Coastal Strategies to Predict *Escherichia coli* Concentrations for Beaches along a 35 km Stretch of Southern Lake Michigan

MEREDITH B. NEVERS AND
RICHARD L. WHITMAN*

U.S. Geological Survey, Great Lakes Science Center, 1100 N. Mineral Springs Road, Porter, Indiana 46304

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To understand the fate and movement of *Escherichia coli* in beach water, numerous modeling studies have been undertaken including mechanistic predictions of currents and plumes and empirical modeling based on hydrometeorological variables. Most approaches are limited in scope by nearshore currents or physical obstacles and data limitations; few examine the issue from a larger spatial scale. Given the similarities between variables typically included in these models, we attempted to take a broader view of *E. coli* fluctuations by simultaneously examining twelve beaches along 35 km of Indiana's Lake Michigan coastline that includes five point-source outfalls. The beaches had similar *E. coli* fluctuations, and a best-fit empirical model included two variables: wave height and an interactive term comprised of wind direction and creek turbidity. Individual beach R^2 was 0.32–0.50. Data training-set results were comparable to validation results ($R^2 = 0.48$). Amount of variation explained by the model was similar to previous reports for individual beaches. By extending the modeling approach to include more coastline distance, broader-scale spatial and temporal changes in bacteria concentrations and the influencing factors can be characterized.

Introduction

Empirical predictive modeling has been used as a real-time, feasible method to improve the accuracy and efficiency of recreational beach water monitoring for human fecal contamination. Most studies have local, limited applications to specific beaches (*1, 2*). These approaches intensively examine a single beach by simultaneously measuring local water quality and weather conditions associated with that beach. Empirical predictive models have been developed for multiple beaches, often in locations with a significant bacterial point source; these models include the beaches that are affected by the contaminant plume (*3, 4*). Likewise, health risk studies have focused on single beaches or on individual point sources and have excluded neighboring beaches (*5, 6*). These epidemiological studies often combine distant beaches and/or different sampling times to develop health-risk guidance for lake or ocean water quality criteria. Attention to individual beaches or well-defined sources has taken priority over investigations of larger scale (distance and time) fluctuations in indicator bacteria and surrogate variables.

Point and nonpoint sources contribute to nearshore fecal indicator bacteria (FIB), and influences of these sources can be measured by specific surrogate parameters used in predictive models. Variables related to point sources may include river discharge and/or gauge height (*7–9*), land use (*10*), and rainfall (*4, 11*). Nearshore physical characteristics, particularly currents (*12, 13*), wave height (*3*), and in marine systems, tides (*14, 15*), that may affect the point-source plume dynamics can also affect the source impacts. In nonpoint-source-dominated systems, FIB counts can fluctuate on smaller, more localized scales due to settling and resuspension (*16*), currents (*13*), and bacteria die-off/inactivation (*17, 18*). If a longer extent of beach length is considered, these small-scale fluctuations in FIB are quantified over a larger distance, increasing variation and complicating understanding of the system.

Few predictive models have been developed that incorporate both beaches with and without a dominant point source. Given the inclusion in predictive models of independent factors such as current speed and direction, wave height, sunlight, rainfall, and physical geography and land use, it is likely that there are large-scale patterns that cause simultaneous fluctuations in FIB at beaches throughout a region. Distinguishing which predictors can be used to describe a long coastline may help improve modeling predictions and understanding of nearshore FIB dynamics.

Here, we examine the similarities between beaches along the Indiana coastline of Lake Michigan in order to develop a broader understanding of the environmental factors that affect *Escherichia coli* concentrations. Whereas previous studies have generally taken a smaller scale approach by examining beaches as defined geographic locations, we have examined the variables that affect multiple beaches that are influenced by point and nonpoint sources. From this information, an exploratory empirical model was developed that attempts to define the simultaneous *E. coli* fluctuations at 12 beaches using independent environmental variables. The study area includes several point-source outlets, but the extent of their impact varies: some beaches far from these sources could be considered nonpoint-source-dominated beaches. Our findings support the contention that regional hydrometeorology should be considered in managing and assessing beach water quality, and there is appreciable interaction between narrow-range and broad-range hydrometeorological factors along nearshore waters. By simultaneously collecting data on FIB and independent variables along a coastline that incorporates numerous beaches and multiple outlets, a greater understanding of FIB variability among and within beaches can be established.

