A Spatial, Multivariable Approach for Identifying Proximate Sources of *Escherichia coli* to Maumee Bay, Lake Erie, Ohio

By Donna S. Francy, Pamela Struffolino, Amie M. G. Brady, and Daryl F. Dwyer

In cooperation with the Ohio Water Development Authority, Cities of Oregon and Toledo,
University of Toledo, and Toledo Metropolitan Area Council of Governments

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Contents

Figures

Table

Conversion Factors and Abbreviations

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
milliliter (mL)	0.06102	cubic inch (in^3)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)

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

$$°F=(1.8x°C)+32$$

Turbidity is reported in Nephelometric Turbidity Units (NTU).

Concentrations of bacteria in water are reported in colonies per 100 milliliters (col/100 mL) or most probable number per 100 milliliters (MPN/100 mL)

Concentrations of bacteria in sediment are reported in most probable number per gram dry weight of sediment (MPN/g_{DW}).

Concentrations that are less than a specified value are reported as <, greater than are reported as >, less than or equal to are reported as ≤, and greater than or equal to are reported as ≥.

A Spatial, Multivariable Approach for Identifying Proximate Sources of *Escherichia coli* to Maumee Bay, Lake Erie, Ohio

By Donna S. Francy, Pamela Struffolino[1], Amie M. G. Brady, and Daryl F. Dwyer[1]

ABSTRACT

Sources of *E. coli* at U.S. beaches are often unknown. Determining the spatial distribution of *E. coli* and identifying factors that can affect concentrations may provide insight into the sources of fecal contamination. This approach was used to investigate a popular bathing beach in northwest Ohio—Maumee Bay State Park (MBSP). In 2003 synoptic studies, water and bed-sediment samples were collected and analyzed for *E. coli* at 24 sites within Maumee Bay, a nearby shipping channel, a major tributary to the bay (Maumee River), and nearshore areas at the mouths of drainage ditches. In 2004, samples were collected at 22 sites identified as "hot spots" of fecal contamination during 2003. Daily samples for *E. coli* were collected at MBSP as part of the Ohio Bathing Beach Monitoring Program. Highest *E. coli* concentrations were found at sites in the Maumee River, the shipping channel, and in or at the mouth of some drainage ditches. These high values were found in bed sediments underlying the deepest waters, which may act as an *E. coli* sink. Low *E. coli* concentrations at sites remote to MBSP indicated that sources from these areas were not important contributors of *E. coli*. Temperature changes in discharge from a local powerplant did not cause an increase in *E. coli* concentrations. A ditch that discharges 75 m east of the bathing beach was shown to be a principal source of *E. coli*. Turbidity and rainfall were positively correlated with *E. coli* concentrations at MBSP. Higher wave heights and wind directions from the north, northeast, or northwest were associated with higher *E. coli* concentrations.

Introduction

To protect the health of visitors, managers of beach recreational areas issue advisories or closings on the basis of standards for concentrations of bacterial indicator organisms. For freshwater beaches, *Escherichia coli* (*E. coli*) is the indicator most commonly used to assess recreational water quality. In spite of increased focus on beach water-quality issues and the passage of the Federal Beaches Environmental Assessment and Coastal Health Act of 2000 (U.S. Congress, 2000), many U.S. beaches continue to be plagued with high bacterial indicator concentrations. Beaches are better monitored than they were in the past, but the sources of fecal contamination that trigger most closings and advisories remain unknown. For example, in 2003, unknown sources of contamination caused approximately 12,000 closings and advisories in the U.S.—68 percent of the year's total for the nation (Natural Resources Defense Council, 2004). Possible sources of contamination include combined and sanitary-sewer overflows; treated wastewater effluents; sewage from private sewage-treatment systems, including septic tanks; fecal pollution from birds, swimmers, or boats; and stormwater runoff. Identifying and mitigating the source of fecal contamination to a particular beach is often complicated by the spatial and temporal variability of bacterial indicator concentrations and the dynamic lake currents, weather patterns, and natural processes that affect these concentrations.

Determining the spatial distribution of *E. coli* in bed sediments throughout an affected area may help identify proximate sources of fecal contamination. Bacteria have been shown to survive longer in sediments than in water (LaLiberte and Grimes, 1982; Burton and others, 1987); therefore, resuspension of *E. coli* from bed sediments, either by dredging or by natural causes, may affect recreational water quality. Evidence for short-term storage (less than a week) of *E. coli* in lake-bottom sediments was found at a Lake Erie bathing beach (Francy and Darner, 1998). In a study of a Lake Michigan beach, bed sediments from a nearby creek were a principal source of *E. coli* affecting recreational water quality (Byappanahalli and others, 2003). In a study of recreational marine beaches in California, the spatial and temporal distribution of indicator bacteria in bed sediments and the overlying water column led to the conclusion that contaminant sources were from inside the bay and the land side of the beach (Boehm and others, 2003).

Similarly, identifying relevant environmental and water-quality factors, such as wind direction, rainfall, and turbidity—all of which can affect *E. coli* concentrations—also may help

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in identifying sources. In a recent study, investigators found that wave height and rainfall affected *E. coli* concentrations at all five Lake Erie beaches tested, but number of birds and current direction affected *E. coli* at only a few of the beaches (Francy and others, 2003). At one of four estuary beaches on Long Island Sound, investigators were unable to relate high enterococci counts to antecedent rainfall. They later found that the cause of contamination was the illegal disposal of boat wastes at a nearby marina (City of Stamford, 2001).

The U.S. Geological Survey, in cooperation with the Ohio Water Development Authority, Cities of Oregon and Toledo, University of Toledo, and Toledo Metropolitan Area Council of Governments, examined spatial and environmental factors in combination to identify sources of fecal contamination near a popular bathing beach in Maumee Bay in northwest Ohio. This report describes how information on spatial patterns of *E. coli* in bed sediments and water led to identifying fecal-contaminant "hot spots" in a study area. Relations between environmental and water-quality factors and *E. coli* concentrations at the bathing beach were used to help corroborate results from spatial studies. This study illustrates how to take first steps towards identifying sources of fecal contamination in an urbanized and hydrologically complicated area with numerous potential sources. Identifying proximate sources enables local water-resource managers to apply more sophisticated source-tracking tools to identify specific sources of fecal contamination and, ultimately, take appropriate mitigation measures.

Environmental Setting

Maumee Bay, in the southwest corner of Lake Erie, borders the cities of Toledo and Oregon (fig. 1). Maumee Bay is a popular recreational destination in Ohio for swimming, boating, fishing, and observing wildlife. In particular, Maumee Bay State Park (MBSP) is recognized as a major attraction in the area and has two swimming beaches—one along the Lake Erie shoreline (fig. 2a) and one inland. The Lake Erie beach is often impaired by high *E. coli* concentrations. If the concentration of *E. coli* exceeds the 5-day geometric mean standard of 126 colonies per 100 milliliters (col/100 mL) established by the State of Ohio (Ohio Environmental Protection Agency, 2002), beach managers at MBSP post a beach advisory. The Lake Erie beach was posted with water-quality advisories on 29 days in 2001, 8 days during 2002, 44 days during 2003, and 20 days during 2004 (Ohio Department of Health, 2004). In addition, waters at other unmonitored locations in Maumee Bay may be unsafe for primary- and secondary-contact recreation, such as boating and swimming.

MBSP is just east of an urbanized and hydrologically complicated area (fig. 1). The Ottawa River drains into northwest Maumee Bay and has a drainage area of 388 km^2 at the USGS streamflow-gaging station 17.5 km upstream from the mouth. The Maumee River at its mouth at Toledo has a drainage area of 17,114 km^2 (Shindel and others, 2002), the largest of any Great Lakes tributary (fig. 2b). The City of Toledo's wastewater-treatment plant discharges effluent into the river approximately 2.1 km upstream from the mouth. The Port of Toledo, at the mouth of the Maumee River, is one of the busiest ports in the Great Lakes. The U.S. Army Corps of Engineers maintains a navigable depth of approximately 8.5 m in a shipping channel that extends 30.6 km offshore (Great Lakes Dredging Team, 1999). Water depths in Maumee Bay are among the shallowest in the Great Lakes; except for the dredged shipping channel, water depths in Maumee Bay are less than 3 m. An inlet to a channel that feeds the intake of a powerplant is also near the mouth of the Maumee River. The powerplant uses water for cooling and discharges water into Maumee Bay that is warmer than the intake water. The Combined Disposal Facility and Grassy Island are two manmade structures built of dredged materials. The City of Oregon's wastewater-treatment plant discharges treated effluent 50 m offshore of the southern side of the Combined Disposal Facility (fig. 2c). Eastward along the Maumee Bay shoreline, drainage ditches were built to drain an area that was formerly swamp and wetlands and is now urban, agricultural, and industrial.

Potential sources of fecal contamination to Maumee Bay and MBSP are numerous. The Maumee River receives inputs from combined sewer overflows (CSOs) and stormwater runoff in Toledo. Inputs upstream from Toledo include runoff from row-crop and animal agricultural activities, septic-tank effluent, and runoff and wastewater effluent from towns and cities. Elevated temperatures from heated effluent from the nearby powerplant could potentially enhance the growth of *E. coli*. Elevated *E. coli* concentrations may also be due to conveyance of fecal contamination from septic tanks, farm fields, or wildlife via drainage ditches. Of particular concern is Berger Ditch, which discharges at the marina at MBSP, 75 m east of the bathing beach (figs. 2d and 2e, site N10). In previous work, high *E. coli* concentrations were consistently found in bed sediments and waters of Berger Ditch (Glatzer and Erichsen, 2003).

Methods of Study

Two types of field studies—synoptic studies and routine monitoring—were done during the recreational seasons (May through September) of 2003 and 2004. Synoptic studies were done in two phases with six field trips in each phase. In phase 1 (2003), water and bed-sediment samples were collected at sites that were selected to ensure good spatial coverage of the study area and that were near possible sources of fecal contamination (fig. 3). Sampling locations included nearshore sites in Maumee Bay and the lower Ottawa River (N), offshore sites within Maumee Bay (O), and sites in the lower Maumee River (M). In 2003, sampling was done at 24 sites on June 24–25, July 29, July 30, September 7, and September 11; a subset of 8 sites was sampled on August 14, 2003.

