In cooperation with Ohio Water Development Authority, Ohio Lake Erie Office, Northeast Ohio Regional Sewer District, and Cuyahoga County Board of Health

Models for Predicting Recreational Water Quality at Lake Erie Beaches

Scientific Investigations Report 2006-5192

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

COVER PHOTOGRAPH: Edgewater Park, Main Beach, looking east to downtown Cleveland, Ohio. (Photo by Ken Frame, U.S. Geological Survey.)

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Suggested citation:
Francy, D.S., Darner, R.A. and Bertke, E.E., 2006, Models for predicting recreational water quality at Lake Erie beaches: U.S. Geological Survey Scientific Investigations Report 2006-5192, 13 p.

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Conversion Factors and Abbreviations

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
milliliter (mL)	0.06102	cubic inch (in^3)

Bacteria concentrations are given as either Colony Forming Units per 100 milliliters (CFU/100 mL) or colonies per 100 milliliters (col/100 mL).

Models for Predicting Recreational Water Quality at Lake Erie Beaches

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Abstract

Data collected from four Lake Erie beaches during the recreational seasons of 2004–05 and from one Lake Erie beach during 2000–2005 were used to develop predictive models for recreational water quality by means of multiple linear regression. The best model for each beach was based on a unique combination of environmental and water-quality explanatory variables including turbidity, rainfall, wave height, water temperature, day of the year, wind direction, and lake level. Two types of outputs were produced from the models—the predicted *Escherichia coli* concentration and the probability that the bathing-water standard will be exceeded. The model for one of beaches, Huntington Reservation (Huntington), was validated in 2005. For 2005, the Huntington model yielded more correct responses and better predicted exceedance of the standard than did current methods for assessing recreational water quality, which are based on the previous day's *E. coli* concentration. Predictions based on the Huntington model have been available to the public through an Internet-based "nowcasting" system since May 30, 2006. The other beach models are being validated for the first time in 2006. The methods used in this study to develop and test predictive models can be applied at other similar coastal beaches.

Introduction

Swim advisories or closings issued by beach managers in the United States are based on standards for concentrations of fecal-indicator bacteria, such as *Escherichia coli* (*E. coli)* or enterococci. Concentrations may change between the time of sampling and the reporting of results (18–24 hours). For example, in Ohio, the current practice is to use results from the previous day's *E. coli* to assess whether to post a recreational water-quality advisory (Ohio Department of Health, 2005). This time lag can lead to beach advisories and closures that cause unwarranted loss of valuable recreation access or to permit swimming when conditions present an unacceptable level of risk. Recognizing this problem and other inadequacies in beach monitoring, the U.S. Environmental Protection Agency (USEPA) initiated the Beaches Environmental Assessment, Closure, and Health (BEACH) Program to reduce the health risks for users of U.S. recreational waters (U.S. Environmental Protection Agency, 1999a).

One goal of the USEPA BEACH Program is development of mathematical models for real-time forecasting. Real-time forecasting may help resolve the delayed notification problems inherent with the present approach to recreational monitoring. In cases where fecal contamination to a beach is point-source dominated, hydrodynamic mixing and transport models can be applied (U.S. Environmental Protection Agency, 1999b). At many Ohio beaches and elsewhere, however, nonpoint or unidentified sources dominate, and multiple linear regression (MLR) models may be more appropriate. MLR models typically make use of easily measured environmental and water-quality variables to estimate bacterial indicator concentrations or the probability of exceeding target concentrations.

Models based on environmental and water-quality variables have been shown to be useful predictors of recreational water quality. They include advisory systems based on rainfall amounts (Ackerman and Weisberg, 2003; Hose and others, 2005) or more complicated models that employ real-time sensors to measure several explanatory variables (Olyphant and others, 2003; Whitman, 2005; Olyphant and Pfister, 2005). Beach-specific models were previously developed for Ohio Lake Erie beaches using MLR techniques and 1 or 2 years of data (Francy and Darner, 2002; Francy and others, 2003). The explanatory variables included wave height, number of birds on the beach, lake-current direction, rainfall, turbidity, and wind direction and speed.

The U.S. Geological Survey (USGS), in cooperation with Ohio Water Development Authority, Ohio Lake Erie Office, Northeast Ohio Regional Sewer District, and Cuyahoga County Board of Health, developed and tested MLR predictive models during a 2-year study. Data were collected to identify and compare the explanatory variables that best described *E. coli* concentrations at five Ohio Lake Erie beaches. This study was also done to compare the performance of predictive models to the current method for assessing recreational water quality and determine whether model results were good enough to be used for future public notifications. At Huntington Reservation, because of 6 years of data collection, investigations were further along than at other beaches, so this model was assessed during an independent (validation) year. The best model for each beach was based on a unique combination of explanatory variables including wave height, antecedent rainfall, turbidity, lake level, water temperature, wind direction, and day of the year. Although the models performed better than the current method to assess recreational water quality, work is ongoing to improve their accuracies.

Methods

Studies were done at five popular Ohio Lake Erie beaches (fig. 1). At the beaches studied, breakwaters and (or) groins restrict water circulation, and large populations of waterfowl frequent the swimming areas. At Lakeview, in Lorain, Ohio, the sources of fecal contamination are largely unknown, but bird excrement may be a major cause of the degradation of water quality. At Huntington Reservation (Huntington), in Bay Village, a western suburb of Cleveland, two outfalls discharge stormwater runoff from a parking lot into the lake, and a creek to the east of Huntington drains a heavily populated area. Potential sources of *E. coli* to Edgewater and Villa Angela, two urban beaches in Cleveland, are stormwater runoff and combined-sewer overflows. At Lakeshore, in the small city of Ashtabula, sources of fecal contamination may include septic-system and wastewater effluents and runoff from gravel parking lots.