Materials and Methods

Twelve recreational beaches on the Indiana coast of Lake Michigan were studied during the summer swimming season of 2004. The beaches extended from Michigan City to Gary, Indiana, a distance of 35 km (Figure 1). Eight of the beaches are within the Indiana Dunes National Lakeshore and Indiana Dunes State Park, and the other four are located in the municipalities of Gary and Ogden Dunes. Among these beaches are five surface water drainages, including the Little Calumet River and its outlet Burns Ditch, Dunes Creek, Derby Ditch, Kintzele Ditch, and Trail Creek.

Beach waters were sampled for FIB from May 26 to August 15, 2004; simultaneously, hydrometeorological conditions were measured at several locations. Daily (seven days/week, between 0700 and 0900) water samples were collected at

* Corresponding author phone: (219) 926-8336 ext. 424; fax: (219) 929-5792; e-mail: rwhitman@usgs.gov.

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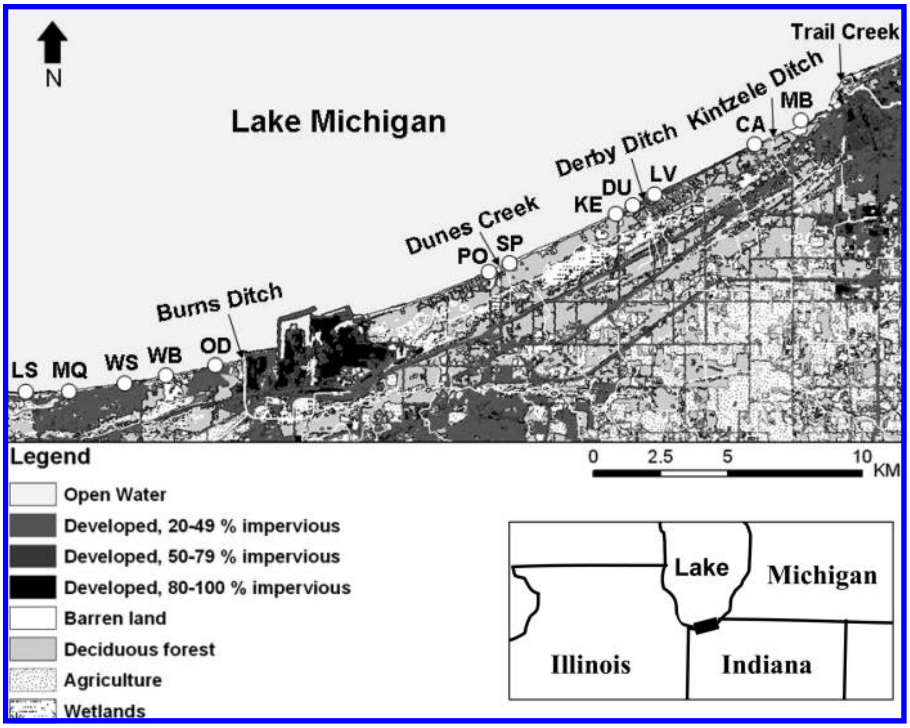

FIGURE 1. Twelve beaches and five outlets in northern Indiana along Lake Michigan. Land use designations include industrial, residential, and agricultural in addition to natural areas. A large portion of the coastal study area is National Park Service land (Indiana Dunes National Lakeshore).

seven beaches: Mount Baldy (MB), Central Avenue (CA), Ogden Dunes (OD), West Beach (WB), Wells Street (WS), Marquette (MQ), and Lake Street (LS) beaches and the Trail Creek, Kintzele Ditch, and Burns Ditch outlets. Two water samples were taken by submerging sterile polyethylene bags 10 cm below the surface in 45 cm deep water. Field conditions were recorded, including air and water temperature, wind speed and direction, and wave height. Water samples were transported to the laboratory on ice, where one sample was analyzed for *E. coli* using Colilert-18 (*19*), which provides results in MPN/100 mL. Between one and four replicates were collected at each beach, depending on beach length, and means were calculated for each beach. The second sample was analyzed for water chemistry variables: turbidity and chlorophyll (Turner Instruments Aquafluor, Sunnyvale, CA), specific conductance (Fisher Scientific Acumet meter, Pittsburgh, PA), and color (Hach spectrophotometer, Loveland, CO).