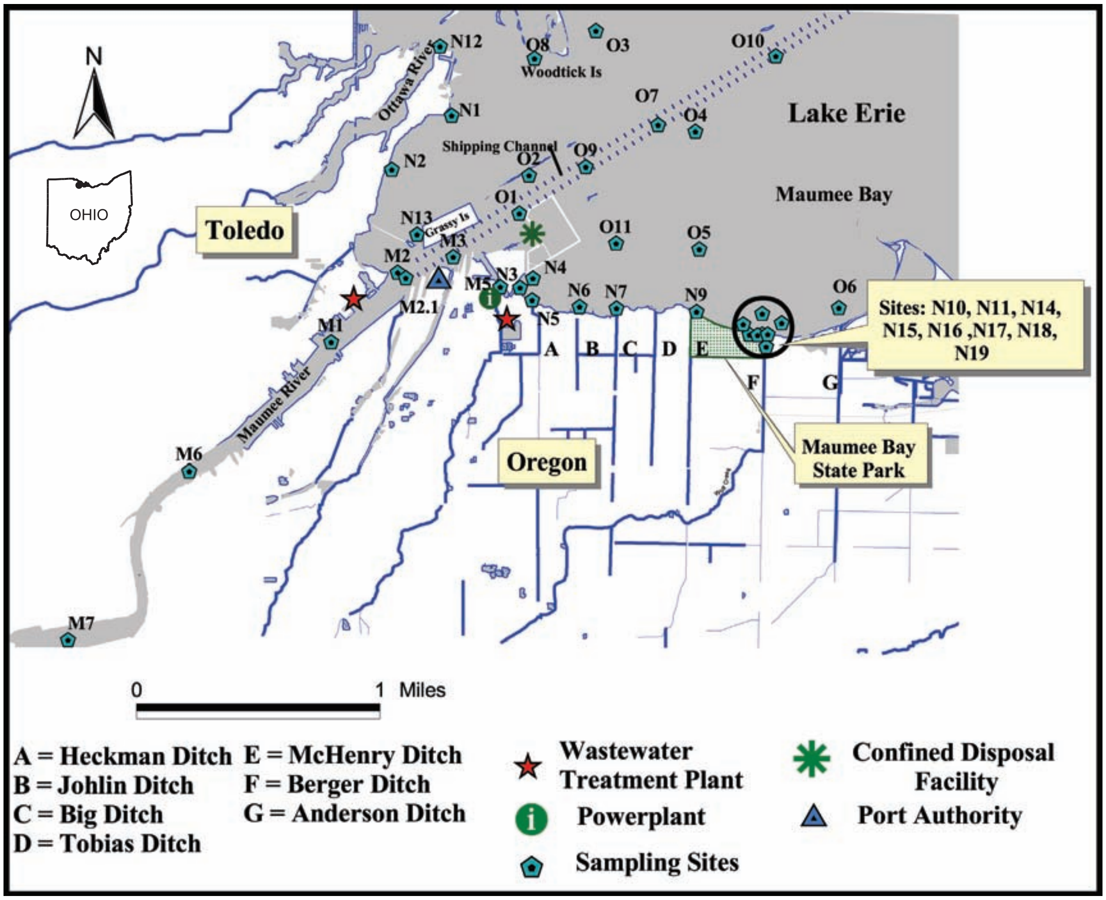


Figure 1. Study area and sampling sites, Maumee Bay, Lake Erie, Ohio.

In phase 2 (2004), sampling sites shown in phase 1 to have elevated *E. coli* concentrations were selected for further, intensive study. During phase 2, water and bed-sediment samples were collected at these fecal contaminant “hot spots” (fig. 4). In 2004, samples were collected from 22 sites on May 12, June 15, July 13, August 16, and August 17; a subset of 9 sites was sampled on March 24 and 27. The locations of synoptic sampling sites during both recreational seasons are listed in Appendix 1. For routine monitoring in 2003 and 2004, a daily water sample for *E. coli* was collected Monday through Thursday at MBSP as part of the Ohio Department of Health’s bathing beach monitoring program (Ohio Department of Health, 2004).

Sample Collection

Two sampling crews were used during phase 1 and phase 2 synoptic studies, enabling sampling to be done between 9:00 a.m. and 2:30 p.m. One crew used a 7.7-m center console boat (“large boat”) to collect samples at Maumee River and offshore sites. A second crew used a jon boat or waded to nearshore sites. For routine monitoring, water samples were collected by the Ohio Department of Health between 12:00 and 1:30 p.m. where the water was 1 m deep in an area of the beach used for swimming. All water-sample bottles were filled about 0.3 m below the water surface using a grab-sampling technique.

During synoptic studies, field crews used special procedures to collect bed sediments. From the large boat, the field crew lowered a clean and sterile Petite Ponar Grab sampler (Wildlife Supply Company, Buffalo, N.Y.) through the water column and collected a sediment sample per the manufacturer’s instructions. After it was brought to the surface, the sampler was drained of excess water, and the sediment was deposited into a clean and sterile washtub (fig. 5a). Two more bed-sediment subsamples were collected from the same location in this manner. Using a sterile spatula, the field crew composited three sediment subsamples in the washtub into a 250-mL labeled, sterile jar and immediately placed the jar in a cooler on ice. After excess sediment was brushed from the sampler, the sampler was decontaminated between sites as follows: (1) brush with dilute soap, (2) rinse with tap water, (3) soak in 0.005 percent bleach solution for 10 to 20 minutes, and (4) soak in 0.005 percent sodium thiosulfate solution for 5 minutes. From the jon boat, bed sediment was collected by diving or wading (fig. 5b). The diver secured the lid on a

A Photograph by Amie Brady, U.S. Geological Survey

B Photograph by John Tertuliani, U.S. Geological Survey

C Photograph by Amie Brady, U.S. Geological Survey

D Photograph by Amie Brady, U.S. Geological Survey

E Photograph by Amie Brady, U.S. Geological Survey

Figure 2. Scenes from the study area. *A*, Lake Erie beach at Maumee Bay State Park (looking south). *B*, Maumee River and downtown Toledo, upstream from the mouth between sampling sites M6 and M7 (looking southwest). *C*, Maumee Bay from the southern side of the Combined Disposal Facility at site N4 (looking southeast). *D*, Berger Ditch near the mouth and sampling site N14 (looking west). *E*, Berger Ditch, upstream from the mouth (looking south).

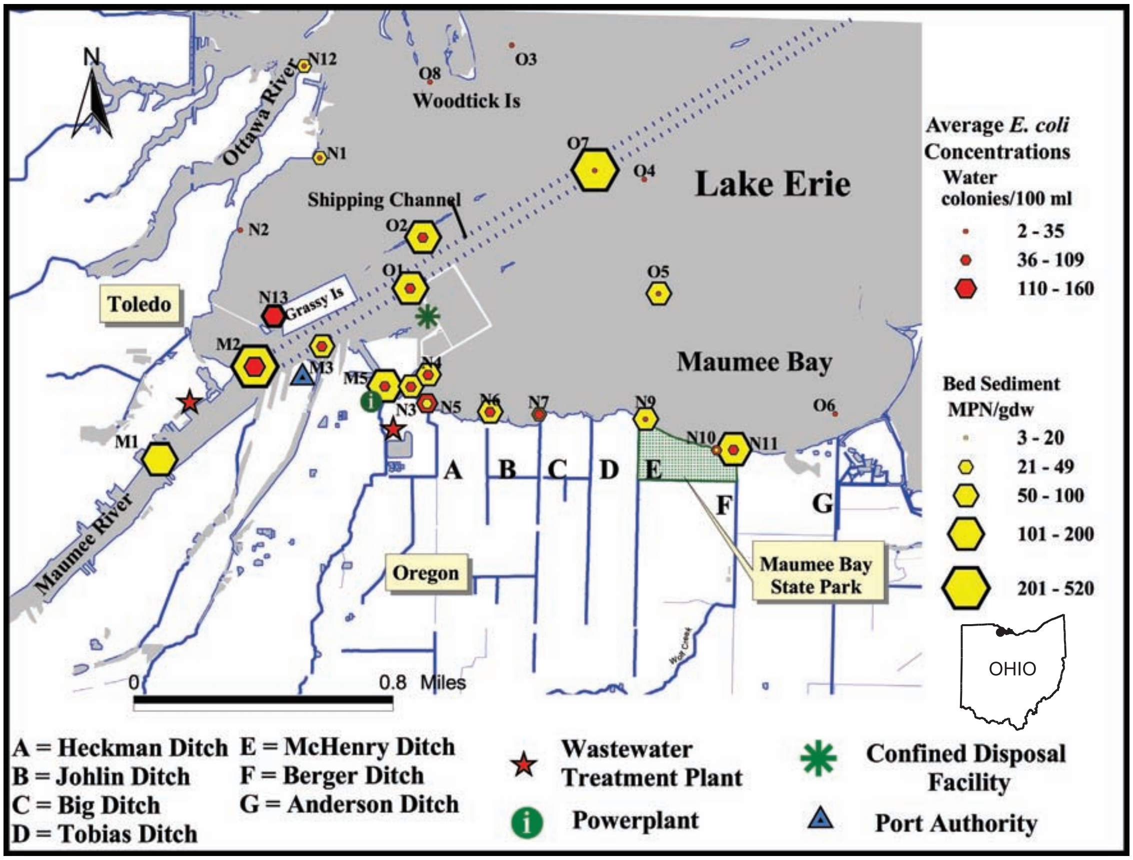


Figure 3. Average *E. coli* concentrations in Maumee Bay area, phase 1 (2003). Samples were collected during the recreational season (May through September) from 24 sites on 5 or 6 occasions at nearshore (N), offshore (O), and Maumee River (M) sites.

sterile 125- or 250-mL labeled sampling jar, dove to the lake bottom, opened the lid upon reaching the bottom, scooped the bottom sediments to obtain a sample, and closed the jar before surfacing. Two more subsamples were collected at each location in this manner and composited in the laboratory.

Analysis of Water and Bed-Sediment Samples

During phase 1 and 2 synoptic studies, water samples were analyzed for concentrations of *E. coli* within 6 hours of collection at the Lake Erie Center Laboratory, Oregon, Ohio, using the modified mTEC membrane-filtration method (U.S. Environmental Protection Agency, 2002). Bed-sediment samples were analyzed for concentrations of *E. coli* within 24 hours of collection at the USGS Ohio Water Microbiology Laboratory in Columbus, Ohio, by use of the Colilert Quantitray method (Idexx Laboratories, Westbrook, Maine). Sample-processing steps for sediment samples developed during an earlier study (Francy and Darner, 1998) were required before analysis. In summary, a 20 g aliquot of composited sediment from the three subsamples was placed into a bottle containing 200 mL of saline buffer; a second aliquot of composited sediment was reserved to determine percent dry weight. The bottle was placed on a shaker for 45 minutes, then removed; suspended materials were allowed to settle for 30 seconds, and the liquid phase was decanted for analysis. Calculations were made (Francy and Darner, 1998) to convert most probable number (MPN) counts to MPN per gram of dry weight sediment (MPN/g_{DW}). For routine monitoring, water samples were analyzed for concentrations of *E. coli* within 6 hours of collection at the City of Toledo Water Plant using the Colilert Quantitray method. Turbidity was determined in routine-monitoring water samples with a Hach Model 2100AN turbidimeter (Hach Company, 1989).

