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Summer *E. coli* Patterns and Responses along 23 Chicago Beaches

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Concentrations of *E. coli* in recreational beach water are highly variable both locally and temporally, but a broader understanding of these fluctuations may be explained through coastal observations. Currently, beach contamination study approaches tend to be site-specific under the belief that politically delineated beaches are unique and management of beaches cannot be regionally oriented. *E. coli* data collected over five years from 23 Chicago beaches clearly identified ambient linked patterns at the regional scale. Temporal fluctuations were similar, with all beaches having simultaneous peaks and troughs of *E. coli* concentrations. Spatially, *E. coli* concentrations for beaches more closely situated were more closely correlated, indicating spatial autocorrelation. Julian day, wave height, and barometric pressure explained up to 40% of the variation, a value comparable to individual, less parsimonious site-specific models. Day of sampling could explain the majority of the variation in *E. coli* concentrations, more so than beach, depth, or time of day. Comparing beaches along a targeted coastline allows a better understanding of inherent background regional fluctuations and, ultimately, better predictions of *E. coli* concentrations in coastal recreational water.

Introduction

Research on indicator bacteria fluctuations in beach water has focused on distinguishing sources of contamination, managing recreational swimming, or characterizing the microbiologic population. Because of scope and funding constraints, many studies are limited to individual beaches, and broader-scale approaches to characterizing indicator bacteria flux have been limited. The origins and fate of bacteria in coastal swimming waters are varied and numerous, and they include nonpoint sources of stormwater (*1, 2*), sand (*3, 4*), algae (*5, 6*), and resident birds (*7*); point sources of rivers, creeks, and sewage (*8*); solar inactivation (*9, 10*); settling; and cellular death. Regardless of the complexity of the system, there is likely large-scale hydrometeorology similarly affecting many coastal waters, so it is possible that patterns of bacteria along certain stretches of coast may be simultaneously characterized.

Using hydrometeorological variables to describe or predict indicator bacteria concentrations is common in empirical models that predict daily changes in bacteria concentrations using point-source variables such as discharge or water quality of a contributing river (*11*) or coastal variables such as wave height or tide stage (*12*). Models are typically restricted to individual beaches or a stretch of coastline similarly impacted by a point-source outfall (*13, 14*). With similar hydrometeorological forcing factors affecting numerous beaches, it may be possible to extend models to include an even greater length of coastline.

Despite the presence of the Chicago River, there are no major point source inputs to Chicago's lakefront beaches. The flow of the Chicago River was reversed in the early 1900s to direct sewage away from nearshore Lake Michigan and drinking water intake conduits. Channels that keep the river flowing away serve as receptacles for sewage-plant discharge. In the event of an overwhelming rain event, the river locks may be opened, allowing excess sewage effluent and combined sewer overflows to enter Lake Michigan, but this happens rarely. Therefore, Chicago's beaches are primarily subject to nonpoint sources of contamination.

The numerous beaches and wealth of data available for Chicago provide an opportunity to explore indicator bacteria in an urban setting devoid of large, direct point sources. In this study, 5 years' worth of indicator bacteria and hydrometeorological data were compiled for Chicago's 23 beaches. The objective was to relate *E. coli* concentrations among beaches across the length of coast and to characterize spatial and temporal patterns in *E. coli* fluctuations. With this understanding, changes in nearshore concentrations of indicator bacteria and the influence of lake-wide variables on these changes may be better understood.

Methods

The 23 Chicago beaches extend along approximately 37 km of lakefront and are managed and monitored by the Chicago Park District. Recreational beach *E. coli* monitoring data were obtained for the years 2000–2005; monitoring typically extended from late May until early September. Beaches were sampled five days a week, including (from north to south) Juneway, Rogers, Howard, Jarvis/Fargo, Loyola, Pratt, North Shore, Hartigan, Thorndale, Osterman, Foster, Montrose, North Avenue, Oak, Ohio, 12th, 31st, 49th, 57th, and 63rd Street, Calumet, Rainbow, and South Shore Beaches (Figure 1). Missing data for late summer 2001 limits that year's representation in the *E. coli* data set for all beaches, and 49th Street Beach was not sampled in 2000 or 2001. Mean number of samples collected for a given beach each year was 72 (±1.0 SE).