Data Collection

Data collection included analysis of daily water samples for *E. coli* and measurement of explanatory variables for model development and testing. Data were collected during the recreational seasons (May through September) of 2004–2005. At Huntington, data from past studies (2000–2003) also were included. At Edgewater and Villa Angela, samples were collected Monday through Friday; sampling at the other three beaches was done Monday through Thursday. Samples were collected between 8 and 11 a.m. in areas of the beach used for swimming where the water was 2 to 3 ft deep. All water-sample bottles were filled about 1 ft below the water surface using a grab-sampling technique (Myers and Wilde, 2003). Because of spatial variability of *E. coli* concentrations, samples were collected at two or three well-spaced sampling points at each beach.

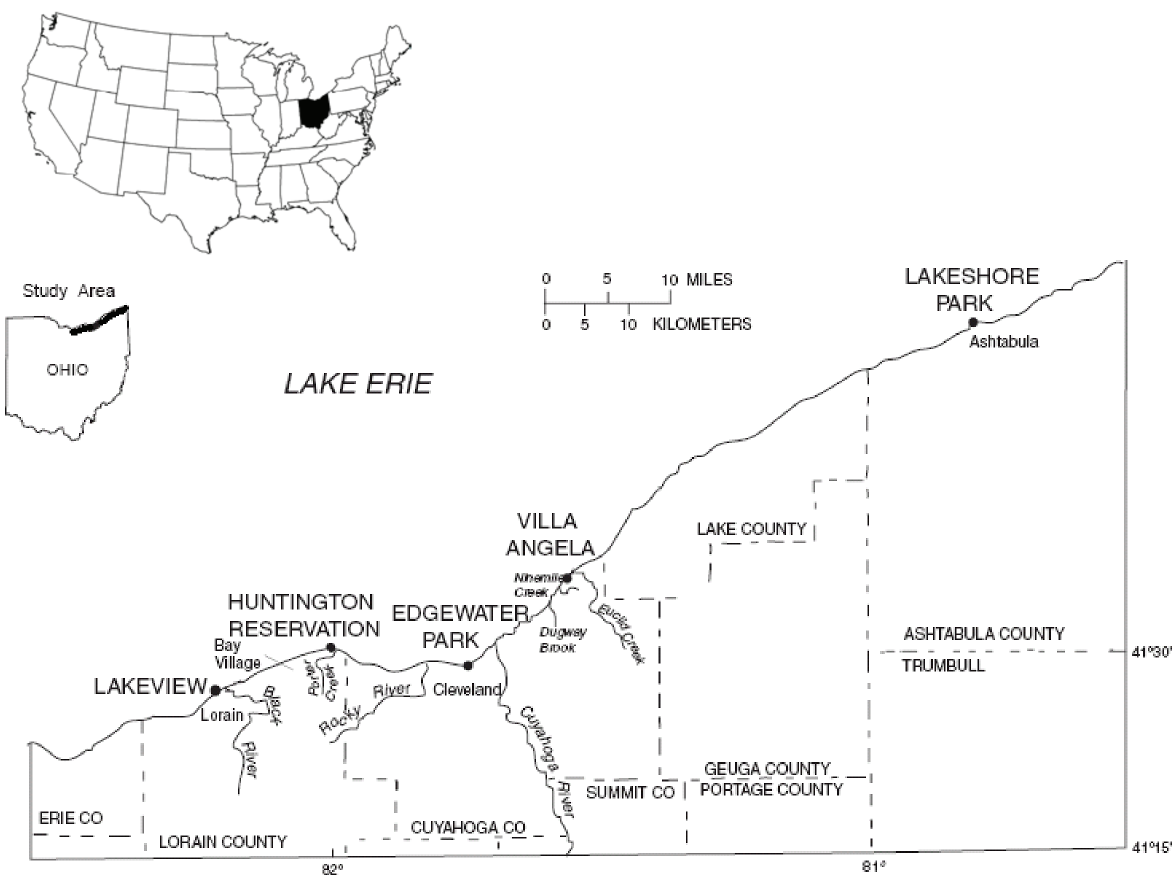


Figure 1. Locations of the five Lake Erie beaches used for studies of predictive modeling.

Water samples were kept on ice until analyzed for concentrations of *E. coli* and turbidity locally by each agency within 6 hours of collection. Samples from Huntington were analyzed by use of the mTEC method (U.S. Environmental Protection Agency, 2000); samples from the other beaches were analyzed by use of the modified mTEC membrane-filtration method (U.S. Environmental Protection Agency, 2002). Turbidity was determined in water samples with laboratory turbidimeters.

Data on explanatory variables were collected by field crews or compiled from a variety of sources. Upon arrival, field crews counted the number of birds on the beach, and they estimated wave-height categories at the time of sample collection. Wave heights were placed into categories based on minimum and maximum heights in each wave train: (1) 0 to 2 ft, (2) 1 to 3 ft, (3) 2 to 4 ft, and (4) 3 to 6 ft or greater. If there were only a few observations in category 4, categories 3 and 4 were combined. Lake-level data were obtained from National Oceanic and Atmospheric Administration (NOAA) station in Fairport Harbor, Ohio, for Lakeshore (NOAA ID 9063053) and the station in Cleveland for the other four beaches (NOAA ID 9063053) (National Oceanic and Atmospheric Administration, 2005a).

Rainfall and wind-direction data were compiled from the National Weather Service local climatology data stations at Hopkins International Airport for Huntington, Villa Angela, and Edgewater; from Lorain County Regional Airport for Lakeview; and from Ashtabula County Airport for Lakeshore (National Oceanic and Atmospheric Administration, 2005b). "R_{d-1}" was the amount of rain, in inches, that fell in the 24-hour period (9 a.m. to 9 a.m.) preceding the morning sampling. Similarly, "R_{d-2}" and "R_{d-3}" were amounts of rain that fell in 24-hour periods 2 days and 3 days preceding the morning sampling, respectively. Additional rainfall variables were computed as follows:

Rainfall weighted 72 hours (Rw72) = $(3^* R_{d-1} + 2^* R_{d-2} + R_{d-3})$

Rainfall weighted 48 hours (Rw48) = $(2^* R_{d-1} + R_{d-2})$

"Wind direction 24" was calculated by summing hourly wind vectors for the 24-hour period preceding sampling and determining the direction of the resultant vector. Wind directions were then placed into categories by examining patterns in plots of *E. coli* concentrations as a function of wind direction 24; processes affecting *E. coli* were also considered to ensure that the wind direction 24 categories could reasonably be explained by physical processes.

