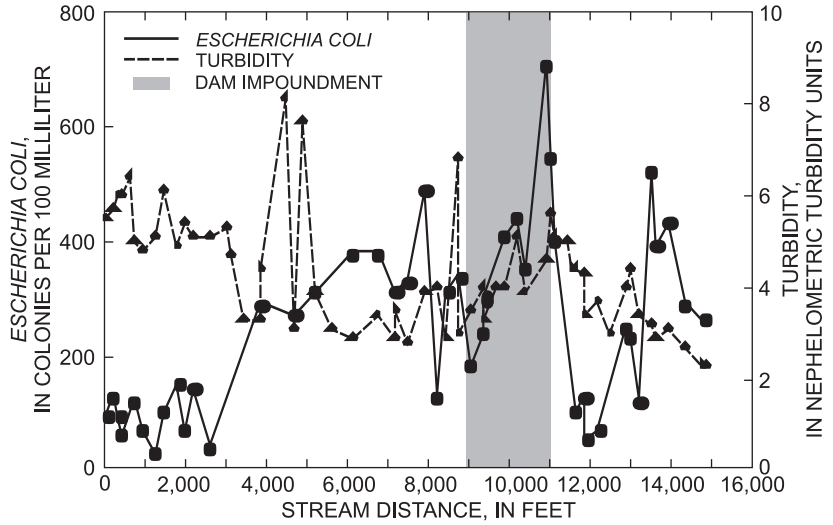


Figure 15. *Escherichia coli* and turbidity in the water column during base-flow conditions, Coatesville study reach, 2002, West Branch Brandywine Creek, Chester County, Pennsylvania.

gested such bacterial regrowth is not likely and that the observed, elevated bacteria concentrations were simply because of direct fecal inputs from unidentified sources. Additional study would be required to confirm the presence or absence of bacterial regrowth within the impoundment area of Dam #4.

Samples from the impoundment area of Dam #4 also were processed for enterococcus bacteria in 2003. Analysis of these data showed that, while *E. coli* concentrations increased through the dam impoundment area, enterococci concentrations decreased sharply (fig. 17). These findings suggest that different processes were acting on enterococci and *E. coli* within the impoundment area of Dam #4. Whitman and others (2003) found, conversely, that enterococci and *E. coli* increased in a similar manner within algal mats in Lake Michigan (the algae was mostly *Cladophora glomerata*). Assuming bacterial regrowth is possible and is taking place within this impoundment, these data indicated an algae/ bacteria symbiotic relation, similar to that found in Lake Michigan, may not be present within the impoundment area of Dam #4. It must be noted, however, that other factors, such as predation, may have also lead to the observed decrease in the enterococci population within the impoundment area of Dam #4. Predation is a common cause of selective bacterial population decreases (Banning and others, 2003) and, therefore, the observed decreases in the population of enterococci may have been simply because of this process. Whereas further study is required to accurately define these processes, the different response exhibited by *E. coli* and enterococci within the same environment indicates a strong correlation between the two bacterial populations is unlikely within the West Branch Brandywine Creek.

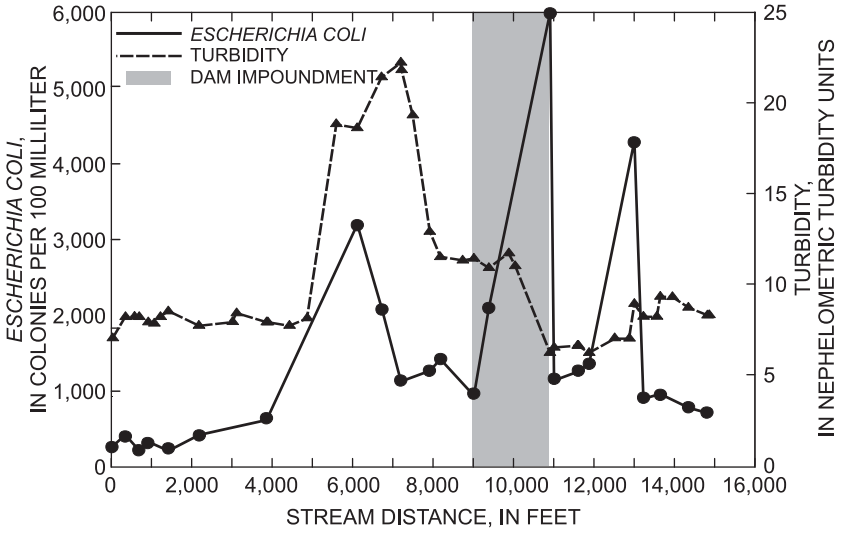


Figure 16. *Escherichia coli* and turbidity in the water column during base-flow conditions, Coatesville study reach, 2003, West Branch Brandywine Creek, Chester County, Pennsylvania.

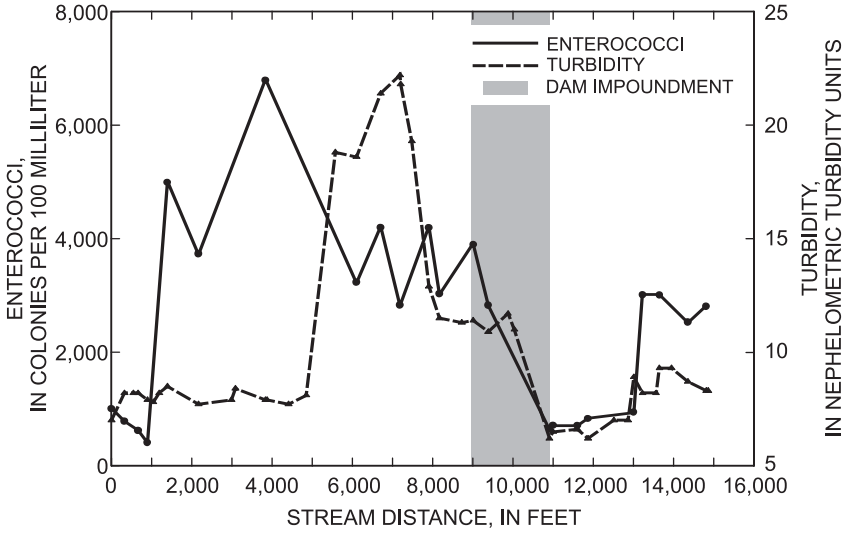


Figure 17. Enterococci and turbidity in the water column during base-flow conditions, Coatesville study reach, 2003, West Branch Brandywine Creek, Chester County, Pennsylvania.

Field Chemistry

Because of the wide variation in land use and associated water use within the watershed, the West Branch Brandywine Creek has extremely variable chemical gradients (changes over distance) that make common field-chemical measurements (temperature, pH, specific conductance, DO, and turbidity) ineffective and (or) impossible to use for the determination of inputs of fecal contamination. Widely variable chemical gradients commonly mask more subtle indications of sewage inputs from sanitary and (or) storm sewers, ground-water discharges from springs, and (or) other indications of flows entering the stream channel. These chemical gradients generally are caused by the industrial signature of the watershed, natural effects of light and temperature throughout the course of a day, and (or) inputs from urban and residential areas. One notable example is the specific-conductance signature through the stream reach dominated by the ISG Plate Inc., steel mill. Specific conductance is sometimes used (in conjunction with other methods) as an indicator of sewage inputs into the fluvial system because untreated wastewater generally has higher specific conductance than natural surface waters. However, within the Coatesville study reach, up to 400,000,000 gal of water per year are withdrawn from the West Branch Brandywine Creek and, to a much lesser extent, local tributaries for use within the ISG Plate Inc., steel mill (R. Ajalli, ISG Plate Inc., oral commun., 2003). This water is withdrawn primarily from the impoundment area of Dam #4, used as process water for various applications, treated to meet required water-quality standards, and discharged back into the West Branch Brandywine Creek approximately 6,500 ft upstream from the intake. This water, in effect, enters a loop and, especially during drought years, may be used repeatedly before finally being released downstream. Whereas this process water meets all required State and Federal standards for water quality and is closely monitored (R. Ajalli, ISG Plate Inc., oral commun., 2003), it is still notably different from natural waters within the West Branch Brandywine Creek and easily masks any small sewage inputs. Specific conductance throughout the Coatesville study reach during the drought of 2002 and during 2003, when higher flows had a greater dilution effect, are shown in figures 18 and 19, respectively.

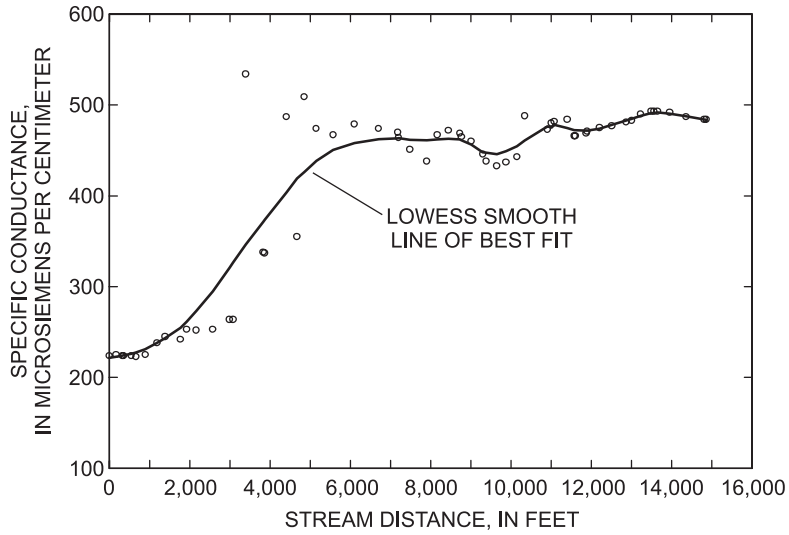


Figure 18. Specific conductance, Coatesville study reach, September 9-12, 2002, West Branch Brandywine Creek, Chester County, Pennsylvania.

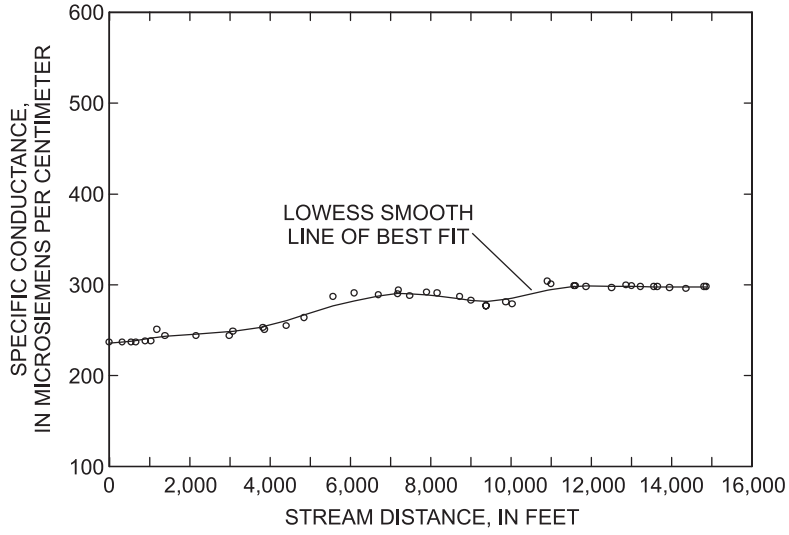


Figure 19. Specific conductance, Coatesville study reach, July 7-9, 2003, West Branch Brandywine Creek, Chester County, Pennsylvania.

Changes in chemical gradients within the fluvial environment are not only notable for their capacity to mask the direct input of fecal material into the fluvial system, but they may also have appreciable effects on the initial colonization of bacteria, the formation of biofilms, and the persistence of certain types of bacteria. For example, research by Costerton and others (1999) has shown that the disease Cystic Fibrosis is caused by a genetic defect that results in elevated salt content in the airway surface fluid within the lungs of humans. Although this is a seemingly minor problem, the elevated salt concentrations subsequently inhibit antimicrobial activity that then allows the colonization of *P. aeruginosa* within a biofilm. Todar (2002) also showed the ability of *E. coli* to sense the presence or absence of various chemicals and (or) gases within the environment and move towards or away from them. In summary, seemingly small chemical variations can have far reaching effects on the presence and (or) persistence of bacteria within the fluvial system and (or) other environments.

On the basis of the bacterial responses to various chemical signatures present within the water column (such as that shown by Todar (2002)), some variability observed in the location of elevated bacteria concentrations throughout the West Branch Brandywine Creek was likely because of the effects of water chemistry. For example, Gibbons Run and Tar Run are similar buried streams that serve as storm sewers throughout the Coatesville, Pa., region. The major difference between the two tributaries is that Tar Run also serves as the outfall for process water from the ISG Plate Inc. steel mill, and as noted above, the effluent from the mill is substantially different (chemically) from the natural waters of the West Branch Brandywine Creek and those of Gibbons Run. This difference in water chemistry is likely partially responsible for the relative lack of *E. coli* within the fluvial sediments collected from Tar Run in 2002 and 2003 (86 and 11,880 col/g of saturated sediment, respectively) as compared to those collected from Gibbons Run (14,580 and 25,920 col/g of saturated sediment, respectively). This determination was based on the fact that, while Gibbons Run exhibited much higher concentrations of *E. coli* within fluvial sediments, Tar Run exhibited much higher concentrations of *E. coli* within the water column (1,500 and 4,400 col/100 mL, respectively) than did Gibbons Run (<1 and 100 col/100 mL, respectively). It must be stated, however, that given the complex nature of the bacterial-attachment process as described above, water chemistry was likely only one factor, among many, affecting this process.

Nutrients and Wastewater Constituents

During 2003, six sites were sampled for nutrients and wastewater constituents along the Coatesville study reach. Five sites were sampled during base flow and included the upstream- and the downstream-most gaging stations on the Coatesville study reach (USGS sites 01480500 and 01480617, respectively); the primary storm-sewer outfall for the City of Coatesville (USGS site ID 01480550); a small natural tributary (USGS site 01480615); and a spring that drains a hillside known to contain residences utilizing on-lot sewage disposal systems (USGS site 395756075485301) (fig. 20). Three sites were sampled during a storm event and included the upstream- and downstream-most stations on the Coatesville study reach, as well as a site at the approximate center of the Coatesville study reach (bridge carrying 1st Avenue over the West Branch Brandywine Creek, USGS site 0148061501). All water-quality sampling sites were selected along the Coatesville study reach in order to target specific areas and types of discharges into the West Branch Brandywine Creek.

USGS sites 01480500, 0148061501, and 01480617 are along the main channel of the West Branch Brandywine Creek and were selected in order to identify contaminants entering the Coatesville study reach from upstream and to bracket the upstream and downstream segments of the study reach. USGS site 01480550 is at the mouth of the primary storm sewer for the City of Coatesville, Pa. Prior to about 1940, this storm sewer flowed as a natural stream on the surface and was known as Gibbons Run; presently (2005), however, the entire stream is buried and flows through culverts beneath the city. Although the City of Coatesville and the surrounding areas utilize separate sanitary- and storm-sewer systems, these systems are older (about 1932) and evidence of connections between the two systems are readily apparent as storm-water runoff indicators commonly flow through the sanitary-sewer system (Richard Lutz, Pennsylvania-American Water Company, oral commun., 2003). USGS site 01480615 is at a small, unnamed tributary that enters the West Branch Brandywine Creek near the approximate center of the Coatesville study reach. This tributary has two main branches that drain a steep hillside underlain by the Octoraro Phyllite; this geologic formation develops steep topography with thin soils and localized areas of losing stream reaches as water flows through fractures and fine granular openings within the weathered zone (Sloto, 1994). Within the drainage of this small tributary are aging residential developments, primarily on the east branch of the tributary, and a large monofill, or slag dump, on the west branch of the tributary. The monofill fills a historical stream valley as observed in Bascom and Stose (1932) and water originating from the monofill area emerges as springs, enters the main channel of the tributary, and, subsequently, flows into the West Branch Brandywine Creek. USGS site 395756075485301 is at a small spring that drains an area adjacent to the impoundment area of Dam #4. The region drained by this small spring is important because it contains the only known on-lot sewage disposal systems in the region. The presence or absence of wastewater indicators from this spring would potentially indicate whether the on-lot sewage disposal systems are, or are not, contributing to the elevated bacteria concentrations observed within the impoundment area of Dam #4.

Analyses of water-quality samples from the water-quality sampling sites indicated that, during base flow, nutrients, such as dissolved nitrate plus nitrite nitrogen and total phosphorus ranged from 2.0 to 3.69 mg/L and 0.008 to 0.091 mg/L, respectively. However, a large percentage of the total nutrient load

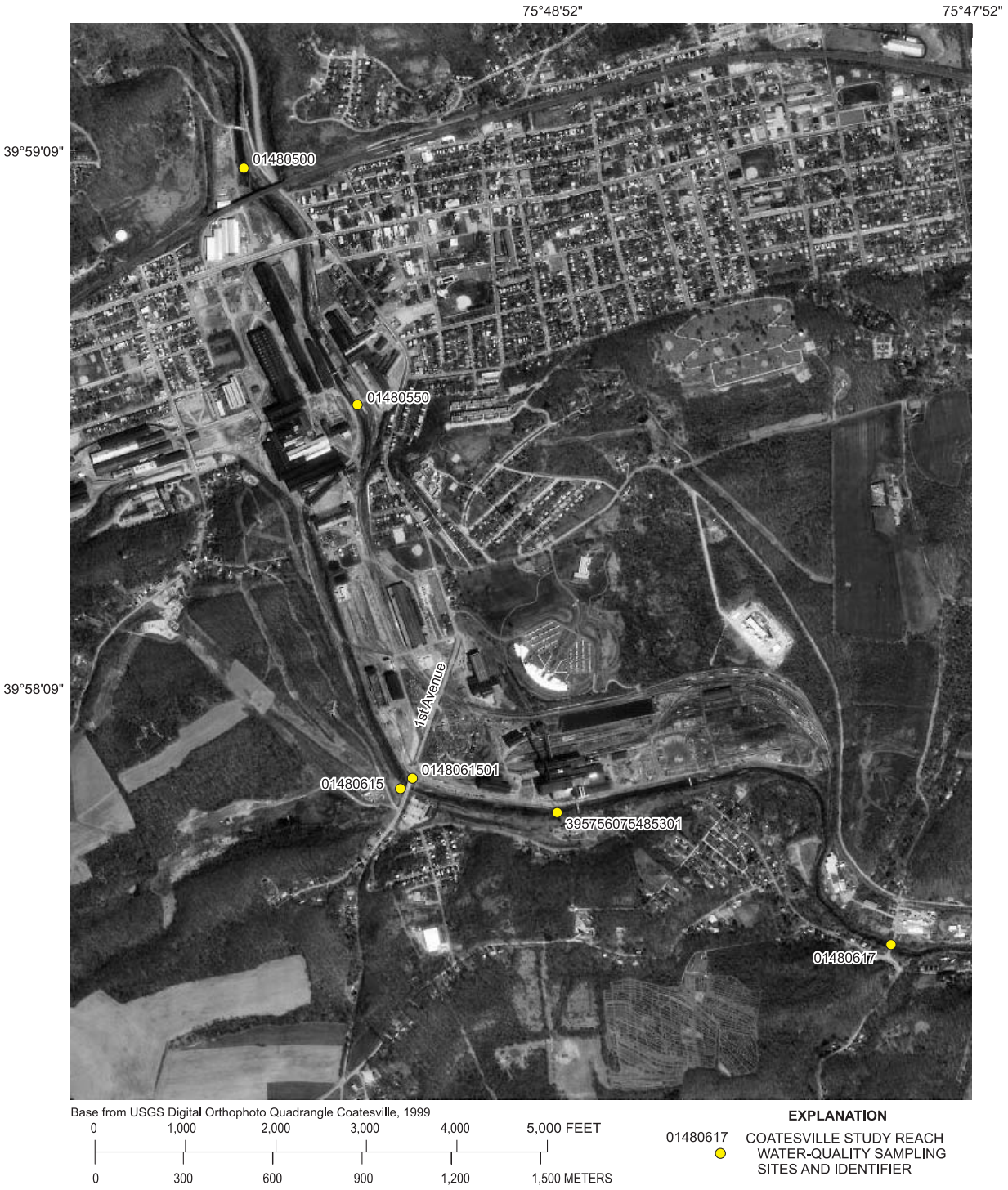


Figure 20. Nutrient and wastewater-constituent sampling sites, Coatesville study reach, West Branch Brandywine Creek, Chester County, Pennsylvania.

originated from the Coatesville region. For example, utilizing mean-daily streamflows from the USGS streamflow-gaging stations 01480500 and 01480617 (54 and 81 ft^3/s, respectively) to determine phosphorus loads for base-flow samples collected on July 10, 2003, approximately 20 lb of phosphorus passed by the upstream-most point on the Coatesville study reach and approximately 40 lb passed by the downstream-most point. The additional 20 lb of phosphorus present at the downstream end of the study reach likely originated from the two wastewater-treatment facilities along the Coatesville study reach; these types of facilities are commonly a source of nutrients including phosphorus. The Coatesville storm-sewer system, however, did not appear to add a substantial nutrient load to the West Branch Brandywine Creek because the phosphorus load determined from the 0.091 mg/L of phosphorus measured at the outfall of Gibbons Run (the primary storm sewer for the city of Coatesville), in conjunction with a measured discharge of 0.59 ft^3/s originating from the Gibbons Run culvert, yielded a phosphorus load of only approximately 0.4 lb/d, or 2 percent, of the 20-lb increase observed through the study reach.

During stormflow, a similar pattern in nutrient loads was present along the Coatesville study reach, although at much higher levels and with a greater percentage of the total load entering from within the Coatesville region. This pattern indicated, again, that the urban / industrial Coatesville region had a more substantial effect on nutrient loads within the Coatesville study reach than did the upstream agricultural areas. Utilizing mean-daily streamflows from the USGS streamflow-gaging stations 01480500 and 01480617 (82 and 144 ft^3/s, respectively) to determine phosphorus loads for stormflow samples collected on August 4, 2003, approximately 150 lb of phosphorus passed by the upstream-most point in the Coatesville study reach and approximately 630 lb passed the downstream-most point. During base flow, these nutrients likely originated from the two wastewater-treatment facilities along the study reach; however, at stormflow, remobilized sediments from behind the three dams along the study reach (Langland and Hainly, 1997), along with runoff from the adjacent watershed (K. Hyer, U.S. Geological Survey, written commun., 2004), likely contributed the bulk of the increase observed in nutrient loads (nutrient concentrations are presented in detail in appendix 2).

Regardless of the source of increased nutrients entering the Coatesville study reach, the observed nutrient concentrations generally can be described as sufficient to promote accelerated aquatic growth. For example, nitrate concentrations above 0.3 mg/L are noted to cause increased plant activity (U.S. Environmental Protection Agency, 1994) and all samples collected within the Coatesville study reach (both base-flow and stormflow samples) had concentrations above 2.0 mg /L. The elevated nutrients within the Coatesville study reach may result in the increased *E. coli* concentrations observed within the impoundment area of Dam #4 because the increased nutrients may support increased algal growth and the resultant symbiotic relation that potentially drives bacterial regrowth as described above.

Wastewater constituents generally indicate direct fecal inputs to the fluvial system such as leaking sewer pipes, failed septic systems, combined sewer overflows, and illegal discharges. Samples were collected concurrently with nutrient samples and analyzed for wastewater constituents. All wastewater constituents were given equal weight for the purposes of this study (all wastewater data are listed in detail in appendix 2). It must be noted, however, that specific wastewater constituents are stronger indicators of fecal contamination than others; for example, cotinine is a relatively strong indicator of fecal contamination (as compared to other constituents) but caffeine can enter the environment either through wastewater or from urban runoff (spilled coffee running off urban parking lots is a potential source of caffeine).

Wastewater constituents during base flow in 2003 primarily originated from the Coatesville storm-sewer system. Gibbons Run (the primary storm sewer for the City of Coatesville) tested positive for 20 of 69 wastewater constituents including strong indicators of fecal contamination such as cotinine. By comparison, only 5 of 69 constituents were detected entering the upstream end of the study reach in the main channel of the West Branch Brandywine Creek. These findings were consistent with data that showed the majority of sites with elevated bacteria concentrations within fluvial sediments along the Coatesville study reach were at, or near, various storm-sewer outfalls. Water sampled from the downstream end of the study reach tested positive for 10 of 69 constituents suggesting that dilution had lowered many of the contaminant levels entering from the Coatesville storm sewer to below the method detection limit for the various wastewater constituents. Waters originating from the small unnamed tributary and the small spring draining the area adjacent to Dam #4 tested positive for 7 and 3 of 69 constituents, respectively, and, therefore, also were not likely introducing substantial concentrations of bacteria into West Branch Brandywine Creek as the result of human-related sewage inputs.

During stormflow, large amounts of suspended sediments within the water column made analysis of certain wastewater constituents by gas chromatography/mass spectrometry (GC/MS) difficult, and surrogate recoveries for this method commonly were poor (these data are presented in appendix 2). On the basis of these surrogate recoveries, reporting limits for certain constituents analyzed by the GC/MS method were raised based on the discretion of the analyst. However, for all constituents, a qualitative determination was possible that, subsequently, allowed for basic evaluation of the data (for example, more confident of detections than non-detections) (S. Smith, U.S. Geological Survey, oral commun., 2004). On the basis of the results of these analyses, 5 of 69 constituents were detected at the upstream end of the study reach, 8 of 69 constituents were detected at the center of the study reach, and 7 of 69 constituents were detected at the downstream end of the study reach. These data indicated no substantial increase in the detected number of wastewater constituents along the Coatesville study reach during stormflow and suggested that point sources (culverts, pipes, and others) of fecal contamination within the Coatesville study

reach probably were not the predominant origin of elevated bacteria concentrations commonly observed during stormflow on the West Branch Brandywine Creek. By reducing the likelihood that point sources (culverts, septic systems, wastewater-treatment facilities, and other sources) are the predominant source of bacteria during stormflows, these data lend support to the findings that elevated bacteria concentrations during stormflows are likely the result of remobilized sessile bacteria stored within fluvial sediments. (It must be noted here that bacteria washed from the land surface of the surrounding watershed must always be considered in this and other scenarios until further study, such as bacterial source tracking, can definitively eliminate this potential source.) This finding becomes important in that if the source of these bacteria is likely from remobilized sediments, these bacteria cannot be strongly linked to fecal contamination and should not generally be considered strong indicators of current fecal contamination.