At each of the remaining beaches, Lakeview (LV), Dunbar (DU), Kemil (KE), State Park (SP), and Porter (PO), and at the Dunes Creek outlet, water samples were collected 3−5 times per week using the same procedures and similarly analyzed.

Water chemistry was measured continuously at Burns Ditch and Kintzele Ditch. Turbidity, specific conductance, temperature, pH, and dissolved oxygen were measured every 15 min by YSI model 6600 (YSI Incorporated, Yellow Springs, OH). Data were downloaded and instruments were recalibrated every two weeks. Data from the four hours preceding *E. coli* sample collection were averaged for analyses. A pressure transducer (In Situ Inc., Laramie, WY) was installed near the mouth of Kintzele Ditch in 1.5 m of water to measure wave height and water level in Lake Michigan every 15 s. Another transducer was placed in Kintzele Ditch approximately 0.6 km upstream from the mouth to record gauge height. Gauge height and streamflow observations for Burns Ditch and the East and West Little Calumet River were acquired from the U.S. Geological Survey gauging stations (04095090 Burns Ditch; 413339087223001 West Little Calumet; and 04094000 East Little Calumet).

Meteorological conditions were recorded by a weather station (Onset Computer Corporation, Pocasset, MA) installed near the Trail Creek outlet. The instrument recorded air temperature, relative humidity, dew point, insolation, wind and gust speed, wind direction, precipitation, and barometric pressure every 15 min. Weather conditions from an existing station located at the Indiana Dunes National Lakeshore were also acquired, including wind speed and direction, precipitation, air temperature, and relative humidity. Wave and weather predictions generated by a model from the NOAA Great Lakes Environmental Research Laboratory were acquired; these incorporated hydrometeorological data from the Gary Regional Airport, including wind direction and speed, current direction and speed, wave direction and height, air temperature, cloud cover, and dew point.

Statistical analyses were performed using SPSS, SAS, and Systat software (*20–22*). All *E. coli* results, measured as MPN/100 mL, were log-transformed prior to analysis.

Results

Two factor (date and beach) ANOVA and mean separation Student−Newman−Keuls post hoc test showed that *E. coli* counts at SP and LS beaches were significantly higher than at other beaches ($P < 0.01$) (Figure 2). SP had the highest ranked mean log *E. coli* (1.85 ± 0.45 SD), and CA had the lowest (1.32 ± 0.59 SD). The coefficient of variation (COV), calculated using untransformed data, was highest for WS and OD, both of which had high standard deviations (Figure 2). Beaches with lowest COVs were LS, MQ, and DU.

Pearson correlations showed that log *E. coli* concentration for 97% of the beach comparisons were significantly related using Benjamini-Hochberg adjusted probabilities ($P < 0.05$) (*23*). A Shapiro-Wilks test indicated that log-transformed *E. coli* concentrations may reasonably be treated as normally distributed at all beaches but LS($P = 0.041$) and OD ($P = 0.009$) (Figure 3).

In hierarchical cluster analysis using squared Euclidean distance (Supporting Information Figure S1), some beaches