Quality Assurance and Quality Control

Because models are only as good as the data used to develop them, strict quality-assurance and quality-control (QA/QC) practices were implemented. Written protocols were distributed to all personnel. The USGS did several onsite QA/QC checks of procedures performed by field and laboratory personnel throughout the recreational season, and any needed corrective actions were immediately taken. Approximately 10 percent of *E. coli* samples were QC samples including split replicates, interagency replicates, field blanks, and positive control reference cultures, described elsewhere (Francy and others, 2005). For turbidity, duplicate aliquots were measured from the same bottle, and measurements that did not agree within 10 percent were repeated. Turbidity reference standards were sent to all laboratories. Results from QC samples were carefully monitored; retests were done and corrective measures were taken when needed.

Data Analysis and Development and Testing of Predictive Models

A daily *E. coli* concentration was calculated by averaging results from multiple sampling points at each beach. Averages were used instead of medians so as not to downweight the influence of extreme measurements. Bacterial concentrations were $\log_{10}$ transformed before data analysis. Because, in previous studies (Francy and others, 2003), relations were shown to differ from year to year at the same beach, at least 2 years of data from each beach were examined and used for model development.

Statistical tests were done and plots were constructed to determine the strength of associations between *E. coli* and explanatory variables measured during the study. These included calculations of correlation coefficients and construction of scatterplots for continuous variables. Box plots were used to understand the distribution of *E. coli* concentrations as a function of categorical variables, such as wave height and wind direction. Analysis of variance (ANOVA) was used to determine the relations between categorical variables and *E. coli* concentrations. The Tukey-Kramer multiple comparison test was used to determine which groups differed from each other (Helsel and Hirsch, 2002, p. 198).

Explanatory variables that showed significant relations to *E. coli* concentrations were used to produce a list of possible MLR models using the Mallows Cp test (Mallows, 1973). The MLR models were ordered so that the coefficient of determination (R^2) was maximized and the Mallows' Cp statistic was minimized. The R^2 of each model is the fraction of the variation in *E. coli* concentrations that can be explained by a combination of explanatory variables. The Cp statistic is a measure of the error in a model with a subset of explanatory variables, relative to the error in a model that incorporates all potential explanatory variables. Models with explanatory variables strongly related to each other (collinear), such as those with multiple rainfall variables, were omitted from the list. Models were then selected for further examination on the basis of the Mallows' Cp ranking. Model statistics were examined and diagnostic tests were done to identify the model(s) for each beach that provided the best linear, unbiased estimator of *E. coli* concentrations (Helsel and Hirsch, 2002, p. 228). These included determination of parameter estimates, Cook's

D values, partial residual plots, and residuals plots. Performing well on model diagnostic tests and having a set of explanatory variables that seemed reasonable and were relatively easy to collect were the criteria for choosing the “best” model for each beach.

Two types of output were produced by the models. The first and obvious output was the predicted *E. coli* concentration. Because prediction intervals were shown to be fairly wide in earlier studies (Francy and Darner, 1998; Francy and others, 2003), a second output variable was developed in the hope of providing a more accurate prediction—the probability of exceeding the Ohio single-sample bathing water standard for *E. coli* of 235 colony-forming units per 100 milliliters (CFU/100 mL). The probability that the predicted value with *n-p* degrees of freedom was greater than 235 CFU/100 mL was computed as prob ($t>x$), where $x = (\log_{10}(235) - \hat{y}) / sep$, t is student’s t, $\hat{y}$ is the regression estimate of the $\log_{10}$ *E. coli*, *sep* is the standard error of prediction of y, n is the number of observations used in the regression, and p is the number of regression coefficients estimated in the regression equation.

For each selected model, a threshold probability associated with too great a risk to allow swimming was determined retrospectively. Threshold probabilities were determined by taking the dataset used to develop the model and finding the probability that provided a reasonable balance between achieving a high number of correct responses and a low number of false negative responses.

Model specificities and sensitivities for the threshold probability technique and predicted *E. coli* concentrations were reported and compared to specificities and sensitivities associated with the current method used to assess recreational water quality. The sensitivity is the proportion of actual exceedances (concentrations > 235 CFU/100 mL) that were predicted correctly. The specificity is the proportion of nonexceedances that were predicted correctly.

For model validation, data were collected during an independent year (a year whose data were not used for model development) to compare the model’s performance with the current method for assessing recreational water-quality. The model developed with data collected in 2000–2004 at Huntington was validated with data collected in 2005. After validation tests, new parameter estimates were determined based on data collected at Huntington from 2000–2005. At the other beaches, model validation will be done in 2006 for data collected during 2004–05.

Relations Between *Escherichia coli* Concentrations and Environmental or Water-Quality Variables

Annual summary statistics for *E. coli* concentrations at the five Lake Erie beaches are listed in table 1. Annual median concentrations of *E. coli* were highest at Lakeview and Lakeshore, ranging from 130 to 380 CFU/100 mL. The percentage of days that the bathing-water standard was exceeded ranged from 8.1 percent at Edgewater in 2004 to 61.2 percent at Lakeview in 2005.