Impervious Surfaces

The effect of impervious surfaces on bacterial contamination was most evident during 2002. The drought of that year was associated with a general decrease in bacteria throughout the watershed, as noted above, and also forced any runoff to enter the stream primarily by way of the existing storm-sewer system (desiccated soils result in the infiltration and storage of smaller runoff events). Likely because of this effect, elevated concentrations of *E. coli* in 2002 were found primarily in sediments at or near storm-sewer outfalls along the Coatesville study reach (although not all storm sewers exhibited elevated bacterial concentrations). The storm sewers with elevated bacteria concentrations drained not only the urban and residential areas of the City of Coatesville but also industrial areas such as the ISG Plate Inc., steel mill and other adjacent facilities (elevated bacteria concentrations within the sediments surrounding industrial storm-sewer outfalls were likely because of the large populations of rodents, bats, birds, and other animals that commonly were observed living within the aging industrial complexes in the region and also within the storm sewers themselves (James O'Brien, ISG Plate Inc., oral commun., 2002)).

As observed in figure 21, sites with elevated *E. coli* concentrations within fluvial sediments were generally in the upstream region of the Coatesville study reach. This upstream region contains most of the known storm-sewer outfalls that directly enter the West Branch Brandywine Creek (from the City of Coatesville and the ISG Plate Inc. facility). Downstream storm sewers, originating largely from the smaller Borough of Modena, generally drain less-paved areas and flow into wetland or overbank areas prior to entering the West Branch Brandywine Creek. These findings were also consistent with those of Tufford and Marshall (2002) in a study of Rawls Creek, S.C., in which data indicated catchments with the largest contiguous impervious areas were, statistically, the greatest sources of fecal coliform bacteria.

The effects of impervious surfaces were not as pronounced during 2003 as in 2002. Even though 2003 was noted by a general increase in all bacteria levels, the primary reasons for the general inability to easily detect localized areas of increased bacterial concentrations were largely attributed to two potential factors: more points of direct access to the stream channel by planktonic bacteria (swales, drains, and (or) other points of entry) and more storms or "flushing events" to redistribute sessile bacteria throughout the reach. Better access for planktonic bacteria was largely attributed in that the soil throughout the region generally was saturated, or close to saturated, and smaller overland flows and **throughflows** were observed to reach the stream (as noted by water-filled swales and flowing springs that were not present in 2002). Consequently, planktonic bacteria also could be washed into the stream at multiple points and were not confined to the storm-sewer outfalls as in 2002. Areas within the fluvial environment that were prone to colonization of sessile bacteria and were not subjected to ero-

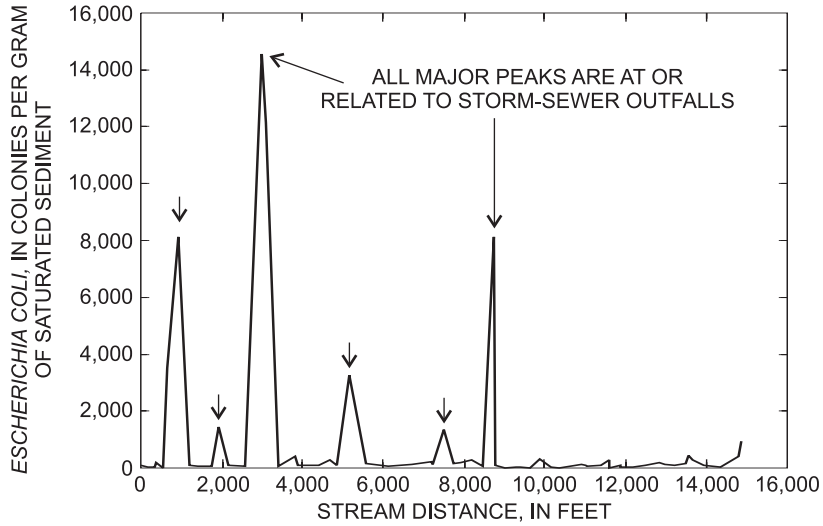


Figure 21. *Escherichia coli* in fluvial sediment during base-flow conditions, Coatesville study reach, 2002, West Branch Brandywine Creek, Chester County, Pennsylvania.

sion in 2002 were subsequently vulnerable to erosion by the high base flow and storm events in 2003. These bacteria were then able to be redistributed throughout the reach in 2003; in 2002, they were confined to isolated areas (such as storm-sewer outfalls). While sampling sites with elevated bacteria levels in 2003 were still generally concentrated in the upstream region of the Coatesville study reach (among the storm-sewer outfalls as shown in figure 22), certain locations could not be directly related to these storm-sewer outfalls as in 2002.

During 2003, high concentrations of bacteria were observed within the sediments of the West Branch Brandywine Creek below the outfall of the Pennsylvania-American Water Company wastewater-treatment facility (approximately 4,853 ft from the upstream end of the study reach to approximately 7,747 ft). Concentrations of *E. coli* in fluvial sediments along this reach were as high as 100 times greater than the median concentration of the Coatesville study reach; however, bacteria concentrations within this stream reach during the previous year did not exceed levels that would be considered background. The origin of these bacteria was unknown; however, interpretation of data, based on field observations and available research, indicated three possible origins; the Pennsylvania-American Water Company wastewater-treatment facility, waterfowl, and (or) storm-sewer outfalls adjacent to the reach.

The first possible origin of the bacteria was the Pennsylvania-American Water Company wastewater-treatment facility. The sanitary and storm-sewer systems of Coatesville, Pa., are not combined, theoretically eliminating the problems commonly associated with combined-sewer overflows (CSO). However, this is an older system (the wastewater-treatment facility was constructed in 1932) with numerous leaks and undocumented hook-ups that, in effect, make the system function as a combined system. For example, as noted above, wastewater constituents that indicate the presence of sewage were detected within the storm-sewer system. Also noted were increased water volumes within the sanitary-sewer system containing storm-water runoff products during various storm events (Richard Lutz, Pennsylvania-American Water Company, oral commun., 2003). However, the Pennsylvania-American Water Company wastewater-treatment facility was upgraded so that if the increased volume of water in the sanitary-sewer system, during a storm, exceeded the capacity of the plant, untreated wastewater would not be discharged into the West Branch Brandywine Creek but would be diverted into a lined holding basin to be immediately treated when volumes returned to normal. According to staff of the Pennsylvania-American Water Company, all exceedences in 2002 and 2003 were contained within the holding basin and would, therefore, not have been the cause of the elevated bacteria observed downstream. This report is consistent with data that showed an *E. coli* concentration of only slightly above 2,000 col/g of saturated sediment within the sediments directly below the outfall of the wastewater-treatment facility in 2003.

The second possible source of the bacteria was waterfowl. Staff from the wastewater-treatment facility observed a large population of Canada geese in the grassy areas surrounding their aeration tanks in the days prior to base-flow sampling; it is possible that, because of the saturated condition of the soil and the paved nature of the overbank area, some fecal matter could have been washed directly into the creek from these overbank areas without being subject to infiltration and soil filtration as would occur in a drier year. Although not substantiated by this study, waterfowl generally are not considered a major source in this case because the concentrations of *E. coli* found within the fluvial sediments of this reach are probably too large to originate from this source alone (nearly 500,000 col/g of saturated sediment at one site). Any fecal matter originating from these geese would have likely been dispersed during transport to the stream, thus, reducing the total amount of bacteria available to enter the stream channel at any given time.

The third possible source, or sources, were the storm-sewer outfalls just downstream from outfall for the Pennsylvania-American Water Company wastewater-treatment facility (project identification numbers CB25TC and CB29TC). The

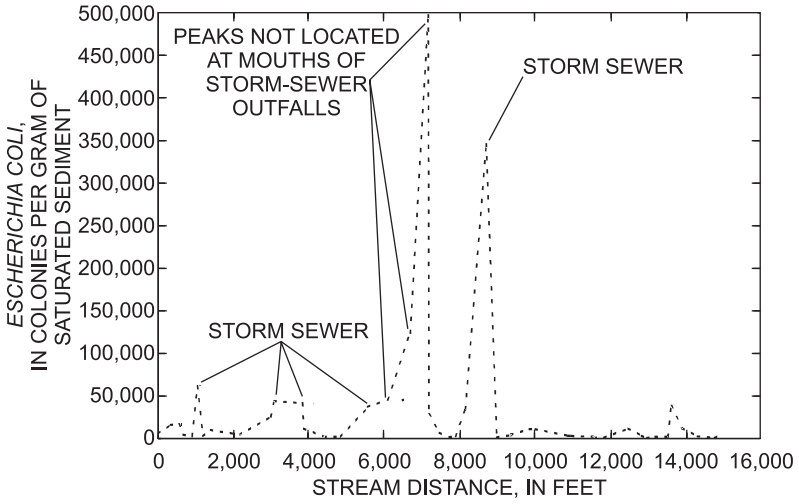


Figure 22. *Escherichia coli* in fluvial sediment during base-flow conditions, Coatesville study reach, 2003, West Branch Brandywine Creek, Chester County, Pennsylvania.

exact origin of these culverts is unknown; however, the construction of the culverts was consistent with other storm sewers in the region. *E. coli* concentrations within sediments collected at the outfall of these culverts measured over 37,000 and 28,000 col/g of saturated sediment in 2003, respectively, and suggested these storm sewers may have been largely responsible for the elevated bacterial concentrations within the fluvial sediments near the outfalls.

Observations of bacteria concentrations within this study, as compared to the description of the sampling location, showed that most sites with elevated bacteria concentrations were at, or near, the air/water interface at the edge of the active stream channel (this observation is made with due attention paid to the bias resulting from a sampling plan that largely targeted point sources along the streambanks). Other research, such as Whitman and Nevers (2003), also found higher concentrations of bacteria in this shallow, near-bank region than in deeper areas of the channel (most studies to date, however, have focused on lacustrine environments). Given that the elevated *E. coli* concentrations downstream of the wastewater-treatment facility also included substantial concentrations of *E. coli* within the fluvial sediments at the bottom of a deep pool (124,200 col/g of saturated sediment at site CB27), these data indicate the bacteria were deposited within this reach by way of remobilized sessile-bacteria populations contained within transported sediments. Planktonic bacteria, as would likely originate from the wastewater-treatment facility and (or) waterfowl, would have had to selectively colonize sediments that data indicate do not reside in a preferred environment for this to occur; thereby reducing the likelihood that the wastewater-treatment facility and (or) waterfowl were the primary sources of this bacteria. Additional data are required to further substantiate these findings.

Sediment and Soil Filtration

As noted above, the area adjacent to the Coatesville study reach is largely utilized for urban and (or) industrial uses and is, consequently, mostly paved or covered with structures. Directly adjacent to the Coatesville study reach, most **riparian** zones were substantially reduced in size, and most wetlands were removed entirely, as a consequence of stream-channel relocation and (or) flood-plain encroachment by industry. The Wagontown study reach, although slightly altered, has remained largely forested with a far greater percentage of available flood-plain, riparian zone, and wetlands (based on field observations). Given the differences between the two reaches, much more runoff from the region surrounding the Wagontown study reach is subject to infiltration and subsequent soil filtration. These field observations suggested that the lower bacteria levels within the water column of the Wagontown study reach (fig. 23) compared to the Coatesville study reach (fig. 24) were, at least in part, because of the relative lack of overland flows across paved areas and the effective filtration of runoff by adjacent wetlands and more substantial riparian zones. For example, the median concentration of *E. coli* within the water column of the Wagontown study reach, during base-flow sampling in 2003, was 195 col/100 mL; within the water column of the Coatesville study reach, the median concentration of *E. coli* was 960 col/100 mL, or almost five times higher, during the same period. Similarly, median enterococci concentrations were 405 col/100 mL within the water column of the Wagontown study reach compared to 2,800 col/100 mL within the water column of the Coatesville study reach.

Even though the Wagontown and Coatesville study reaches are separated by approximately 1 mi, the bacteria concentrations observed within the water column at the upstream end of the Coatesville study reach (above the city of Coatesville storm-sewer outfalls) were consistent with those observed along the Wagontown study reach (even though a tributary known as Rock Run enters the West Branch Brandywine Creek

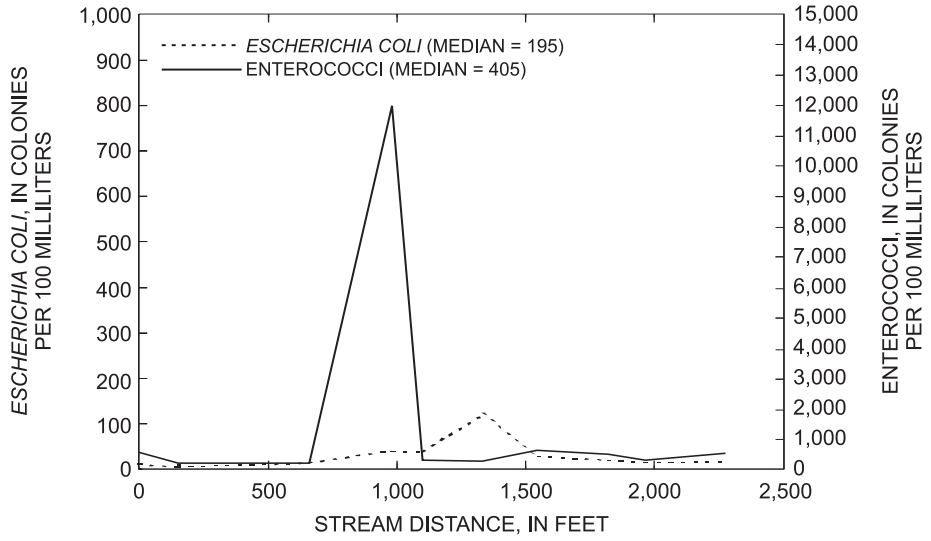


Figure 23. *Escherichia coli* and enterococci concentrations in the water column during base-flow conditions, Wagontown study reach, 2003, West Branch Brandywine Creek, Chester County, Pennsylvania.

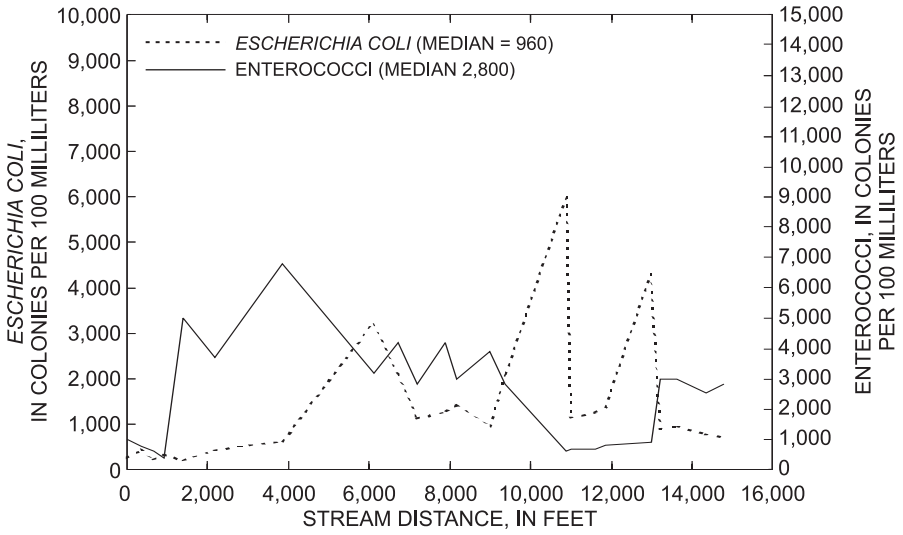


Figure 24. *Escherichia coli* and enterococci concentrations in the water column during base-flow conditions, Coatesville study reach, 2003, West Branch Brandywine Creek, Chester County, Pennsylvania.

between the two study reaches and commonly contains elevated bacteria concentrations). For example, the median *E. coli* concentration for the first 900 ft of the Coatesville study reach was 300 col/100 mL during base flow in 2003. This concentration is generally consistent with the median *E. coli* concentration of 195 col/100 mL observed during base flow in 2003 along the upstream Wagontown study reach. Similarly, the median enterococci concentration for the first 900 ft of the Coatesville study reach was 680 col/100 mL, which is also more consistent with the median enterococci concentration of 405 col/100 mL observed along the Wagontown study reach. These data indicate the reduced wetland and riparian areas within the Coatesville study reach are likely not as effective in the filtration of bacteria from runoff. Of course, the Coatesville study reach includes storm sewers that discharge directly into the creek, whereas storm sewers are not present in the Wagontown study reach.

Other studies have shown the filtering capacity of wetlands and riparian areas and lend support to this interpretation of data from the Coatesville and Wagontown study reaches. Hench and others (2003) found that small constructed wetlands greatly reduced the amount of chemical and microbial contaminants that were introduced to a stream from domestic septic systems (single household) and that vegetated wetlands were more efficient than non-vegetated wetlands (gravel pack only). Also of note were the findings by Hench and others (2003) that the capacity of constructed wetlands to filter wastewater was observed to diminish over time, thus, allowing more bacteria to pass in subsequent years. Tufford and Marshall (2002) observed that the presence of stormwater retention ponds that concentrate and infiltrate stormwater attenuated fecal coliform bacteria levels and a large stormwater detention basin that concentrated and released stormwater through a small culvert with no infiltration did not. Further, Hunter and others (1992) compared soil matrix throughflow to overland runoff and found the soil matrix to be an efficient filter for bacteria.

Bacterial data collected from fluvial sediments, within this study, could not with any certainty identify specific sites where sediment filtration was occurring and (or) failing along the West Branch Brandywine Creek because the sampling plan did not target this issue. Bacterial analyses along the Wagontown study reach (where most dominant wetlands were located) were switched from fecal coliform and fecal streptococcus bacteria to enterococcus bacteria in 2003; this change in bacterial analyses made comparisons between 2002 and 2003 data impossible. However, data analysis did identify a specific area along the Wagontown study reach at which future study may prove beneficial. During 2002, a small spring was sampled near the downstream end of the Wagontown study reach; because of the drought of 2002, this spring was one of the few springs observed to flow within the study area. This spring drains a small wetland area adjacent to a facility cited prior to 2002 for discharging raw sewage into the West Branch Brandywine Creek (D. Town, Chester County Health Department, oral commun., 2002). This spring had a generally high concentration of fecal coliform bacteria within the sediments near its source compared to other sites along the Wagontown study reach (fig. 25). During 2003, much more water was present within this same wetland area, and water was observed to predominantly drain from the wetland area by way of numerous swales as well as from various springs. The largest of these flowing swales was sampled near the downstream end of the Wagontown study reach and showed a generally high concentration of *E. coli* within the fluvial sediments at the mouth of the swale. The spring sampled in 2002, however, did not have an elevated concentration of either *E. coli* or enterococci (fig. 26). Although climatic and runoff influences on this site likely affect the observed concentrations of various bacteria along this reach, knowledge of the prior discharge of untreated sewage along with the observed elevated concentrations of bacteria adjacent to the wetland area indicate that some level of filtration is potentially occurring, or may have occurred along this reach; again, additional study is required to support this observation.

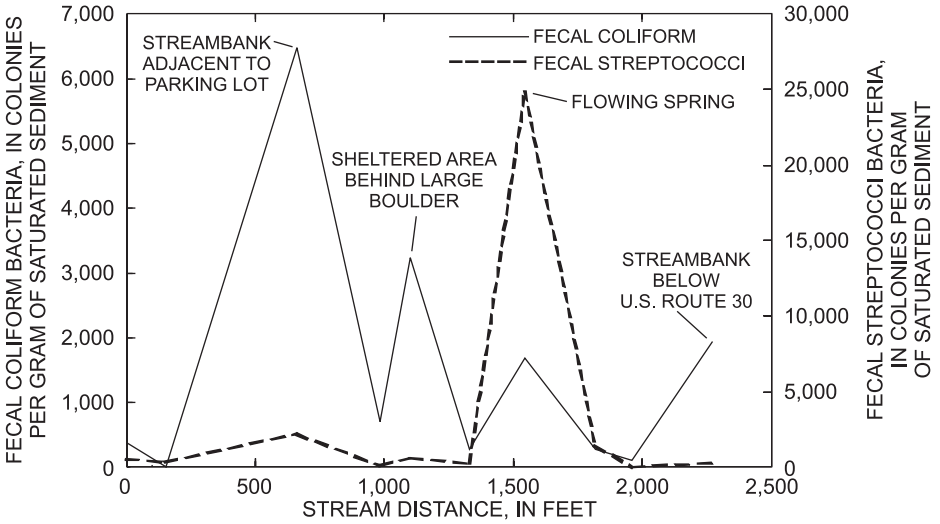


Figure 25. Fecal coliform bacteria and fecal streptococcus bacteria concentrations in fluvial sediment during base-flow conditions, Wagontown study reach, 2002, West Branch Brandywine Creek, Chester County, Pennsylvania.

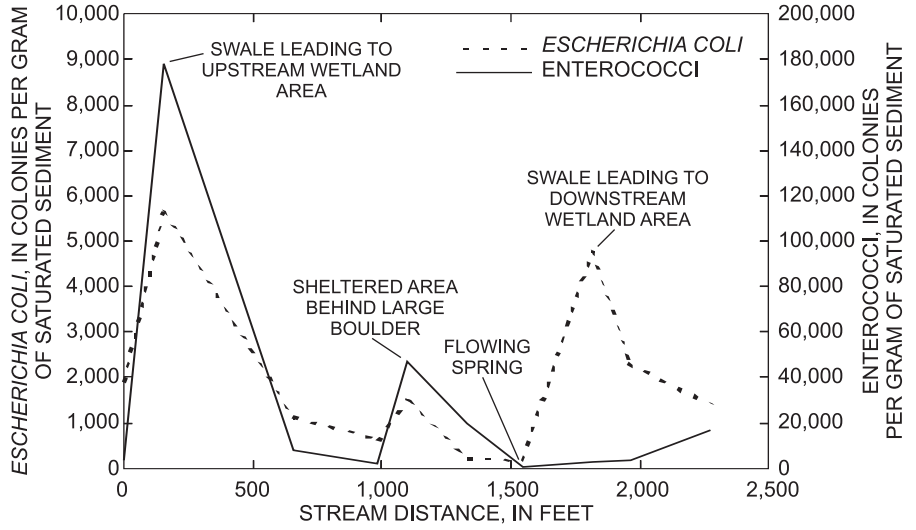


Figure 26. *Escherichia coli* and enterococci concentrations in fluvial sediment during base-flow conditions, Wagontown study reach, 2003, West Branch Brandywine Creek, Chester County, Pennsylvania.

Dams

Three dams currently are present within the Coatesville study reach on the West Branch Brandywine Creek (various other dams were historically present but have been removed). The first dam is an approximately 5-ft tall, low-head, run-of-the-river dam at the upstream end of the Coatesville study reach (fig. 27). This dam serves as the control structure for USGS streamflow-gaging station 01480500 (West Branch Brandywine Creek at Coatesville, Pa.), and the crest of this dam marks the beginning of the Coatesville study reach (station 0). The second dam is a slightly smaller, low-head, run-of-the-river dam approximately 3 ft high (fig. 28). The crest of the second dam is approximately 2,500 ft downstream from the first dam on the Coatesville study reach (station 2,500); this second dam is unique in that it lies completely within a channelized section of stream within the steel mill. Although not apparent in figure 28, access to the second dam was limited because of safety concerns and no samples were collected directly at the dam crest; however, samples collected at stations 2,167 and 2,575 bracketed the dam. The final and largest dam is Dam #4 at station 10,905 (fig. 29). This approximately 20-ft high, run-of-the-river dam currently serves to divert water into the steel mill for industrial use and lies within a stream reach characterized by various soil, bedrock, and concrete banks.

While *E. coli* concentrations increased through the impoundment of Dam #4 and substantially decreased immediately downstream of the spillway in both 2002 and 2003 (figs. 30 and 31), the smaller dam at station 2,500 had a lesser effect on *E. coli* concentrations. Two major differences between the structures may account for this variation in bacterial response. First, Dam #4 is much larger and, regardless of a large sediment wedge behind the dam, it slows and impounds water much more effectively than the dam at station 2,500. This greater capacity of Dam #4 to impede the flow of water is illustrated in figures 30 and 31 by the observed effect on turbidity as

Figure 27. Dam at station 0 on Coatesville study reach, West Branch Brandywine Creek, Chester County, Pennsylvania. Flow is from right to left. (Photograph by P.J. Cinotto, USGS)

Figure 28. Dam at station 2,500 on Coatesville study reach, West Branch Brandywine Creek, Chester County, Pennsylvania. View looking upstream. (Photograph by P.J. Cinotto, USGS)

water flows through each impoundment area. Dam #4 shows a substantial effect on turbidity especially during the higher flows of 2003; the smaller dam at station 2,500 has virtually no effect on turbidity. Second, Dam #4 had an additional source of nutrients originating from the Coatesville region. As noted above, introduction of these additional nutrients along with a longer residence time (slower water) likely increased the capacity of algae to proliferate within the impoundment area of the dam and potentially caused higher bacterial concentrations because of bacterial regrowth.