Water samples were collected by submerging sterile polyethylene bags below the water surface in 45 cm deep water. Between two and five replicates were collected at each beach, depending on the size of the beach. During each beach visit, field conditions were recorded, including air and water temperature, wind speed and direction, and wave height. Water samples were analyzed for *E. coli* using Colilert, which is a defined substrate technology (*15*) that provides results in most probable number per 100 mL of water (MPN/100 mL). Colilert provides results comparable to the traditional membrane filtration technique (*16, 17*).

Empirical Modeling. *E. coli* data from 2000–2004 were used in modeling exercises. Data for hydrometeorological conditions were acquired from numerous sources. Because of the lack of availability of certain instruments for the entire period examined, several variables from different sources were normalized and combined, including wave height (measured to nearest 0.001 m), insolation (measured to the nearest MJ/m2), atmospheric pressure (measured to nearest

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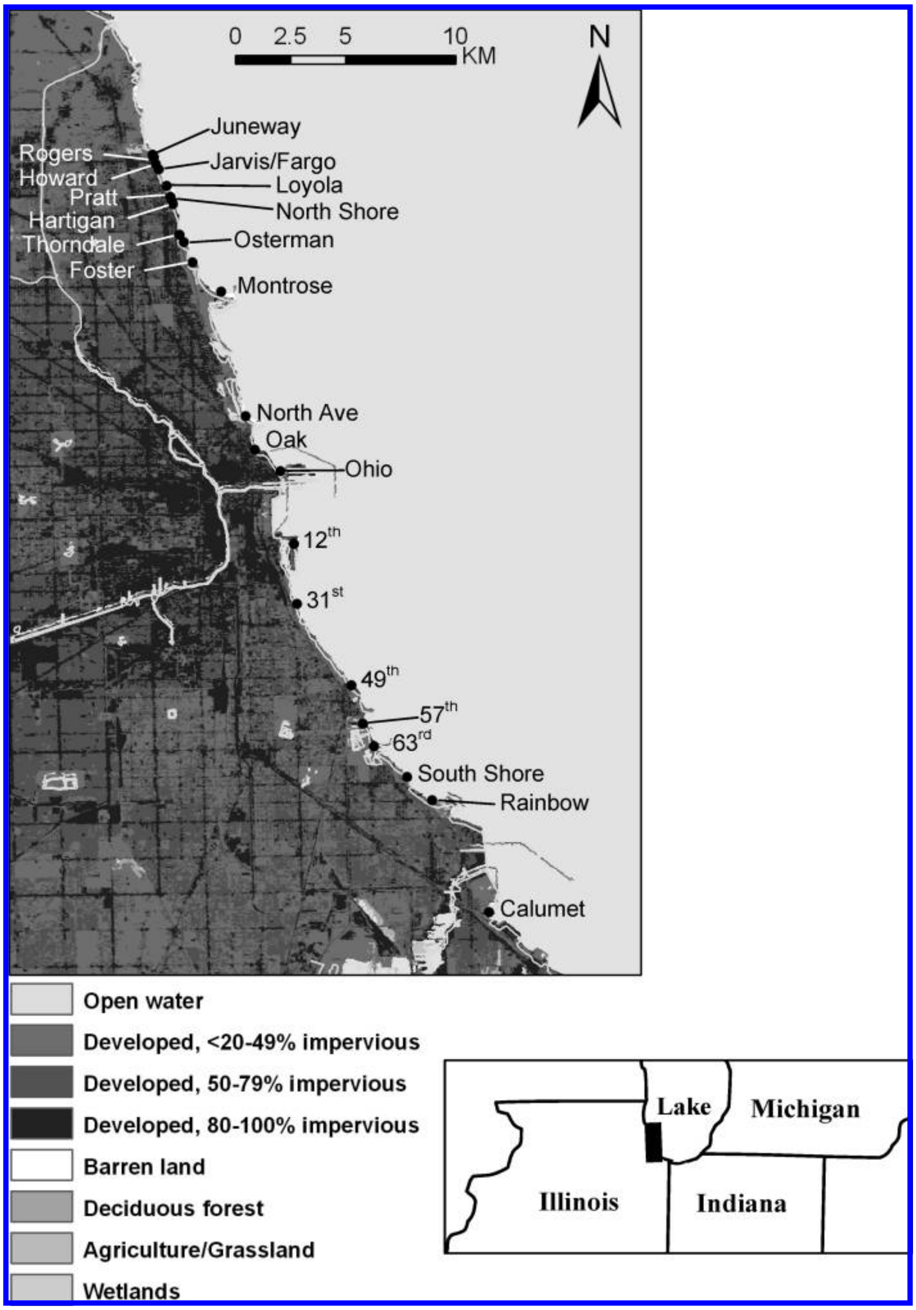