For Huntington, correlations between *E. coli* concentrations and potential explanatory variables were determined for data collected during 2000–2004 (table 2, left side of the solid line). R_{d-1}, turbidity, and $\log_{10}$ turbidity were positively and significantly related to *E. coli* for 2000–2004 combined and for each of the 5 years examined separately (data not shown). Number of birds, day of the year, R_{d-3}, water temperature, and lake level were weakly or not significantly related to concentrations of *E. coli*. Because both R_{d-1} and R_{d-2} (daily rainfall variables) were significantly related to *E. coli*, Rw48 was included as an additional variable. Rw48 was more highly correlated with *E. coli* than the single-day rainfall variables.

For Edgewater, Villa Angela, Lakeshore, and Lakeview, correlations between *E. coli* concentrations and potential explanatory variables were determined for data collected during 2004–2005 (table 2). R_{d-1}, Rw48, and $\log_{10}$ turbidity were positively and significantly related to *E. coli* at all beaches. The strongest relations between number of birds or day of the year and *E. coli* were found at Lakeview. At Edgewater, Villa Angela, and Lakeshore, but not at Lakeview, weighted rainfall variables (Rw48 or Rw72) were more highly correlated with *E. coli* than single-day rainfall variables. Water temperature was a significant variable for all beaches except Edgewater. Lake level was negatively and significantly related to *E. coli* at all beaches except Lakeshore.

The relations between categorical explanatory variables and *E. coli* were examined graphically and statistically. At all beaches, median *E. coli* concentrations increased with increasing wave height, and statistically significant differences were found among most of the wave-height categories. For example, at Villa Angela, statistically significant differences in *E. coli* concentrations were found between wave-height category 0 to 2 ft and other categories (fig. 2). Wind direction was found to be significantly related to *E. coli* concentrations at Lakeview and Villa Angela, but not at Huntington, Lakeshore, or Edgewater. At Villa Angela, southwesterly winds (173–254°) were associated with significantly higher *E. coli* concentrations than other wind directions (fig. 2). Because no physical factors seemed to explain this phenomenon, wind direction 24 was not used in model development at Villa Angela. At Lakeview, southerly winds (91–270°) were associated with the highest *E. coli* concentrations (data not shown). Southerly winds tend to calm the beach waters and may lead to more birds in the area.

Table 1. Summary statistics of *Escherichia coli (E. coli)* concentrations at five Lake Erie beaches, 2000–2005.

[CFU/100 mL is colony-forming units per 100 milliliters]

Beach	Number of samples	Daily *E. coli* concentrations[a], in CFU/100 mL			Number (percent) of days bathing-water standard[b] was exceeded
		Median	Minimum	Maximum	
Edgewater					
2004	99	51	5	890	8 (8.1)
2005	93	58	2	1,900	16 (17.2)
Villa Angela					
2004	99	49	1	6,900	19 (19.2)
2005	89	110	2	4,200	32 (36.0)
Huntington					
2000	51	110	8	6,600	12 (23.5)
2001	50	44	3	1,200	10 (20.0)
2002	52	43	4	1,800	11 (21.2)
2003	54	58	2	730	6 (11.1)
2004	54	31	3	1,500	7 (13.0)
2005	58	34	1	2,400	8 (13.8)
Lakeview					
2004	46	280	54	4,200	27 (58.7)
2005	49	380	11	3,500	30 (61.2)
Lakeshore					
2004	44	130	18	14,000	16 (36.4)
2005	45	240	9	5,200	23 (51.1)

[a] The daily concentrations of *E. coli* were determined by calculating the average of two or three point samples.

[b] Days the concentration of *E. coli* exceeded the single-sample maximum bathing-water standard of 235 CFU/100 mL.

Table 2. Pearson's r correlations between $\log_{10}$ *Escherichia coli (E. coli)* concentrations and explanatory variables at five Lake Erie beaches, 2000–2005.

[Relations that were significant at $p < 0.05$ are in italics and bold]

Variable	Huntington 2000-2004	Edgewater 2004-2005	Villa Angela 2004-2005	Lakeshore 2004-2005	Lakeview 2004-2005	Huntington 2000-2005
Birds, number at time of sampling	-0.10	***0.15***	***0.21***	-0.18	***0.33***	0.03
Day of the year	0.09	***0.15***	-0.13	***0.26***	***0.43***	***0.15***
R_{d-1} [a]	***0.34***	***0.30***	***0.36***	***0.35***	***0.29***	***0.36***
R_{d-2} [a]	***0.20***	***0.22***	0.09	0.20	-0.02	***0.22***
R_{d-3} [a]	0.08	0.10	0.09	***0.31***	-0.04	0.08
Rw_{48} [b]	***0.37***	***0.37***	***0.37***	***0.40***	***0.24***	***0.40***
Rw_{72} [b]	--	***0.38***	--	***0.46***	--	--
Turbidity	***0.51***	***0.40***	***0.38***	***0.37***	0.18	***0.48***
$\log_{10}$ turbidity	***0.54***	***0.44***	***0.31***	***0.52***	***0.31***	***0.51***
Water temperature	***0.13***	0.09	***0.34***	***0.36***	***0.49***	< 0.01
Lake level	-0.11	***-0.25***	***-0.16***	-0.12	***-0.30***	***-0.16***

[a]R_{d-1} was the rainfall amount, in inches, in the 24-hour period preceding sampling; R_{d-2} and R_{d-3} were the rainfall amounts 2 and 3 days, respectively, before sampling.

[b]Rw_{48} and Rw_{72} were the rainfall amounts, in inches, in the 48- and 72-hour periods, respectively, before sampling, with the most recent rainfall receiving the most weight.