The elevated concentrations of *E. coli* observed within the impoundment of Dam #4 decreased dramatically downstream from the spillway of Dam #4 in 2002 and 2003 (figs. 30 and 31). This rapid decrease in *E. coli* concentrations within the water column, as well as the absence of bacteria within the fluvial sediments directly downstream, indicated that *E. coli* were

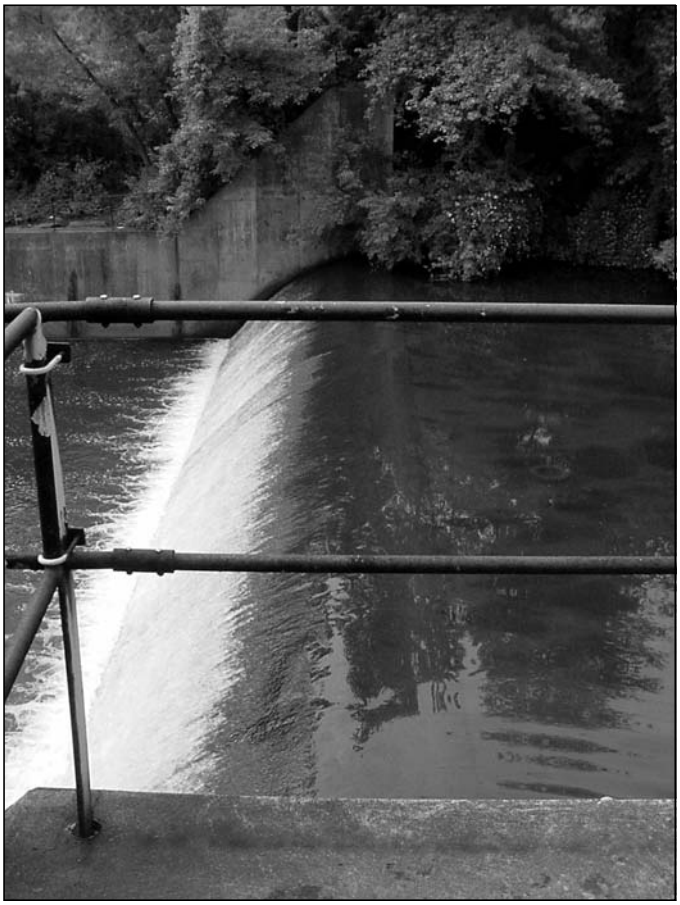


Figure 29. Dam at station 10,905 (Dam #4) on Coatesville study reach, West Branch Brandywine Creek, Chester County, Pennsylvania. Flow is from right to left. (Photograph by P.J. Cinotto, USGS)

removed at, or immediately adjacent to, the spillway by an undefined process. The smaller dam, upstream at station 2,500, did not have this population decrease and had little effect on the *E. coli* concentration. The same pattern of population decrease was not as readily apparent for enterococci because populations of these bacteria decreased within the impoundment area of Dam #4 before they reached the spillway (fig. 32); therefore, it was unclear if enterococci populations were affected by processes similar to *E. coli* once they reached the dam crest. Numerous other studies, such as Town (2001), have documented similar decreases in bacterial concentrations downstream of dams and (or) other instream structures; however, even at the larger Dam #4, insufficient energy was likely available to account for this population decrease by mechanical processes (rupture of the cell walls and subsequent death of the bacteria) (S. Haack, U.S. Geological Survey, written commun., 2004). Therefore, although this study does point out that relatively larger dams (as compared to small low-head dams), or other instream structures, can, and do, affect bacteria concentrations within the fluvial environment, the actual process remains unclear and requires additional study

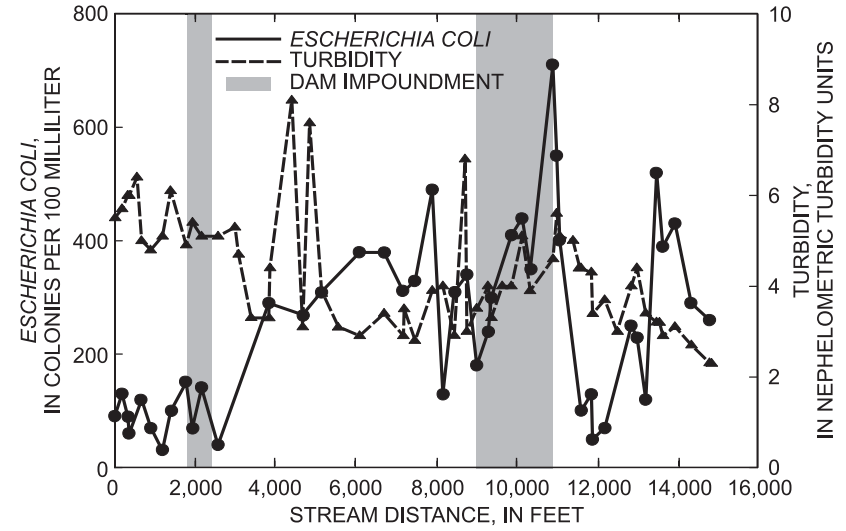


Figure 30. *Escherichia coli* and turbidity in the water column during base-flow conditions, Coatesville study reach, 2002, West Branch Brandywine Creek, Chester County, Pennsylvania.

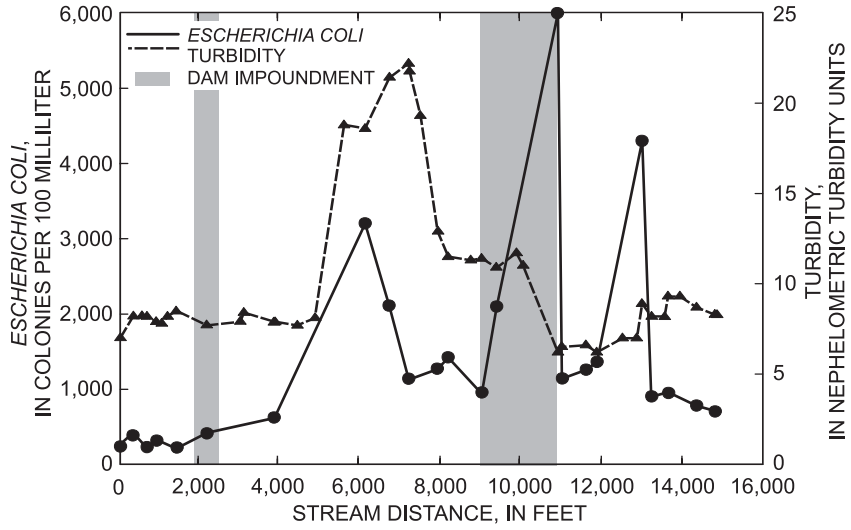


Figure 31. *Escherichia coli* and turbidity in the water column during base-flow conditions, Coatesville study reach, 2003, West Branch Brandywine Creek, Chester County, Pennsylvania.

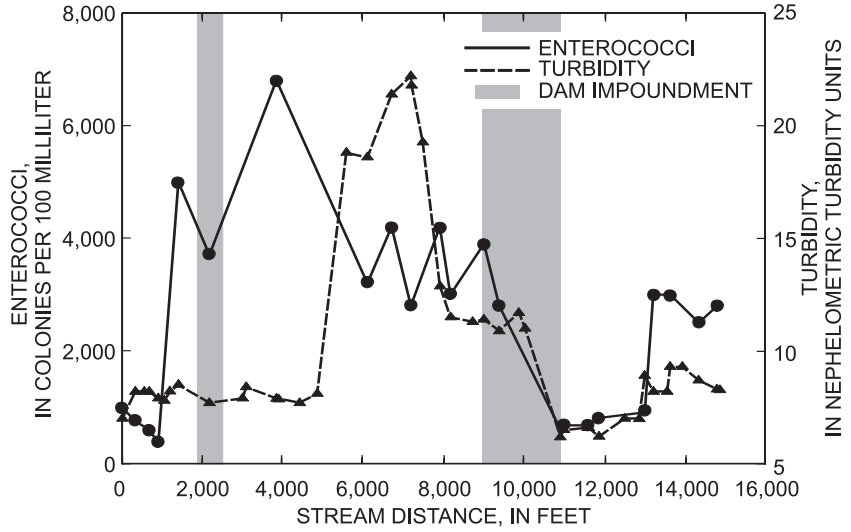


Figure 32. Enterococci and turbidity in the water column during base-flow conditions, Coatesville study reach, 2003, West Branch Brandywine Creek, Chester County, Pennsylvania.

Turbidity

Turbidity, or the suspended matter in the water column, generally is derived from five major sources in the study area of the West Branch Brandywine Creek: erosion of streambanks; erosion of the streambed; top soil and sediments from overland flows; biological sources, such as algae and plankton; and (or) industrial discharges. Turbidity is quantified by measuring the scattering of light as it passes through the suspended particles and water. The units of measure of turbidity used in this study were nephelometric turbidity units, or NTU; loosely translated, nephelometric means "the measure of cloudiness." Turbidity measurements do not, therefore, differentiate between one source or type of suspended material as opposed to any other. Any material that scatters light within the water column is measured as turbidity.

Bacteria are not found uniformly throughout a stream reach with complex land usages and (or) widely varying chemical gradients such as the West Branch Brandywine Creek. Therefore, the general relation of turbidity to bacteria will be inconsistent because sediments containing various concentrations of bacteria are mobilized by water originating from many sources. For example, isolated thunderstorms are common in the West Branch Brandywine Creek Basin throughout the summer months. If the storm is in the upper reaches of the basin, turbidity will be derived primarily from the top soil of agricultural areas; if the storm is over the city of Coatesville, turbidity will be derived from sediment originating from, and adjacent to, stormwater outfalls. Each of these storms could, therefore, have a much different turbidity-to-bacteria relation because the sediment sources vary. As an added consideration, bacteria can and do die off and (or) attach to surfaces as they are transported downstream; this die off and (or) attachment also, potentially, affects the relation between bacteria and turbidity at any given point on the stream, especially during lower flows.

The variable relation between *E. coli* and turbidity observed on the West Branch Brandywine Creek is shown in figures 33 through 36. The coefficient of determination, R^2, is a measure of variability accounted for by the regression relations in the observed indicator bacteria concentration compared to turbidity. The closer the R^2 value is to 1.00, the less variability is present in the data. If an R^2 value indicates the possibility of a valid statistical trend, a p-value must be calculated to validate the relation. The p-value measures the "believability" of the level of significance of the statistical test. If the p-value is less than 0.05, the test is considered significant and the trend, as represented by the regression line, can be assumed to be real. Further statistical analysis can be conducted if one or more data points appear to have undue effect or "leverage" on a regression relation. The Cook's distance statistic is a measure of this effect. For most data sets, data point with Cook's distance values above approximately 2 may be considered to have a significant leverage effect on the regression.

The relations of *E. coli* to turbidity under base-flow conditions in 2002 and 2003 on the Coatesville study reach are shown in figures 33 and 34. Regression analysis of these base-flow

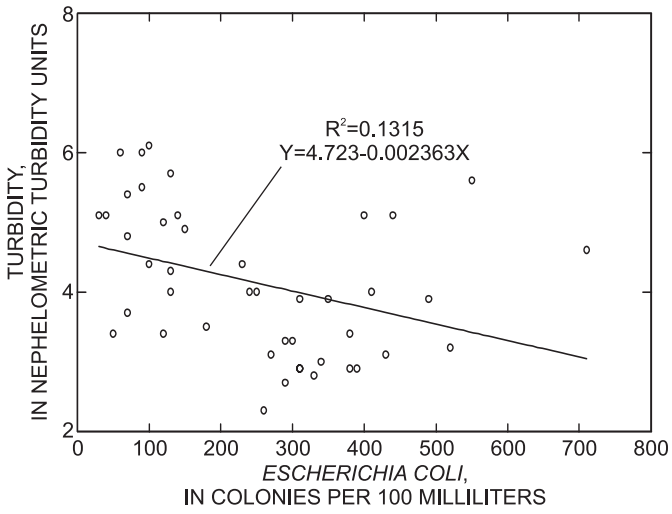


Figure 33. Relation between base-flow turbidity and *Escherichia coli* bacteria in the water column within Coatesville study reach, 2002, West Branch Brandywine Creek, Chester County, Pennsylvania.

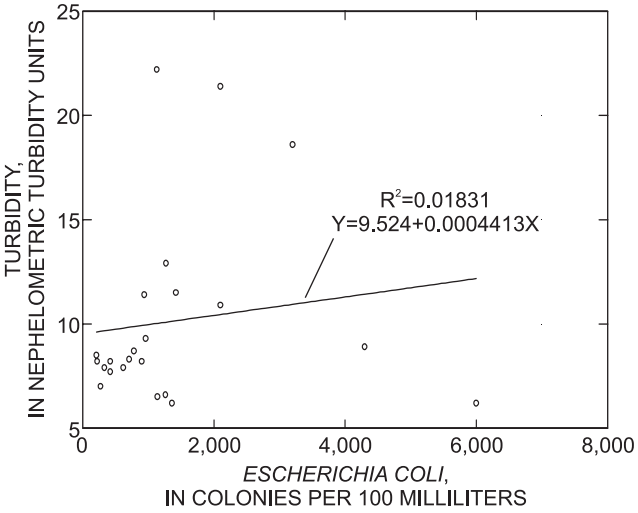


Figure 34. Relation between base-flow turbidity and *Escherichia coli* bacteria in the water column within Coatesville study reach, 2003, West Branch Brandywine Creek, Chester County, Pennsylvania.

data did not yield a statistically valid relation with R^2 values of 0.13 and 0.02, respectively. The relations of *E. coli* bacteria to turbidity under stormflow conditions in 2002 and 2003 on the Coatesville study reach are shown in figures 35 and 36. Regression analysis of data from a storm event in 2003 on the Coatesville study reach presented a similarly poor statistical relation between *E. coli* and turbidity, with an R^2 of 0.21. However, regression analysis of data from a storm event in 2002 presented a stronger statistical relation between *E. coli* and turbidity, with an R^2 of 0.94 and a p-value of 0.00. These data indicated that, during stormflow, the sources of the turbidity-causing sediments and the bacterial concentrations within those sediments were likely different. It should be noted, however, that whereas the R^2 and p-value indicated a strong relation between *E. coli* and turbidity within the 2002 stormflow data set, analysis of the Cook's Distance statistic yields a value of >8 for a single data point at the upper end of the regression line (9,000 col/mL of *E. coli* and 17.1 NTU) (fig. 35). This data point had too strong of an effect on the overall data set to make any legitimate conclusions about the overall relation between *E. coli* and turbidity for this sampling event. In summary, the West Branch Brandywine Creek had too much variation to establish a strong correlation between bacteria, such as *E. coli*, and turbidity for any one hydrologic event.

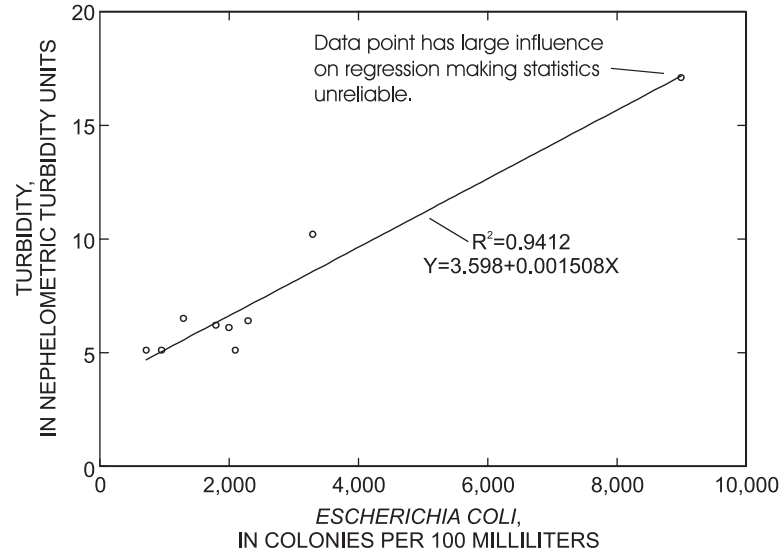


Figure 35. Relation between stormflow turbidity and *Escherichia coli* bacteria in the water column within Coatesville study reach, 2002, West Branch Brandywine Creek, Chester County, Pennsylvania.

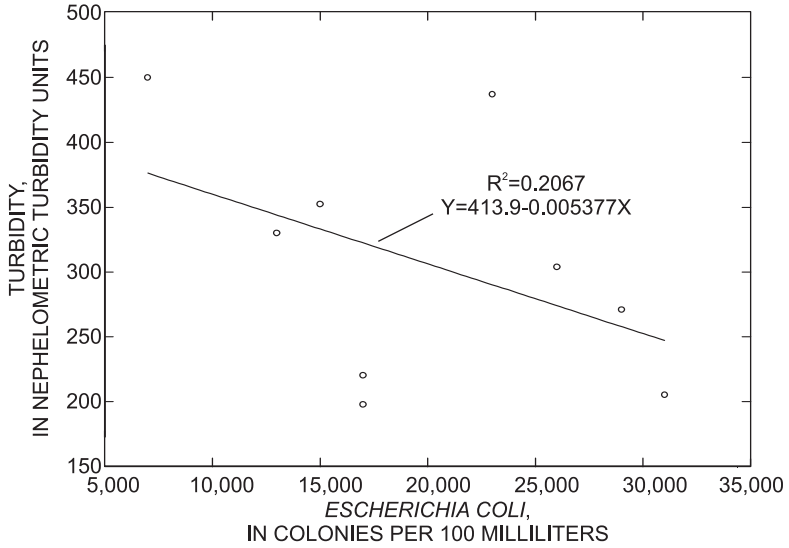


Figure 36. Relation between stormflow turbidity and *Escherichia coli* bacteria in the water column within Coatesville study reach, 2003, West Branch Brandywine Creek, Chester County, Pennsylvania.

A larger data set that included all *E. coli* and turbidity data collected from the Coatesville and Wagontown study reaches during base flow and stormflow was analyzed (n = 95). The relation between turbidity and *E. coli* strengthened slightly as the effects of individual outliers were reduced. Regression analysis of this larger data set yielded a slightly stronger, but still weak, statistical relation between *E. coli* bacteria and turbidity with an R^2 value of 0.67 and a p-value of 0.00 (fig. 37). This regression analysis of the larger data set generally indicated that higher turbidity levels usually can indicate higher bacterial concentrations, however, no absolute determination of bacteria concentration based on turbidity would be feasible on this reach of stream. Simply stated, suspended sediments commonly contained *E. coli*, but the relation was too sporadic on the West Branch Brandywine Creek to use turbidity as a feasible surrogate for estimated bacteria concentrations.

Questions were present as to whether the turbidity-to-bacteria relation would strengthen if data were collected from a single point along the stream rather than from multiple points along the study reach as discussed above. Therefore, in 2003, an autosampler and an Analyte turbidity probe were installed at the downstream end of the Coatesville study reach (in USGS streamflow-gaging station 01480617, West Branch Brandywine Creek at Modena, Pa.). The Analyte turbidity probe was calibrated and checked according to manufacturer's specifications prior to sampling and initial data were confirmed by comparing measurements from the Analyte probe to turbidity measurements from a YSI water-quality sonde. This autosampler was programed to collect samples every 30 minutes from a fixed location while USGS personnel also were concurrently collecting the spatial storm samples discussed above. Eleven samples were subsequently collected by the autosampler (appendix 5) and a regression analysis was performed to test the strength of the relation of turbidity to bacteria at this site (fig. 38). This test yielded an equally poor statistical relation with an R^2 of 0.13 and a p-value of 0.27.

The wide variety of environmental factors within the West Branch Brandywine Creek, such as large industrial inputs, localized areas of impervious cover, storm-sewer systems, dams, reduction of riparian zones, and (or) other factors, all adversely affected the relation between the bacteria and turbidity. Large data sets were required to obtain any level of statistical significance and outliers were common, making utilization of turbidity as a surrogate for bacterial analysis impractical throughout the study area. It should be noted that other research by Rasmussen and Ziegler (2003) showed that bacteria and turbidity can yield a moderately strong and consistent relation. However, environmental conditions, primarily the utilization of much larger drainage areas, were different in that study. The use of larger watersheds in the regression analysis by Rasmussen and Ziegler (six sites ranging from 759 to 59,756 mi^2) likely reduced the effect of any single environmental factor on the overall regression analyses. The largest drainage area in this study was at the downstream end of the Coatesville study reach and drained only 55 mi^2; therefore, the statistical relation between bacteria and turbidity is much more sensitive to minor environmental effects. For example, the input from a single storm-sewer outfall and (or) a small eroding bank generally contributed a much larger percentage of the overall volume of bacteria and (or) suspended sediment to the smaller Coatesville study reach than to the larger river utilized by Rasmussen and Zeigler (2003).

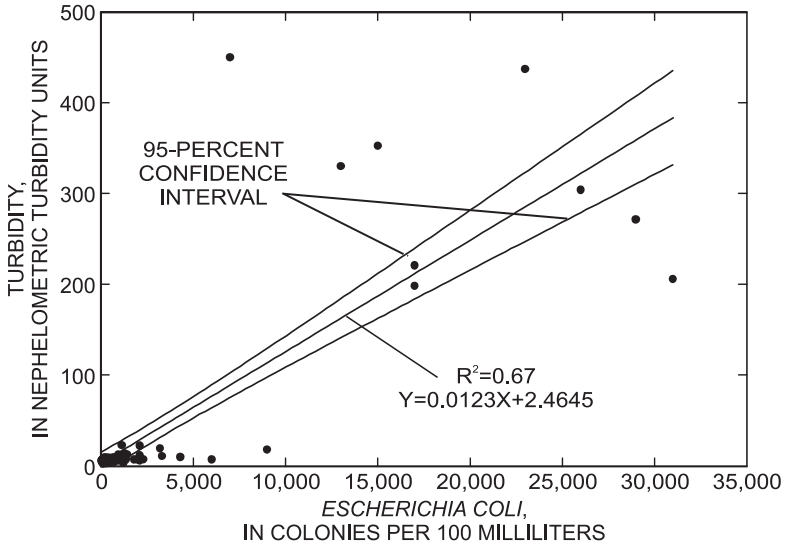


Figure 37. Relation between turbidity and *Escherichia coli* bacteria in the water column within Coatesville and Wagontown study reaches, 2002-2003, West Branch Brandywine Creek, Chester County, Pennsylvania.

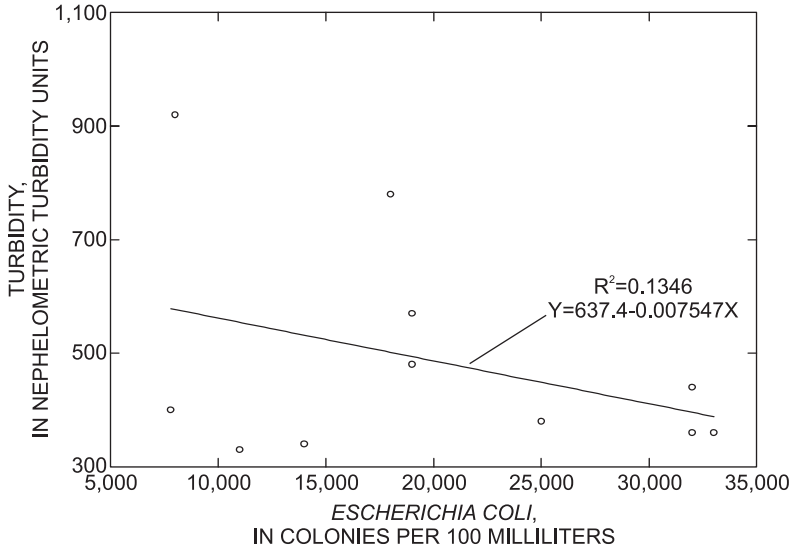


Figure 38. Relation between stormflow turbidity and *Escherichia coli* bacteria at U.S. Geological Survey streamflow-gaging station 01480617, West Branch Brandywine Creek, Chester County, Pennsylvania.

Potential Sources of Bacteria on Selected Reaches of the West Branch Brandywine Creek

Sediment

The concentrations of sessile bacteria stored within stream sediments can be 3-4 orders of magnitude higher than that contained within the water column. These bacteria are commonly subject to remobilization during periods of above-average streamflows and (or) other erosional events. As a consequence of the remobilization of this stored bacteria supply, elevated concentrations of bacteria observed within the water column during storm events are likely because of remobilized sessile bacteria and not a direct sewage source, such as the discharge of raw sewage. Reducing streambank and streambed erosion will reduce the available sediment supply and, subsequently, reduce the bacteria remobilized within the stream during storm events. Of note is that wetter years generally can have higher concentrations of bacteria within fluvial sediments and other environments throughout the watershed than dry years.

Storm Sewers

Storm sewers discharging directly into a stream, without proper stormwater management, concentrate bacteria and other contaminants into a single point and commonly bypass the natural filters created by wetlands and riparian zones. As a result, high concentrations of bacteria generally are observed within the sediments adjacent to, and within, the outfall of storm sewers that drain impervious areas. These impervious areas do not have to be urban or even residential because the source of the bacteria may be waterfowl, rodents, bats, dogs, deer, and other animals; however, it is the combination of concentration and removal of natural filtering mechanisms that causes this geographic source. Simply adding detention basins that allow for infiltration of runoff has been shown to decrease bacterial concentrations as a “filter” has been placed back in-line. However, human-made structures, such as artificial wetlands, and even over-taxed natural wetlands, require on-going maintenance because bacteria, and other constituents, have been shown to overload and saturate the sediments, thereby reducing the filtering capability of the structures over time.

Bacterial Regrowth

Data indicate that increased *E. coli* concentrations observed within the impoundment area of a dam may be the result of a symbiotic relation with aquatic growth and may not be the result of the direct input of fecal contamination to the impoundment area. This potential, natural population increase is termed bacterial regrowth. The same potential regrowth effect was not observed in the enterococci population within the same impoundment area, and enterococci populations were shown to actually decrease. These data indicate that different types of bacteria may have different responses to environmental variations within impoundment areas and (or) other regions. Bacteria have previously been shown to potentially exhibit regrowth in the presence of certain types of algae (*Chlorella* and (or) *Cladophora glomerata*) by McFeters and others (1978) and Whitman and others (2003). This regrowth, if feasible, presents a natural source of bacteria often utilized as fecal indicators. This finding would potentially limit the use of certain types of bacteria as an indicator of fecal contamination within specific environments. The impoundment areas of lakes and reservoirs, as well as fluvial environments, that may have algal blooms are potentially most affected by the false indications of fecal contamination caused by this process.