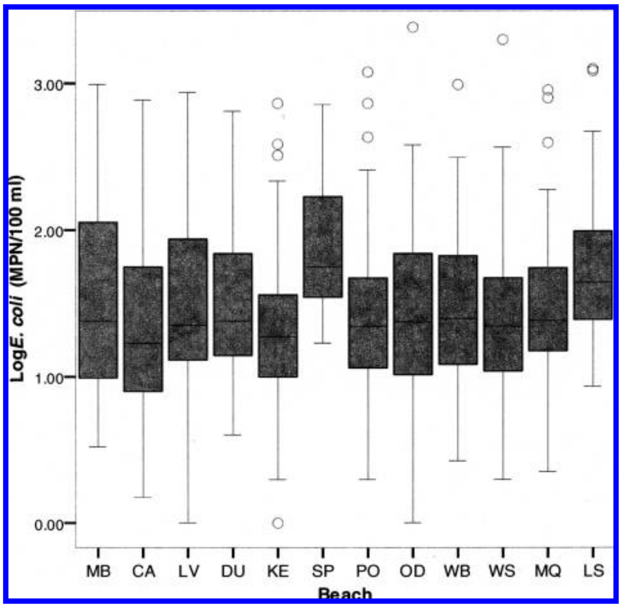

FIGURE 2. Distribution of *E. coli* concentrations at the 12 beaches. Box indicates the 25th and 75th percentiles, with the median as a solid line in the box. Whiskers are the range of values, without outliers. Outliers are indicated by open circles and indicate cases 1.5−3 box-lengths from the upper or lower bounds of the box.

tended to cluster by physical proximity: KE, DU, and LV were clustered, as were WS and MQ, followed by WB. The next beach to cluster with the second group was a distant, seemingly unrelated beach (PO). The beaches last to cluster with others were OD and CA.

A plot of Pearson coefficients between beach pairs with geographic distance revealed no spatial pattern between beaches. Further, a correlogram for distance to nearest point source outfall showed no significant relationship between log-mean *E. coli* concentration at a beach and distance to the nearest drainage outlet. Similarly, there was no significant relationship between COV or variance for *E. coli* counts and physical distance to the nearest outlet. It was expected that variation would increase with increasing distance from a point source outfall and that *E. coli* counts would decrease similarly. Confounding the pattern was a low mean *E. coli* concentration and a high COV at OD relative to its proximity to Burns Ditch (1.14 km) and a high mean *E. coli* at LS despite its distance from Burns Ditch (7.56 km).

Daily gauge height was compared throughout the watershed at sites in the West and East Little Calumet River, Kintzele Ditch, and Burns Ditch to assess the relative influence of these stream areas on beach loading. According to Pearson correlation with Benjamini-Yekutieli adjustment (*24*), discharge measurements at all locations were correlated with one another, with the exception of Burns Ditch, even after lagging by one day to account for travel time (Supporting Information Table S2). The low correlation of each upstream site with Burns Ditch is probably due to lake interactions at the gauge location, as indicated by the strong correlation between gauge height and lake surface elevation ($R = 0.865$, $P < 0.001$). Mean *E. coli* concentrations for the study beaches were more closely related to the two gauging stations nearest the lake ($P < 0.01$).

Empirical Modeling

LS and SP were not included in the empirical modeling exercises because the mean and variance of *E. coli* at those beaches were significantly higher than at other study beaches ($P < 0.01$).

Of the environmental independent variables measured at beaches and streams, only a subset was selected for inspection as potential regressors. Candidate variables were evaluated for degree of independence or potential colinearity. Variables that were potentially related (e.g., wave height and turbidity; stream gauge height and rainfall) were retained if their Pearson correlation was <0.6. Measurements of the same metric in different locations (e.g., wind, discharge, wave heights) were reduced to one representative location. Initial variables were selected to maximize the number of observable days during the sampling season and simultaneously maintain parsimony of variables used. Nine variables were considered: one-day lagged *E. coli*, lake turbidity at each beach, turbidity in Burns Ditch and in Kintzele Ditch, wave height measured near Kintzele Ditch (average for 4 hours prior to sample collection), total rainfall at Indiana Dunes National Lakeshore (total for 4 hours prior to sample collection), gauge height of Burns Ditch and Kintzele Ditch (24 h average), and the interactions of turbidity in Burns Ditch and Kintzele Ditch with the onshore, alongshore, and offshore components of wind speed in Portage, Indiana; total N for the usable data set was 483 (Supporting Information Table S3). Autocorrelations were examined with one-day lagged *E. coli* counts, which resulted in an R^2 of 0.01, meaning that *E. coli* was uncorrelated with previous day's *E. coli*. Model selection was determined by the Akaike Information Criteria (AIC), minimizing AIC and retaining parsimony of variables (*25*). Information criteria use for model selection helps limit overfitting and biased error estimates and eliminates exaggerated type 1 errors due to excessive multiple testing (*26*).