During phase 1, a bed-sediment sample from each site was analyzed for particle-size distribution at the USGS Sediment Laboratory in Louisville, Ky. This determination consisted of a sand/fine separation and a five-point fine analysis. For the sand/fine analysis, the composited sediment was processed through a wet sieve, dried, and weighed to determine the percentage of sediment finer than 0.062 mm (Guy, 1969). The fines were captured and allowed to settle for 2–3 weeks. The water was decanted, and using the pipet method, the fractions finer than 0.002, 0.004, 0.008, 0.016, and 0.031

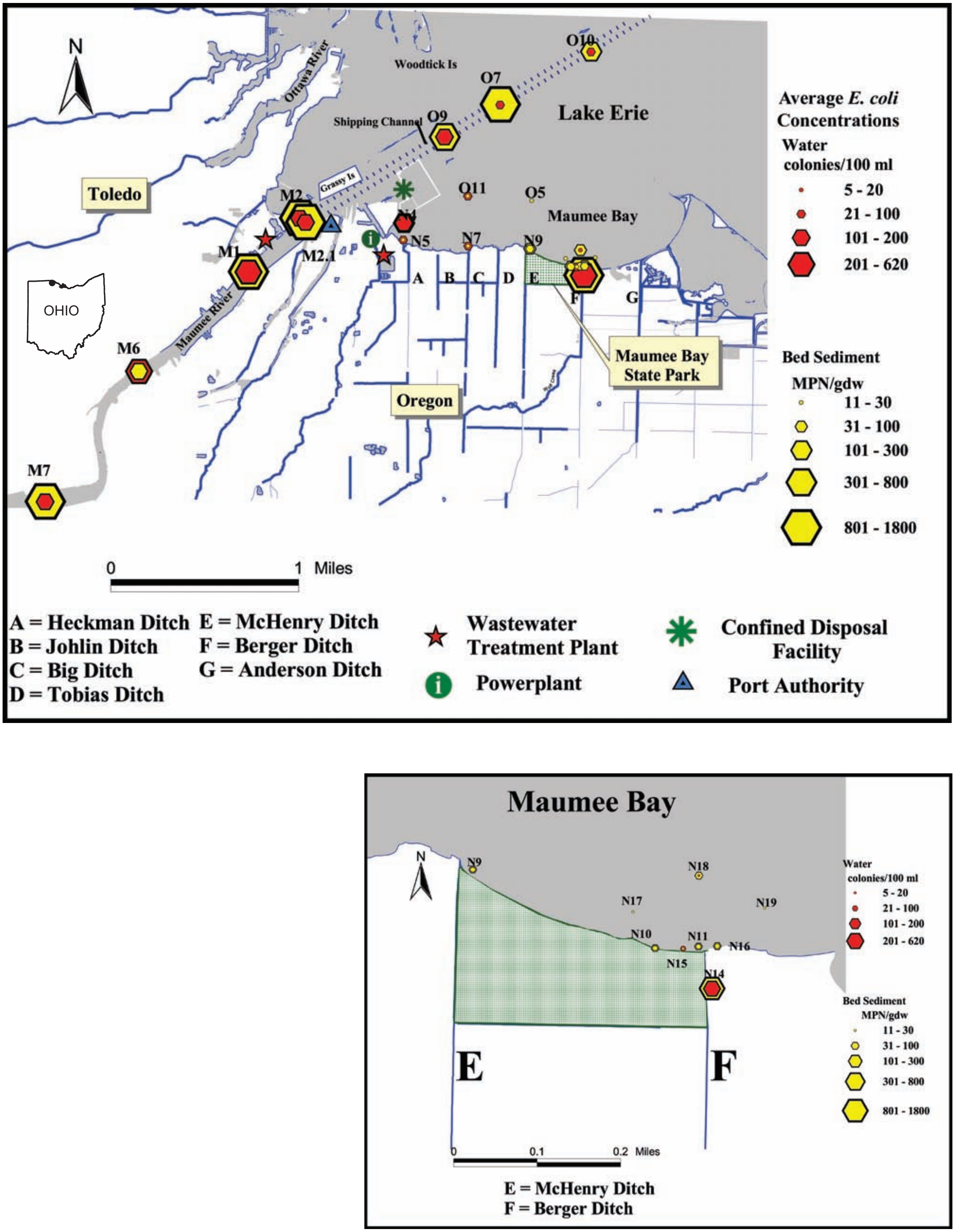
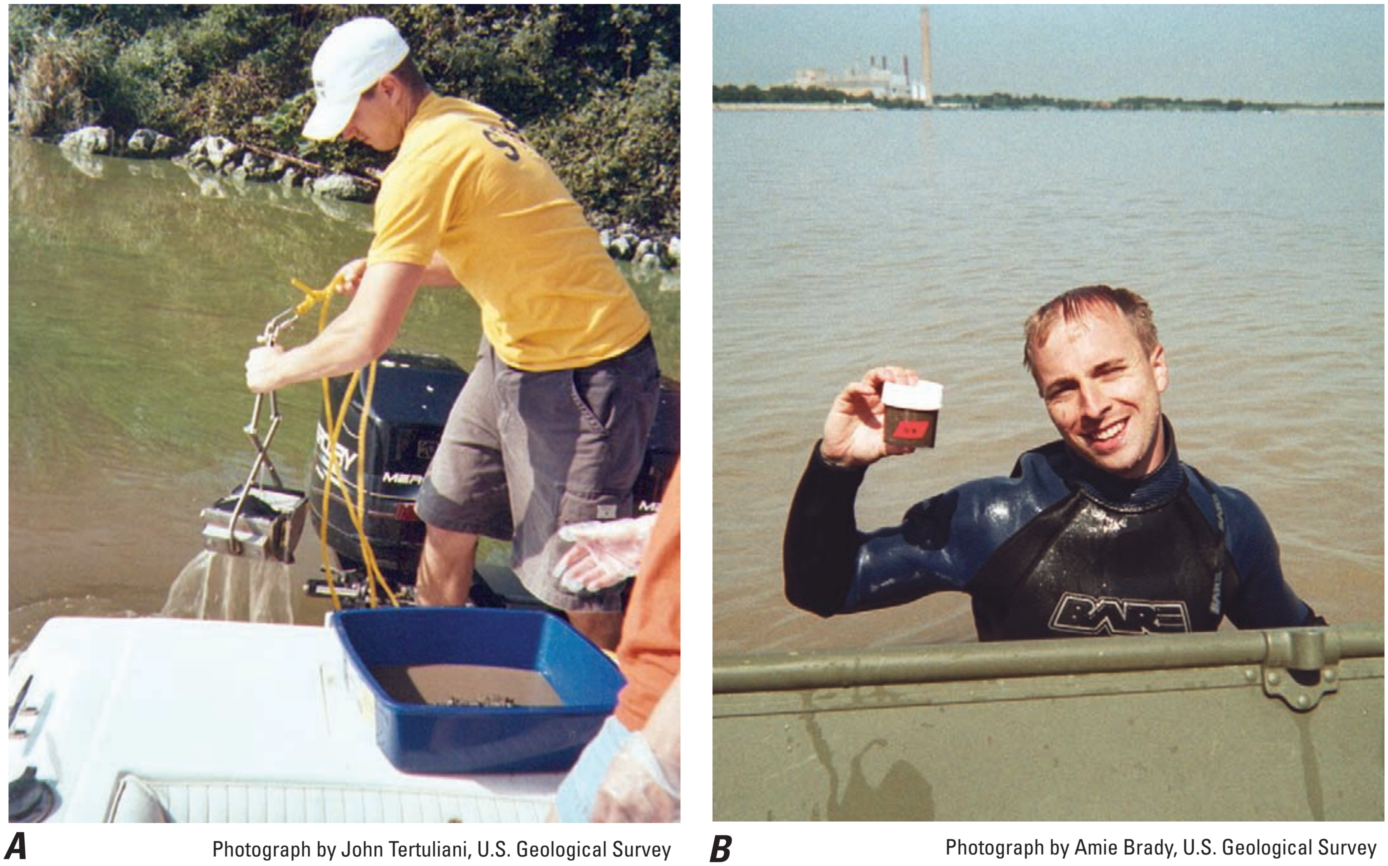


Figure 4. Average *E. coli* concentrations in Maumee Bay area, phase 2 (2004). Samples were collected from 22 sites during the recreational season (May through September) on 5 occasions at nearshore (N), offshore (O), and Maumee River (M) sites.



Photograph by John Tertuliani, U.S. Geological Survey

Photograph by Amie Brady, U.S. Geological Survey

Figure 5. Sediment sampling techniques. *A*, To collect a bed-sediment sample, the field crew used a sterile Petite Ponar Grab sampler and deposited three subsamples into a clean and sterile washtub. *B*, When feasible, bed sediment was collected into three sterile 125- or 250-mL sampling jars at the site by diving or wading.

mm were determined (Guy, 1969). The percentages of particles in each size classification (clay, silt, and sand) were calculated by means of a computer program that uses available data and interpolates results (Stevens and Hubbell, 1986). Weighted values for particle size were calculated as follows: Weighted particle-size index = (percent clay) + 2 x (percent silt) + 3 x (percent sand). Samples were classified into one of four categories on the basis of their index values: 125 to 166, fine (>50 percent clay); 182 to 205, medium fine; 230 to 260, medium coarse (>50 percent sand); 261 to 300, coarse (>90 percent sand).

Environmental Data

Ancillary environmental data were collected by field crews or compiled from a variety of sources. In synoptic studies, field crews located sampling sites using a global positioning system and measured water depths using a fathometer. In routine monitoring, field personnel estimated wave heights and number of birds and bathers at the time of sample collection. Data from the USGS-operated streamflow-gaging station at the Maumee River at Waterville (USGS station 04193500) were used to estimate streamflow (Shindel and others, 2004, 2005).

Daily weather data were compiled from several agencies. Daily rainfall amounts and wind speed and direction data were obtained from the National Weather Service station at Toledo Metcalf Field (National Oceanic and Atmospheric Administration, 2004a), 16 km south of Maumee Bay. Daily weather data were also measured by the City of Oregon at the wastewater-treatment plant, about 1.5 km inland from the bay. Water-level data were obtained from a NOAA-operated station near the mouth of the Maumee River in Toledo, Ohio (NOAA ID 90663085; National Oceanic and Atmospheric Administration, 2004b).