Protocols for Assessment of Fecal Contamination Using Sandbag Samplers and Optical-Brightener Monitoring

Description of Method and Equipment

As noted earlier, approximately 99 percent of bacteria in nature are present as attached, or sessile, bacteria (Potera, 1998). This sessile bacteria population can, thus, be more representative of conditions within the fluvial environment than free-floating, or planktonic, bacteria; however, the great variability that occurs within natural sediments (variable particle sizes, organic content, mineralogy, and (or) other factors) commonly can reduce the ability to accurately interpret data collected from them. Research conducted by Nix and Merry (1990) suggests a method whereby much of the variability associated with natural sediments may be reduced and the larger sessile bacteria population may be assessed. The Nix and Merry method initially called for 300 g of sterile construction-grade sand to be enclosed in a nylon bag and suspended in the stream for approximately 1 week. During this time, bacteria would attach to the sand and, in effect, the samplers would take a 1-week “swab” of the stream. For this study, however, a modified version of the Nix and Merry method was implemented. As noted above, various bacteria appear to preferentially attach and persist within sediment based, partly, on the particle distribution or grain size of that sediment; therefore, the Nix and Merry method was modified to specifically target *E. coli* bacteria by sieving construction-grade, **quartzose** sand to a particle size conducive for the persistence of *E. coli*, which in this case was 0.5 to 1.0 mm. This size range, however, was based on a small preliminary data set, and the current, more comprehensive, data set, as noted above, now indicates a slightly finer particle distribution should likely have been utilized (from 0.25 to 0.5 mm) for this study.

Results From Trial Installation of Sandbag and Optical-Brightener Samplers

Fifteen of the modified sandbag samplers (fig. 39) were installed at 15 different sites along the Coatesville study reach (no samplers were installed along the Wagontown study reach because of a limitation in the number of samples that could be processed by the laboratory). Regardless of any potential error resulting from too coarse of sediment within the bags, the sandbag samplers generally worked as anticipated (all data collected are presented in appendix 4); analysis of these sandbags found that *E. coli* concentrations generally were similar in both the sandbags and natural sediments (fig. 40), and enterococci concentrations generally were lower in the sandbags than in natural sediments (fig. 41). The poor results for enterococci were likely because the particle distribution within the sandbags was too coarse and did not provide an environment that enterococci prefer to colonize; however, further study is required to confirm this. As in all bacterial analyses, outliers occurred and results at lower concentrations were generally noisy (see Limitations of Samplers section). Refinements to the composition of the sandbag samplers are also suggested on the basis of the research previously cited, as well as research by Rogers (2002). These refinements generally involve the composition of the sand filling the nylon bag; this refinement could include one or more of the following steps: adding iron to the sand (allows iron-reducing bacteria to potentially condition the sand substrate and cre-

Figure 39. Sandbag and optical-brightener samplers (pick for scale). (Photograph by P.J. Cinotto, USGS)

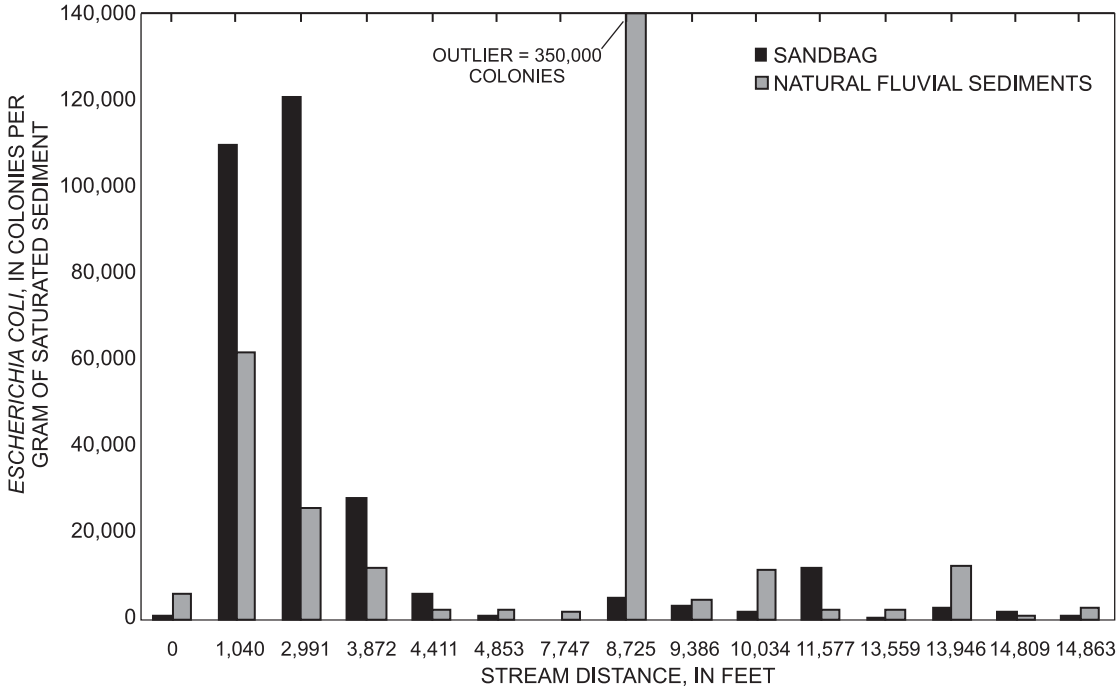


Figure 40. *Escherichia coli* concentrations in sandbags and natural fluvial sediment, Coatesville study reach, 2003, West Branch Brandywine Creek, Chester County, Pennsylvania.

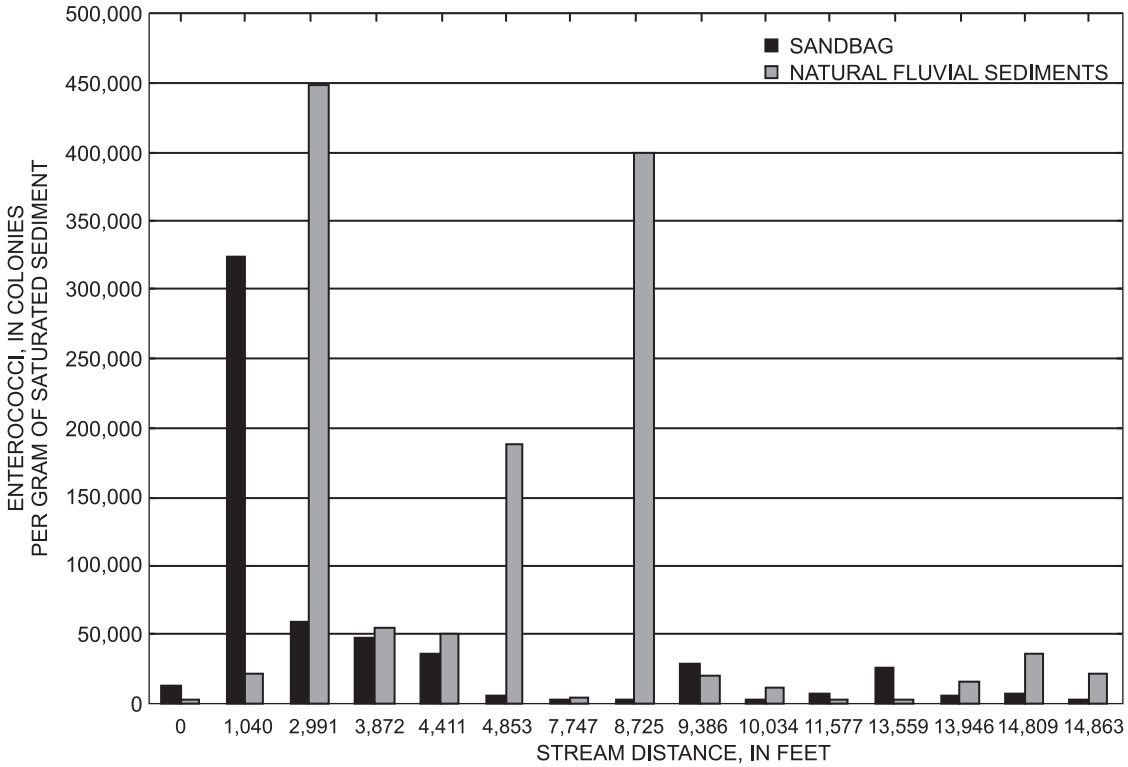


Figure 41. Enterococci concentrations in sandbags and natural fluvial sediment, Coatesville study reach, 2003, West Branch Brandywine Creek, Chester County, Pennsylvania.

ate a better environment for attachment of fecal-indicator bacteria), and (or) adding potassium (as per Rogers, 2002, bacteria preferentially attach to potassium rich minerals, such as potassium feldspars, in nutrient-poor environments). It also should be noted that sandbags are possibly not the best solution for all sites and (or) all climatic conditions. During severe drought conditions, for example, bacteria levels generally are lower in all environments and many outfalls that may be tested could be dry. In these cases, samples from wet, natural sediments may prove to be a better solution for the detection of potential sources of bacterial contamination. Also, given that bacteria are able to preferentially colonize sediments, stream reaches having extreme fluctuations in water quality may, or may not, provide a suitable location for sandbag placement. Protocols and guidance for each method are described in the next section.

In addition to sandbag samplers, additional samplers were added to detect optical brighteners in the water column (R.L. Whitman, U.S. Geological Survey, oral commun., 2003); an example of an optical-brightener sampler is shown in figure 39 along with a sandbag bacteria sampler. Optical brighteners are additives used in common household detergents; optical brighteners are common in wastewater and are present in most sewage. Therefore, if optical brighteners are detected, along with elevated fecal-indicator bacteria concentrations, a human source can be associated with the bacterial contamination. The basic principle of the optical-brightener technique is that optical brighteners will fluoresce, or glow brightly, when exposed to long-wavelength (356 nm) ultraviolet (UV) light. Application of the method calls for perforated, vinyl-coated bags containing sterile, analytical-quality cotton (balls, pads, or bulk) to be installed along with each sandbag. The cotton used for testing must be unwashed, so no optical brighteners will have been previously added and, therefore, under UV light, these unwashed cotton balls will appear black (they will not glow). If the cotton comes into contact with, and subsequently absorbs, water containing high concentrations of optical brighteners, the cotton will fluoresce (glow bright blue) when exposed to long-wavelength UV light.

Results from this study found only two positive optical-brightener tests; both positive samplers were at the outfalls of wastewater-treatment facilities. Because of treatment by the respective facilities at these two sites, however, the concentrations of *E. coli* during base flow were only <1 and 80 col/100 mL. None of the storm-sewer outfalls returned a positive result for optical brighteners even though the chemical analysis noted above indicated some sewage was present. These results highlight that optical brighteners are present in most sewage (even treated effluent), but the concentration of optical brighteners detectable by this method is likely high and could not be quantified by this study.

The benefit of the optical-brightener method is in its simplicity and cost-effectiveness; however, the method has some limitations. This method can only be expected to produce a "positive" or "negative" result and then, as noted above, only when the concentrations of optical brighteners are high in the water column. Therefore, data from these optical-brightener samplers must be interpreted as either "definitely present" or "possibly absent." To assist with interpretation, a set of standards are made from common liquid laundry detergent. These standards will not provide a measure of concentration but will serve to greatly improve the ability of the analyst to detect a "positive" result (these bags can become fouled in the environment). Optical brighteners also degrade in bright sunlight; the use of vinyl-coated bags protects the cotton and optical brighteners from direct sunlight while still providing adequate contact with streamflow. Protocols and guidance for this method are described below.

Application of Method for Assessment of *Escherichia Coli* and (or) Enterococcus Bacteria

The following instructions detail the construction, installation, and analysis of bacteria and optical-brightener samplers along with a comprehensive list of materials required. The construction and use of these samplers is based on principles determined from this and previous studies. All methods and techniques utilized were developed within the last 15 years; however, these methods have not been widely utilized to date. Potential areas where improvements might be beneficial have been noted below as applicable; however, additional data must be collected prior to any modifications. The user of these methods should adhere to all basic field and laboratory methods and techniques to assure quality control and quality assurance as defined in Clesceri and others (1998).

Construction of Samplers

The sandbag and optical-brightener samplers may be constructed utilizing materials from the equipment list provided below. Care should be taken during construction of the samplers because consistency is important in this process. During construction, care also should be taken to prevent bacterial contamination of the materials. The work area should be sterilized using a dilute bleach solution and rinsed thoroughly, rubber gloves should be worn, and all sterilized materials should be stored in sterile plastic bags.

Complete construction of the sandbag samplers as follows:

1. Dry the contents of a 40-lb bag of general-purpose construction sand by placing smaller portions in a drying oven, heating it over a hot plate, or simply spreading it in the sun. This process may take a full day; however, this process will save much time during the sieving, which will remove all but a small fraction of the original volume.
2. Sieve the dry sand and separate the particle range appropriate for the targeted bacteria (a size range of 0.25 - 0.5 mm for *E. coli* and 0.125 - 0.25 mm for enterococci was shown to be effective, however, this data set is statistically weak, relies on observations alone, and is specific to this data set). *Caution:* Note that the enterococcus data set presented above (fig. 41) is noisy;

this likely indicates that the 0.125 - 0.25 mm size range will require refinement as future data are added. Refer to the detailed description above for more information on this topic.

3. Weigh 300 g **aliquots** of the applicable sieved sand in standard weigh boats and steam-sterilize in an autoclave. Note: The sand will be wet subsequent to steam-sterilization, which is why the aliquots must be pre-weighed and sterilized individually.
4. Pour the sterile sand into a nylon stocking and knot BOTH ends (the factory-sewn seam may separate under load in the field). The nylon stockings are not sterilized at this stage, however, they are assumed to be sterile from the manufacturer. Additional steam sterilization, as noted below, can address this concern, if required.
5. Place the sandbag in a sterile container and set aside (a sterile bucket with a lid works well for bulk applications). Additional steam sterilization usually is not required; however, if sterilization of the completed bag is desired, use a lower temperature to prevent melting or weakening the nylon.

Complete construction of the optical-brightener samplers as follows:

1. Obtain laboratory-grade cotton (balls, pads, or bulk) and check with the 356-nm UV light to assure that the cotton does not contain optical brighteners. The cotton should remain dark if unwashed and will fluoresce (glow brightly) if it has been washed. The occasional small piece of cotton that fluoresces generally is unavoidable; however, the vast majority of the cotton should appear black under the UV light. High-quality cotton from scientific-supply companies generally works better than that purchased from the local drug store.
2. Obtain Hubco Protexo sand-sample bags or an equivalent. These bags are palm-sized, vinyl-coated, light-canvas bags used for the collection of drill cuttings. Most environmental supply companies will carry these bags or an equivalent. Use a standard hole punch and evenly perforate the bags approximately 20 times (all the way through the bag, so there are at least 20 holes per side). These holes should be evenly spaced to allow water to flow through while the cotton is held inside.
3. Place approximately five cotton balls in each bag (or a piece about the size of two golf balls if using pad- or bulk-type cotton).
4. Tie the bag securely and set aside (these bags do not have to be sterilized).

Immediately prior to installation in the field, securely tie the sandbag to the end of a length of masonry cord. Place a small loop in the cord approximately 5 in. above the sandbag and tie the optical-brightener sampler to this loop; the weight of the sandbag will help keep the optical-brightener sampler submerged. An optional mesh bag may be secured over the entire assembly and secured to the masonry cord. The mesh bags generally serve to protect the samplers and (or) possibly contain a sampler if it becomes detached from the masonry cord. The masonry cord can then be affixed to the metal anchor ring, as described in the installation of samplers section below, and cut to length as dictated by the site conditions.

Installation of Samplers

1. Locate a position whereby the sampler will hang into a slightly shaded part of the stream with steady flow, but with slow enough velocities as not to destroy the sandbag (the sandbag should easily remain submerged and should not “skip” on, or near, the surface). Even though sandbags are tough, the sand can be pushed through the nylon mesh in fast flows. If sand is pushed through the mesh, the sample will not be valid because bacteria will not likely be able to attach to the sand in these conditions.
2. If possible, measure pH, dissolved oxygen, temperature, and specific conductance at the site to determine if extreme values are present relative to the local conditions. If measurements vary appreciably, bacteria may not attach to sediments at the site.
3. After the attachment location is determined, an approximately 4-in. piece of galvanized plumbers strap should be cut, wrapped around the steel ring, and fastened to the culvert pipe, bridge, tree, or other object with a masonry anchor or ring-shank nail (fig. 42). This permanent ring will allow additional samplers to be placed in the same location during subsequent sampling events.

Figure 42. Mounting hardware for sandbag and optical-brightener samplers. (Photograph by P.J. Cinotto, USGS)

4. Tie the masonry cord holding the samplers securely to the ring with sufficient cord length to allow the samplers to rest on the bottom, or in no greater than about 2 ft of

water, without so much slack that they can be washed out of the flow. If the samplers are found dry, the sample will not be valid because the sand must remain moist.

5. Samplers can be installed in streams, at the mouth of culverts, or in springs provided that water is present and flowing. In deep water (greater than 2 ft deep), the samplers should be suspended near the surface.
6. If no flow is present, the sandbag and optical-brightener samplers will not be effective. In the case of no, or low, streamflow, bacteria samples should be collected from moist, natural sediment (primarily sandy sediments, if available) at the location in question. These bacteria samples may be analyzed along with the sandbag samplers as described below.
7. Samplers can be installed during any flow regime (low-flow periods or the occasional high flows during or just after a storm event); however, data collected over extended periods of base flow are likely to be substantially easier to interpret. Bacterial resolution during base-flow periods will likely be better because background bacteria levels generally will not be elevated (potentially masking smaller bacterial sources). Bacteria within the water column, during base-flow periods, are also more likely to be planktonic, meaning they are more likely to have originated from leaks and other inputs instead of being remobilized from the stream channel. Optical-brightener sampling also will be more effective during dry periods because wastewater will be more concentrated and, thus, more likely to be detected.
8. After installation, the samplers should be left in the stream for approximately 1 week. This time frame, as used in this study, was arbitrary; however, the time allowed was considered to be of sufficient duration to allow bacteria to attach in sufficient numbers to be representative of environmental conditions. Even though the residence time in the stream may, ultimately, be refined on the basis of data from future studies, it should be noted that consistency is important in relating data collected at one site to another. For example, if a study begins with a sampling duration of 1 week, that period should be maintained throughout the study.
9. Upon removal from the stream, sandbag and optical-brightener samplers should be placed in a sterile container, placed on ice, and transported to the laboratory following the same guidelines as established for samples collected from the water column.

Analysis

Simplified methods of analysis for the determination of bacteria concentrations in sediment and optical brighteners have been created for use in this study and are presented below. Analytical results for bacteria are reported in “colonies per gram of saturated sediment,” because moisture content of sediments are not determined by this method in the laboratory. If laboratory capabilities are sufficient, the following method may be amended to adjust for actual dry-sediment volume and, thus, improve the precision of the overall analysis. However, given the inherent variability present in all bacterial analyses, the overall accuracy of the bacteria analysis will not likely be greatly improved by the implementation of this additional method.

Natural Sediment and Sandbag Samplers

1. At the laboratory, the sediment samples should be carefully set aside for 30 minutes and allowed to settle.
2. At the end of this 30-minute period, any remaining residual water should be gently decanted and discarded.
3. Carefully weigh out approximately 20 g of the wet sediment avoiding large pieces of gravel and organic debris in the sample if analyzing natural sediment samples.
4. Add the sediment to a 100-mL volumetric flask or other similar, sterile, container.
5. Dilute to the 100-ml mark with a sterile buffer solution. Buffers prevent osmotic shock and encourage the appropriate electrostatic environment to dislodge bacteria from sediment particles (S. Haack, U.S. Geological Survey, written commun. 2004).
6. Shake the flask for 45 seconds. Ideally, a laboratory wrist-action shaker should be utilized, but use of this shaker is generally impractical for smaller laboratories because of cost.
7. Allow the sample to settle for 30 to 45 seconds. In this short time period, the bacteria will remain in suspension while most coarse sediments will settle out.
8. Analyze this supernatant by way of standard membrane filtration techniques that are applicable for the type of bacteria being sought. It should be noted that natural sediment samples can contain large percentages of silts and clays. These fine sediments generally do not settle easily, can plug filters, alter the shape of bacterial colonies on the plates, and generally can make counting bacterial colonies more difficult. Using sieved sand and the sandbag samplers greatly reduces this problem.
9. Apply a dilution factor to the final count to account for the creation of the initial solution. Two simplified methods are presented here for use in basic laboratories that are common at most municipal levels; one for natural sediment samples and one for sandbag samples. Note that this method for determining a dilution factor was developed based on specific laboratory limitations within this study; an acceptable dilution factor may be determined for each individual sample by weight alone.

$$\text{Weight of sample (g)}\ A/1.65 = B\ \text{(mL)}$$

100 mL (total volume) - B = C (g)

A + C = D = total weight (g)

A / D = E = weight of the sample divided by the total weight

1 / E = F = final dilution factor

SANDBAG SAMPLE DILUTION-FACTOR METHOD: Determine the submerged specific weight of the material used in the sandbag as follows, if the material is not quartzose sand. If quartzose sand is used, use a submerged specific weight (γ_s) of 1.65 and skip this step; again, the dilution factor may be determined for each individual sample by weight:

1. Fill a 500-L beaker three-quarters full with the same sand used to fill the sandbag samplers.
2. Fill beaker with de-ionized water and drain by decanting the water (to saturate the sand).
3. Using a 100-mL graduated cylinder, tare and weigh out approximately 20 g of the saturated sand and note the weight (a).
4. Fill to the 100-mL mark with de-ionized water and note the final weight in grams (b).
5. (b - a) = weight of deionized water added (c).
6. 100 - (c) = weight of the water displaced by the saturated sediment in grams (d); note that 1 mL of deionized water weighs 1 g.
7. (a) / (d) = submerged specific weight (γ_s) of sand used in sampler.
8. Carefully repeat this process 10-15 times and take the average value.
9. Use this computed submerged specific weight (γ_s) to determine the dilution factor.

Weight of sample (g) A/ γ_s = B (mL)

100 mL (total volume) - B = C (g)

A + C = D = total weight (g)

A / D = E = weight of the sample divided by the total weight

1 / E = F = final dilution factor

Optical-Brightener Samplers

1. Prior to analysis of cotton from the optical-brightener samplers, the analyst will likely observe that the cotton is very fouled by sediment, algae, iron, and (or) other staining agents. These stains can make a definitive “positive” or “negative” determination quite difficult. To increase the accuracy of interpretation and prevent bias, a simple set of four standards is created and utilized as a comparative scale. Most liquid laundry detergents will work for the creation of these standards (for this study, liquid “Tide with bleach alternative” was used). For the standards, create the following three dilutions of the liquid laundry detergent and apply the solution to clean cotton (the same cotton as used in the samplers) in individual 50-mL beakers or similar glassware; a blank standard also is included and is composed of a plain piece of cotton wetted with de-ionized water.
    1. 0 (Plain cotton sample)
    2. 1:10,000
    3. 1:1,000
    4. 1:100
2. Disassemble the optical-brightener sample bags and carefully place the samples in individual glass beakers. Using forceps, gently spread the cotton to expose the cleaner inside portions of the cotton (the inside of the cotton will have also absorbed any optical brighteners).
3. In a darkened room, illuminate the still-wet sample and standards with long-wave UV light (356 nm).
4. If the sample glows brighter than the lowest standard, the sample is “positive” and an anthropogenic input of wastewater is suspected.
5. If the sample does not appear brighter than the lowest standard, the sample is “negative” and an anthropogenic input of wastewater is not present in concentrations high enough to detect; wastewater may still be present.
6. As a note of caution, the ability to create a set of standards would suggest that optical-brightener concentration also could be estimated; however, any attempt to do this estimation should be approached with great caution because the basic analysis is designed to be qualitative and not quantitative. Detailed laboratory analysis of the chemical composition of the water should be used for analysis of any wastewater concentrations.

Equipment List for Construction and Installation of Samplers

1. Quartzose (mostly quartz) construction sand (available at most home centers)
2. Oven or hot plate to dry sand (sand often comes wet and does not sieve easily)
3. Miscellaneous glassware
4. Sieves as defined by data from this study (U.S.A. Standard testing sieves)
    a. Catch pan (to hold in sand so sieves can be shaken)
    b. 0.125 mm (lower end of enterococci range)
    c. 0.25 mm (lower end of *E. coli* range and upper end of enterococci range)

   d. 0.5 mm (upper end of *E. coli* range)
   e. 2.0 mm (to break up clumps and protect finer sieves)
   f. Lid (to hold in sand so sieves can be shaken)
5. Scale (to weigh out portions and fill bags)
6. Autoclave (to steam-sterilize sand and other equipment)
7. Nylon bags (nylon stockings were used for this study)
8. Hubco Protexo sand-sample bags or equivalent (to hold cotton)
9. Unwashed cotton balls, cotton pads, or bulk cotton
10. Hole punch (to perforate Hubco Protexo bags)
11. Masonry cord (or other small, strong cord to anchor samplers)
12. Heavy nylon-mesh sample bags (optional; available from most scientific supply companies)
13. 1- to 2-in. chrome-plated steel rings to tie samplers to (the smooth rings will not wear through the cord)
14. Plumber's strap (for affixing rings to culverts, trees, or other objects)
15. 1/4-in. concrete anchors (concrete anchors will securely fasted samplers to concrete and (or) stone objects)
16. Cordless drill with 1/4-in. masonry drill bit (for concrete anchors)
17. Ring-shank nails (ring-shank nails will securely fasten samplers to wooden objects)

Limitations of Samplers

The initial design of sandbag and optical-brightener samplers was based on the work of Nix and Merry (1990) and numerous discussions with others. Techniques presented within these protocols were then, subsequently, refined on the basis of the limited data collected during this study. Because of the preliminary nature of these techniques, revisions to the design and implementation of the samplers is anticipated during future use. As noted above, revisions to the particle size within the sandbags, the composition of the sand filling, and sampler placement may all require alteration in the future. The analyst should maintain careful notes on composition of the sandbags, sandbag placement in the stream, and field or laboratory conditions, to allow for these future modifications. Sandbag bacteria data were also noisy at lower bacteria concentrations. These variable data at lower concentrations illustrates the need for the determination of statistical limits below which the concentration of bacteria cannot be measured or reported accurately; these limits are termed "method detection limits" and "method reporting limits," respectively. Method detection limits and (or) method reporting limits could not be determined within the scope of this study because the data set of 15 sandbag and optical-brightener samples was statistically too small. These limits will be necessary in the future in order to report and analyze data with an acceptable degree of statistical certainty. Outliers are common in any assessment of natural bacterial populations. Data collected from sandbag samplers and natural sediment should be compared with caution because bacterial concentrations can vary substantially between the two data sets. As discussed previously, natural sediment is variable; because of this variability, outliers will likely be more common when sampling these natural sediments.