A model selected by AIC from the group of candidate regressors included two variables:

Log *E. coli* = Zwaveht + (Zavgturb × wdir) + error

where Zwaveht is the *Z*-score of lake wave height and Zavgturb × wdir =is the *Z*-score of the average of turbidity in Burns Ditch and Kintzele Ditch multiplied by wind direction. Here, wind direction is divided into onshore, offshore, and alongshore components because these directions have historically been important factors in influencing bacteria counts (*3*) (onshore waves, 315−360° and 0−44° = 1.0; alongshore 45−134° and 225−314° = 0.5; and offshore, 135−224° = 0).

Data from the entire set were randomly selected to serve as the training set; the model thus developed, using 65% of the data points, yielded an adjusted R^2 of 0.35. The root-mean-square error (RMSE) for the model was 0.46. For validation of the model, using the remaining 35% of the data set, R^2 was 0.48 and RMSE was 0.42. All variables were significant. There was no evidence of autocorrelation among the overall modeled equation (Durbin-Watson $D = 1.509$, df = 531).

We compared model results for individual beaches based on the same set of available descriptive variables using the entire data set (Figure 4). Using AIC, best-fit models resulted in adjusted R^2 ranging from 0.34 to 0.57 (Table 1). Most models incorporated the interactive term of wind direction and Burns Ditch and Kintzele Ditch turbidity, which accounted for a large percentage of the variation, in most cases upward of 30%. Additionally, all but three beaches had wave height in their models.

Discussion

FIB can originate from numerous sources, both point and nonpoint, with different relative impacts on concentrations at recreational beaches. Point sources in the study region include creeks and rivers that discharge near the recreational beaches. Some of these sources have been identified as direct sources of FIB (*9, 27*), specifically, human fecal bacteria (*3, 13*). Once FIB are present in beach water, narrow-range and