Concentrations of *E. coli* in Water and Bed Sediments During Synoptic Studies

Phase 1, Spatial Survey

The magnitudes of average *E. coli* concentrations from phase 1 synoptic surveys at 24 sites (16 sites sampled 5 times and 8 sites sampled 6 times) are represented by the size of the red and yellow octagons for water and bed sediments, respectively (fig. 3). Average *E. coli* concentrations (instead of medians) were used so that the influence from extreme measurements would be well represented. The individual measurements for each site and associated averages and standard deviations are listed in Appendix 2. In water, average *E. coli* concentrations ranged from 2 to 161 col/100 mL. *E. coli* concentrations in water were highest at Maumee River sites (M1and M2) and at nearshore sites near the mouth of the Maumee River (N13 and N5). They were lowest at offshore sites (O3, O4, O5, O6, O7, O8) and nearshore sites by Toledo (N1, N2, and N12) and west of MBSP (N9). Average *E. coli* concentrations in bed sediments ranged from 3 to 520 MPN/g_{DW}. The two highest average *E. coli* concentrations in bed sediments were at sites in the Maumee River (M2) and the shipping channel (O7). Bed-sediment *E. coli* concentrations were also elevated at the mouth of Berger Ditch (N11) as compared to other sites in the vicinity (N9, N10, O6).

Phase 1 data can be used to examine the relations between particle size, water depth, and *E. coli* concentrations in the study area. Figure 6 shows the relation between weighted particle-size index and average *E. coli* concentration at each site, with key sites labeled. Although the sites with the highest average *E. coli* concentrations were associated with fine bed sediments (O7 and M2), this was not true for every site. For example, at site N11, bed sediments were coarse, yet average *E. coli* concentration was elevated. At the other end, at site M3, bed sediments were fine, yet average *E. coli* concentration was low. Water depths at sampling points ranged from 0.3 to 9.6 m (fig. 7) with a median of 1.2 m. *E. coli* concentrations in bed sediments in shallow waters less than 1.5 m deep ranged from <1 to 660 MPN/g_{DW}, and many were <50 MPN/g_{DW}. In contrast, samples collected where waters were greater than 3 m deep had *E. coli* concentrations from 50 to 1,900 MPN/g_{DW}, and no samples were <50 MPN/g_{DW}. All samples from water depths greater than 3 m were collected from Maumee River or shipping-channel sites; these were the sites where bed sediments were fine.

Concentrations of *E. coli* in water and bed sediments and water temperatures between the intake (M5) and outfall (N3) of the powerplant were examined (fig. 8). Although temperatures were higher in the outfall waters (median = 25.8°C) than intake waters (median = 22.7°C), *E. coli* concentrations in water and bed sediments were not higher at the outfall than at the intake. In fact, the median bed-sediment *E. coli* concentration was lower at the powerplant outfall (36 MPN/g_{DW}) than at the intake (99 MPN/g_{DW}).

During Phase 1, the fecal contaminant "hot spots" were identified as Maumee River sites, nearshore sites near the river and the mouth of Berger Ditch, and sites in the shipping channel. Low *E. coli* concentrations found at sites north and west of the shipping channel indicated that remote sources were not important contributors of *E. coli*. Similarly, low *E. coli* concentrations at nearshore sites west of MBSP indicated that westerly nearshore sources were not causing elevated concentrations at MBSP. Although higher *E. coli* concentrations in bed sediments were generally associated with finer sediment particles, several outliers were found; this may be because the presence or absence of a contaminant source has more influence on the *E. coli* concentration than the particle size of bed sediments. Elevated *E. coli* concentrations (50 MPN/g_{DW}) were consistently found in bed sediments underlying the deepest waters; this was especially true of the shipping channel, which may act as a sediment/*E. coli* sink. The results indicate that temperature changes from the powerplant did not cause an increase in *E. coli* concentrations.

Phase 2, Intensive Sampling at Fecal Contaminant "Hot Spots"

On the basis of phase 1 results, phase 2 sampling locations were selected as follows (fig. 4):

- Maumee River sites upstream from phase 1 site M2 (M6 and M7) were added to evaluate potential upstream sources.
- A second site at the mouth of the Maumee River (M2.1) was added to compare a deeper site in the shipping channel to a phase 1 shallow sampling site outside the main channel (M2).
- Two additional shipping-channel sites (O9 and O10) flanking the phase 1 site (O7) were added to further evaluate the shipping channel as an *E. coli* sink.
- An additional site between the shipping channel and MBSP (O11) was added to evaluate transport of *E. coli* from the shipping channel to the bathing beach.
- Additional sites in Berger Ditch (N14) and surrounding the mouth of Berger Ditch (N15, N16, N17, and N18) were added to augment data collected at sites N10 and N11 and evaluate Berger Ditch as a source of *E. coli* to MBSP.

Data collected during the phase 2 recreational season (fig. 4) corroborate the findings during phase 1. During phase 2, the highest average *E. coli* concentrations in water were found at Maumee River sites and in Berger Ditch. For sediments, average *E. coli* concentrations were highest in the Maumee River, shipping channel, and Berger Ditch. The individual mea-

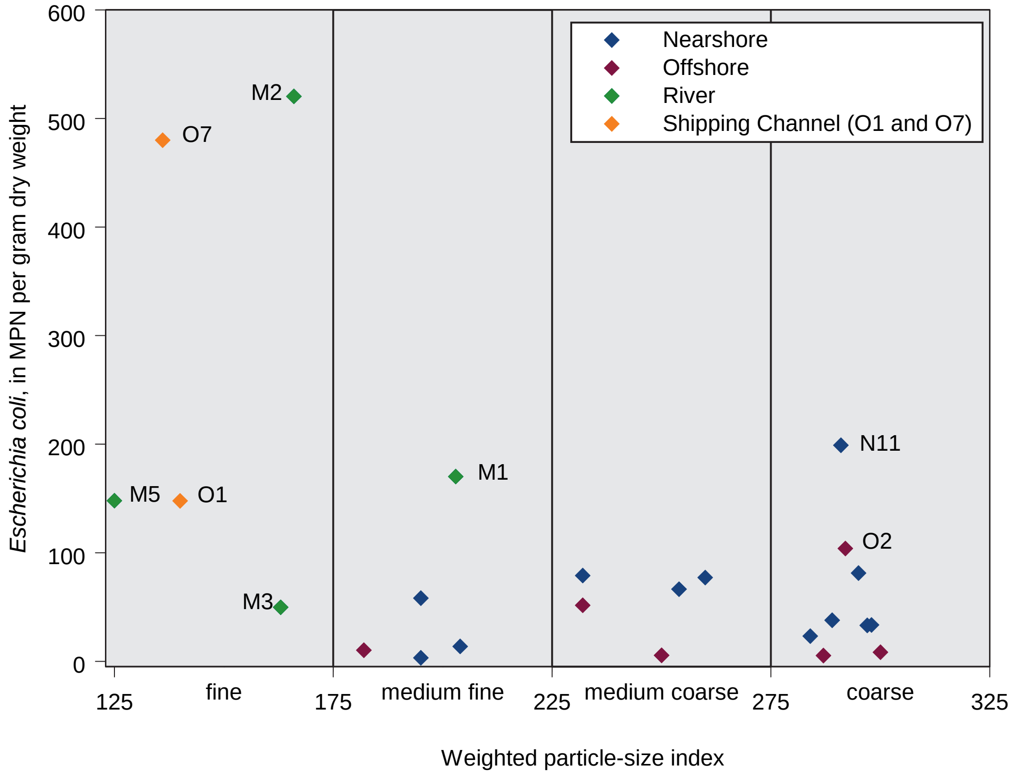


Figure 6. Relation between weighted particle-size index and average *E. coli* concentration at 24 sites, phase 1 (2003). Weighted particle-size index was calculated as (percent clay) + 2 * (percent silt) + 3 * (percent sand).

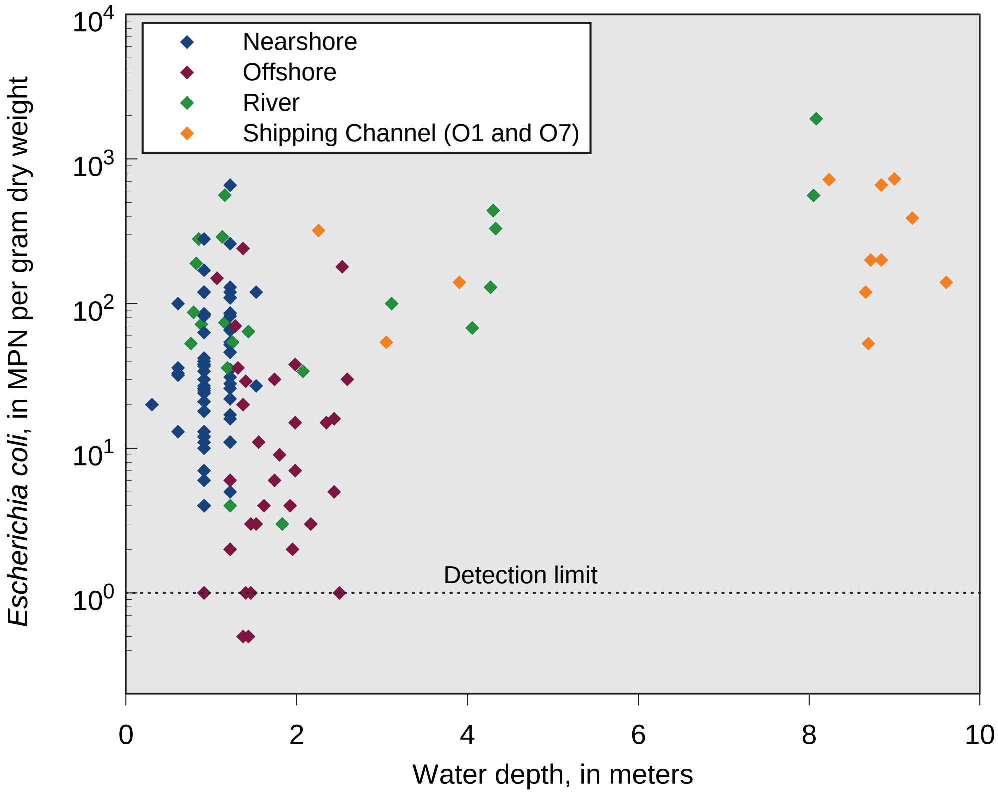


Figure 7. Relation between water depth and concentrations of *E. coli* in bed-sediment samples, phase 1 (2003).