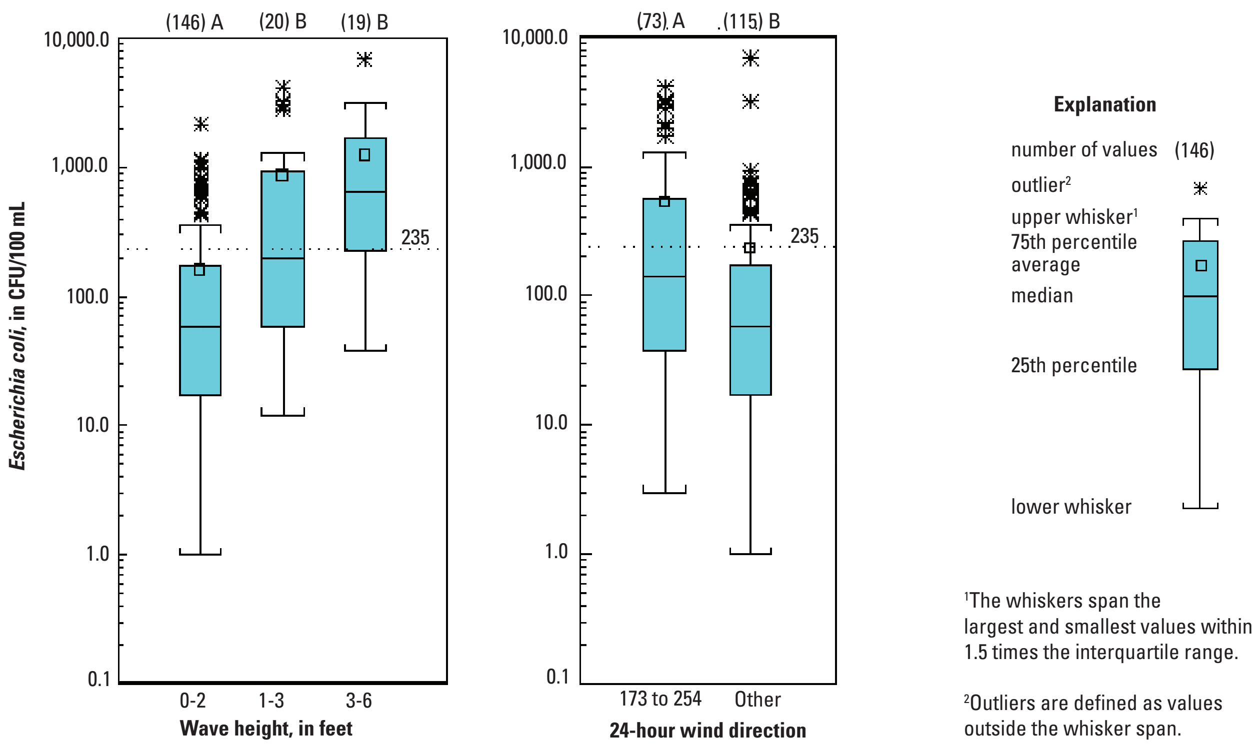


Figure 2. *Escherichia coli* concentrations in water by wave height and 24-hour wind direction, Villa Angela, 2004–2005. Results of Tukey's test are presented as letters; concentrations with at least one letter in common do not differ significantly. The Ohio single-sample maximum bathing-water standard of 235 colony-forming units per 100 milliliters (CFU/100 mL) is indicated by dotted lines and used as a benchmark.)

Development and Validation of Beach-Specific Predictive Models

A list of possible models was produced for each beach, along with their Mallow's Cp statistic and R^2 values. From the list, one best model for each beach was selected; R^2 values ranged from 0.35 for Lakeshore to 0.44 for Lakeview (table 3, above the solid line). All of the best beach models incorporated $\log_{10}$ turbidity as an explanatory variable, and four out of five models incorporated a rainfall variable. Lake level was used only at Edgewater, and wind direction and day of the year only at Lakeview. Wave height and water temperature were used in three and two beach models, respectively.

Determination of Model Output Values

The MLR models were used to predict output values for the data used to develop the models. For the output as predicted *E. coli*, no further calculations were needed because the threshold is, by default, set at 235 CFU/100 mL. The output as the probability requires determination of a threshold probability—the lowest (most conservative) probability that produces the most correct responses and (or) fewest false negative responses (Francy and others, 2003). This concept can be best explained by examining the plot for the Huntington 2000–2004 best model with a 29 percent threshold (fig. 3) and then explaining the process used to determine the 29 percent threshold. The plot is divided into four quadrants by a vertical line through 2.37 ($\log_{10}$ of 235 CFU/100 mL) on the x-axis and a horizontal line through the threshold probability of 29. By raising or lowering the horizontal probability line, one can determine the best threshold probability. This determination is somewhat subjective. For example, a threshold of 50 would have produced the highest number of correct responses (215) but would also have produced a high number of false negatives (28). Thresholds between 35 and 45 do little to reduce the number of false negatives. Selecting a threshold of 29, however, still maintains a high number of correct responses (210) but reduces the false negatives to a more acceptable level (18) and represents a compromise between false negative and false positive responses. In addition, setting the threshold to a lower value such as 29 enables the beach manager to err on the safe side. Thresholds, determined for the other beaches in this manner, ranged from 29 to 38 percent (table 4, above the solid line).

The responses from models that predict *E. coli* concentrations and threshold probabilities were compared to use of the previous day's *E. coli* (table 4). For all beaches, the percentages of correct predictions were higher using the model than using the previous day's *E. coli*. For Huntington 2000–2004 and Edgewater, model specificities using threshold probabilities were relatively high (90.2 and 94.9 percent), but model sensitivities (59.1 and 59.3 percent) were the lowest among the threshold probability responses for all beaches. The specificities may be high at Huntington and Edgewater because the *E. coli* concentration did not exceed the standard for most of the days sampled (table 1). In contrast, at Lakeview and Lakeshore, model specificities using the threshold probability were less than those found using the current method and were relatively low (52.6 and 68 percent), but model sensitivities using the threshold probability were high (92.9 and 92.3 percent). The sensitivities may be high at Lakeview and Lakeshore because the standard was frequently exceeded in the datasets used to develop the models (table 1). In comparing the two model output values, use of predicted *E. coli* concentrations resulted in higher specificities, and use of threshold probabilities resulted in higher sensitivities. In fact, at all beaches, sensitivities were substantially higher using the threshold probability than using the predicted *E. coli* or the previous day's *E. coli*.