Limitations of the Investigation

The sampling plan and data collected during this study were subject to the limitations of available laboratory equipment, field and laboratory personnel, time, and budgetary constraints. Some data sets within this study are statistically small, and additional data are required to increase the statistical certainty of some relations. Additional data also are required to quantify specific environmental parameters such as soil moisture, potential combined-sewer problems, bacterial regrowth, and (or) other parameters. Methods developed during the course of this study are preliminary and modifications are anticipated as more data become available. Potential improvements to methods are listed throughout the text where applicable. This study was conducted by sampling individual events over the course of 2 years. This sampling plan, therefore, resulted in the collection of individual "snapshots" during the 2-year period from which various determinations were made. Long-term (longer than 10 years) and (or) continuous data collection are generally required to make statistically sound determinations relating to any long-term trends.

Competition for resources must be considered in the interpretation of any data regarding biofilms. As generally observed throughout nature, organisms and (or) assemblages of organisms present in the same ecological niche must compete for available resources and, ultimately, survival. Research has shown that biofilms are also subject to this same natural, competitive process. For example, Banning and others (2003) point out that, under certain conditions, biofilms may represent sites of intensified competition for limiting or specific nutrients. Simplified, this research suggests that biofilms can compete for limited resources and potentially destroy other, weaker biofilms. Changes in environmental conditions and (or) available resources within the fluvial environment may, therefore, prove detrimental for one type of bacteria and (or) beneficial for another. Consequently, localized areas of little or no bacterial contamination within fluvial sediments and (or) the water column may not be because of the lack of bacteria but instead the lack of conditions conducive to the persistence of that particular

bacteria type. Although the specific study of this issue was beyond the scope of this study, an understanding of the potential effects on bacterial populations resulting from this concept is important in the interpretation of all bacterial data.

Summary and Conclusions

Up to 99 percent of all bacteria within nature are present as sessile or attached bacteria; however, most current (2004) methods to assess bacteria only assess those bacteria that are planktonic, or free-floating, within the water column. These current methods, therefore, do not adequately assess the processes that effect the overall fluvial system; in effect, these methods identify the presence of the problem but not the extent. Assessment and understanding of the larger sessile bacteria population, as well as the planktonic population, is critical to understanding the biological and physical processes that drive various bacterial concentrations within the fluvial system. In cooperation with the Chester County Water Resources Authority and the Chester County Health Department, the U.S. Geological Survey (USGS) began a study in 2001 to identify potential sources of fecal-indicator bacteria within the West Branch Brandywine Creek in Chester County, Pa., gain a better understanding of bacteria occurrence and distribution within the fluvial system, and develop protocols to assist water-resource managers in the detection of point and nonpoint sources of fecal contamination within the fluvial system.

The study encompassed two reaches of the West Branch Brandywine Creek—the Coatesville study reach and the Wagontown study reach. The Coatesville study reach is on the West Branch Brandywine Creek as it flows through the city of Coatesville, the Borough of South Coatesville, and the Borough of Modena. The Wagontown study reach is on the West Branch Brandywine Creek as it flows near the town of Wagontown, in Chester County, Pa. The Coatesville study reach flows through a predominantly urban/industrial region and the Wagontown study reach flows through a predominantly forested region. Sixty-four base-flow sampling sites, 15 stormflow sampling sites, and 15 sandbag sampling sites were located throughout the Coatesville study reach. Ten base-flow sampling sites were located throughout the Wagontown study reach; no storm samples were collected from this reach.

Samples were collected and processed for various bacteria in natural fluvial sediment, the water column, and artificial sediments in samplers (sandbags). Samples collected from fluvial sediments were analyzed for *E. coli*, enterococcus, fecal coliform, and fecal streptococcus. Sediment samples were collected as single-point grab samples from wet, fluvial sediments exposed to flow from potential fecal-contamination sources. Samples collected from the water column were analyzed for *E. coli*, enterococcus, fecal coliform, and fecal streptococcus bacteria. Chemical measurements were made for temperature, dissolved oxygen, pH, turbidity, and specific conductance at all sites where bacteria samples were collected. Samples from selected sites on the Coatesville study reach were analyzed to detect potential wastewater constituents and (or) nutrients. Fifteen modified sandbag samplers installed along the Coatesville study reach were analyzed for *E. coli* and enterococci. All bacteria samples were analyzed at the Chester County Health Department Laboratory, and water-quality samples were analyzed at the USGS National Water-Quality Laboratory. Quality-assurance and quality-control techniques were applied to the collection of all samples following USGS guidelines.

Complex processes control many of the factors that determine when, where, and how much bacteria will attach within the fluvial environment as well as the availability of those bacteria to enter the water column. These processes are related to natural factors, such as sediment particle size, climatic conditions, aquatic growth, and competing organisms; and (or) anthropogenic influences, such as impervious surfaces adjacent to the stream, stormwater-management practices, reduction of wetlands and riparian zones, presence of instream structures, and (or) variations in water quality. Also of note is that because of the complexity of the fluvial system, and the diverse biologic response to stresses within that system, various bacteria are not likely to correlate well with one another; this conclusion was indicated by the relative differences shown between *E. coli* and enterococci concentrations within similar fluvial environments.

Data collected during this study indicate that particle distribution (grain size) is a potential factor controlling bacteria concentrations within fluvial sediments. *E. coli* had grater median concentrations in the particle-size range of 0.125 to 0.5 mm (fine to medium sand) than in other particle-size classes, and enterococci had greater median concentrations in the particle-size range of 0.062 to 0.25 mm (silt and clay to fine sand) than in other particle-size classes. Further data are required from other fluvial systems to determine if a broad comparison between fluvial systems is possible or if these data are valid only for the West Branch Brandywine Creek.

During 2003, six sites were sampled for nutrients and wastewater constituents along the Coatesville study reach. Analyses of the water-quality samples collected during base flow indicated nutrient such as dissolved nitrate plus nitrite nitrogen and total phosphorus ranged from 2.0 to 3.69 mg/L and 0.008 to 0.091 mg/L, respectively. A large percentage of the total nutrient load originated from the Coatesville region. During stormflow, a similar pattern in nutrient loads was present along the Coatesville study reach. This pattern indicated that the urban/industrial Coatesville area had a more substantial effect on nutrient loads within the study reach than did the upstream agricultural areas.

Wastewater constituents generally indicate direct fecal inputs to the fluvial system such as leaking sewer pipes, failed septic systems, combined sewer overflows, and illegal discharges. Samples were collected concurrently with nutrient samples and analyzed for wastewater constituents. Wastewater constituents during base flow in 2003 primarily originated from the Coatesville storm-sewer system. The primary storm sewer for the city of Coatesville tested positive for 20 of 69 wastewater constituents. By comparison, only 5 of 69 constituents were

detected entering the upstream end of the study reach in the main channel of the West Branch Brandywine Creek. Water sampled from the downstream end of the study reach tested positive for 10 of 69 constituents suggesting that dilution had lowered many of the contaminant levels entering from the Coatesville storm sewer to below the method detection limit for the various wastewater constituents. During stormflow, 5 of 69 constituents were detected at the upstream end of the study reach, 8 of 69 constituents were detected at the center of the study reach, and 7 of 69 constituents were detected at the downstream end of the study reach. These data indicated no significant increase in the detected number of wastewater constituents along the Coatesville study reach during stormflow and indicated point sources (culverts, pipes, and so forth) of fecal contamination within the Coatesville study reach were not the likely origin of bacteria contamination during stormflow on the West Branch Brandywine Creek.

Impervious surfaces affected bacterial contamination. This result was most evident in 2002. Elevated concentrations of *E. coli*, in 2002, were found primarily in sediments at or near storm-sewer outfalls along the Coatesville study reach (although not all storm sewers had elevated bacterial concentrations). Elevated *E. coli* concentrations within fluvial sediments were generally in the upstream region of the Coatesville study reach. This upstream region contains most of the known storm-sewer outfalls that directly enter the West Branch Brandywine Creek.

During 2003, high concentrations of bacteria were observed within the sediments of the West Branch Brandywine Creek below the outfall of a wastewater-treatment facility. Concentrations of *E. coli* in fluvial sediments along this reach were as high as 100 times greater than the median concentration of the Coatesville study reach; however, bacteria concentrations within this stream reach during the previous year did not exceed levels that would be considered background. The origin of these bacteria was unknown; however, data interpretation indicate storm sewers may have been largely the cause for the detected bacterial concentrations within the fluvial sediments near the outfalls. Most sites with elevated bacteria concentrations were at or near the air/water interface at the edge of the active steam channel.

Lower bacteria concentrations within the water column of the Wagontown study reach than in the Coatesville study reach were attributed to the lack of overland flows across paved areas and the effective filtration of runoff by adjacent wetlands and more substantial riparian zones. The median concentration of *E. coli* within the water column of the Wagontown study reach, during base-flow sampling in 2003, was 195 col/100 mL; within the water column of the Coatesville study reach, the median concentration of *E. coli* was 960 col/100 mL during the same period. The bacteria concentrations within the water column at the upstream end of the Coatesville study reach (above the city of Coatesville storm-sewer outfalls) were consistent with those observed along the Wagontown study reach. The median *E. coli* concentration for the first 900 ft of the Coatesville study reach was 300 col/100 mL during base flow in 2003.

Bacterial data collected from fluvial sediments as part of this study could not with any certainty identify specific sites where sediment filtration was occurring and (or) failing along the West Branch Brandywine Creek because the sampling plan did not target this issue. Although climatic and runoff effects likely affect the observed concentrations of various bacteria along this reach, knowledge of the prior discharge of untreated sewage along with the observed elevated concentrations of bacteria adjacent to the wetland area indicate that some level of filtration is potentially occurring, or may have occurred along this reach. Additional study is required to support this observation.

Dams or other instream structures can, and do, affect bacteria concentrations within the fluvial environment. However, the actual process remains unclear and requires additional study.

The regression analysis of both base-flow and stormflow data did not yield statistically valid relations between *E. coli* bacteria and turbidity. High turbidity levels usually can indicate higher bacterial concentrations, but the relation was too sporadic on the West Branch Brandywine Creek to use turbidity as a feasible surrogate to estimate bacteria concentrations.

Analysis of sandbag samplers found that *E. coli* concentrations generally were similar in both the sandbags and natural sediments, and enterococci concentrations generally were lower in the sandbags than in natural sediments. The poor results for enterococci were likely because the particle distribution within the sandbags was too coarse and did not provide an environment that enterococci prefer to colonize; however, further study is required to confirm this conclusion. In addition to sandbag samplers, additional samplers were added to detect optical brighteners in the water column. Detection of optical brighteners, along with an elevated fecal-indicator bacteria concentration, is indicative of an anthropogenic source of fecal contamination. Results from this study found only two positive optical-brightener tests; both positive samplers were at the outfalls of wastewater-treatment facilities. The optical-brightener method has some limitations. This method can only be expected to produce a “positive’ or “negative” result and at concentrations that can not be quantified.

Generally, throughout this study, previously suspected sources of elevated bacteria concentrations, such as wastewater-treatment facilities and on-lot sewage disposal systems, were not found to directly contribute to increased bacterial concentrations observed within the study area of the West Branch Brandywine Creek The primary sources of elevated bacteria concentrating throughout the study area were generally found to be related to natural processes occurring within the environment and anthropogenic influences centered around urban and industrial runoff issues. Whereas natural processes, such as climatic conditions, are generally beyond the control of water-resource managers, anthropogenic influences shown to effect bacterial concentrations in the West Branch Brandywine Creek can be corrected to potentially reduce bacterial concentrations within the fluvial environment. Reduction of nutrient loads from agricultural and urban areas can decrease aquatic growth within impoundment areas, thereby reducing the potential for

bacterial regrowth. Restoration of wetland and riparian zones may allow for infiltration of surface-water runoff, thereby filtering out much bacteria by way of bank filtration. Implementing stormwater-runoff structures that promote infiltration and do not allow direct input of stormwater from urban areas to enter the steam may reduce bacteria levels by means of sediment filtration. Reducing streambank and streambed erosion may reduce bacteria concentrations during stormflows by minimizing the amount of sessile bacteria washed into the stream as the streambank and streambed are eroded. Detecting and eliminating direct inputs of sewage that result from aging infrastructure can obviously reduce the direct input of planktonic bacteria to the water column. In summary, a natural, functioning stream is more likely to have lower concentrations of bacteria in both the water column and the fluvial sediment than a stream that has been extensively modified by humans.

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Appendix 1–Site Descriptions

Table 1-1. Descriptions of base-flow sampling sites on Coatesville study reach, West Branch Brandywine Creek, 2002 and 2003, Chester County, Pennsylvania.[1]

[~, approximately; USGS, U.S. Geological Survey; W.B., West Branch; SR, Pennsylvania State Route]

Stream distance from upstream end of project reach (feet)	U.S. Geological Survey project identification number[2]	U.S. Geological Survey station identification number	Latitude	Longitude	Years sampled	Site description	Location of sediment-sample collection
0	CB1	01480500	39°59′06.7″	75°49′37.2″	2002, 2003	Dam adjacent to USGS streamflow-gaging station 01480500.	Streambed of W.B. Brandywine directly behind dam crest near center of channel.
178	CB4	01480502	39°59′05.1″	75°49′36.5″	2002	Mid-channel bar; directly upstream from abandoned concrete bridge.	Edge of W.B. Brandywine on right side of bar near downstream end.
326	CB5	01480506	39° 59′04.0″	75°49′35.2″	2002, 2003	Mid-channel bar; directly upstream of large railroad bridge.	Edge of W.B. Brandywine at downstream tip of bar.
361	CB6	395904075493401	39°59′04.1″	75°49′34.4″	2002	Outfall; ~0.5 ft diameter pipe, ~4 ft landward from left edge of water, under large railroad bridge. Dry in 2002.	Edge of W.B. Brandywine within small swale.
551	[3]CB7TC	395903075493301	39°59′02.8″	75°49′32.8″	2002, 2003	Outfall; Coatesville storm sewer, ~2-ft diameter pipe, ~30 ft landward from left edge of water. Flowing in 2002 and 2003.	From bottom of swale leading to mouth of pipe, ~5 ft landward from W.B. Brandywine.
666	CB8	01480514	39°59′01.7″	75°49′32.4″	2002, 2003	Point bar on right bank; directly across from various Coatesville storm-sewer outfalls.	Edge of W.B. Brandywine near center of bar.
898	CB9	395901075493101	39°59′01.0″	75°49′31.2″	2002, 2003	Outfall; Coatesville storm sewer, ~2-ft diameter pipe, ~30 ft landward from left edge of water. Dry in 2002 and 2003.	Streambank at edge of W.B. Brandywine, directly below swale.
1,040	CB9BTC	395900075493001	39°59′00.0″	75°49′30.1″	2003	Outfall; Coatesville storm sewer, ~2-ft diameter pipe, ~30 ft landward from left edge of water. Flowing in 2003.	From bottom of swale leading to mouth of pipe, ~5 ft landward from W.B. Brandywine.
1,192	CB10	01480522	39°58′57.4″	75°49′28.8″	2002, 2003	Mid-channel bar with left-side channel leading to Coatesville storm-sewer outfall upstream under SR30 bridge. Outfall was dry in 2002 and flowing in 2003.	From edge of W.B. Brandywine, along right side of left channel, near downstream end of bar.

Table 1-1. Descriptions of base-flow sampling sites on Coatesville study reach, West Branch Brandywine Creek, 2002 and 2003, Chester County, Pennsylvania.[1] —Continued

[~, approximately; USGS, U.S. Geological Survey; W.B., West Branch; SR, Pennsylvania State Route]

Stream distance from upstream end of project reach (feet)	U.S. Geological Survey project identification number[2]	U.S. Geological Survey station identification number	Latitude	Longitude	Years sampled	Site description	Location of sediment-sample collection
1,395	CB11	395855075492801	39°58′55.2″	75°49′28.0″	2002, 2003	Outfall; Coatesville storm sewer, ~2-ft diameter pipe, ~30 ft landward from left edge of water. Dry in 2002 and 2003.	Streambank at edge of W.B. Brandywine, directly below swale.
1,774	CB12	01480532	39°58′53.0″	75°49′28.4″	2002	Mid-channel bar.	Edge of W.B. Brandywine on right side of bar near the center.
1,931	CB13	395850075492801	39° 58′50.0″	75°49′28.3″	2002	Outfall; 3, 1-3-ft diameter pipes in stone-masonry wall on right bank. Likely a storm sewer from mill. Dry in 2002.	Edge of W.B. Brandywine directly below largest pipe on right side of channel.
2,167	CB14	395848075492701	39° 58′48.0″	75°49′26.7 ″	2002, 2003	Outfall; 2-ft diameter pipe with concrete spillway ~15 landward from left edge of water. Dry in 2002 and 2003.	Edge of W.B. Brandywine at base of concrete spillway.
2,575	CB15	01480548	39°58′42.9″	75°49′23.1″	2002	Mid-channel bar directly downstream of low-head dam.	Edge of W.B. Brandywine at upstream tip of bar.
2,991	[4]CB16TC	01480550	39°58′41.1″	75°49′21.0″	2002, 2003	Outfall; large brick and concrete culvert on left bank known as Gibbons Run. Gibbons Run is primary storm sewer for City of Coatesville. Flowing in 2002 and 2003.	Bed of Gibbons Run within culvert.
3,085	CB17TC	395840075492001	39°58′40.1″	75°49′20.3″	2002, 2003	Outfall; 2-ft diameter culvert with stone-masonry spillway ~15 ft landward from left edge of water. Culvert is storm sewer that drains area above ISG Plate Inc. Flowing in 2002 and 2003.	Bottom edge of stone-masonry spillway (slightly above left edge of W.B. Brandywine).
3,397	CB18TC	395837075491901	39°58′37.2″	75°49′19.4″	2002	Outfall; 2-ft diameter culvert in concrete wall ~10 ft landward from right edge of water. Flowing in 2002 and 2003.	Bottom of swale leading to mouth of culvert ~5 ft landward from W.B. Brandywine.
3,835	CB19	01480564	39°58′33.8″	75°49′21.4″	2002, 2003	Mid-channel bar directly downstream of bridge leading into mill building.	Edge of W.B. Brandywine at downstream tip of bar.

Table 1-1. Descriptions of base-flow sampling sites on Coatesville study reach, West Branch Brandywine Creek, 2002 and 2003, Chester County, Pennsylvania.[1] —Continued

[~, approximately; USGS, U.S. Geological Survey; W.B., West Branch; SR, Pennsylvania State Route]

Stream distance from upstream end of project reach (feet)	U.S. Geological Survey project identification number[2]	U.S. Geological Survey station identification number	Latitude	Longitude	Years sampled	Site description	Location of sediment-sample collection
3,872	CB20TC	01480580	39°58′33.6″	75°49′22.5″	2002, 2003	Outfall; ~4-ft × 4-ft rectangular culvert in concrete wall below mill building on right bank. Known as Tar Run; culvert serves as Coatesville storm sewer and outfall for process water from ISG Plate Inc. Flowing in 2002 and 2003.	Bed of Tar Run within culvert.
4,411	[4]CB21TC	01480614	39°58′30.3″	75°49′27.8″	2003, 2003	Outfall; ~15-ft × 10-ft culvert in concrete wall below mill building on right bank. Known as Sucker Run; culvert serves as Coatesville storm sewer. Flowing in 2002 and 2003.	At mouth of Sucker Run culvert along edge of W.B. Brandywine (no sediment within culvert).
4,677	CB22	014806141	39°58′26.8″	75°49′27.4″	2002	Point bar on left bank.	Edge of W.B. Brandywine near center of bar.
4,853	CB23TC	395826075492701	39°58′25.7″	75°49′26.7″	2003, 2003	Pennsylvania American Water Company, sewage-treatment facility outfall on left bank. Flowing in 2002 and 2003.	Edge of W.B. Brandywine, directly downstream from outfall at first location where effluent would contact the sediments of the stream bank.
5,150	CB24	395823075492501	39°58′23.2″	75°49′25.2″	2002	Outfall; 2-ft diameter pipe with flap-type cover ~5 ft landward from left edge of water. Dry in 2002.	Edge of W.B. Brandywine in the mouth of swale leading to pipe.
5,574	CB25TC	395819075492401	39°58′19.0″	75°49′23.7″	2002, 2003	Outfall; ~4-ft × 4-ft culvert ~5 ft landward from left edge of water. Flowing in 2002 and 2003.	Mouth of culvert.
6,101	CB26	0148061452	39°58′14.0″	75°49′22.0″	2002, 2003	Mid-channel bar at downstream nose of pier #2 on railroad bridge, very small.	Edge of W.B. Brandywine at downstream tip of bar.
6,703	CB27	014806146	39°58′08.4″	75°49′19.4″	2002, 2003	Deep pool in W.B. Brandywine.	Streambed, center of channel, center of pool, in W.B. Brandywine.
7,183	CB28	014806147	39°58′04.7″	75°49′17.2″	2002, 2003	Point bar on left bank in W.B. Brandywine.	Edge of W.B. Brandywine near center of bar.

Table 1-1. Descriptions of base-flow sampling sites on Coatesville study reach, West Branch Brandywine Creek, 2002 and 2003, Chester County, Pennsylvania.[1] —Continued

[~, approximately; USGS, U.S. Geological Survey; W.B., West Branch; SR, Pennsylvania State Route]

Stream distance from upstream end of project reach (feet)	U.S. Geological Survey project identification number[2]	U.S. Geological Survey station identification number	Latitude	Longitude	Years sampled	Site description	Location of sediment-sample collection
7,201	CB29TC	395804075491601	39°58’ 04.1″	75°49′16.4″	2002, 2003	Outfall; ~4-ft × 7-ft concrete culvert ~5 ft landward from left edge of water. Flowing in 2002 and 2003.	Mouth of culvert.
7,481	CB30	395802075491501	39°58′01.5″	75°49′14.8″	2002, 2003	Outfall; 2-ft diameter culvert with concrete spillway ~10 ft landward from left edge of water. Dry in 2002, flowing in 2003 (too little to sample).	2002 sediment collected from edge of W.B. Brandywine near base of spillway; 2003 sediment taken from mouth of culvert at top of spillway.
7,747	[4]CB31TC	01480615	39°57′58.9″	75°49′14.1″	2002, 2003	Unnamed tributary channel on right bank near intersection of 1st Avenue and Newlinville Road in South Coatesville. Flowing in 2002 and 2003.	Streambed of tributary channel ~20 ft upstream from W.B. Brandywine.
7,906	CB32	0148061502	39°57′58.5″	75° 49′12.0″	2002, 2003	Pool in W.B. Brandywine.	Streambed, center of channel, center of pool, in W.B. Brandywine.
8,170	CB33	0148061506	39° 57′57.7″	75° 49′08.7″	2002, 2003	Riffle in W.B. Brandywine.	Streambed, center of channel, center of riffle, in W.B. Brandywine.
8,446	CB34	0148061508	39° 57′57.3″	75°49’ 05.1″	2002	Run in W.B. Brandywine.	Streambed, center of channel, center of run, in W.B. Brandywine.
8,725	CB35TC	395758075490101	39°57′57.6″	75°49′01.4″	2002, 2003	Outfall; ~4-ft × 4-ft culvert ~2 ft landward from left edge of water. Culvert almost entirely plugged with sediment; serves as storm sewer for adjacent mill complex. Flowing in 2002 and 2003.	Within culvert ~3 ft landward from mouth.
8,767	CB36	0148061516	39°57′57.1″	75°49′00.0″	2002	Point bar on left bank.	Edge of W.B. Brandywine near upstream tip of bar where small chute forms.
9,008	CB36B	0148061520	39°57′56.8″	75°48′57.8″	2002, 2003	Left streambank directly downstream of rip-rap spur dikes.	Edge of W.B. Brandywine.
9,298	CB37	395756075485401	39°57′56.5″	75°48′54.3″	2002	Outfall; 2-ft diameter concrete culvert ~5 ft landward from left edge of water. Not flowing in 2002.	Mouth of culvert.
9,381	CB38	0148061526	39°57′56.7″	75°48′53.0″	2002, 2003	Left streambank where concrete wall meets left edge of water.	Edge of W.B. Brandywine.

Table 1-1. Descriptions of base-flow sampling sites on Coatesville study reach, West Branch Brandywine Creek, 2002 and 2003, Chester County, Pennsylvania.[1] —Continued

[~, approximately; USGS, U.S. Geological Survey; W.B., West Branch; SR, Pennsylvania State Route]

Stream distance from upstream end of project reach (feet)	U.S. Geological Survey project identification number[2]	U.S. Geological Survey station identification number	Latitude	Longitude	Years sampled	Site description	Location of sediment-sample collection
9,381	CB38BTC	395756075485301	39°57′56.0″	75°48′53.0″	2003	Spring, not flowing in 2002. Located ~15 ft landward from right edge of water.	Within flow from spring ~2 ft from source.
9,646	[4]CB39TC	395757075485001	39°57′57.1″	75°48′50.1″	2002	Outfall; 2-ft diameter concrete culvert in concrete wall forming left bank. Skimmer around outfall in 2002. Not flowing in 2002.	Edge of W.B. Brandywine directly below pipe on left side of channel.
9,873	CB40TC	395757075484701	39°57′57.3″	75°48′46.9″	2002, 2003	Spring; located ~15 ft landward from right edge of water. Not flowing in 2002, flowing in 2003.	2002 sediment collected from edge of W.B. Brandywine in small delta formed by flow from spring; 2003 sediment taken from same delta; however, above edge of W.B. Brandywine.
10,034	CB41BTC	395758075484501	39°57′58.0″	75°48′45.0″	2003	Spring, not flowing in 2002. Located ~15 ft landward from right edge of water.	Within flow from spring ~2 ft from source.
10,144	CB41	0148061544	39°57′57.5″	75°48′43.5″	2002	Right streambank directly downstream of rip-rap.	Edge of W.B. Brandywine.
10,340	CB42	0148061548	39°57′58.7″	75°48′41.1″	2002	Inlet; 20-ft × 10-ft gated inlet on left bank for mill process water.	Edge of W.B. Brandywine directly below inlet on left side of channel.
10,905	[4]CB43	0148061552	39°57′59.7″	75°48′33.9″	2002, 2003	Dam locally known as Dam #4.	Streambed of W.B. Brandywine directly behind dam crest near center of channel.
11,001	CB44	0148061556	39°57′59.8”	75°48′32.8″	2002, 2003	Mid-channel bar forming below plunge-pool at dam.	Edge of W.B. Brandywine at upstream tip of bar.
11,078	CB45	0148061558	39°58′00.2″	75°48′30.3″	2002	Pool in W.B. Brandywine in left channel near downstream tip of mid-channel bar.	Streambed, center of left channel, center of pool, in W.B. Brandywine.
11,402	CB46TC	0148061560	39°58′01.0″	75°48′27.8″	2002	Outfall; 5-ft diameter concrete culvert with skimmer and access stairs. Not flowing in 2002.	Within culvert directly at mouth.