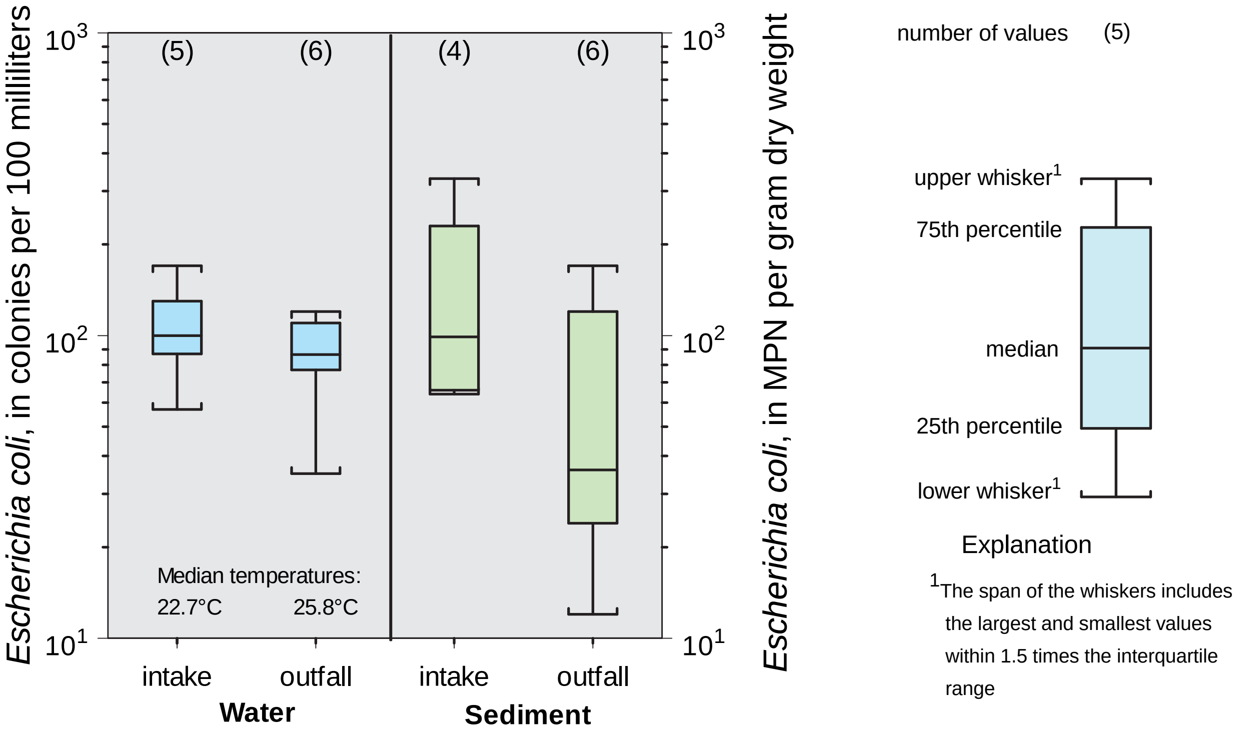


Figure 8. Concentrations of *E. coli* in water and bed sediments and water temperatures in the intake to (M5) and outfall from (N3) the powerplant in synoptic studies, 2003.

surements for each site and associated averages and standard deviations are listed in Appendix 3.

In figure 9a, concentrations of *E. coli* in water are shown for five sampling days at Maumee River sites in downstream order and at increasing distance offshore from the mouth of the river. Results from site M2 are not included on the graph because M2 is outside of the main channel. Except for the synoptic sampling on May 12, *E. coli* concentrations in water increased or remained the same downstream from M7 to M2.1 and decreased further offshore in the shipping channel (O9 to O10). Results are not as definitive in the same type of graph for bed sediments (fig. 9b). *E. coli* concentration peaks were found on some sampling dates at sites M6, M2.1, and O7, and concentrations on four out of five dates were higher at O7 than at the other two shipping-channel sites (O9 and O10). The water data do not indicate a single, large source of *E. coli* in the sampled segment of the Maumee River; rather, the data indicate that sources of *E. coli* may be distributed throughout this segment and in areas upstream from site M7. The bed-sediment data indicate that site O7 is an *E. coli* sink; although stream velocity was not measured, it may decrease in the channel at this point.

In figures 10a and 10b, concentrations of *E. coli* are shown for five sampling days at sites in and around Berger Ditch (fig. 4 inset). Concentrations of *E. coli* were highest in Berger Ditch (N14) and decreased with increasing distance from Berger Ditch. In sediments, *E. coli* concentration peaks were found at site N10 on July 13 and August 16. Site N10 is at MBSP, near an old beach ridge where *E. coli* may become trapped in the bed sediments. Alternatively, an additional source of *E. coli* may be the beach itself. Insights can be gained from the June 15 sampling, when antecedent 24-hour rainfall was 0.38 cm and total rainfall for the previous week was the greatest among all the sampling dates—6.7 cm. In bed sediments, a peak at site N18 on June 15 may have resulted from sources in Berger Ditch or from the shipping channel. Overall, the data indicate that Berger Ditch is a principal source of *E. coli* to Maumee Bay, that offshore sources are less important, and that N10 and N18 may serve as depositional areas for *E. coli* in bed sediments.

Relations of Water-Quality or Environmental Variables to *E. coli* Concentrations at Maumee Bay State Park During Routine Monitoring

Statistical tests were done to evaluate quantitatively the relations between environmental or water-quality variables and *E. coli* concentrations in water at MBSP. These relations can be used in future studies to predict when standards will be

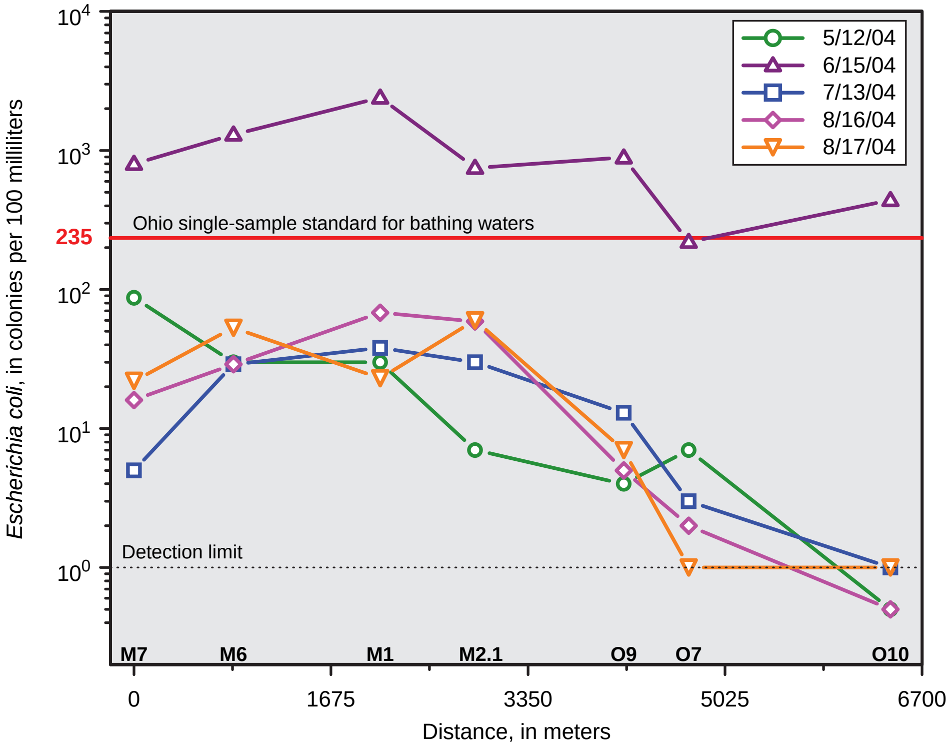


Figure 9*A*. Concentrations of *E. coli* in downstream order at Maumee River sites and increasing distance offshore from the mouth of the Maumee River, phase 2 (2004), in water.

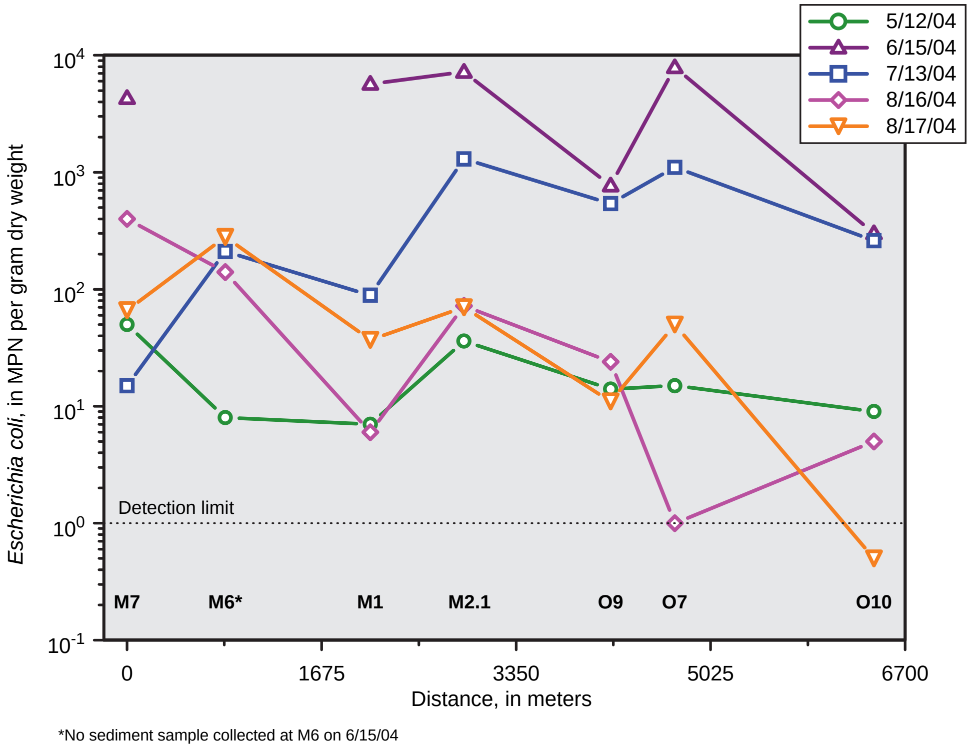


Figure 9*B*. Concentrations of *E. coli* in downstream order at Maumee River sites and increasing distance offshore from the mouth of the Maumee River, phase 2 (2004), in bed sediments.