Model Validation

Models perform fairly well when predicting responses to data used for their development. A better test of a model is to predict responses for an independent period. The 2000–2004 Huntington model was tested in 2005, and model responses were compared to use of the previous day's *E. coli* (table 5). The percentages of correct predictions and specificities using either model output were in the same range as those found using the previous day's *E. coli*. However, use of the previous day's *E. coli* provided fewer predictions (41) than the model (50) because no samples were collected on Sundays. The difference between the model responses and the current method responses is most pronounced when examining the sensitivities. Using both output values from the model, four out of eight exceedances (50 percent sensitivity) during 2005 were correctly predicted. Using the previous day's *E. coli*, none of the exceedances was predicted, resulting in a sensitivity of zero.

The data collected at Huntington during 2005 were added to the 2000–2004 dataset, and a new model was developed. Correlation coefficients that describe the relations between explanatory variables and *E. coli* for Huntington 2000–2005 are listed in table 2 (right side of solid line). As in 2000–2004, the relations between *E. coli* and R_{d-1}, R_{d-2}, Rw48, turbidity, and $\log_{10}$ turbidity were significant for the 2000–2005 dataset. With the additional year, day of the year and lake level were significantly related to *E. coli* for 2000–2005 and were therefore added as possible explanatory variables during the 2000–2005 model-development process.

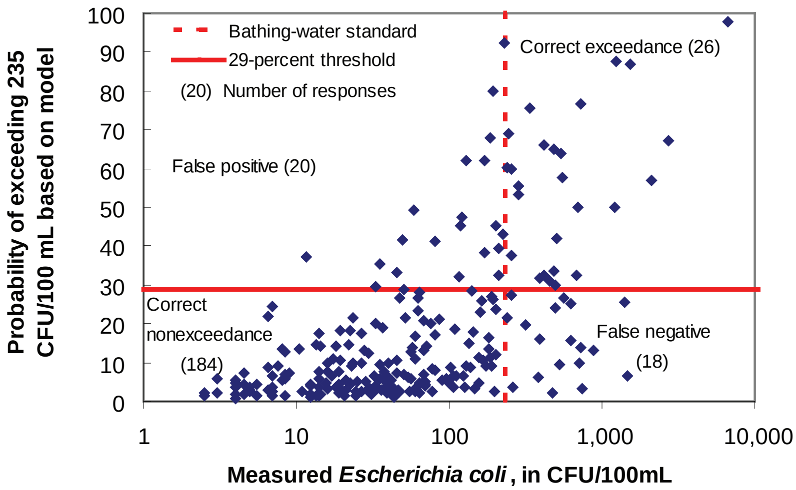
Table 3. Variables and regression statistics for beach models.

[The adjusted R^2 indicates the fraction of the variation in *Escherichia coli* concentration explained by the model, adjusted for number of variables in the model]

Beach	Time period of data for model development	Adjusted R^2 of model	Variables in model	Parameter estimates	Significance of variable
Huntington	2000 -2004	0.38	y-intercept	0.914	<0.0001
			Wave height	0.144	0.0018
			Rw_{48}[b]	0.301	<0.0001
			Log_{10} turbidity	0.563	<0.0001
Edgewater	2004-2005	0.40	y-intercept	1.817	<0.0001
			Lake level	-0.407	<0.0001
			Rw_{72}[b]	0.084	0.0013
			Wave height	0.240	<0.0001
			Log_{10} turbidity	0.318	0.0004
Villa Angela	2004-2005	0.38	y-intercept	-1.279	0.0031
			Water temperature	0.114	<0.0001
			R_{d-1}[a]	0.555	0.0011
			Wave height	0.236	0.0026
			Log_{10}turbidity	0.410	0.0051
Lakeshore	2004-2005	0.35	y-intercept	0.613	0.1725
			Water temperature	0.054	0.0089
			Rw_{72}[b]	0.137	0.0271
			Log_{10} turbidity	0.476	0.0011
Lakeview	2004-2005	0.44	y-intercept	-0.167	0.6279
			Wind direction	0.100	0.0001
			Day of the year	0.010	<0.0001
			Log_{10} turbidity	0.406	<0.0001
Huntington	2000-2005	0.42	y-intercept	-0.219	0.3482
			Wave height	0.134	0.0016
			Rw_{48}[b]	0.292	<0.0001
			Log_{10} turbidity	0.592	<0.0001
			Day of the year	0.006	<0.0001

[a] R_{d-1} was the rainfall amount, in inches, in the 24-hour period preceding sampling.

[b] Rw_{48} and Rw_{72} were the rainfall amounts, in inches, in the 48- and 72-hour periods, respectively, before sampling, with the most recent rainfall receiving the most weight.



Probability	Total correct	False +	False -
50	215	5	28
45	213	9	26
40	211	12	25
35	208	16	24
31	210	19	19
30	210	19	19
29	210	20	18
28	207	23	18
27	207	24	17
26	205	27	16

29-percent threshold

Figure 3. Establishment of the threshold probability for Huntington 2000–2004 model. (CFU/mL is colony-forming units per 100 milliliters.)

Table 4. Numbers of correct responses and the sensitivities and specificities of model responses with indicated thresholds and predicted *Escherichia coli (E. coli)* concentrations compared to previous day's *E. coli* concentrations (current method for assessing recreational water quality).