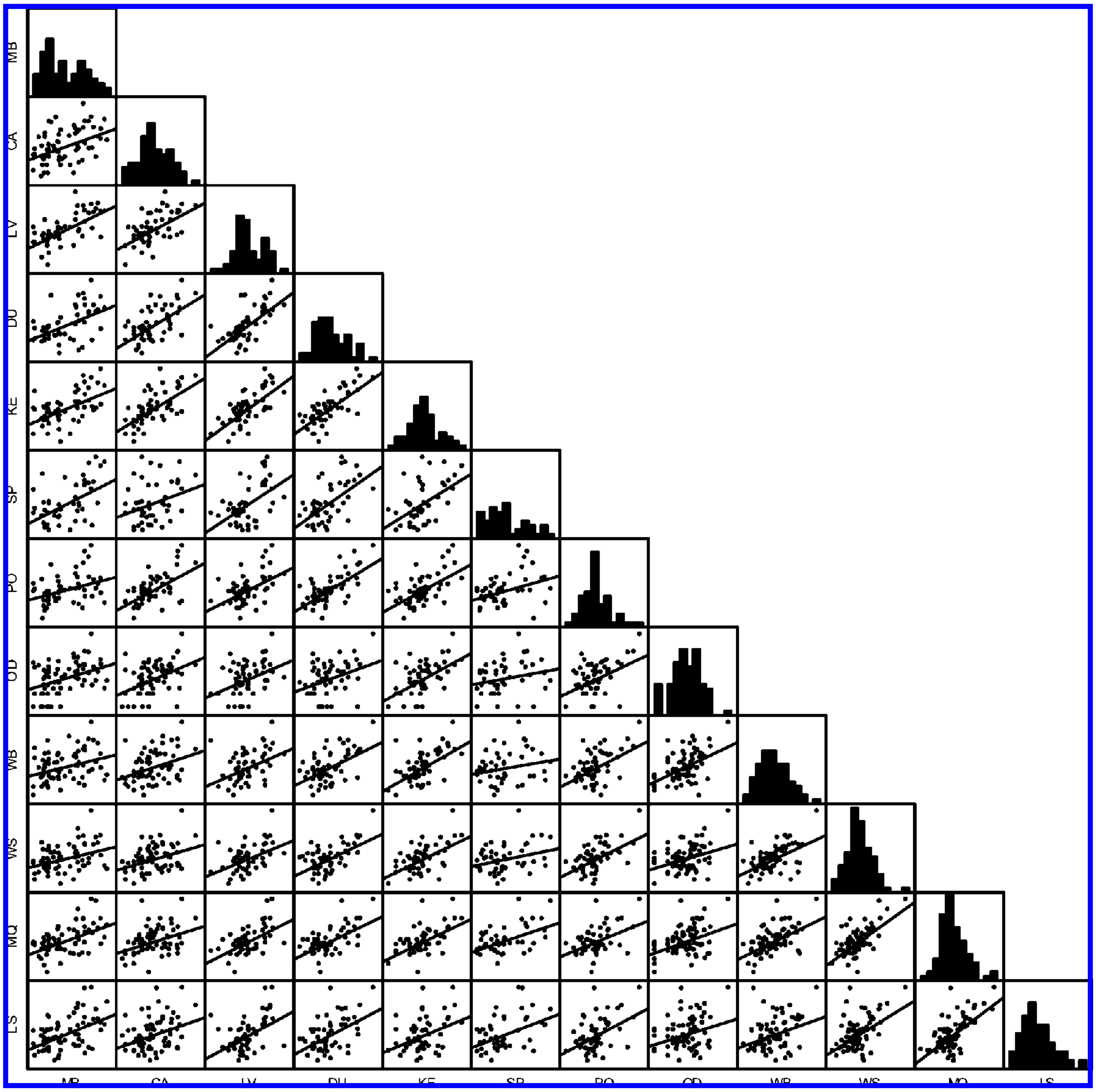

FIGURE 3. Scatterplot matrix highlighting the interrelatedness of *E. coli* concentrations at the 12 beaches examined in this study. Histograms indicate distribution of data; linear regression line associates best fit between each two beaches' *E. coli* data.

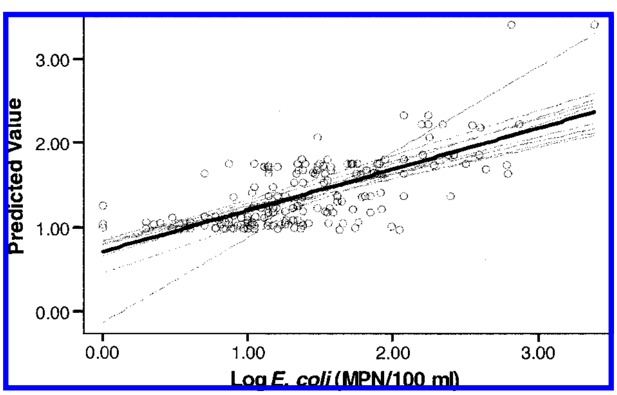

FIGURE 4. Empirical model for *E. coli* counts at 10 beaches in model with log *E. coli* count vs unadjusted predicted value using the validation data set. Fit lines are for individual beaches; overall best-fit regression line is in bold.

broad-range hydrometeorological factors and sources interact to affect their concentrations. Their continuous presence along the beach in sources such as algae and beach sand (*16, 28*) also contribute to local concentration fluctuations. The dynamics of river plumes, dilution, nearshore and offshore currents, settling of bacteria, and biological bacterial responses including mortality and inactivation all affect the amount of FIB at a recreational beach.

By considering a longer shoreline and taking a broader view of processes of the nearshore area, a better understanding of these dynamics can be gained. Cluster analysis indicates that similar, local sources or forces act on groups of beaches; in particular, the grouping of KE, DU, and LV highlights their proximity and also the similarity among nonpoint source dominated beaches. The same can be said of WS and MQ, except that they may be impacted by nearby Burns Ditch. While these closely situated beaches could justifiably be modeled for similarities together, the addition to the hierarchical cluster of physically distant beaches indicates that larger-scale patterns are present.