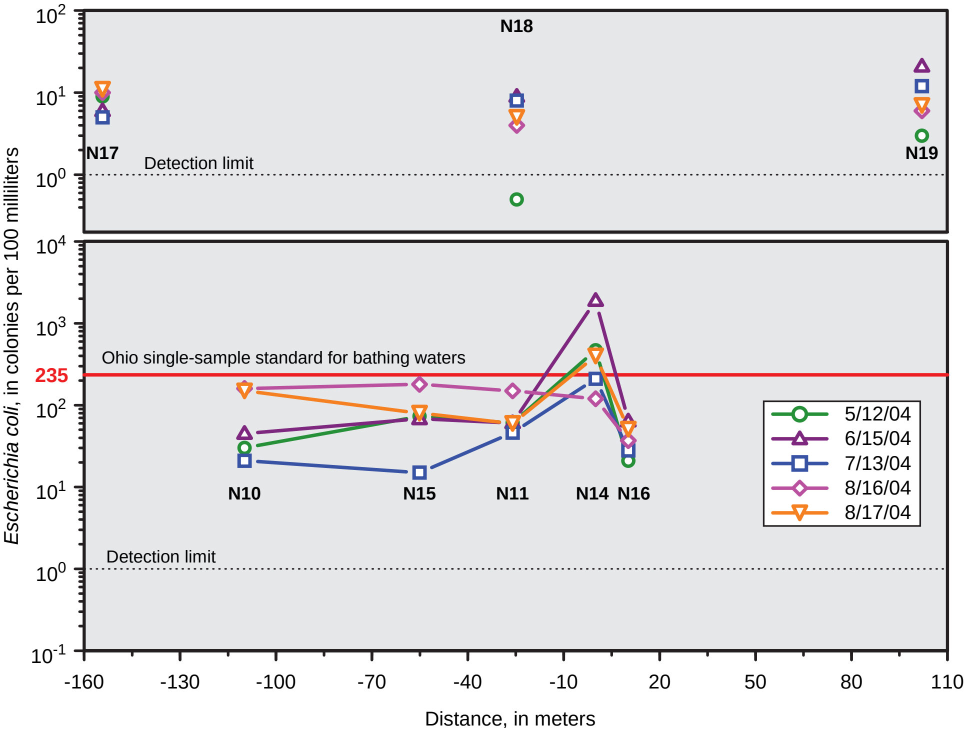


Figure 10*A*. Concentrations of *E. coli* at sites in and around Berger Ditch (N14) and in distance from the mouth of Berger Ditch, phase 2 (2004), in water. (Results from the three northern sites (N17, N18, and N19) are shown separately and are not connected by lines to those from the other sites because they are further offshore.)

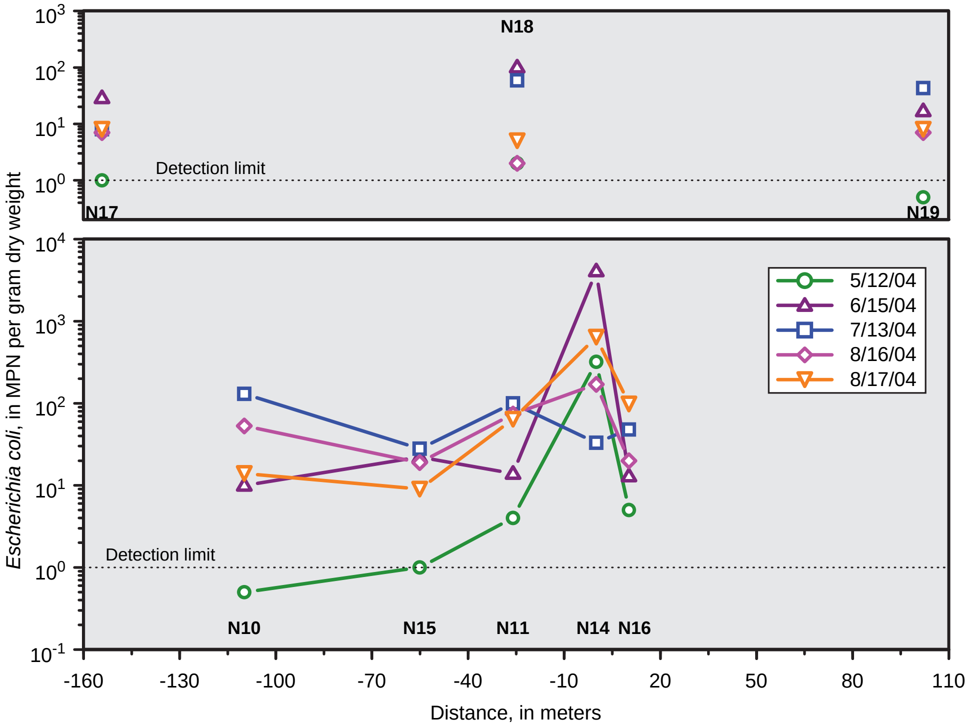


Figure 10*B*. Concentrations of *E. coli* at sites in and around Berger Ditch (N14) and in distance from the mouth of Berger Ditch, phase 2 (2004), in bed sediments. (Results from the three northern sites (N17, N18, and N19) are shown separately and are not connected by lines to those from the other sites because they are further offshore.)

exceeded and the water considered unsafe for recreational use (Francy and others, 2003).

Pearson's *r* correlation coefficients between $\log_{10}$ *E. coli* concentrations and continuous variables for 2003, 2004, and the two years combined are listed in table 1. Several rainfall variables were developed using data from two sources—the City of Oregon ("Rainfall Oregon") and Toledo Metcalf Field ("Rainfall Metcalf"). "Rainfall 24" was the amount of rain that fell in the 24-hour period (10 a.m. to 10 a.m.) preceding the routine sampling. "Rainfall 48" and "Rainfall 72" were the amounts of rain that fell in the 24-hour periods 2 days and 3 days, respectively, before the routine sampling. They were used to determine whether there was a lag between rainfall in the watershed and elevated *E. coli* at MBSP. Among these rainfall variables, only "Rainfall 24" was significantly related to *E. coli*, and the "Rainfall Oregon" data showed a stronger relation than the "Rainfall Metcalf" data. "Date" is based on the chronological day of year and the hypothesis that *E. coli* may accumulate over the course of the recreational season; however, "Date" was not significantly related to *E. coli* at MBSP. "Streamflow 7 a.m." is the instantaneous streamflow of the Maumee River at Waterville at 7 a.m. on the day of sampling; "Streamflow mean" is the mean streamflow at this site for the 24-hour period specified. "Streamflow mean today" was weakly related to *E. coli* in 2003, but not in 2004. Turbidity was statistically related to *E. coli* for all three datasets. Although "bathers yesterday" was related to *E. coli* in 2004, no data were compiled for 2003 to confirm this finding.

The relations between *E. coli* concentrations and two categorical environmental variables—wind direction and wave height—also were examined. *E. coli* concentrations as a function of wind direction at Oregon at the time of sampling are shown in figure 11. During 2003 and 2004, all *E. coli* concentrations at MBSP greater than1,000 MPN/100 mL and 11 out of 15 values in the 235- to 1,000-MPN/100 mL range were associated with wind directions from the north, northeast, or northwest (yellow-shaded areas on fig. 11). (The Ohio single-sample standard for bathing waters is 235). Confirming this qualitative observation, the results of a Wilcoxon rank-sum test (Helsel and Hirsch, 1992, p. 118) showed that *E. coli* concentrations associated with north, northeast, or northwest winds were significantly higher than those associated with winds from all other directions ($p = 0.0049$). Wave heights at MBSP were placed into three categories based on minimum and maximum heights in each wave train: (1) 0 to 0.6 m, (2) 0.3 to 1 m, and (3) 0.6 to 1.2 m (fig. 12). Because data were collected by different field personnel and estimated each year in a different manner in 2003 and 2004, the two years were not

Table 1. Pearson's *r* correlations between log *E. coli* concentrations in water at Maumee Bay State Park and environmental or water-quality factors, 2003 and 2004.

[The p-value is shown in parentheses; correlations significant at $\alpha < 0.05$ are red and bolded; ND, not determined; <, less than]

Factors	2003	2004	Combined
Rainfall Metcalf 24 hr	**0.33 (0.0272)**	0.19 (0.1718)	**0.28 (0.0044)**
Rainfall Oregon 24 hr	**0.36 (0.0158)**	**0.44 (0.0010)**	**0.39 (<0.0001)**
Rainfall Metcalf 48 hr	0.25 (0.1033)	-0.12 (0.3954)	0.08 (0.4032)
Rainfall Oregon 48 hr	0.10 (0.5160)	-0.16 (0.2582)	0.02 (0.8771)
Rainfall Metcalf 72 hr	0.17 (0.2745)	-0.08 (0.5530)	0.04 (0.7150)
Rainfall Oregon 72 hr	0.02 (0.8961)	-0.02 (0.8784)	<0.01 (0.9885)
Date	-0.14 (0.3572)	0.13 (0.3590)	-0.02 (0.8340)
Birds today	0.27 (0.1135)	-0.20 (0.1481)	0.01 (0.8932)
Bathers today	ND	**-0.34 (0.0133)**	ND
Bathers yesterday	ND	**0.35 (0.0318)**	ND
Streamflow at 7 a.m. today	0.28 (0.0577)	0.08 (0.5623)	0.17 (0.0963)
Streamflow (mean) today	**0.30 (0.0444)**	0.08 (0.5497)	0.18 (0.0737)
Streamflow (mean) yesterday	0.20 (0.1858)	0.12 (0.3842)	0.15 (0.1410)
Turbidity	**0.50 (0.0004)**	**0.40 (0.0062)**	**0.48 (<0.0001)**
Water level	**0.50 (0.0004)**	0.26 (0.0607)	0.18 (0.0681)
Water temperature	-0.15 (0.3171)	-0.14 (0.3394)	**-0.21 (0.0432)**

combined. Median *E. coli* concentrations generally increased with increasing wave height. The results of an analysis of variance and Tukey's test (Helsel and Hirsch, 1992, p. 157) confirm that in 2003, the *E. coli* concentrations in the two wave categories were significantly different from each other; in 2004, the two lowest wave-height categories were significantly different from the highest category (fig. 12).