Table 1-1. Descriptions of base-flow sampling sites on Coatesville study reach, West Branch Brandywine Creek, 2002 and 2003, Chester County, Pennsylvania.[1] —Continued

[~, approximately; USGS, U.S. Geological Survey; W.B., West Branch; SR, Pennsylvania State Route]

Stream distance from upstream end of project reach (feet)	U.S. Geological Survey project identification number[2]	U.S. Geological Survey station identification number	Latitude	Longitude	Years sampled	Site description	Location of sediment-sample collection
11,577	CB47TC	0148061562	39°58′00.7″	75°48′25.9″	2002, 2003	South Coatesville and Modena, sewage-treatment facility outfall on right bank. Rip-rap apron below outfall. Flowing in 2002 and 2003.	Directly below outfall where effluent contacts the streambank.
11,604	CB48	0148061564	39°58′01.0″	75°48′25.2″	2002, 2003	Pool in W.B. Brandywine.	Streambed, center of channel, center of pool, in W.B. Brandywine.
11,866	CB49	0148061568	39°58′00.3″	75°48′22.0″	2002, 2003	Point bar on right bank.	Edge of W.B. Brandywine near upstream tip of bar where small chute forms.
11,893	CB50	0148061572	39°58′00.4″	75°48′21.3″	2002	Riffle in W.B. Brandywine.	Streambed, right side of channel, center of riffle, in W.B. Brandywine.
12,200	CB51	0148061576	39°57′59.1″	75°48′16.7″	2002	Point bar on right bank.	Edge of W.B. Brandywine near upstream tip of bar.
12,508	CB52TC	0148061580	39°57′57.5″	75°48′14.7″	2002, 2003	Outfall; two, 3-ft diameter corrugated steel culverts. Flowing in 2002 and 2003.	Within culvert ~2 ft landward from mouth.
12,862	CB55TC	0148061584	39°57′54.0″	75°48′14.8″	2002, 2003	Unnamed, small tributary channel on right bank. Not flowing in 2002, flowing in 2003.	2002 sediment collected from edge of W.B. Brandywine in small delta formed by flow from tributary; 2003 sediment taken from streambed of tributary channel ~20 ft upstream from W.B. Brandywine.
13,002	CB56	0148061588	39°57′53.2″	75°48′14.3″	2002, 2003	Pool in W.B. Brandywine.	Streambed, center of channel, center of pool, in W.B. Brandywine.
13,224	CB57	0148061592	39°57′50.5″	75°48′15.4″	2002, 2003	Right streambank directly downstream of overhead pipeline	Edge of W.B. Brandywine.
13,487	CB59	0148061596	39°57′47.7″	75°48′15.2″	2002	Left streambank at swale that leads to large storage tank observed to overflow in 2002.	Edge of W.B. Brandywine in center of swale.
13,559	CB58TC	014806161	39°57′45.6″	75°48′14.0″	2002, 2003	Unnamed tributary channel formed by old mill race. Leads to various springs. Flowing in 2002 and 2003.	Streambed of tributary channel ~20 ft upstream from W.B. Brandywine.

Table 1-1. Descriptions of base-flow sampling sites on Coatesville study reach, West Branch Brandywine Creek, 2002 and 2003, Chester County, Pennsylvania.[1] —Continued

[~, approximately; USGS, U.S. Geological Survey; W.B., West Branch; SR, Pennsylvania State Route]

Stream distance from upstream end of project reach (feet)	U.S. Geological Survey project identification number[2]	U.S. Geological Survey station identification number	Latitude	Longitude	Years sampled	Site description	Location of sediment-sample collection
13,647	CB60	0148061597	39°57′45.5″	75°48′13.1″	2002, 2003	Point bar on left bank ~20 ft directly downstream of 0.5-ft diameter PVC pipe. Flowing in 2002 and 2003.	Edge of W.B. Brandywine near upstream tip of bar where small chute forms.
13,946	CB61TC	014806162	39°57′44.8″	75°48′12.0″	2002, 2003	Unnamed tributary channel on left bank immediately upstream from USGS streamflow-gaging station 01480617. Flowing in 2002 and 2003.	Streambed of tributary channel ~20 ft upstream from W.B. Brandywine.
14,355	CB62	014806168	39°57′42.3″	75°48′07.6″	2002, 2003	Right streambank below several older houses.	Edge of W.B. Brandywine.
14,809	[4]CB64	01480617	39°57′41.2″	75°48′02.9″	2002, 2003	Mid-channel bar adjacent to USGS streamflow-gaging station 01480617.	Edge of W.B. Brandywine at downstream tip of bar.
14,862	CB66TC	0148061802	39°57′40.3″	75°48′01.5″	2002, 2003	Dennis Run.	Streambed of tributary channel ~50 ft upstream from W.B. Brandywine.

[1]All samples from the water column were collected directly from the thalweg, or most dominant flow, of the W.B. Brandywine, tributary, or pipe.
[2]U.S. Geological Survey project identification numbers are assigned in the order they were initially located and not in downstream order as are U.S. Geological Survey station identification numbers.
[3]TC denotes that sample was collected from within flow originating from tributary channel or outfall.
[4]Also a stormflow sampling site.

Table 1-2. Descriptions of stormflow sampling sites on Coatesville study reach, West Branch Brandywine Creek, 2002 and 2003, Chester County, Pennsylvania.[1]

[ft, feet; ~, approximately; W.B., West Branch; USGS, U.S. Geological Survey; SR, Pennsylvania State Route]

Stream distance from upstream end of project reach (ft)	U.S. Geological Survey project identification number[2]	U.S. Geological Survey station identification number	Latitude	Longitude	Years sampled	Site description
0	CBS6	01480500	39°59′11.2″	75°49′38.0″	2002, 2003	Bridge carrying Glencrest East Road over W.B. Brandywine directly upstream of USGS streamflow-gaging station 01480500.
187	CBS7	01480504	39°59′04.8″	75°49′36.3″	2002, 2003	Abandoned concrete bridge immediately downstream from USGS streamflow-gaging station 01480500.
1,019	CBS5	01480518	39°58′58.5″	75°49′29.1″	2002, 2003	Bridge carrying SR30 (Business) over W.B. Brandywine.
2,991	[3,4]CBS13TC	01480550	39°58′41.1″	75°49′21.0″	2002, 2003	Mouth of Gibbons Run culvert at confluence with W.B. Brandywine.
2,995	CBS12	01480552	39°58′40.7″	75°49′21.0”	2002, 2003	Bridge carrying private road within ISG Plate Inc. property over W.B. Brandywine; directly adjacent to Gibbons Run culvert.
3,922	CBS10	01480584	39°58′32.9″	75°49′22.8″	2002, 2003	Bridge carrying private road within ISG Plate Inc. property over W.B. Brandywine; directly adjacent to Tar Run culvert.
4,411	[4]CBS9TC	01480614	39°58′30.3″	75°49′27.8″	2002, 2003	Mouth of Sucker Run culvert at confluence with W.B. Brandywine; accessed by way of overhead walkway.
6,023	CBS15	014806145	39°58′14.4″	75°49′22.0″	2002, 2003	Bridge carrying railroad within ISG Plate Inc. property; located between Sucker Run culvert and 1st Avenue bridge.
7,747	[4]CBS3TC	01480615	39°57′58.3″	75°49′14.4″	2002, 2003	Abandoned bridge over tributary to W.B. Brandywine near intersection of 1st Avenue and Newlinville Road; sampling site is in gravel parking area ~100 ft upstream from confluence with W.B. Brandywine.
7,754	CBS4	0148061501	39°57′58.9″	75°49′13.0″	2002, 2003	Bridge carrying 1st Avenue over W.B. Brandywine near intersection with Newlinville Road.
9,646	[4]CBS16TC	395757075485001	39°57′57.1″	75°48′50.1″	2002, 2003	Outfall; 2-ft diameter concrete culvert in concrete wall forming left bank. Skimmer around outfall in 2002. Not flowing in 2002.
10,905	[4]CBS19	0148061552	39°57′59.9″	75°48′33.9″	2002, 2003	Dam locally known as Dam #4; samples collected from platform on left side of spillway.
13,946	CBS21TC	01480616	39°57′46.8″	75°48′10.8″	2002, 2003	Abandoned bridge over unnamed tributary channel on left bank immediately upstream from USGS streamflow-gaging station 01480617; ~100 ft upstream from confluence with W.B. Brandywine.
14,512	[4]CBS2	01480617	39°57′41.7″	75°48′04.9″	2002, 2003	Bridge carrying Union Street over W.B. Brandywine at USGS streamflow-gaging station 01480617.
14,862	CBS1TC	01480618	39°57′39.0″	75°48′02.8″	2002, 2003	Bridge carrying South Brandywine Avenue over Dennis Run ~100 ft upstream from confluence with W.B. Brandywine.

[1]All samples from the water column were collected directly from the thalweg, or most dominant flow, of the W.B. Brandywine, tributary, or pipe.
[2]U.S. Geological Survey project identification numbers are assigned in the order they were initially located and not in downstream order as are U.S. Geological Survey station identification numbers.
[3]TC denotes that sample was collected from flow originating from tributary channel or outfall.
[4]Also a base-flow sampling site.

Table 1-3. Descriptions of base-flow sampling sites on Wagontown study reach, West Branch Brandywine Creek, 2002 and 2003, Chester County, Pennsylvania.[1]

[ft, feet; ~, approximately; W.B., West Branch; SR, Pennsylvania State Route]

Stream distance from upstream end of project reach (ft)	U.S. Geological Survey project identification number[2]	U.S. Geological Survey station identification number	Latitude	Longitude	Years sampled	Site description	Location of sediment-sample collection
0	A1	01480428	40°00′21.5″	75°49′32.4″	2002, 2003	Left streambank ~400 ft upstream of SR340 bridge.	Left edge of W.B. Brandywine.
152	A2	04180429	40°00′20.1″	75°49′31.7″	2002, 2003	Right streambank, ~250 ft upstream of SR 340 bridge, where chute drains a small wetland area during higher flows.	Right edge of W.B. Brandywine near bottom of chute that carries high flows through wetland area.
662	A3	014804302	40°00′15.6″	75°49′28.5″	2002, 2003	Right streambank, ~250 ft downstream of SR 340 bridge, adjacent to parking area where runoff forms small sediment splay.	Right edge of W.B. Brandywine in small sediment splay from parking area.
982	A4	014804304	40°00′12.9″	75°49′ 26.5″	2002, 2003	Right streambank adjacent to area containing old storage tanks in the flood plain.	Right edge of W.B. Brandywine.
1,100	A5	014804306	40°00′11.9″	75°49′25.9″	2002, 2003	Right side of W.B. Brandywine near a large boulder that captures sediment in flow shadow.	Behind boulder in fine sediments that have settled out.
1,331	A6	014804308	40°00′09.6″	75°49′25.8″	2002, 2003	Small, pronounced rock riffle (weir) in W.B. Brandywine; destroyed by high flows in 2003.	Right edge of W.B. Brandywine in fine sediments that have settled out behind riffle.
1,546	A7	400008075492601	40°00′07.5″	75°49′26.3″	2002, 2003	Spring, flowing in 2002 and 2003, that drains wetland area on right overbank.	Right edge of W.B. Brandywine directly at spring-discharge point.
1,816	A8	014804326	40°00′05.5″	75°49′28.2″	2002, 2003	Right streambank at chute that drains a wetland area during higher flows; wetland feeds various small springs, including site A7.	Right edge of W.B. Brandywine near bottom of chute that carries high flows through wetland area.
1,963	A9	014804328	40°00′04.0″	75°49′28.6″	2002, 2003	Left streambank ~200 ft upstream of U.S. 30-bypass bridge.	Left edge of W.B. Brandywine.
2,274	A10	01480433	40°00′01.2″	75°49′27.1″	2002, 2003	Right streambank ~100 ft downstream of U.S. 30-bypass bridge.	Right edge of W.B. Brandywine.

[1]All samples from the water column were collected directly from the thalweg, or most dominant flow, of the W.B. Brandywine, tributary, or pipe.

[2]U.S. Geological Survey project identification numbers are assigned in the order they were initially located and not in downstream order as are U.S. Geological Survey station identification numbers.

Appendix 2–Coatesville Study Reach Data Tables

Table 2-1. Results of laboratory analyses and field determinations for bacteria concentrations in water and fluvial sediments at base flow on Coatesville study reach, West Branch Brandywine Creek and tributaries, September 9, 2002, to September 12, 2002, Chester County, Pennsylvania.

[ft, feet; col/100 mL, colonies per 100 milliliters; col/g, colonies per gram; mm, millimeter; <, less than]

Stream distance from upstream end of project reach (ft)	U.S. Geological Survey project identification number[1]	U.S. Geological Survey station identification number	Date sampled (mm-dd-yyyy)	Time sampled	*Escherichia coli* in water (col/100 mL)	*Escherichia coli* in sediment (col/g saturated sediment)	Observed sediment particle distribution (mm)
0	CB1	01480500	09-09-2002	0734	90	70	0.5-1
178	CB4	01480502	09-09-2002	0822	130	27	0.5-1
326	CB5	04180506	09-09-2002	0835	90	16	1-2
361	CB6	395904075493401	09-09-2002	0845	60	167	0.062-0.125
551	[2]CB7TC	395903075493301	09-09-2002	0854	290	11	0.062-0.125
666	CB8	01480514	09-09-2002	0907	120	3,510	2-4
898	CB9	395901075493101	09-09-2002	0915	70	8,100	0.25-0.5
1,192	CB10	01480522	09-09-2002	0935	30	86	1-2
1,395	CB11	395855075492801	09-09-2002	0955	100	49	1-2
1,774	CB12	01480532	09-09-2002	1012	150	49	0.5-1
1,931	CB13	395850075492801	09-09-2002	1030	70	1,458	0.5-1
2,167	CB14	395848075492701	09-09-2002	1045	140	70	0.125-0.25
2,575	CB15	01480548	09-09-2002	1125	40	38	0.062-0.125
2,991	CB16TC	01480550	09-09-2002	1141	100	1,480	0.5-1
3,085	CB17TC	395840075492001	09-09-2002	1154	<1	12,150	0.25-0.5
3,397	CB18TC	395837075491901	09-10-2002	1230	<1	43	0.062-0.125
3,835	CB19	01480564	09-10-2002	1205	290	378	1-2
3,872	CB20TC	01480580	09-10-2002	1155	1,500	86	0.25-0.5
4,411	CB21TC	01480614	09-10-2002	1140	60	70	0.25-0.5
4,677	CB22	014806141	09-10-2002	1120	270	270	0.5-1
4,853	CB23TC	395826075492701	09-10-2002	1110	<1	92	0.25-0.5
5,150	CB24	395823075492501	09-10-2002	1050	310	3,240	0.5-1
5,574	CB25TC	395819075492401	09-10-2002	1035	<1	135	0.25-0.5
6,101	CB26	0148061452	09-10-2002	1000	380	43	0.5-1
6,703	CB27	014806146	09-10-2002	0945	380	119	1-2
7,183	CB28	014806147	09-10-2002	0925	310	216	0.5-1
7,201	CB29TC	395804075491601	09-10-2002	0910	10	124	0.125-0.25

Table 2-1. Results of laboratory analyses and field determinations for bacteria concentrations in water and fluvial sediments at base flow on Coatesville study reach, West Branch Brandywine Creek and tributaries, September 9, 2002, to September 12, 2002, Chester County, Pennsylvania.—Continued

[ft, feet; col/100 mL, colonies per 100 milliliters; col/g, colonies per gram; mm, millimeter; <, less than]

Stream distance from upstream end of project reach (ft)	U.S. Geological Survey project identification number[1]	U.S. Geological Survey station identification number	Date sampled (mm-dd-yyyy)	Time sampled	*Escherichia coli* in water (col/100 mL)	*Escherichia coli* in sediment (col/g saturated sediment)	Observed sediment particle distribution (mm)
7,481	CB30	395802075491501	09-10-2002	0900	330	1,350	<0.062
7,747	CB31TC	01480615	09-10-2002	0845	50	151	0.25-0.5
7,906	CB32	0148061502	09-10-2002	0830	490	178	4-5.7
8,170	CB33	0148061506	09-11-2002	1225	130	297	4-5.7
8,446	CB34	0148061508	09-11-2002	1215	310	54	1-2
8,725	CB35TC	395758075490101	09-11-2002	1151	160	8,100	0.125-0.25
8,767	CB36	0148061516	09-11-2002	1140	340	86	0.125-0.25
9,008	CB36B	0148061520	09-11-2002	1125	180	8	0.125-0.25
9,298	CB37	395756075485401	09-11-2002	1110	240	32	0.062-0.125
9,381	CB38	0148061526	09-11-2002	1055	300	14	0.125-0.25
9,646	CB39TC	395757075485001	09-11-2002	1035	20	3	0.5-1
9,873	CB40	395757075484701	09-11-2002	1015	410	324	0.25-0.5
10,144	CB41	0148061544	09-11-2002	1000	440	27	<0.062
10,340	CB42	0148061548	09-11-2002	0936	350	8	<0.062
10,905	CB43	0148061552	09-11-2002	0915	710	119	<0.062
11,001	CB44	0148061556	09-11-2002	0900	550	81	0.5-1
11,078	CB45	0148061558	09-11-2002	0845	400	59	<0.062
11,402	CB46TC	0148061560	09-11-2002	0830	10	65	0.062-0.125
11,577	CB47TC	0148061562	09-12-2002	1220	<1	270	0.125-0.25
11,604	CB48	0148061564	09-12-2002	1218	100	8	0.5-1
11,866	CB49	0148061568	09-12-2002	1205	130	108	0.25-0.5
11,893	CB50	0148061572	09-12-2002	1150	50	16	1-2
12,200	CB51	0148061576	09-12-2002	1135	70	32	1-2
12,508	CB52TC	0148061580	09-12-2002	1115	<1	97	0.125-0.25
12,862	CB55	0148061584	09-12-2002	1057	250	173	0.25-0.5
13,002	CB56	0148061588	09-12-2002	1040	230	124	1-2
13,224	CB57	0148061592	09-12-2002	1024	120	92	0.25-0.5
13,487	CB59	0148061596	09-12-2002	0950	520	140	0.062-0.125

Table 2-1. Results of laboratory analyses and field determinations for bacteria concentrations in water and fluvial sediments at base flow on Coatesville study reach, West Branch Brandywine Creek and tributaries, September 9, 2002, to September 12, 2002, Chester County, Pennsylvania.—Continued

[ft, feet; col/100 mL, colonies per 100 milliliters; col/g, colonies per gram; mm, millimeter; <, less than]

Stream distance from upstream end of project reach (ft)	U.S. Geological Survey project identification number[1]	U.S. Geological Survey station identification number	Date sampled (mm-dd-yyyy)	Time sampled	*Escherichia coli* in water (col/100 mL)	*Escherichia coli* in sediment (col/g saturated sediment)	Observed sediment particle distribution (mm)
13,559	CB58TC	014806161	09-12-2002	0940	20	432	0.5-1
13,647	CB60	0148061597	09-12-2002	0926	390	297	0.25-0.5
13,946	CB61	014806162	09-12-2002	0910	430	65	1-2
14,355	CB62	014806168	09-12-2002	0850	290	16	<0.062
14,809	CB64	01480617	09-12-2002	0830	260	378	0.25-0.5
14,862	CB66TC	0148061802	09-12-2002	0815	3,300	945	0.5-1

[1]U.S. Geological Survey project identification numbers are assigned in the order they were initially located and not in downstream order as are U.S. Geological Survey station identification numbers.

[2]TC denotes that sample was collected from flow originating from tributary channel or outfall.

Table 2-2. Results of field determinations for selected water-quality constituents at base flow on Coatesville study reach, West Branch Brandywine Creek, September 9, 2002, to September 12, 2002, Chester County, Pennsylvania.[1]

[ft, feet; °C, degrees Celsius; mg/L, milligrams per liter; NTU, nephelometric turbidity units; µS/cm, microsiemens per centimeter at 25°C]

Stream distance from upstream end of project reach (ft)	U.S. Geological Survey project identification number[2]	U.S. Geological Survey station identification number	Water temperature (°C)	Dissolved oxygen (mg/L)	pH (standard units)	Turbidity (NTU)	Specific conductance (µS/cm)
0	CB1	01480500	17.7	8.4	7.5	6	224
178	CB4	01480502	17.5	8.9	7.5	6	225
326	CB5	04180506	17.6	9.2	7.6	6	224
361	CB6	395904075493401	17.6	9.2	7.6	6	224
551	[3]CB7TC	395903075493301	17.6	9.5	7.5	6	224
666	CB8	01480514	17.7	9.8	7.6	5	223
898	CB9	395901075493101	18.0	9.8	7.7	5	225
1,192	CB10	01480522	17.8	10.2	7.6	5	238
1,395	CB11	395855075492801	18.0	10.4	7.7	6	245
1,774	CB12	01480532	18.4	10.8	7.8	5	242
1,931	CB13	395850075492801	18.6	11.2	7.9	5	253
2,167	CB14	395848075492701	19.0	11.5	8.0	5	252
2,575	CB15	01480548	19.7	13.0	8.5	5	253
2,991	CB16TC	01480550	20.0	12.8	8.6	5	264
3,085	CB17TC	395840075492001	20.9	13.0	8.7	5	264
3,397	CB18TC	395837075491901	24.0	12.9	8.7	3	534
3,835	CB19	01480564	22.9	13.3	8.8	3	338
3,872	CB20TC	014806145	21.9	12.9	8.7	4	337
4,411	CB21TC	014806147	22.6	12.5	9.0	8	487
4,677	CB22	041806141	21.7	13.1	8.9	3	355
4,853	CB23TC	395826075492701	21.9	10.8	8.2	8	509
5,150	CB24	395823075492501	21.8	11.3	8.4	4	474
5,574	CB25TC	395819075492401	21.1	11.1	8.3	3	467
6,101	CB26	0148061452	20.6	10.6	8.0	3	479
6,703	CB27	014806146	20.2	10.1	7.9	3	474
7,183	CB28	014806147	19.9	9.1	7.8	3	470
7,201	CB29TC	395804075491601	19.7	8.8	7.7	3	464
7,481	CB30	395802075491501	19.5	8.6	7.6	3	451

Table 2-2. Results of field determinations for selected water-quality constituents at base flow on Coatesville study reach, West Branch Brandywine Creek, September 9, 2002, to September 12, 2002, Chester County, Pennsylvania.[1]—Continued

[ft, feet; °C, degrees Celsius; mg/L, milligrams per liter; NTU, nephelometric turbidity units; µS/cm, microsiemens per centimeter at 25°C]

Stream distance from upstream end of project reach (ft)	U.S. Geological Survey project identification number[2]	U.S. Geological Survey station identification number	Water temperature (°C)	Dissolved oxygen (mg/L)	pH (standard units)	Turbidity (NTU)	Specific conductance (µS/cm)
7,747	CB31TC	014806151	No data	No data	No data	No data	No data
7,906	CB32	0148061502	19.3	7.8	7.5	4	438
8,170	CB33	0148061506	22.4	12.4	8.8	4	467
8,446	CB34	0148061508	22.2	12.0	8.6	3	472
8,725	CB35TC	395758075490101	21.7	11.4	8.4	7	469
8,767	CB36	0148061516	21.6	11.0	8.5	3	465
9,008	CB36B	0148061520	21.4	10.8	8.4	3	460
9,298	CB37	395756075485401	21.0	9.5	8.1	4	446
9,381	CB38	0148061526	21.0	9.8	8.2	3	438
9,646	CB39TC	395757075485001	20.8	9.1	7.9	4	433
9,873	CB40	395757075484701	20.9	9.1	7.8	4	437
10,144	CB41	0148061544	20.9	8.3	7.9	5	443
10,340	CB42	0148061548	21.2	6.2	7.8	4	488
10,905	CB43	0148061552	21.2	6.0	7.5	5	473
11,001	CB44	0148061556	21.4	7.4	7.6	6	480
11,078	CB45	0148061558	21.3	7.6	7.6	5	482
11,402	CB46TC	0148061560	21.5	7.5	7.6	5	484
11,577	CB47TC	0148061562	19.4	10.3	8.0	4	466
11,604	CB48	0148061564	19.4	10.3	8.0	4	466
11,866	CB49	0148061568	19.2	10.2	8.1	4	469
11,893	CB50	0148061572	19.5	10.4	8.1	3	471
12,200	CB51	0148061576	19.6	10.8	8.2	4	475
12,508	CB52TC	0148061580	19.6	10.8	8.1	3	477
12,862	CB55	0148061584	19.3	10.5	8.1	4	481
13,002	CB56	0148061588	19.0	10.1	8.0	4	483
13,224	CB57	0148061592	18.6	9.4	7.8	3	490
13,487	CB59	0148061596	18.3	8.4	7.7	3	493

Table 2-2. Results of field determinations for selected water-quality constituents at base flow on Coatesville study reach, West Branch Brandywine Creek, September 9, 2002, to September 12, 2002, Chester County, Pennsylvania.[1]—Continued

[ft, feet; °C, degrees Celsius; mg/L, milligrams per liter; NTU, nephelometric turbidity units; µS/cm, microsiemens per centimeter at 25°C]

Stream distance from upstream end of project reach (ft)	U.S. Geological Survey project identification number[2]	U.S. Geological Survey station identification number	Water temperature (°C)	Dissolved oxygen (mg/L)	pH (standard units)	Turbidity (NTU)	Specific conductance (µS/cm)
13,559	CB58TC	014806161	18.3	8.4	7.7	3	493
13,647	CB60	0148061597	18.2	7.9	7.7	3	493
13,946	CB61	014806162	18.1	7.7	7.6	3	492
14,355	CB62	014806168	18.2	7.5	7.6	3	487
14,809	CB64	01480617	18.1	7.6	7.5	2	484
14,862	CB66TC	0148061802	18.1	7.6	7.5	2	484

[1]All water-quality constituents were measured within the main channel of the West Branch Brandywine Creek.