FIGURE 1. Land use for Chicago area and locations of study beaches.

0.001 cm Hg), and wind direction relative to true north (deg). For 2000−2003, wave height was measured using a wave meter maintained by the US Army Corps of Engineers at a Chicago water intake crib (41.92° N 87.57° W); the gauge was removed in early 2004. Daily data entries for wave height were the mean wave height for 4−10 a.m. Because of the large variation in insolation measurements throughout the city, a mean was calculated for 2000−2003 from two instruments: one located 45 km north of Juneway Beach (at Illinois Beach State Park) and another located near Ohio Street Beach (at Navy Pier). Data were obtained from the NOAA National Climatic Data Center and the Chicago Department of Transportation. Each daily entry for insolation was for the 24-h period ending at 10 a.m. for a given day. Barometric pressure and wind direction data were obtained from the airport at Gary, Indiana for 2000−2003. Barometric pressure data were entered in the database as the mean pressure for the period of 4−10 a.m. on a given day. Mean wind direction for 4−10 a.m. was calculated and coded in four components: onshore, offshore, up-coast, and down-coast, based on the average orientation relative to the Chicago shoreline.

In 2004, the solar insolation, barometric pressure, and wind direction information were obtained from a weather station located at 63rd Street Beach. Measurements were recorded every 15 min, and means for the period 4−10 a.m. were used in the database. Insolation was recorded as 24-h total. Lake Michigan wave height and water temperature were measured using a pressure transducer (In Situ Inc., Laramie, WY) installed at 63rd Street Beach in 1.5 m of water. Means for 4−10 a.m. was used in calculations. Wind direction for the regression analysis was coded as described above.

Statistical analyses were conducted using SPSS and SAS software (*18, 19*). All *E. coli* data were log-transformed prior to analysis. Values reported as above the upper detection limit (>2419 MPN/100 mL) were eliminated from the analyses after determining that frequency of occurrence (1.7%) had little effect on statistical inferences. Lower detection limit was set at 1 MPN/100 mL; <1% of the samples were below

TABLE 1. Descriptive Statistics for the 23 Chicago Beaches Included in the Study[a]