The high variation in *E. coli* counts at the two beaches not included in the region-wide assessment, LS and SP, may be due to their particular physical characteristics. LS is situated near a significant breakwall that probably affects local circulation patterns and the behavior of the Burns Ditch plume, resulting in higher variation in FIB compared to nearby beaches. This type of phenomenon is seen at 63rd Street Beach in Chicago where a near-enclosure inhibits flushing circulation, causing the elevated *E. coli* counts that

TABLE 1. Comparison of Individual Beaches for the Overall Model and Individually Developed Models for the Beaches [a]

	R_o	adj. R^2_i	RMSE	avgturb*wdir	wave height	rain	KDgauge	BDgauge	turb	KDturb	BDturb	lec_mn1
MB	0.575	0.475	0.494		0.397		0.430	0.207				
CA	0.660	0.565	0.382	0.289	0.326	0.291					−0.199	
LV	0.662	0.411	0.452	0.360	0.275							
DU	0.688	0.482	0.358	0.647		0.220						
KE	0.630	0.455	0.448	0.342	0.223	0.310						
PO	0.715	0.543	0.391	0.574				0.273				
OD	0.633	0.388	0.545	0.411	0.203							
WB	0.596	0.344	0.418		0.389					0.328		
WS	0.669	0.522	0.366	0.321	0.272				0.216			−0.175
MQ	0.576	0.516	0.334	0.182			0.314	0.220	0.206			

[a] Pearson correlation coefficient (R_o) is the predicted vs. actual *E. coli* concentration after regressing for all points less the subject beach (leave one out) using only Avgturb × wdir and wave height. R^2_i is the coefficient of determination for individual beach models selected by AIC. RMSE = root mean square error for that regression. Squared semipartial correlations coefficients (sr^2) are presented for each significant variable in the resulting individual beach prediction equation.

have been historically observed (*29*). In the case of SP, the high coefficient of variation could be linked to the high spatial heterogeneity in *E. coli* distribution. The two sampling transects are on either side of Dunes Creek and thus depend on directional movement of the creek plume (*30*), which probably contributed to several outliers retained in the data set.

Model Variables. The variables selected for the overall model developed in this study included wave height and the interaction of turbidity in two of the outlets with wind direction. The inclusion of creek-based and lake-based variables indicates that there are point and nonpoint-source influences impacting the *E. coli* concentrations. Point sources have traditionally been implicated as the primary impact on FIB loadings in the nearshore beach, but our study indicates that wave height, which is often associated with resuspending shoreline nonpoint sources (*16, 31*), may also be important.

Turbidity in creeks is often associated with high rainfall and hence discharge events that can carry large quantities of FIB to the lake. Turbidity has therefore been used in numerous models and is typically highly correlated with *E. coli* counts (*1*). However, the impact of creek water quality on receiving waters depends greatly on the direction the plume takes, a function of currents and wind direction. At several of the beaches in this study, *E. coli* counts are typically associated with north winds that force creek water toward the beaches (*3, 4*).

Individual beaches close to an outlet often have *E. coli* counts closely correlated with *E. coli* concentrations in the creek or stream. This was the case with significant correlations found between Burns Ditch and OD ($P = 0.001$), Dunes Creek and SP ($P = 0.001$), and Kintzele Ditch and CA ($P = 0.012$). In some instances, beaches far from a point source had *E. coli* counts that were related to the presumed source of the *E. coli* (e.g., MQ and Burns Ditch; DU and Dunes Creek), and in other cases beaches close to a source had *E. coli* counts not well-correlated with nearby outlet (e.g., CA and Kintzele Ditch). Wind direction often influences this relationship by forcing the plume in one direction or another. So, while turbidity in the creeks is an important component of the system, loading and dilution of water from the creek and river outlets are not alone enough to account for *E. coli* distribution.