Beach model	Threshold probability	Number of samples	Response (percent)		
			Correct predictions	Specificity[a]	Sensitivity[b]
Huntington 2000-2004	29	248	84.7	90.2	59.1
	Predicted *E. coli*	248	86.7	97.5	36.4
	Previous day's *E. coli*	171	76.6	86.5	30.0
Edgewater 2004-2005	29	185	89.7	94.9	59.3
	Predicted *E. coli*	185	88.1	98.7	25.9
	Previous day's *E. coli*	142	79.6	90.6	28.0
Villa Angela 2004-2005	31	183	78.7	85.0	62.0
	Predicted *E. coli*	183	79.8	97.0	34.0
	Previous day's *E. coli*	139	64.0	75.3	38.1
Lakeview 2004-2005	38	94	76.6	52.6	92.9
	Predicted *E. coli*	94	74.5	63.2	82.1
	Previous day's *E. coli*	67	68.6	72.7	66.7
Lakeshore 2004-2005	32	89	78.6	68.0	92.3
	Predicted *E. coli*	89	76.4	86.0	64.1
	Previous day's *E. coli*	65	69.2	78.8	59.4
Huntington 2000-2005	27	306	85.9	90.9	61.5
	Predicted *E. coli*	306	85.6	96.4	32.7
	Previous day's *E. coli*	213	76.5	87.0	25.0

[a] Specificity was the proportion of nonexceedance responses that were correctly predicted as safe for swimming.

[b] Sensitivity was the proportion of exceedance responses that were correctly predicted as unsafe for swimming.

Table 5. Responses of the Huntington 2000–2004 model in 2005 and comparison to responses obtained with previous day's *Escherichia coli (E. coli)* concentrations (current method for assessing recreational water quality).

Prediction based on	Number of samples	Response (percent)		
		Correct predictions	Specificity	Sensitivity
Model threshold, 29 percent	50	82.0	88.1	50.0
Model-predicted *E. coli*	50	88.0	95.2	50.0
Previous day's *E. coli*	41	75.6	88.6	0.00

A list of possible models was developed for Huntington based on 2000–2005 data along with Mallow's Cp statistics and R^2 values. The best model contained the variables wave height, Rw48, $\log_{10}$ turbidity, and day of the year with an R^2 of 0.42 (table 3). The predicted *E. coli* and threshold probability from the Huntington 2000–2005 model (table 4, below the solid line) yielded similar responses as those for the Huntington 2000–2004 model. The 2000–2005 Huntington model will be validated in 2006; it will also be used a predictive tool by beach managers.

Future Work

During exploratory data analysis, and later in development of MLR models for five Lake Erie beaches, it was evident that there was a unique set of explanatory variables for each beach. Similarly, in an investigation of four Lake Michigan beaches in Illinois and Indiana, Olyphant (2005) found that the method used to develop predictive models was transferable, but the form of each model was unique and required site-specific calibration. The important explanatory variables in the Indiana study were wind speed and direction, waves, lake stage, rainfall, sunshine, and temperature. The explanatory variables used in Lake Erie beach models were turbidity (five beaches), rainfall (four beaches), wave height (three beaches), water temperature (two beaches), day of the year (two beaches), wind direction (one beach), and lake level (one beach).

The current study suggests that MLR predictive models can do better than use of the previous day's *E. coli* in assessing current recreational water-quality conditions, even during an independent year. Both the predicted *E. coli* concentration and probability outputs did considerably better at predicting exceedance of the *E. coli* standard than the current method. Because probability output thresholds are set by beach managers or modelers, however, they can be adjusted to minimize false negative responses and thus may provide more protection for public health than use of predicted *E. coli* concentrations. Regardless of which model output is used, at Huntington, the current method failed to accurately predict any of the eight exceedances, whereas the model accurately predicted four of them during an independent year. Consequently, predictions based on the Huntington 2000–2005 model and the threshold probability have been presented to the public through an Internet-based "nowcasting" system since May 30, 2006. Because validation was done for only a single year at a single beach, the Huntington model again and the other beach models for the first time are being validated in 2006.

As the models are validated in 2006, steps may be taken to further refine and improve them. One possible improvement, tested at several beaches during 2005, is to replace categorical wave heights with a less subjective measuring method. During 2005, a survey rod was placed in the water at the sampling location for 1 minute, during which field crews noted the minimum and maximum heights. Additionally, during 2005 at Edgewater, a pressure transducer was installed on a buoy placed in the bathing area. The hourly nearshore wave heights collected with the buoy showed site-specific wave fluctuations not evident in offshore data and were more accurate than categorical wave heights. Because turbidity is an important variable at five beaches, plans call for installation of probes at each beach to obtain continuous turbidity measurements instead of one measurement at the time of sample collection. Data from a local rain gage may also improve the predictive ability of the model at Lakeshore because in previous studies, fecal contamination at Lakeshore was identified to be primarily local in origin. Lastly, a rapid detection method for *E. coli* that involves an antibody-antigen binding mechanism (Lee and Deininger, 2004) is being tested at Edgewater and Villa Angela to determine whether the results may be useful in a predictive model.

Combining hydrodynamic modeling with MLR modeling may improve the predictive ability of models at beaches with identified point sources. In an Australian study, sewage plumes that were predicted to surface were coded as 1 because of possible dispersal by wind and surface movements; sewage plumes that were predicted to remain below the surface were coded as 0 (Krogh and Robinson, 1996). This "plume entrapment" variable generated by near-field oceanographic models was found to be a significant variable in regression models.

The procedures detailed in this report can be used by others to develop predictive models at coastal beaches; all that is needed is an existing monitoring program and a basic knowledge of statistics and computer software. Equipment costs for data collection are minimal because most of the data required for predictive models are available from other agencies or are easily measured at the beach. As a model proves to be a useful tool at a particular beach, beach managers may decide to invest in more expensive equipment to measure environmental conditions in real time. If validation tests are successful, beach managers may also decide to develop an Internet-based system that provides model predictions to the beach-going public 7 days a week. Currently, weekend estimates are not commonly available because most laboratories are not staffed on weekends.

Predictive models are meant to augment existing beach monitoring programs, not to replace them, and must be continuously tested and refined. For example, if changes are made to improve water quality at the beach (for example, bird-deterrent devices are installed, leaking sewerlines are repaired), new models can be developed using data collected after the improvements have been initiated. Additional data and refined variables can be added to models to improve predictions and to better protect public health.