Wind direction may be an influential factor behind the intensity of other variables at MBSP. In our data set, all five rainfall amounts greater than 1.3 cm and all 14 turbidity values greater than 75 NTU were associated with north, northeast, or northwest winds (data not shown). All five wave heights placed in the highest category in 2003 and all six in 2004 were associated with north, northeast, or northwest winds. However, only about one-half of these elevated rainfall amounts, turbidity values, and wave heights were associated with *E. coli* values greater than 235 MPN/100 mL. Further, not all north, northeast, or northwest winds were associated with elevated turbidity, rainfall, wave height, or *E. coli* concentrations. The interrelations between wind direction, turbidity, rainfall, wave height, and *E. coli* concentrations are complicated and can only be better understood through use of multivariate statistical techniques, which was beyond the scope of this study.

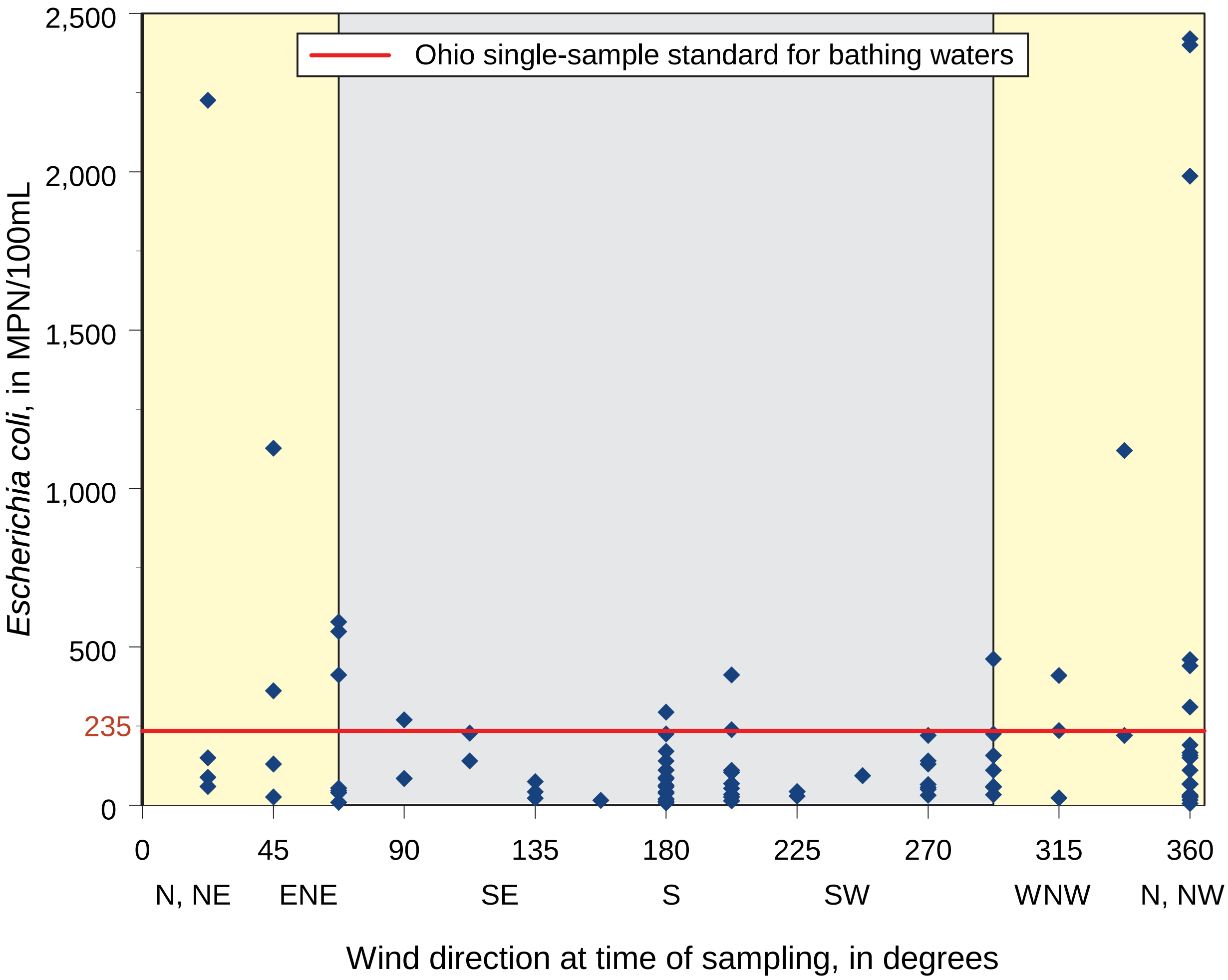


Figure 11. Concentrations of *E. coli* at Maumee Bay State Park as a function of wind direction at the time of sampling, 2003 and 2004. The yellow-shaded areas indicate winds from north, northeast, or northwest.

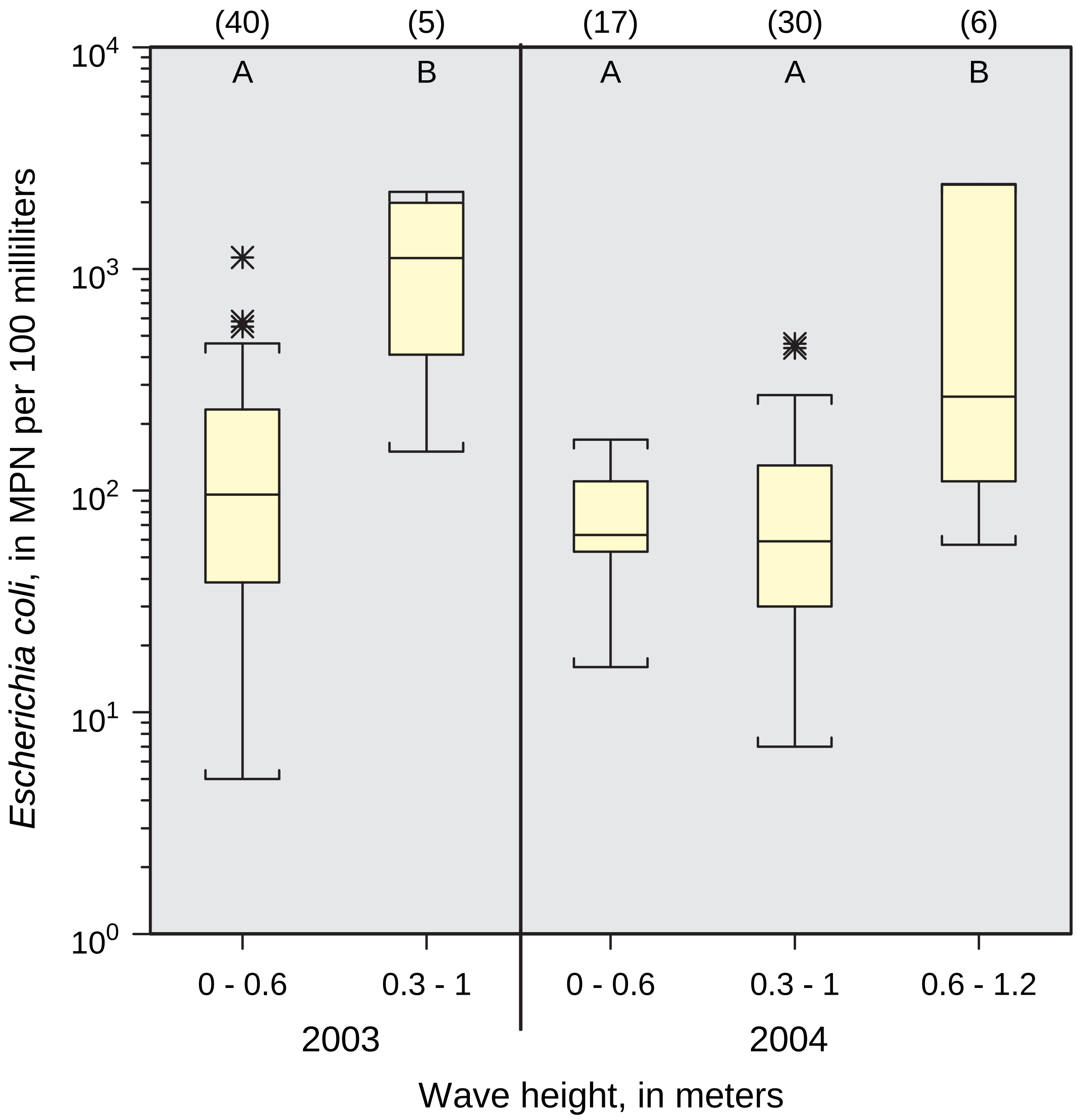


Figure 12. Concentrations of *E. coli* at Maumee Bay State Park based on wave height at the time of sampling, 2003 and 2004. (Results of Tukey-Kramer multiple comparison test on the $\log_{10}$-transformed data are presented as letters, and medians with a letter in common do not differ significantly at $\alpha = 0.05$.) Refer to figure 8 for explanation of boxplots.

Conclusions

The U.S. Geological Survey, in cooperation with the Ohio Water Development Authority, Cities of Oregon and Toledo, University of Toledo, and Toledo Metropolitan Area Council of Governments, examined spatial and environmental factors in combination to identify sources of fecal contamination to Maumee Bay, Ohio.

Identifying the factors that showed a relation to *E. coli* can be used to help identify sources and predict when *E. coli* concentrations are elevated. The strength of the relation between rainfall in the previous 24-hour period and *E. coli*, and not between rainfall 2 or 3 days before and *E. coli*, indicates that fecal contamination is most likely of local origin. This was further supported by results showing that Oregon rainfall amounts (collected from a site 1.5 km inland) were more strongly related to *E. coli* concentrations than the Metcalf rainfall amounts (collected from a site 16 km inland). Turbidity and wave height were related to *E. coli* concentrations. This may be because *E. coli* in bed sediments were resuspended into the water column during times of increased wave heights. Wind direction was a good predictor of *E. coli* concentrations—winds from the north, northeast, or northwest resulted in the highest *E. coli* concentrations. Winds from these directions could cause fecal contamination from local sources such as Berger Ditch to remain in the nearshore shallow areas; in contrast, southerly winds would provide a mechanism for transporting fecal contamination out to the open lake.

The two-phased approach to spatial sampling that was used in this study—identifying hot spots of *E. coli* in water and bed sediments and focusing additional sampling efforts around them—is a useful approach that helps further the understanding of fecal-contaminant sources in a study area. Low *E. coli* concentrations at sites north and west of the shipping channel indicated that remote sources were not important contributors of *E. coli*. Although fecal contamination may originate from multiple sources in and around MBSP, elevated *E. coli* concentrations in Berger Ditch and spatial patterns around the mouth of Berger Ditch indicated that Berger Ditch is a principal source. In addition, *E. coli* may be originating from the beach itself. High levels of *E. coli* were often associated with bed sediments collected from the deepest waters (and with the smallest particle sizes) including the shipping channel, which may act as an *E. coli* sink. Heated effluent from a nearby powerplant did not result in elevated *E. coli* concentrations, as was previously suspected.