The relationship between waves and FIB is complex. High waves are commonly associated with high FIB that originate from nonpoint, beach-specific sources such as sand (*16, 32*), algae (*28, 33*), or birds (*34, 35*). Surface turbulence, especially in the form of breaking waves, can decrease light penetration and thus decrease the rate of FIB mortality (*29*). Turbulence can also increase sediment resuspension of FIB along the lake bottom (*36*) or in bacteria-laden foreshore sands (*16*), or it can keep in suspension FIB delivered from outside sources. The interaction of lake level and wave height can increase this impact, similar to tidal effects in marine waters (*14, 37*). Similar relationships with lake-level changes have been documented in Lake Winnipeg (*38*). In addition to its potential for association with rain events, this explanatory variable may describe some of the variation in *E. coli* on days without rainfall. Waves in the study area are generally less than 20 cm but can range as high as 1 m (Supporting Information Table S3).

Model Comparisons. Model results for the 10 beaches using the entire data set ($R^2 = 0.40$, $N = 531$) were similar to those obtained in previous studies for individual beaches. Published results have had R^2 of 0.29 ($N = 72$) to 0.58 ($N = 53$) for beaches on Lake Erie (*1*) and R^2, as calculated (*39*), of 0.45 ($N = 81$) to 0.62 ($N = 86$) for individual beaches on Lake Michigan (*40*). Individual beaches using our overall model had R^2 ranging from 0.32 to 0.50 (median $N = 59$), using the entire data set. It has been stressed that models are beach-dependent and should rely on variables measured nearby, but results here indicate that a broader view of the system is possible. Variables measured far along the shoreline may be useful surrogate indicators for phenomena occurring across an entire or several watersheds, and it is likely that collecting additional years of data would strengthen the evidence of these region-wide phenomena.

Deterministic hydrodynamic models have been proposed to predict FIB, but unless sources are overt and nearby, these models cannot yet incorporate the highly dynamic and complex nature of FIB contamination. Hydrodynamics account for only a portion of the spatial and temporal variations of viable FIB populations. Among the numerous factors that influence variation are different rates of mortality, inactivation, resuscitation, and multiplication of FIB, reservoirs of FIB along the beach shores, and the presence of plant material and bird and animal feces on beaches and in associated streams. Most of the present deterministic models do not include many of these factors, however, so they may not yield as robust predictions as empirical approaches. It has been argued that hydrodynamic modeling has the advantage of working under fewer restraints and assumptions, yet the efficacy of its use has been largely restricted to beaches that have simple and well-defined forcing factors (e.g., sewage effluents, rivers, tidal influences). As shown here, two derived variables that have biological and physical importance can help predict and understand the factors responsible for *E. coli* population fluctuations within and between 10 beaches along an extended stretch of southern Lake Michigan.

Empirical models are generally most robust and elegant when parsimonious, so best results are generally derived from specific questions, in this case, how do you predict FIB concentration using the most complete but efficient set of explanatory variables? Most modelers limit the spatial extent of their study in order to decrease variation and increase predictive reliability. In doing so, however, much may be lost in our understanding of the factors affecting FIB distribution along shorelines. Only by integrating, comparing, and contrasting beaches over various temporal and spatial scales can we understand the similarities and differences between complex water bodies. This holistic approach allows us to view coastlines as systems rather than as a series of isolated, idiosyncratic, unique beaches. The extent that may be included will depend on beach characteristics, and differences in marine systems or alternate indicators may influence the regional range. We concede that beach-specific modeling is most efficient for developing predictive tools for local monitoring and perhaps some source characterization, but the resident FIB cannot be understood without knowledge and inclusion of surrounding (broad scale) hydrometeorological and biological influences. This is especially true when FIB flux has a strong nonpoint source component.

This premise allowed us to model effectively *E. coli* for 10 beaches along 35 km of Lake Michigan shoreline with only two variables: wave height and an interactive wind direction/turbidity term averaged from two locations. Coefficients of variation and associated errors showed that the resulting model was in the range of previously published results for a single beach, leading us to conclude that, in many situations, an extended coastline could be modeled at least as efficiently and effectively as an individual beach. Further, the findings show that the beaches in question have more in common than not, and these similarities should be considered even when developing local models. Grouping beaches leads to more economy of effort, more realistic expectations, and a better understanding of the fluctuations of FIB and the biological, environmental, and ambient conditions that best explain them.

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Supporting Information Available

Figure S1 and Tables S2 and S3. This material is available free of charge via the Internet at http://pubs.acs.org.

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