[2]U.S. Geological Survey project identification numbers are assigned in the order they were initially located and not in downstream order as are U.S. Geological Survey station identification numbers.

[3]U.S. Geological Survey project identification numbers ending with TC indicate the measurement was made adjacent to the flowing tributary or outfall within the main channel of the West Branch Brandywine Creek.

Table 2-3. Results of field determinations for selected water-quality constituents at flowing tributaries to West Branch Brandywine Creek under base-flow conditions on Coatesville study reach, September 9, 2002, to September 12, 2002, Chester County, Pennsylvania.[1]

[ft, feet; °C, degrees Celsius; mg/L, milligrams per liter; NTU, nephelometric turbidity units; µS/cm, microsiemens per centimeter at 25°C]

Stream distance from upstream end of project reach (ft)	U.S. Geological Survey project identification number[2]	U.S. Geological Survey station identification number	Water temperature (°C)	Dissolved oxygen (mg/L)	pH (standard units)	Turbidity (NTU)	Specific conductance (µS/cm)
551	CB7TC	395903075493301	16.0	9.4	7.4	9	615
2,991	CB16TC	01480550	20.5	11.2	7.6	0	490
3,085	CB17TC	395840075492001	17.0	11.5	8.2	2	344
3,397	CB18TC	395837075491901	26.8	7.9	7.2	3	1,170
3,872	CB20TC	01480580	17.0	8.8	7.9	5	655
4,411	CB21TC	01480614	23.0	11.3	9.0	5	508
4,853	CB23TC	395826075492701	21.8	11.3	8.5	0	483
5,574	CB25TC	395819075492401	20.4	8.0	7.5	3	531
7,201	CB29TC	395804075491601	18.0	8.9	8.1	4	840
7,747	CB31TC	01480615	16.6	8.8	7.6	3	355
8,725	CB35TC	395758075490101	19.3	8.4	8.0	7	1,040
9,646	CB39TC	395757075485001	24.6	9.2	7.6	0	803
11,402	CB46TC	0148061560	20.8	7.4	8.3	3	510
11,577	CB47TC	0148061562	22.1	8.6	7.1	0	457
12,508	[3]CB52TC	0148061580	No data	No data	No data	No data	No data
13,559	CB58TC	014806161	18.0	8.3	7.7	3	468
14,862	CB66TC	0148061802	15.4	7.6	7.0	2	198

[1]All water-quality constituents were measured within flow from tributaries, springs, or outfalls to the West Branch Brandywine Creek.

[2]U.S. Geological Survey project identification numbers are assigned in the order they were initially located and not in downstream order as are U.S. Geological Survey station identification numbers.

[3]Insufficient flow to measure water-quality constituents with water-quality sonde.

Table 2-4. Results of laboratory analyses and field determinations for bacteria concentrations in water and selected water-quality constituents at stormflow on Coatesville study reach, West Branch Brandywine Creek and flowing tributaries, September 16, 2002, Chester County, Pennsylvania.[1]

[ft, feet; col/100 mL, colonies per 100 milliliters; °C, degrees Celsius; mg/L, milligrams per liter; NTU, nephelometric turbidity units; µS/cm, microsiemens per centimeter at 25°C; <, less than]

Stream distance from upstream end of project reach (ft)	U.S. Geological Survey project identification number[2]	U.S. Geological Survey station identification number	Time sampled	*Escherichia coli* in water (col/100 mL)	Water temperature (°C)	Dissolved oxygen (mg/L)	pH (standard units)	Turbidity (NTU)	Specific conductance (µS/cm)
0	CBS6	01480500	1035	2,300	21.1	8.1	7.5	6	220
187	CBS7	01480504	1030	1,300	20.9	8.8	7.6	6	222
1,019	CBS5	01480518	1015	2,000	20.8	9.2	7.7	6	230
2,991	[3]CBS13TC	01480550	0940	<1	21.1	7.6	7.6	3	466
2,995	CBS12	01480552	0950	720	21.0	9.7	7.9	5	235
3,922	CBS10	01480584	0930	2,100	20.9	8.9	7.7	5	277
4,411	CBS9TC	01480614	0920	700	21.3	9.8	8.4	4	473
6,023	CBS15	014806145	0900	960	21.3	8.5	7.7	5	387
7,747	CBS3TC	01480615	0840	13,000	17.3	8.0	7.6	3	347
7,754	CBS4	0148061501	0846	1,800	21.1	8.1	7.6	6	372
9,646	CBS16TC	395757075485001	0830	970	23.7	7.1	7.6	8	750
10,905	CBS19	0148061552	0815	3,300	21.3	6.0	7.5	10	360
13,946	CBS21TC	01480616	0800	330	18.8	8.0	7.7	2	242
14,512	CBS2	01480617	0740	9,000	21.5	6.8	7.5	17	336
14,862	CBS1TC	01480618	0730	70	18.5	7.9	7.3	2	200

[1]Water-quality constituents were measured in flowing tributaries to the main channel of the West Branch Brandywine Creek where denoted by a "TC" suffix.
[2]U.S. Geological Survey project identification numbers are assigned in the order they were initially located and not in downstream order as are U.S. Geological Survey station identification numbers.
[3]TC denotes that sample was collected from flow originating from tributary channel or outfall.

Table 2-5. Results of field determinations and laboratory analyses for bacteria concentrations in water and fluvial sediments at base flow on Coatesville study reach, West Branch Brandywine Creek and tributaries, July 7, 2003, to July 10, 2003, Chester County, Pennsylvania.

[ft, feet; col/100 mL, colonies per 100 milliliters; col/g, colonies per gram; mm, millimeters; <, less than]

Stream distance from upstream end of project reach (ft)	U.S. Geological Survey project identification number[1]	U.S. Geological Survey station identification number	Date sampled (mm-dd-yy)	Time sampled	*Escherichia coli* in water (col/100 mL)	Enterococci in water (col/100 mL)	*Escherichia coli* in sediment (col/g saturated sediment)	Enterococci in sediment (col/g saturated sediment)	Observed sediment particle distribution (mm)
0	CB1	01480500	07-09-03	1043	270	990	5,994	3,240	0.5-1
326	CB5	04180506	07-09-03	1030	420	760	16,200	4,266	1-2
551	[2]CB7TC	395903075493301	07-09-03	1020	190	1,290	16,740	39,960	0.1-0.2
666	CB8	01480514	07-09-03	1012	220	600	4,752	29,700	1-2
898	CB9	395901075493101	07-09-03	1005	330	380	2,808	43,200	0.25-0.5
1,040	CB9BTC	395900075493001	07-09-03	0945	420	1,380	61,560	22,140	0.062-0.125
1,192	CB10	01480522	07-09-03	0932	<1	<1	2,808	480,600	1-2
1,395	CB11	395855075492801	07-09-03	0923	210	5,000	10,260	194,400	0.125-0.25
2,167	CB14	395848075492701	07-09-03	0909	420	3,700	4,482	48,060	0.25-0.5
2,991	CB16TC	01480550	07-09-03	0845	<1	110	25,920	448,200	1-2
3,085	CB17TC	395840075492001	07-09-03	0834	20	10	44,280	221,400	0.25-0.5
3,835	CB19	01480564	07-09-03	0823	620	6,800	41,580	610,200	0.25-0.5
3,872	CB20TC	01480580	07-09-03	0818	4,400	36,000	11,880	54,540	0.25-0.5
4,411	CB21TC	01480614	07-09-03	0803	1,060	7,800	1,998	51,300	0.5-1
4,853	CB23TC	395826075492701	07-09-03	0750	80	700	2,106	189,000	0.125-0.25
5,574	CB25TC	395819075492401	07-08-03	1215	210	650	37,260	27,540	0.25-0.5
6,101	CB26	0148061452	07-08-03	1200	3,200	3,200	45,900	56,160	0.5-1
6,703	CB27	014806146	07-08-03	1151	2,100	4,200	124,200	480,600	0.125-0.25
7,183	CB28	014806147	07-08-03	1134	1,130	2,800	496,800	631,800	0.25-0.5
7,201	CB29TC	395804075491601	07-08-03	1115	80	370	28,620	5,767,200	0.062-0.125
7,481	CB30TC	395802075491501	07-08-03	1050	110	440	7,020	4,482	0.125-0.25
7,747	CB31TC	01480615	07-08-03	1040	150	250	1,728	4,482	1-2
7,906	CB32	0148061502	07-08-03	1032	1,270	4,200	3,078	14,580	0.125-0.25
8,170	CB33	0148061506	07-08-03	1015	1,420	3,000	34,560	340,200	1-2
8,725	CB35TC	395758075490101	07-08-03	0947	11,000	36,000	345,600	399,600	0.25-0.5
9,008	CB36B	0148061520	07-08-03	0933	940	3,900	1,620	57,780	0.125-0.25

Table 2-5. Results of field determinations and laboratory analyses for bacteria concentrations in water and fluvial sediments at base flow on Coatesville study reach, West Branch Brandywine Creek and tributaries, July 7, 2003, to July 10, 2003, Chester County, Pennsylvania.—Continued

[ft, feet; col/100 mL, colonies per 100 milliliters; col/g, colonies per gram; mm, millimeters; <, less than]

Stream distance from upstream end of project reach (ft)	U.S. Geological Survey project identification number[1]	U.S. Geological Survey station identification number	Date sampled (mm-dd-yy)	Time sampled	*Escherichia coli* in water (col/100 mL)	Enterococci in water (col/100 mL)	*Escherichia coli* in sediment (col/g saturated sediment)	Enterococci in sediment (col/g saturated sediment)	Observed sediment particle distribution (mm)
9,381	CB38	0148061526	07-08-03	0920	2,100	2,800	4,212	253,800	0.062-0.125
9,386	CB38BTC	395756075485301	07-08-03	0902	40	80	4,428	20,520	0.25-0.5
9,873	CB40TC	395757075484701	07-08-03	0836	180	460	11,340	22,140	0.25-0.5
10,034	CB41BTC	395758075484501	07-08-03	0815	190	400	11,340	12,420	0.25-0.5
10,905	CB43	0148061552	07-07-03	1042	6,000	610	3,402	2,538	1-2
11,001	CB44	0148061556	07-07-03	1030	1,140	680	3,240	38,880	0.5-1
11,577	CB47TC	0148061562	07-07-03	1015	<1	<1	2,160	2,862	0.25-0.5
11,604	CB48	0148061564	07-07-03	1009	1,260	680	1,080	2,970	1-2
11,866	CB49	0148061568	07-07-03	1001	1,360	810	1,080	44,820	0.062-0.125
12,508	CB52TC	0148061580	07-07-03	0946	270	590	11,880	68,580	0.125-0.25
12,862	CB55TC	0148061584	07-07-03	0934	1,000	1,060	3,240	25,380	0.25-0.5
13,002	CB56	0148061588	07-07-03	0925	4,300	910	864	2,538	1-2
13,224	CB57	0148061592	07-07-03	0915	900	3,000	2,160	65,880	0.125-0.25
13,559	CB58TC	014806161	07-07-03	0901	300	610	2,160	1,728	0.25-0.5
13,647	CB60	0148061597	07-07-03	0848	960	3,000	38,340	28,620	0.25-0.5
13,946	CB61TC	014806162	07-07-03	0841	190	840	12,420	15,120	0.25-0.5
14,355	CB62	014806168	07-07-03	0834	780	2,500	2,646	6,588	0.062-0.125
14,809	CB64	01480617	07-07-03	0826	710	2,800	864	35,640	0.25-0.5
14,862	CB66TC	0148061802	07-07-03	0820	160	850	2,862	22,140	0.5-1

[1]U.S. Geological Survey project identification numbers are assigned in the order they were initially located and not in downstream order as are U.S. Geological Survey station identification numbers.
[2]TC denotes that sample was collected from flow originating from tributary channel or outfall.

Table 2-6. Results of field determinations for selected water-quality constituents at base flow on Coatesville study reach, West Branch Brandywine Creek, July 7, 2003, to July 10, 2003, Chester County, Pennsylvania.[1]

[ft, feet; °C, degrees Celsius; mg/L, milligrams per liter; NTU, nephelometric turbidity units; µS/cm, microsiemens per centimeter at 25°C]

Stream distance from upstream end of project reach (ft)	U.S. Geological Survey project identification number[2]	U.S. Geological Survey station identification number	Water temperature (°C)	Dissolved oxygen (mg/L)	pH (standard units)	Turbidity (NTU)	Specific conductance (µS/cm)
0	CB1	01480500	21.4	9.1	7.5	7	237
326	CB5	01480506	21.3	9.2	7.6	8	237
551	[3]CB7TC	395903075493301	21.3	9.3	7.6	8	237
666	CB8	01480514	21.3	9.3	7.6	8	237
898	CB9	395901075493101	21.3	9.3	7.6	8	238
1,040	CB9BTC	395900075493001	21.2	9.1	7.6	8	238
1,192	CB10TC	01480522	21.0	8.8	7.5	8	251
1,395	CB11	395855075492801	21.0	9.0	7.5	8	244
2,167	CB14	395848075492701	21.2	9.2	7.5	8	244
2,991	CB16TC	01480550	21.3	9.3	7.7	8	244
3,085	CB17TC	395840075492001	21.3	9.4	7.7	8	249
3,835	CB19	01480564	21.2	9.1	7.6	8	253
3,872	CB20TC	01480580	21.2	9.1	7.6	8	251
4,411	CB21TC	01480614	21.2	8.9	7.6	8	255
4,853	CB23TC	395826075492701	21.0	8.8	7.4	8	264
5,574	CB25TC	395819075492401	22.5	10.2	8.2	19	287
6,101	CB26	0148061452	22.3	10.0	8.0	19	291
6,703	CB27	014806146	22.1	9.8	7.9	21	289
7,183	CB28	014806147	21.9	9.7	7.9	22	290
7,201	CB29TC	395804075491601	21.8	9.6	7.9	22	294
7,481	CB30TC	395802075491501	21.7	9.4	7.9	19	288
7,747	CB31TC	01480615	No data	No data	No data	No data	No data
7,906	CB32	0148061502	21.6	9.5	7.9	13	292
8,170	CB33	0148061506	21.5	9.6	7.9	12	291
8,725	CB35TC	395758075490101	21.3	9.4	7.8	11	287
9,008	CB36B	0148061520	21.3	9.2	7.8	11	283
9,381	CB38	0148061526	21.2	8.9	7.8	11	277
9,386	CB38BTC	395756075485301	21.2	8.9	7.8	11	277
9,873	CB40TC	395757075484701	21.0	8.8	7.7	11	281

Table 2-6. Results of field determinations for selected water-quality constituents at base flow on Coatesville study reach, West Branch Brandywine Creek, July 7, 2003, to July 10, 2003, Chester County, Pennsylvania.[1]—Continued

[ft, feet; °C, degrees Celsius; mg/L, milligrams per liter; NTU, nephelometric turbidity units; µS/cm, microsiemens per centimeter at 25°C]

Stream distance from upstream end of project reach (ft)	U.S. Geological Survey project identification number[2]	U.S. Geological Survey station identification number	Water temperature (°C)	Dissolved oxygen (mg/L)	pH (standard units)	Turbidity (NTU)	Specific conductance (µS/cm)
10,034	CB41BTC	395758075484501	21.0	8.7	7.6	11	279
10,905	CB43	0148061552	21.0	10.2	7.9	6	304
11,001	CB44	0148061556	21.0	9.9	7.9	6	301
11,577	CB47TC	0148061562	20.9	9.9	7.9	7	299
11,604	CB48	0148061564	20.9	9.9	7.8	7	299
11,866	CB49	0148061568	20.9	9.9	7.8	6	298
12,508	CB52TC	0148061580	20.8	9.8	7.8	7	297
12,862	CB55TC	0148061584	20.8	9.6	7.8	7	300
13,002	CB56	0148061588	20.7	9.6	7.8	9	299
13,224	CB57	0148061592	20.7	9.5	7.7	8	298
13,559	CB58TC	014806161	20.6	9.4	7.7	8	298
13,647	CB60	0148061597	20.5	9.4	7.7	9	298
13,946	CB61TC	014806162	20.4	9.3	7.5	9	297
14,355	CB62	014806168	20.4	9.3	7.6	9	296
14,809	CB64	01480617	20.5	9.4	7.6	8	298
14,862	CB66TC	0148061802	20.5	9.4	7.6	8	298

[1]All water-quality constituents were measured within the main channel of the West Branch Brandywine Creek.

[2]U.S. Geological Survey project identification numbers are assigned in the order they were initially located and not in downstream order as are U.S. Geological Survey station identification numbers.

[3]TC denotes that sample was collected from flow originating from tributary channel or outfall.

Table 2-7. Results of field determinations for selected water-quality constituents at flowing tributaries to West Branch Brandywine Creek at base flow on Coatesville study reach, July 7, 2003, to July 10, 2003, Chester County, Pennsylvania.[1]

[ft, feet; °C, degrees Celsius; mg/L, milligrams per liter; NTU, nephelometric turbidity units; µS/cm, microsiemens per centimeter at 25°C]

Stream distance from upstream end of project reach (ft)	U.S. Geological Survey project identification number	U.S. Geological Survey station identification number	Water temperature (°C)	Dissolved oxygen (mg/L)	pH (standard units)	Turbidity (NTU)	Specific conductance (µS/cm)
551	[2]CB7TC	395903075493301	16.5	9.8	7.4	9	536
1,040	CB9BTC	095900075493001	16.0	4.4	6.6	12	624
1,192	CB10TC	01480522	19.4	9.1	7.4	0	288
2,991	CB16TC	01480550	16.6	9.7	7.5	3	513
3,085	CB17TC	395840075492001	14.8	10.2	7.0	5	473
3,872	CB20TC	01480580	15.3	9.1	7.4	2	657
4,411	CB21TC	01480614	19.4	9.7	8.0	5	353
4,853	CB23TC	395826075492701	20.8	8.9	7.3	No data	466
5,574	CB25TC	395819075492401	16.3	8.2	7.4	No data	455
7,201	CB29TC	395804075491601	15.8	9.0	7.5	2	935
7,481	CB30TC	395802075491501	No data	No data	No data	No data	No data
7,747	CB31TC	01480615	21.6	9.4	7.8	15	289
8,725	CB35TC	395758075490101	16.8	7.8	7.6	4	1,020
9,386	CB38BTC	395756075485301	12.8	10.5	6.8	0	210
9,873	CB40TC	395757075484701	15.7	9.7	7.3	25	208
10,034	CB41BTC	395758075484501	19.0	9.4	7.9	12	420
11,577	CB47TC	0148061562	19.1	10.1	7.5	1	414
12,508	CB52TC	0148061580	15.4	6.5	7.3	3	482
12,862	CB55TC	0148061584	21.0	3.0	7.1	9	560
13,559	CB58TC	014806161	17.1	9.6	7.4	7	228
13,946	CB61TC	014806162	16.2	10.1	7.4	2	184
14,862	CB66TC	0148061802	16.7	10.4	7.3	4	195

[1]All water-quality constituents were measured within flow from tributaries, springs, or outfalls to the West Branch Brandywine Creek.

[2]U.S. Geological Survey project identification numbers are assigned in the order they were initially located and not in downstream order as are U.S. Geological Survey station identification numbers.

Table 2-8. Wastewater constituents in water at base flow on Coatesville study reach, West Branch Brandywine Creek, July 10, 2003, Chester County, Pennsylvania.

[µg/L, micrograms per liter; <, less than; M, presence verified, not quantified; E, estimated value; shading indicates detected compound]

Wastewater constituent	Reporting limit	Unit	U.S. Geological Survey station identification number					Field blank
			01480500	01480550	01480615	395756075485301	01480617	
1,4-Dichlorobenzene	0.5	µg/L	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
1-Methylnaphthalene	.5	µg/L	<.5	M	<.5	<.5	<.5	<.5
2,6-Dimethylnaphthalene	.5	µg/L	<.5	<.5	<.5	<.5	<.5	<.5
2-Methylnaphthalene	.5	µg/L	<.5	<.5	<.5	<.5	<.5	<.5
3-beta-Coprostanol	2.0	µg/L	<2	E 2	<2	<2	M	<2
3-Methyl-1(H)-indole (Skatole)	1.0	µg/L	<1	<1	<1	<1	<1	<1
3-tert-Butyl-4-hydroxy anisole (BHA)	5.0	µg/L	<5	<5	<5	<5	<5	<5
4-Cumylphenol	1.0	µg/L	<1	<1	<1	<1	<1	<1
4-n-Octylphenol	1.0	µg/L	<1	<1	<1	<1	<1	<1
4-tert-Octylphenol	1.0	µg/L	<1	<1	<1	<1	<1	<1
5-Methyl-1H-benzotriazole	2.0	µg/L	<2	<2	<2	<2	<2	<2
Acetophenone	.5	µg/L	E .2	<.5	<.5	<.5	E .1	<.5
Acetyl hexamethyl tetrahydronaphthalene (AHTN)	.5	µg/L	<.5	E .3	<.5	<.5	<.5	<.5
Anthracene	.5	µg/L	<.5	<.5	<.5	<.5	<.5	<.5
Anthraquinone	.5	µg/L	<.5	<.5	<.5	<.5	<.5	<.5
Benzo[a]pyrene	.5	µg/L	<.5	<.5	<.5	<.5	<.5	<.5
Benzophenone	.5	µg/L	<.5	<.5	<.5	<.5	<.5	<.5
beta-Sitosterol	2.0	µg/L	<2	E 1	<2	M	<2	<2
beta-Stigmastanol	2.0	µg/L	<2	<2	<2	<2	<2	<2
Bisphenol A	1.0	µg/L	<1	<1	<1	<1	<1	<1
Bisphenol A, d3 (surrogate)	.1	percent	100	118	112	96.0	109	69.6
Boron	13	µg/L	30	40	130	50	50	<13
Bromacil	.5	µg/L	<.5	<.5	<.5	<.5	<.5	<.5
Bromoform	.5	µg/L	<.5	<.5	<.5	<.5	<.5	<.5
Caffeine	.5	µg/L	M	.5	<0.5	<.5	M	<.5
Caffeine-C13 (surrogate)	.1	percent	113	136	129	128	122	126
Camphor	.5	µg/L	<.5	<.5	<.5	<.5	<.5	<.5
Carbaryl	1.0	µg/L	<1	<1	<1	<1	<1	<1
Carbazole	.5	µg/L	<.5	<.5	<.5	<.5	<.5	<.5

Table 2-8. Wastewater constituents in water at base flow on Coatesville study reach, West Branch Brandywine Creek, July 10, 2003, Chester County, Pennsylvania.—Continued

[µg/L, micrograms per liter; <, less than; M, presence verified, not quantified; E, estimated value; shading indicates detected compound]

Wastewater constituent	Reporting limit	Unit	U.S. Geological Survey station identification number					Field blank
			01480500	01480550	01480615	395756075485301	01480617	
Chloride	0.2	mg/L	23.5	7.5	32.2	20.6	30.3	<0.2
Chlorpyrifos	.5	µg/L	<.5	<.5	<.5	<.5	<.5	<.5
Cholesterol	2.0	µg/L	<2.0	6.0	<2.0	<2.0	E 2.0	<2.0
Cotinine	1.0	µg/L	<1.0	M	<1.0	<1.0	<1.0	<1.0
d-Limonene	.5	µg/L	<.5	E .2	<.5	<.5	<.5	<.5
Decafluorobiphenyl (surrogate)	.1	percent	69.6	90.9	83.3	80.0	73.9	78.3
Diazinon	.5	µg/L	<.5	<.5	<.5	<.5	<.5	<.5
Dichlorvos	1.0	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
Fluoranthene	.5	µg/L	<.5	<.5	E .1	<.5	<.5	<.5
Fluoranthene, d10 (surrogate)	.1	percent	113	132	129	128	122	126
Hexadydrohexamethylcyclopentabenzopyran (HHCB)	.5	µg/L	<.5	E .1	<.5	<.5	<.5	<.5
Indole	.5	µg/L	<.5	<.5	<.5	<.5	<.5	<.5
Isoborneol	.5	µg/L	<.5	<.5	<.5	<.5	<.5	<.5
Isophorone	.5	µg/L	<.5	<.5	<.5	<.5	<.5	<.5
Isopropylbenzene	.5	µg/L	<.5	<.5	<.5	<.5	<.5	<.5
Isoquinoline	.5	µg/L	<.5	<.5	<.5	<.5	<.5	<.5
Menthol	.5	µg/L	<.5	E.2	<.5	<.5	<.5	<.5
Metalaxyl	.5	µg/L	<.5	<.5	<.5	<.5	<.5	<.5
Methyl salicylate	.5	µg/L	<.5	M	<.5	<.5	<.5	<.5
Metolachlor	.5	µg/L	M	M	<.5	<.5	M	<.5
N,N-diethyl-meta-toluamide (DEET)	.5	µg/L	E .1	M	E.1	<.5	E .1	<.5
Naphthalene	.5	µg/L	<.5	E .1	<.5	<.5	<.5	<.5
Nonylphenol, diethoxy- (total)	5.0	µg/L	<5.0	<5.0	<5.0	<5.0	E 2.0	<5.0
Octylphenol, diethoxy-	1.0	µg/L	<1.0	<1.0	M	<1.0	<1.0	<1.0
Octylphenol, monoethoxy-	1.0	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
p-Cresol	1.0	µg/L	<1.0	M	<1.0	<1.0	<1.0	<1.0
para-Nonylphenol (total)	5.0	µg/L	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
Pentachlorophenol	2.0	µg/L	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0
Phenanthrene	.5	µg/L	<.5	<.5	<.5	<.5	<.5	<.5

Table 2-8. Wastewater constituents in water at base flow on Coatesville study reach, West Branch Brandywine Creek, July 10, 2003, Chester County, Pennsylvania.—Continued

[µg/L, micrograms per liter; <, less than; M, presence verified, not quantified; E, estimated value; shading indicates detected compound]

Wastewater constituent	Reporting limit	Unit	U.S. Geological Survey station identification number					Field blank
			01480500	01480550	01480615	395756075485301	01480617	
Phenol	0.5	µg/L	<0.5	0.9	1.1	0.8	E 0 .4	1.0
Prometon	.5	µg/L	<.5	<.5	<.5	<.5	<.5	<.5
Pyrene	.5	µg/L	<.5	<.5	M	<.5	<.5	<.5
Tetrachloroethylene	.5	µg/L	<.5	E .1	<.5	<.5	<.5	<.5
Tri(2-butoxyethyl)phosphate	.5	µg/L	<.5	<.5	<.5	<.5	<.5	<.5
Tri(2-chloroethyl)phosphate	.5	µg/L	<.5	<.5	<.5	<.5	<.5	<.5
Tributyl phosphate	.5	µg/L	<.5	<.5	<.5	<.5	<.5	<.5
Triclosan	1.0	µg/L	<1.0	M	<1.0	<1.0	<1.0	<1.0
Triethyl citrate (ethyl citrate)	.5	µg/L	<.5	<.5	<.5	<.5	<.5	<.5
Triphenyl phosphate	.5	µg/L	<.5	<.5	<.5	<.5	<.5	<.5
Tris(dichlorisopropyl)phosphate	.5	µg/L	<.5	<.5	<.5	<.5	<.5	<.5

Table 2-9. Nutrients in water at base flow on Coatesville study reach, West Branch Brandywine Creek, July 10, 2003, Chester County, Pennsylvania.