The next step would be to develop an understanding of the influence of Berger Ditch on *E. coli* concentrations in Maumee Bay and at MBSP. This could be done by computing *E. coli* loads in Berger Ditch and relating the loads to concentrations of *E. coli* at MBSP. These data could also be used to determine the quantity of water released into Maumee Bay from Berger Ditch, which could then be used by resource managers to implement remediation measures. For example, it has been proposed that a wetland be created near MBSP and that flow from Berger Ditch be diverted into the wetland to naturally treat entrained fecal contaminants.

Although the spatial and environmental data collected during this study do not definitively identify sources of fecal contamination, they do provide sufficient indirect evidence for narrowing the search to proximate sources. This approach can be used as a precursor to more expensive and widely used microbial-source-tracking techniques. A similar spatial, multivariable approach should enable water-resource managers who work in hydrologically complicated areas to target contaminant-source investigations to specific areas, thereby making the best use of available time and resources for diagnosis and remediation of fecal contamination.

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Appendix 1. Locations of sampling sites, Maumee Bay, Ohio, 2003 and 2004.

Site ID	Latitude	Longitude	Description	Sampled 2003	Sampled 2004
			Maumee River		
M1	41°40'59"	83°29'05"	Maumee River upstream of Toledo Wastewater Plant	x	x
M2	41°41'49"	83°28'00"	Maumee River near mouth	x	x
M2.1	41°41'44"	83°27'55"	Maumee River near mouth in shipping channel		x
M3	41°42'01"	83°27'12"	Maumee River near mouth of Otter Creek	x	
M5	41°41'40"	83°26'27"	Maumee River near intake Bay Shore Power Plant	x	
M6	41°39'24"	83°31'12"	Maumee River downstream of marina		x
M7	41°38'12"	83°31'57"	Maumee River upstream of Anthony Wayne Bridge		x
			Nearshore		
N1	41°43'40"	83°27'17"	Maumee Bay near Dry Tree Point	x	
N2	41°43'00"	83°28'12"	Maumee bay near Point Place	x	
N3	41°41'40"	83°26'09"	Maumee Bay near outfall Bay Shore Power Plant	x	
N4	41°41'47"	83°25'56"	Maumee Bay near outfall Oregon Wastewater Plant	x	x
N5	41°41'31"	83°25'57"	Maumee Bay near mouth of Heckman Ditch	x	x
N6	41°41'28"	83°25'12"	Maumee Bay near Bayshore	x	
N7	41°41'27"	83°24'38"	Maumee Bay near mouth of Big Ditch	x	x
N9	41°41'26"	83°23'22"	Maumee Bay near mouth of McHenry Ditch	x	x
N10	41°41'11"	83°22'32"	Maumee Bay at Maumee Bay State Park	x	x
N11	41°41'12"	83°22'20"	Maumee Bay at mouth of Berger Ditch	x	x
N12	41°44'28"	83°27'30"	Ottawa River near mouth	x	
N13	41°42'15"	83°27'46"	Maumee Bay west of Grassy Island	x	
N14	41°41'03"	83°22'16"	Berger Ditch near mouth		x
N15	41°41'11"	83°22'24"	Maumee Bay at breakwall one		x
N16	41°41'12"	83°22'15"	Maumee Bay east of marina at Maumee Bay State Park		x
N17	41°41'18"	83°22'34"	Maumee Bay northwest of Maumee Bay State Park		x
N18	41°41'26"	83°22'20"	Maumee Bay north of Berger Ditch		x
N19	41°41'20"	83°22'03"	Maumee Bay northeast of Berger Ditch		x
			Offshore		
O1	41°42'33"	83°26'11"	Maumee Bay near spoil	x	
O2	41°42'59"	83°26'03"	Maumee Bay near shoal	x	
O3	41°44'43"	83°25'04"	Maumee Bay east of Woodtick Peninsula	x	
O4	41°43'34"	83°23'28"	Maumee Bay near shipping channel	x	
O5	41°43'34"	83°24'01"	Maumee Bay north of Tobias Ditch	x	x
O6	41°41'33"	83°21'09"	Maumee Bay near mouth of Anderson Ditch	x	
O7	41°43'34"	83°24'02"	Maumee Bay at shipping channel	x	x
O8	41°44'21"	83°26'01"	Maumee Bay southwest of Woodtick Peninsula	x	
O9	41°43'06"	83°25'10"	Maumee Bay at shipping channel near mile marker 3		x
O10	41°44'27"	83°22'14"	Maumee Bay at shipping channel near mile marker 8		x
O11	41°42'13"	83°24'40"	Maumee Bay north of Big Ditch		x

Appendix 2. Concentrations of *Escherichia coli (E. coli)* in water and bed sediments, 2003.

[E, esimated value; <, less than; >, greater than]

Site ID	*E. coli* in water, in colonies per 100 milliliters							
	June 24 or 25	**July 29**	**July 30**	**August 14**	**September 7**	**September 11**	**Average**	**Standard deviation**
M1	120	250	130	-	87	220	160	70
M2	64	200	110	130	100	220	140	61
M3	E 85	180	83	-	90	E 57	99	47
M5	57	170	100	-	87	130	110	43
N1	E 4	E 11	E 5	-	E 12	< 1	7	5
N2	E 7	E 14	22	-	73	E 19	27	26
N3	93	120	35	-	110	80	88	33
N4	E 40	200	77	90	82	E 53	90	57
N5	680	97	E 22	23	E 37	E 52	150	260
N6	< 1	64	55	240	65	23	75	85
N7	E 61	70	42	-	62	E 32	53	16
N9	29	49	E 12	-	E 16	21	25	15
N10	E 53	93	22	-	130	E 19	63	48
N11	220	E 14	150	24	42	40	82	84
N12	36	40	E 12	-	29	53	34	15
N13	80	180	220	87	150	240	160	67
O1	33	100	E 51	61	62	68	62	22
O2	E 46	72	67	-	74	58	63	12
O3	< 1	< 1	E 7	-	E 7	E 3	4	3
O4	< 1	E 9	E 5	-	E 13	E 4	6	5
O5	E 7	E 3	E 3	-	E 24	E 3	8	9
O6	45	E 2	E 2	-	E 5	E 3	11	19
O7	E 4	20	E 4	E 13	48	E 5	16	17
O8	< 1	E 2	< 1	-	E 3	E 2	2	1

Site ID	*E. coli*, in most probable number of colonies per gram dry weight of sediment							
	June 24 or 25	**July 29**	**July 30**	**August 14**	**September 7**	**September 11**	**Average**	**Standard deviation**
M1	-	280	190	-	290	87	210	94
M2	-	74	65	3	560	1900	520	800
M3	34	72	53	-	36	54	50	16
M5	-	130	68	-	330	64	150	120
N1	4	13	84	-	37	27	33	31
N2	2	7	38	-	17	5	14	15
N3	46	24	12	-	170	26	56	65
N4	27	110	66	54	86	120	77	35
N5	18	34	25	13	32	20	24	8
N6	28	280	63	18	52	46	81	99
N7	4	82	42	-	13	26	33	31
N9	86	40	35	-	30	100	58	32
N10	1	6	4	-	4	4	4	2
N11	11	110	120	660	260	33	200	240
N12	11	16	22	-	130	10	38	52
N13	31	85	120	36	82	120	79	39
O1	200	53	120	54	320	140	150	100
O2	30	240	150	-	70	29	100	91
O3	1	9	6	-	11	4	6	4
O4	7	15	3	-	15	2	8	6
O5	6	30	180	-	4	38	52	73
O6	3	< 1	1	-	36	20	12	16
O7	> 660	140	720	200	730	390	470	270
O8	16	2	6	-	3	1	6	6

Appendix 3. Concentrations of *Escherichia coli (E. coli)* in water and bed sediments, 2004.

[E, estimated value; <, less than; >, greater than]

Site ID	*E. coli* in water, in colonies per 100 milliliters						
	May 12	**June 15**	**July 13**	**August 16**	**August 17**	**Average**	**Standard deviation**
M1	E 30	2400	38	68	23	510	1000
M2	E 25	730	E 26	45	120	190	300
M2.1	E 7	750	E 30	59	60	180	320
M6	E 30	1300	29	29	53	290	570
M7	87	800	E 5	E 16	22	190	340
N4	E 32	440	30	120	38	130	180
N5	E 19	200	6	E 14	E 18	51	83
N7	E 12	220	E 5	23	E 13	55	93
N9	E 40	E 15	20	25	E 8	22	12
N10	E 30	45	E 21	160	150	81	68
N11	E 61	61	46	150	60	76	42
N14	470	1900	E 210	120	400	620	730
N15	73	68	E 15	180	80	83	60
N16	E 21	64	28	37	51	40	17
N17	E 9	E 6	E 5	E 10	E 11	8	3
N18	< 3	E 9	E 8	E 4	E 5	6	3
N19	E 3	21	E 12	E 6	E 7	10	7
O5	< 1	45	< 1	< 1	E 1	10	20
O7	E 7	E 220	E 3	E 2	E 1	47	97
O9	E 4	E 890	E 13	E 5	E 7	180	400
O10	< 1	E 440	E 1	< 1	E 1	89	200
O11	E 5	28	E 8	67	43	30	26

Site ID	*E. coli,* in most probable number of colonies per gram dry weight of sediment						
	May 12	**June 15**	**July 13**	**August 16**	**August 17**	**Average**	**Standard deviation**
M1	7	5700	88	6	37	1200	2500
M2	13	1200	94	8	130	290	510
M2.1	36	> 7200	1300	72	70	1700	3100
M6	8		210	140	280	160	120
M7	50	4300	15	400	66	970	1900
N4	53	240	26	66	> 350	150	140
N5	2	42	28	15	17	21	15
N7	1	35	11	23	16	17	13
N9	4	25	34	12	270	69	110
N10	< 1	10	130	53	14	42	53
N11	4	14	100	74	64	51	41
N14	320	> 4100	32	170	640	1000	1700
N15	1	22	28	19	9	16	11
N16	5	12	48	20	98	37	38
N17	1	29	8	7	8	11	11
N18	2	100	59	2	5	34	44
N19	< 1	17	43	7	8	15	16
O5	< 1	91	21	4	1	24	38
O7	15	> 7900	1100	1	50	1800	3400
O9	14	> 770	540	24	11	270	360
O10	9	300	260	5	< 1	120	150
O11	2	13	19	64	13	22	24