Summary and Conclusions

A goal of the U.S. Environmental Protection Agency (USEPA) Beaches Environmental Assessment, Closure, and Health (BEACH) Program is development of mathematical models for real-time forecasting to help resolve the delayed notification problems inherent with the present approach to recreational monitoring. At many beaches where nonpoint or unidentified sources dominate, multiple linear regression (MLR) models based on easily measured environmental and water-quality variables may be the most appropriate type of model for estimating bacterial indicator concentrations or the probability of exceeding target concentrations.

The U.S. Geological Survey (USGS), in cooperation with Ohio Water Development Authority, Ohio Lake Erie Office, Northeast Ohio Regional Sewer District, and Cuyahoga County Board of Health, developed and tested MLR predictive models for *E. coli* concentrations at five Ohio Lake Erie beaches—Lakeview (Lorain, Ohio), Huntington Reservation (Bay Village, Ohio), Edgewater and Villa Angela (Cleveland, Ohio), and Lakeshore (Ashtabula, Ohio). At one beach, Huntington Reservation (Huntington), investigations were further along than at other beaches, so the Huntington model was assessed during an independent or validation year (a year whose data were not used for model development).

Data collection included analysis of daily water samples for *E. coli* and measurement of explanatory variables for model development and testing. Data were collected during the recreational seasons (May through September) of 2004–05. At Huntington, data from past studies (2000–2003) also were included. Among the environmental variables were single-day and weighted rainfall variables. Single-day variables included rainfall that fell in a previous 24-hour period; weighted rainfall included rainfall that fell in the 48- or 72-hour antecedent period, with the most recent rainfall receiving the most weight (Rw48 and Rw72, respectively). Wind direction was calculated by summing hourly wind vectors for the 24-hour period preceding sampling and determining the direction of the resultant vector. Wave height was visually estimated and placed into one of four categories.

A daily *E. coli* concentration was calculated by averaging results from multiple sampling points at each beach. Bacterial concentrations were $\log_{10}$ transformed before data analysis. At least 2 years of data from each beach were examined and used for model development. Explanatory variables that showed significant relations to *E. coli* concentrations were used to produce a list of possible MLR models using the Mallows Cp test. The MLR models were ordered so that the coefficient of determination (R^2) was maximized and the Mallows' Cp statistic was minimized. Model statistics were examined and diagnostic tests were done to identify the model(s) for each beach that provided the best linear, unbiased estimator of *E. coli* concentrations.

The two types of output produced by the models were predicted *E. coli* concentration and the probability of exceeding the Ohio single-sample bathing water standard for *E. coli* of 235 colony-forming units per 100 milliliters (CFU/100 mL). For each selected model, a threshold probability associated with too great a risk to allow swimming was determined retrospectively. Threshold probabilities were determined by taking the dataset used to develop the model and finding the probability that provided a reasonable balance between achieving a high number of correct responses and a low number of false negative responses.

From a list of possible models, one best model for each was selected; R^2 values ranged from 0.35 for Lakeshore to 0.44 for Lakeview. All of the best beach models incorporated $\log_{10}$ turbidity as an explanatory variable, and four out of five models incorporated a rainfall variable. Weighted rainfall variables (Rw48 and Rw72) were used in three beach models instead of single-day rainfall variables. Lake level was used only at Edgewater, and wind direction and day of the year only at Lakeview. Wave height and water temperature were used in three and two beach models, respectively.

The responses from models that predict *E. coli* concentrations and threshold probabilities were compared to use of the previous day's *E. coli* (current method). Model threshold probabilities ranged from 29 to 38 percent. For all beaches, the percentages of correct predictions were higher using the model than using the previous day's *E. coli*.

The model developed with data collected in 2000–2004 at Huntington was validated with data collected during an independent period (2005). Using either model output, the percentages of correctly predicting nonexceedance of the bathing-water standard (specificity) were in the same range as the percentage found using the previous day's *E. coli*. The difference between the model responses and the current method responses was most pronounced when examining the percentages of correctly predicting exceedance of the bathing-water standard (sensitivity). Using both output values from the model, four out of eight exceedances (50 percent sensitivity) during 2005 were correctly predicted. Using the previous day's *E. coli*, none of the exceedances was predicted.

Principal conclusions and implications for future work are the following:

- It was evident that there was a unique set of explanatory variables for each beach. The explanatory variables used in Lake Erie beach models were turbidity (five beaches), rainfall (four beaches), wave height (three beaches), water temperature (two beaches), day of the year (two beaches), wind direction (one beach), and lake level (one beach).
- This study suggests that MLR predictive models can do better than use of the previous day's *E. coli* in assessing current recreational water-quality conditions, even during an independent year. Because validation was done for only a single year at a single beach, the Huntington model and other beach models are being validated in 2006.
- As the models are validated in 2006, steps may be taken to further refine and improve them. Possible improvements include obtaining more accurate measurements of wave heights, measuring continuous turbidity, obtaining data from local rain gages, and incorporating rapid analytical methods for *E. coli* into the models. Combining hydrodynamic modeling with MLR modeling also may improve the predictive ability of models at beaches with identified point sources.
- The procedures detailed in this report can be used by others to develop predictive models at coastal beaches. Through an Internet-based system, models can be useful tools that provide predictions to the beach-going public 7 days a week.
- If changes are made to improve water quality at a beach, new models can be developed using data collected after the improvements have been initiated. Additional data and refined variables can be added to models to improve predictions and to better protect public health.

Acknowledgments

The authors thank Lester Stumpe, Mark Citriglia, and Eva Hatvani of the Northeast Ohio Regional Sewer District; Jill Lis of the Cuyahoga County Board of Health; Jack Kurowski of the Lorain City Health Dept.; Brenda Stephens of the Ashtabula Township Park Commission; and students Timothy Roberts and Paula Carver.

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