[mg/L, milligrams per liter; E, estimated value; <, less than]

Nutrient name	Reporting limit	Unit	U.S. Geological Survey station identification number					Field blank
			01480500	01480550	01480615	395756075485301	01480617	
Nitrogen, ammonia	0.041	mg/L	<0.041	0.05	<0.041	<0.041	<0.041	<0.041
Nitrogen, ammonia + organic nitrogen, filtered	.10	mg/L	.30	.32	E .10	.14	.31	<.10
Nitrogen, ammonia + organic nitrogen, unfiltered	.10	mg/L	.35	.39	.15	E .05	.39	<.10
Nitrogen, nitrite	.008	mg/L	E .006	.012	<.008	<.008	.014	<.008
Nitrogen, nitrite + nitrate	.060	mg/L	3.18	3.69	2.76	2.00	3.59	<.06
Phosphorus, filtered	.0044	mg/L	.035	.083	.022	.008	.057	<.004
Phosphorus, unfiltered	.0037	mg/L	.059	.091	.029	.008	.077	<.004
Phosphorus, phosphate, ortho	.018	mg/L	.02	.07	E .01	<.02	.04	<.02

Table 2-10. Results of laboratory analyses and field determinations for bacteria concentrations in water and selected water-quality constituents at stormflow on Coatesville study reach, West Branch Brandywine Creek and flowing tributaries, August 4, 2003, Chester County, Pennsylvania.[1]

[ft, feet; col/100 mL, colonies per 100 milliliters; °C, degrees Celsius; mg/L, milligrams per liter; NTU, nephelometric turbidity units; µS/cm, microsiemens per centimeter at 25°C]

Stream distance from upstream end of project reach (ft)	U.S. Geological Survey project identification number	U.S. Geological Survey station identification number	Time sampled	*Escherichia coli* in water (col/100 mL)	Enterococci in water (col/100 mL)	Water temperature (°C)	Dissolved oxygen (mg/L)	pH (standard units)	Turbidity (NTU)	Specific conductance (µS/cm)
0	[2]CBS6	01480500	1033	17,000	73,000	21.8	7.1	7.5	198	184
187	CBS7	01480504	1023	31,000	93,000	21.4	10.0	7.5	205	182
1,019	CBS5	01480518	1015	17,000	106,000	21.3	11.0	7.5	220	178
2,991	[3]CBS13TC	01480550	1005	15,000	34,000	20.0	10.6	7.4	78	426
2,995	CBS12	01480552	0954	29,000	146,000	21.2	10.6	7.4	271	168
3,922	CBS10	01480584	0945	26,000	131,000	21.3	10.8	7.4	304	173
4,411	CBS9TC	01480614	0935	26,000	102,000	21.3	10.8	7.5	190	206
6,023	CBS15	014806145	0920	15,000	137,000	21.3	10.8	7.5	352	187
7,747	CBS3TC	01480615	0835	910	7,400	16.1	11.1	8.0	58	300
7,754	CBS4	0148061501	0845	23,000	137,000	21.2	9.9	7.4	437	192
9,646	CBS16TC	395757075485001	0910	13,000	97,000	20.8	12.8	8.2	420	430
10,905	CBS19	0148061552	0900	7,000	147,000	21.3	10.1	7.4	450	185
13,946	CBS21TC	01480616	0821	4,900	70,000	19.5	9.7	7.2	22	148
14,512	CBS2	01480617	0755	13,000	89,000	22.3	4.8	7.7	330	214
14,862	CBS1TC	01480618	0810	40,000	166,000	19.3	10.7	7.2	112	158

[1]Water-quality constituents in table were measured in flowing tributaries to the main channel of the West Branch Brandywine Creek where denoted by a "TC" suffix.
[2]U.S. Geological Survey project identification numbers are assigned in the order they were initially located and not in downstream order as are U.S. Geological Survey station identification numbers.
[3]TC denotes that sample was collected from flow originating from tributary channel or outfall.

Table 2-11. Wastewater constituents in water at stormflow on Coatesville study reach, West Branch Brandywine Creek, August 4, 2003, Chester County, Pennsylvania.

[µg/L, micrograms per liter; <, less than; E, estimated value; M, presence verified, not quantified; shading indicates detected compound]

Wastewater constituent	Reporting limit	Unit	U.S. Geological Survey station identification number		
			01480500	0148061501	01480617
1,4-Dichlorobenzene	0.5	µg/L	[1] <5.0	E 0.2	E 0.2
1-Methylnaphthalene	.5	µg/L	<5.0	<5.0	<5.0
2,6-Dimethylnaphthalene	.5	µg/L	<5.0	<5.0	<5.0
2-Methylnaphthalene	.5	µg/L	<5.0	<5.0	<5.0
3-beta-Coprostanol	2.0	µg/L	<5	<5	<5
3-Methyl-1(H)-indole (Skatole)	1.0	µg/L	<5	<5	<5
3-tert-Butyl-4-hydroxy anisole (BHA)	5.0	µg/L	<5	<5	<5
4-Cumylphenol	1.0	µg/L	<5	<5	<5
4-n-Octylphenol	1.0	µg/L	<5	<5	<5
4-tert-Octylphenol	1.0	µg/L	<5	<5	<5
5-Methyl-1H-benzotriazole	2.0	µg/L	<5	<5	<5
Acetophenone	.5	µg/L	<5.0	<5.0	<5.0
Acetyl hexamethyl tetrahydronaphthalene (AHTN)	.5	µg/L	<5.0	<5.0	<5.0
Anthracene	.5	µg/L	<5.0	<5.0	E .3
Anthraquinone	.5	µg/L	<5.0	<5.0	<5.0
Benzo[a]pyrene	.5	µg/L	<5.0	E .3	E .4
Benzophenone	.5	µg/L	<5.0	<5.0	<5.0
beta-Sitosterol	2.0	µg/L	<5	<5	<5
beta-Stigmastanol	2.0	µg/L	<5	<5	<5
Bisphenol A	1.0	µg/L	<5	M	<5
Bisphenol A, d3 (surrogate)	.1	percent	82.1	91.7	35.0
Boron	13	µg/L	20	30	30
Bromacil	.5	µg/L	<5.0	<5.0	<5.0
Bromoform	.5	µg/L	<5.0	<5.0	<5.0
Caffeine	.5	µg/L	<5.0	<5.0	<5.0
Caffeine-C13 (surrogate)	.1	percent	82.1	104	59.1
Camphor	.5	µg/L	<5.0	<5.0	<5.0
Carbaryl	1.0	µg/L	<5	<5	<5
Carbazole	.5	µg/L	<5.0	<5.0	<5.0
Chloride	.2	mg/L	16.8	17.9	19.3
Chlorpyrifos	.5	µg/L	<5.0	<5.0	<5.0
Cholesterol	2.0	µg/L	8	<5	<5
Cotinine	1.0	µg/L	<5	<5	<5
d-Limonene	.5	µg/L	<5.0	<5.0	<5.0
Decafluorobiphenyl (surrogate)	.1	percent	136	95.8	77.3
Diazinon	.5	µg/L	<5.0	<5.0	<5.0
Dichlorvos	1.0	µg/L	<5.00	<5.00	<5.00
Fluoranthene	.5	µg/L	E .3	.7	.8

Table 2-11. Wastewater constituents in water at stormflow on Coatesville study reach, West Branch Brandywine Creek, August 4, 2003, Chester County, Pennsylvania.—Continued

[µg/L, micrograms per liter; <, less than; E, estimated value; M, presence verified, not quantified; shading indicates detected compound]

Wastewater constituent	Reporting limit	Unit	U.S. Geological Survey station identification number		
			01480500	0148061501	01480617
Fluoranthene, d10 (surrogate)	0.1	percent	96.4	100	54.5
Hexadydrohexamethylcyclopentabenzopyran (HHCB)	.5	µg/L	<5.0	<5.0	<5.0
Indole	.5	µg/L	<5.0	<5.0	<5.0
Isoborneol	.5	µg/L	<5.0	<5.0	<5.0
Isophorone	.5	µg/L	<5.0	<5.0	<5.0
Isopropylbenzene	.5	µg/L	<5.0	<5.0	<5.0
Isoquinoline	.5	µg/L	<5.0	<5.0	<5.0
Menthol	.5	µg/L	<5.0	<5.0	<5.0
Metalaxyl	.5	µg/L	<5.0	<5.0	<5.0
Methyl salicylate	.5	µg/L	<5.0	<5.0	<5.0
Metolachlor	.5	µg/L	<5.0	<5.0	<5.0
N,N-diethyl-meta-toluamide (DEET)	.5	µg/L	.6	.6	<5.0
Naphthalene	.5	µg/L	<5.0	E .1	E .1
Nonylphenol, diethoxy- (total)	5.0	µg/L	<5	<5	<5
Octylphenol, diethoxy-	1.0	µg/L	<5	<5	<5
Octylphenol, monoethoxy-	1.0	µg/L	<5	<5	<5
p-Cresol	1.0	µg/L	<5	<5	<5
para-Nonylphenol (total)	5.0	µg/L	<5	<5	<5
Pentachlorophenol	2.0	µg/L	<5	<5	<5
Phenanthrene	.5	µg/L	<5.0	<5.0	E.3
Phenol	.5	µg/L	1.0	<5.0	<5.0
Prometon	.5	µg/L	<5.0	<5.0	<5.0
Pyrene	.5	µg/L	E .3	.6	.7
Tetrachloroethylene	.5	µg/L	<5.0	<5.0	<5.0
Tri(2-butoxyethyl)phosphate	.5	µg/L	<5.0	2	<5.0
Tri(2-chloroethyl)phosphate	.5	µg/L	<5.0	<5.0	<5.0
Tributyl phosphate	.5	µg/L	<5.0	<5.0	<5.0
Triclosan	1.0	µg/L	<5	<5	<5
Triethyl citrate (ethyl citrate)	.5	µg/L	<5.0	<5.0	<5.0
Triphenyl phosphate	.5	µg/L	<5.0	<5.0	<5.0
Tris(dichlorisopropyl)phosphate	.5	µg/L	<5.0	<5.0	<5.0

[1]Reporting limit raised to 5.0 in most samples at request of U.S. Geological Survey National Water-Quality Laboratory because of large amounts of suspended solids in storm samples; where possible, original reporting limit was maintained.

Table 2-12. Nutrients in water at stormflow on Coatesville study reach, West Branch Brandywine Creek, August 4, 2003, Chester County, Pennsylvania.

[mg/L, milligrams per liter; E, estimated value]

Parameter name	Reporting limit	Unit	U.S. Geological Survey station identification number		
			01480500	0148061501	01480617
Nitrogen, ammonia	0.041	mg/L	E 0.04	E 0.03	E 0.02
Nitrogen, ammonia + organic nitrogen, filtered	.10	mg/L	.45	.50	.39
Nitrogen, ammonia + organic nitrogen, unfiltered	.10	mg/L	.98	2.4	2.0
Nitrogen, nitrite	.008	mg/L	.008	.019	.009
Nitrogen, nitrite + nitrate	.060	mg/L	2.14	2.00	2.18
Phosphorus, filtered	.0044	mg/L	.060	.091	.087
Phosphorus, unfiltered	.0037	mg/L	.28	.80	.67
Phosphorus, phosphate, ortho	.018	mg/L	.04	.06	.06

Appendix 3–Wagontown Study Reach Data Tables

Table 3-1. Results of laboratory analyses and field determinations for bacteria concentrations in water and fluvial sediments at base flow on Wagontown study reach, West Branch Brandywine Creek and tributaries, September 18, 2002, Chester County, Pennsylvania.

[ft, feet; col/100 mL, colonies per 100 milliliters; col/g, colonies per gram; mm, millimeters; <, less than]

Stream distance from upstream end of project reach (ft)	U.S. Geological Survey project identification number	U.S. Geological Survey station identification number	Date sampled (mm-dd-yyyy)	Time sampled	Fecal coliform bacteria in water (col/100 mL)	Fecal streptococci bacteria in water (col/100 mL)	Fecal coliform bacteria in sediment (col/g saturated sediment)	Fecal streptococci bacteria in sediment (col/g saturated sediment)	Observed sediment particle distribution (mm)
0	A1	01480428	09-18-2002	0842	80	480	378	540	1-2
152	A2	01480429	09-18-2002	0905	160	370	0	324	0.5-1
662	A3	014804302	09-18-2002	1135	140	260	6,480	2,214	0.062-0.125
982	A4	014804304	09-18-2002	1120	180	290	702	108	2-4
1,100	A5	014804306	09-18-2002	1106	100	350	3,240	594	<0.062
1,331	A6	014804308	09-18-2002	1050	160	230	270	216	0.5-1
1,546	A7	400008075492601	09-18-2002	1030	190	270	1,674	24,840	0.062-0.125
1,816	A8	014804326	09-18-2002	1015	240	290	270	1,458	0.062-0.125
1,963	A9	014804328	09-18-2002	1000	190	370	108	3	0.5-1
2,274	A10	01480433	09-18-2002	0945	180	480	1,944	270	0.5-1

Table 3-2. Results of field determinations for selected water-quality constituents at base flow on Wagontown study reach, West Branch Brandywine Creek, September 18, 2002, Chester County, Pennsylvania.[1]

[ft, feet; °C, degrees Celsius; mg/L, milligrams per liter; NTU, nephelometric turbidity units; µS/cm, microsiemens per centimeter at 25°C]

Stream distance from upstream end of project reach (ft)	U.S. Geological Survey project identification number[2]	U.S. Geological Survey station identification number	Water temperature (°C)	Dissolved oxygen (mg/L)	pH (standard units)	Turbidity (NTU)	Specific conductance (µS/cm)
0	A1	01480428	17.1	9.3	7.6	5	204
152	A2	01480429	17.1	9.5	7.7	5	204
662	A3	014804302	18.1	10.0	7.9	4	202
982	A4	014804304	18.0	10.2	8.0	4	142
1,100	A5	014804306	18.0	10.2	8.0	4	202
1,331	A6	014804308	17.8	10.2	7.9	5	203
1,546	A7	400008075492601	17.7	10.2	8.0	4	203
1,816	A8	014804326	17.4	10.1	7.8	5	212
1,963	A9	014804328	17.1	10.0	7.7	5	214
2,274	A10	01480433	17.0	10.0	7.7	5	216

[1]All water-quality constituents were measured within the main channel of the West Branch Brandywine Creek.

[2]U.S. Geological Survey project identification numbers are assigned in the order they were initially located and not in downstream order as are U.S. Geological Survey station identification numbers.

Table 3-3. Results of laboratory analyses and field determinations for bacteria concentrations in water and fluvial sediments at base flow on Wagontown study reach, West Branch Brandywine Creek and tributaries, July 17, 2003, Chester County, Pennsylvania.

[ft, feet; col/100 mL, colonies per 100 milliliters; col/g, colonies per gram; mm, millimeters; <, less than]

Stream distance from upstream end of project reach (ft)	U.S. Geological Survey project identification number	U.S. Geological Survey station identification number	Date sampled	Time sampled	*Escherichia coli* in water (col/100 mL)	Enterococci in water (col/100 mL)	*Escherichia coli* in sediment (col/g saturated sediment)	Enterococci in sediment (col/g saturated sediment)	Observed sediment particle distribution (mm)
0	A1	01480428	07-17-2003	1045	110	570	1,890	4,050	0.5-1
152	A2	01480429	07-17-2003	1035	50	230	5,616	178,200	0.125-0.25
662	A3	014804302	07-17-2003	1020	140	240	1,134	8,100	0.5-1
982	A4	014804304	07-17-2003	1007	400	12,000	648	1,998	0.5-1
1,100	A5	014804306	07-17-2003	1012	380	310	1,458	46,980	1 -2
1,331	A6	014804308	07-17-2003	1000	1,210	280	216	19,980	0.5-1
1,546	A7	400008075492601	07-17-2003	0945	280	620	162	756	0.25-0.5
1,816	A8	014804326	07-17-2003	0917	210	500	4,752	2,700	<0.062
1,963	A9	014804328	07-17-2003	0912	160	310	2,322	3,780	1 -2
2,274	A10	01480433	07-17-2003	0900	180	520	1,404	17,280	0.25-0.5

Table 3-4. Results of field determinations for selected water-quality constituents at base flow on Wagontown study reach, West Branch Brandywine Creek, July 17, 2003, Chester County, Pennsylvania.[1]

[ft, feet; °C, degrees Celsius; mg/L, milligrams per liter; NTU, nephelometric turbidity units; µS/cm, microsiemens per centimeter at 25°C]

Stream distance from upstream end of project reach (ft)	U.S. Geological Survey project identification number[2]	U.S. Geological Survey station identification number	Water temperature (°C)	Dissolved oxygen (mg/L)	pH (standard units)	Turbidity (NTU)	Specific conductance (µS/cm)
0	A1	01480428	20.3	10.0	7.9	2	230
152	A2	01480429	20.2	10.1	7.9	4	230
662	A3	014804302	20.0	9.9	7.9	2	232
982	A4	014804304	20.0	10.0	7.8	2	232
1,100	A5	014804306	20.0	10.0	7.8	3	232
1,331	A6	014804308	19.9	10.0	7.8	3	232
1,546	A7	400008075492601	19.9	10.0	7.6	4	233
1,816	A8	014804326	19.3	9.9	7.7	4	239
1,963	A9	014804328	19.0	9.9	7.6	3	243
2,274	A10	01480433	19.1	9.9	7.5	3	243

[1]All water-quality constituents were measured within the main channel of the West Branch Brandywine Creek.

[2]U.S. Geological Survey project identification numbers are assigned in the order they were initially located and not in downstream order as are U.S. Geological Survey station identification numbers.

Appendix 4–Sandbag and Optical Brightener Data Table

Table 4-1. Descriptions of sandbag-sampling sites and laboratory determinations for bacteria concentrations and optical-brightener presence on Coatesville study reach, July 3, 2003, to July 10, 2003, West Branch Brandywine Creek, Chester County, Pennsylvania.

[ft, feet; col/g, colonies per gram; W.B., West Branch; ~, approximately]

Stream distance from upstream end of project reach (ft)	U.S. Geological Survey project identification number[1]	U.S. Geological Survey station identification number	Description of sandbag location and attachment point	*Escherichia coli* concentration within sandbag (col/g saturated sediment)	Enterococci concentration within sandbag (col/g saturated sediment)	Optical-brightener presence (positive or negative)
0	CB1	01480500	Along right bank of W.B. Brandywine; ~5 ft upstream of dam crest; attached to tree on streambank	550	13,200	Negative
1,040	CB9BTC	395900075493001	At mouth of Coatesville storm sewer culvert, ~30 ft landward from left edge of water; attached to debris at mouth of culvert.	110,000	324,500	Negative
2,991	CB16TC	01480550	At mouth of Coatesville storm sewer culvert (Gibbons Run); attached to culvert.	121,000	58,850	Negative
3,872	CB20TC	01480580	At mouth of Coatesville storm sewer and industrial process water outfall (Tar Run); attached to culvert.	28,050	47,850	Negative
4,411	CB21TC	01480614	At mouth of Coatesville storm sewer culvert (Sucker Run); attached to culvert.	5,995	36,300	Negative
4,853	CB23TC	395826075492701	At mouth of Pennsylvania American Water Company, wastewater-treatment facility culvert; attached to culvert.	715	5,115	Positive
7,747	CB31TC	01480615	Under abandoned bridge over tributary to W.B. Brandywine near intersection of 1st Avenue and Newlinville Road; attached to bridge.	110	2,310	Negative
8,725	CB35TC	395758075490101	Approximately 4 ft back from mouth into a ~4-ft × 4-ft storm-sewer culvert that serves industrial area; attached to culvert.	4,950	3,300	Negative
9,381	CB38BTC	395756075485301	At source of spring located ~15 ft landward from right edge of water; attached to tree at spring.	3,080	29,150	Negative
10,034	CB41BTC	395758075484501	At source of spring located ~15 ft landward from right edge of water; attached to tree at spring.	1,760	3,465	Negative
11,577	CB47TC	0148061562	At mouth of corrugated steel pipe discharging effluent from South Coatesville and Modena, wastewater-treatment facility; attached to culvert.	12,100	7,590	Positive
13,559	CB58TC	014806161	At abandoned lock structure within unnamed tributary channel, formed by old mill race, approximately 15 ft upstream from confluence with W.B. Brandywine; attached to lock.	385	25,300	Negative

Table 4-1. Descriptions of sandbag-sampling sites and laboratory determinations for bacteria concentrations and optical-brightener presence on Coatesville study reach, July 3, 2003, to July 10, 2003, West Branch Brandywine Creek, Chester County, Pennsylvania.—Continued

[ft, feet; col/g, colonies per gram; W.B., West Branch; ~, approximately]

Stream distance from upstream end of project reach (ft)	U.S. Geological Survey project identification number[1]	U.S. Geological Survey station identification number	Description of sandbag location and attachment point	*Escherichia coli* concentration within sandbag (col/g saturated sediment)	Enterococci concentration within sandbag (col/g saturated sediment)	Optical-brightener presence (positive or negative)
13,946	CB61	014806162	Under abandoned bridge over unnamed tributary channel ~100 ft upstream from confluence with W.B. Brandywine; attached to bridge.	2,695	5,060	Negative
14,809	CB64	01480617	On downstream right side of mid-channel bar adjacent to USGS streamflow-gaging station 01480617; attached to tree.	1,650	6,325	Negative
14,862	CB66TC	0148061802	Under bridge Carrying South Brandywine Avenue over Dennis Run ~100 ft upstream from confluence with W.B. Brandywine; attached to bridge.	715	2,750	Negative

[1]U.S. Geological Survey project identification numbers are assigned in the order they were initially located and not in downstream order as are U.S. Geological Survey station identification numbers.

Appendix 5–2003 Streamflow-Gaging Station 01480617 Data Table

Table 5-1. Results of laboratory analysis and field determinations for selected water-quality constituents and bacteria concentrations in water at stormflow at U.S. Geological Survey streamflow-gaging station 01480617, West Branch Brandywine Creek at Modena, August 4, 2003, Chester County, Pennsylvania[1]

[ft^3/s, cubic feet per second; col/100 mL, colonies per 100 milliliters; °C, degrees Celsius; mg/L, milligrams per liter; NTU, nephelometric turbidity units; µS/cm, microsiemens per centimeter at 25°C]

Time	Streamflow (ft^3/s)	*Escherichia coli* (col/100 mL)	Enterococci (col/100 mL)	Water temperature (°C)	Dissolved oxygen (mg/L)	pH (standard units)	Turbidity (NTU)	Specific conductance (µS/cm)
0558	817	7,800	19,000	22.5	4.9	7.6	400	312
0628	569	32,000	110,000	23.2	4.8	8.1	440	121
0658	360	32,000	110,000	23.1	4.7	8.2	360	119
0728	470	33,000	98,000	22.8	4.7	8.0	360	166
0758	418	11,000	116,000	22.3	4.8	7.7	330	214
0828	314	8,000	76,000	22.1	4.9	7.6	920	212
0858	251	18,000	92,000	22.1	4.9	7.6	780	203
0928	209	19,000	127,000	22.0	4.9	7.5	570	198
0958	184	19,000	42,000	22.1	5.0	7.5	480	201
1028	169	25,000	147,000	22.2	5.0	7.5	380	204
1058	164	14,000	155,000	22.3	5.0	7.5	340	206

[1]All water-quality constituents were measured within the main channel of the West Branch Brandywine Creek.

Glossary

The terms in this glossary were compiled from numerous sources. Some definitions have been modified for use within the report.

Aliquot A portion of a solution or sample.

Fluvial Relating to a river or stream; as in "fluvial sediment."

Lacustrine Relating to a lake; as in "lacustrine sediment."

Planktonic Passively floating or weakly swimming; as in "planktonic bacteria."

Quartzose Composed mainly of quartz; as in "quartzose sandstone."

Riparian Relating to, living, or located on the bank of a river or stream; as in "riparian zone."

Run-of-the river dam A dam that cannot store large amounts of water and must allow water to pass (generally over a spillway) at the same rate at which it enters the impoundment area.

Sessile Attached, not free to move; as in "sessile bacteria."

Thalweg The deepest, highest velocity, path of the stream.

Throughflow The lateral movement of water through the shallow, unsaturated zone during and immediately after a precipitation event.