	N	geometric mean	mean ($\log_{10}$)	SE	variance	95% confidence intervals lower	95% confidence intervals upper
Juneway	326	45.9	1.66	0.044	0.64	1.58	1.75
Rogers	327	43.8	1.64	0.046	0.70	1.55	1.73
Howard	309	45.9	1.66	0.045	0.56	1.57	1.75
Jarvis/Fargo	323	43.4	1.64	0.044	0.64	1.55	1.72
Loyola	291	52.8	1.72	0.046	0.61	1.63	1.81
Pratt	326	50.0	1.70	0.043	0.61	1.61	1.78
North Shore	324	45.7	1.66	0.045	0.64	1.57	1.75
Hartigan	326	42.6	1.63	0.045	0.66	1.54	1.72
Thorndale	323	68.0	1.83	0.040	0.51	1.75	1.91
Osterman	323	61.4	1.79	0.042	0.56	1.71	1.87
Foster	323	59.4	1.77	0.041	0.55	1.69	1.86
Montrose	328	76.7	1.88	0.039	0.50	1.81	1.96
North Ave.	326	48.2	1.68	0.041	0.56	1.60	1.76
Oak	324	46.3	1.67	0.040	0.53	1.59	1.74
Ohio	325	39.4	1.60	0.040	0.53	1.52	1.67
12th	325	55.0	1.74	0.042	0.57	1.66	1.82
31st	331	62.0	1.79	0.042	0.60	1.71	1.88
49th	234	33.8	1.53	0.054	0.69	1.42	1.64
57th	329	70.1	1.85	0.039	0.49	1.77	1.92
63rd	337	140.0	2.15	0.037	0.46	2.07	2.22
South Shore	327	66.8	1.83	0.039	0.51	1.75	1.90
Rainbow	330	68.3	1.83	0.038	0.48	1.76	1.91
Calumet	323	65.9	1.81	0.039	0.50	1.74	1.90

[a] Beaches are listed in order from north to south. N = total number of samples; geomean = geometric mean for *E. coli* concentrations of all samples; mean($\log_{10}$) = mean of log-transformed *E. coli* concentrations; SE = standard error of the mean ($\log_{10}$).

the detection limit. Analysis of variance was used for comparing *E. coli* concentrations between years, followed by a Student−Newman−Keuls posthoc test. Multidimensional scaling for a two-dimensional matrix was performed using Euclidean distance measure; stress value reported is Kruskal's stress formula, and R^2 is the proportion of the variance of the data accounted for by corresponding distances. Correlations between beaches were reported as Pearson's *R*. Geographical distance between individual beaches was reported as the linear distance between the center point of each swimming beach as measured using aerial photographs. Pearson correlations were reported for *E. coli* and hydrometeorological variables.

Results

Overall, 63rd Street Beach had the highest mean *E. coli* concentration (2.2 ± 0.04 SE MPN/100 mL; geometric mean=140), significantly higher than all other beaches (Table 1). Beaches with the lowest mean *E. coli* concentrations were Ohio, Rogers, Jarvis-Fargo, Hartigan, and 49th Street. Generally, beaches along the southern coast were among those with higher mean *E. coli* counts; notable exceptions were the high means at Thorndale and Montrose beaches and a low mean concentration at 49th Street.

E. coli concentrations were highest in 2004, with a mean of 2.12 MPN/100 mL ± 0.014 SE (geometric mean = 86), and lowest in 2002, with a mean of 1.65 log MPN/100 mL ± 0.02 SE (geometric mean = 44). With the exception of 2004, mean *E. coli* concentrations increased monthly, with an increase from May to August. In 2004, *E. coli* concentration was higher in July than in August.

Multidimensional scaling based on Euclidean distance was used to compare *E. coli* concentrations among beaches (see Figure S1 in the Supporting Information). The ordination reveals two groupings that are geographically divided, with beaches north and south of the Chicago River and Navy Pier comprising different groups. MDS stress was 0.095. The northern beaches are tightly grouped together, and among the southern beaches, a loose grouping is apparent, with Calumet and Rainbow most closely related.

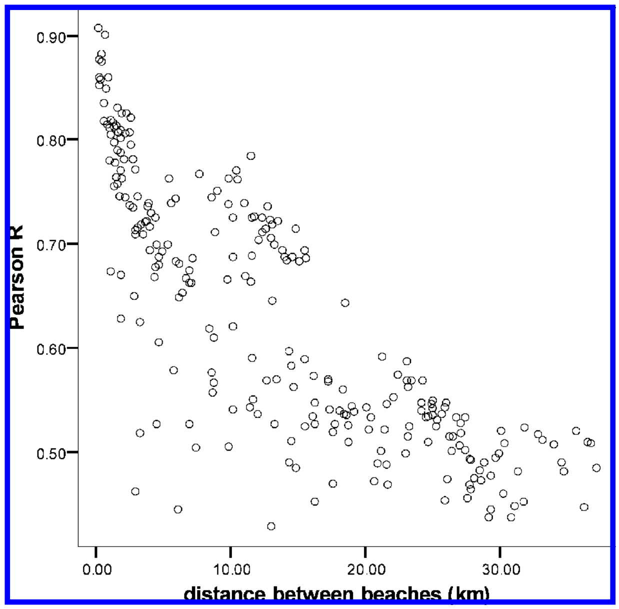

FIGURE 2. Relationship between Pearson correlation coefficient (*R*) for *E. coli* concentrations and geographical distance (km) for each pairing of the 23 Chicago beaches for the years 2000−2005.

A correlation between geographical distance and *E. coli* counts revealed a pattern where Pearson *R* for *E. coli* counts at any two beaches decreased as the geographical distance between the two beaches increased (Figure 2). The relationship was similar when comparisons were limited to northern or southern beaches alone, which provides support for the multidimensional scaling groups.

Fluctuations among beaches over time revealed similar peaks and troughs in *E. coli* concentrations: the extreme highs

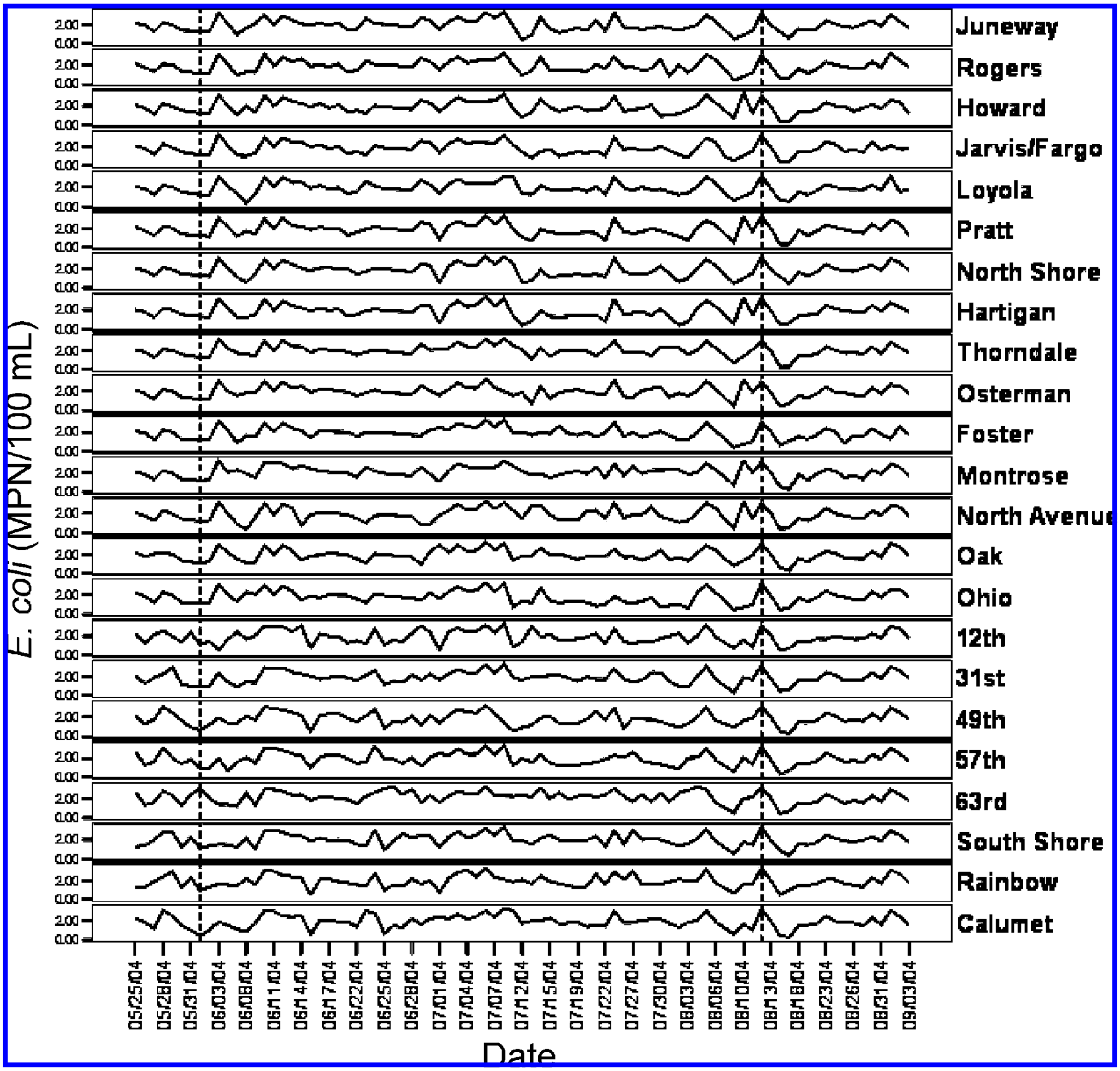

FIGURE 3. Log *E. coli* concentrations (MPN/100 mL) at each of Chicago's 23 beaches over the summer of 2004. Dashed lines on 6/1/04 and 8/12/04 highlight the similarity in peaks and troughs for *E. coli* concentrations at all of the study beaches.

and extreme lows were simultaneous for most beaches (Figure 3). A repeated measures analysis resulted in significant differences among beaches ($F = 3.579$, df = 22, $P < 0.001$); without 63rd Street, Montrose, and Thorndale in the analysis, there was no difference among beaches ($F = 1.145$, df = 19, $P = 0.298$). A Fourier analysis indicated that there was no temporal periodicity in *E. coli* counts beyond the individual sampling date for neither the individual beaches nor the aggregated *E. coli* data set.

Several hydrometeorological parameters were significantly correlated with *E. coli* counts, including wind speed, air temperature, and cumulative rainfall. Of all the parameters measured, wave height had the closest correlation with *E. coli* counts ($R = 0.530$, $P < 0.001$). Colinearity among variables was examined and none was found.

Because there was spatial correlation among beaches (Figure 2), each beach was individually regressed. Using AIC (Akaike's Information Criterion), Z-standardized wave height, Julian Day and barometric pressure were consistently selected as significant predictors of *E. coli* concentration for all beaches. Further examination of these data showed that there was general first order temporal correlation among the dependent variable, with 14 of the 23 beaches failing to reject Bonferroni-adjusted Durbin-Watson test statistics. To avoid time-dependent correlation, only odd calendar days were used in regression analyses. Durbin-Watson testing inferred autocorrelation for only 2 of the 23 beaches examined.

A linear regression analysis was conducted for each beach using the entire 2000–2004 data set to determine how well *E. coli* counts could be explained; using AIC, wave height, barometric pressure, and Julian day were selected as significant independent variables ($p < 0.05$). After adjustments for spatial and temporal correlations these regressors continued to show significant contribution ($p \leq 0.05$) to least-squares regression modeling by beach (Figure 4). Adjusted coefficients of determination (adj. R^2) ranged from 0.20 (SE = 0.54) to 0.41 (0.68), with an overall median of 0.31 (0.60).

Discussion

Chicago's location on Lake Michigan is an important asset to the city, providing aesthetic, economic development,

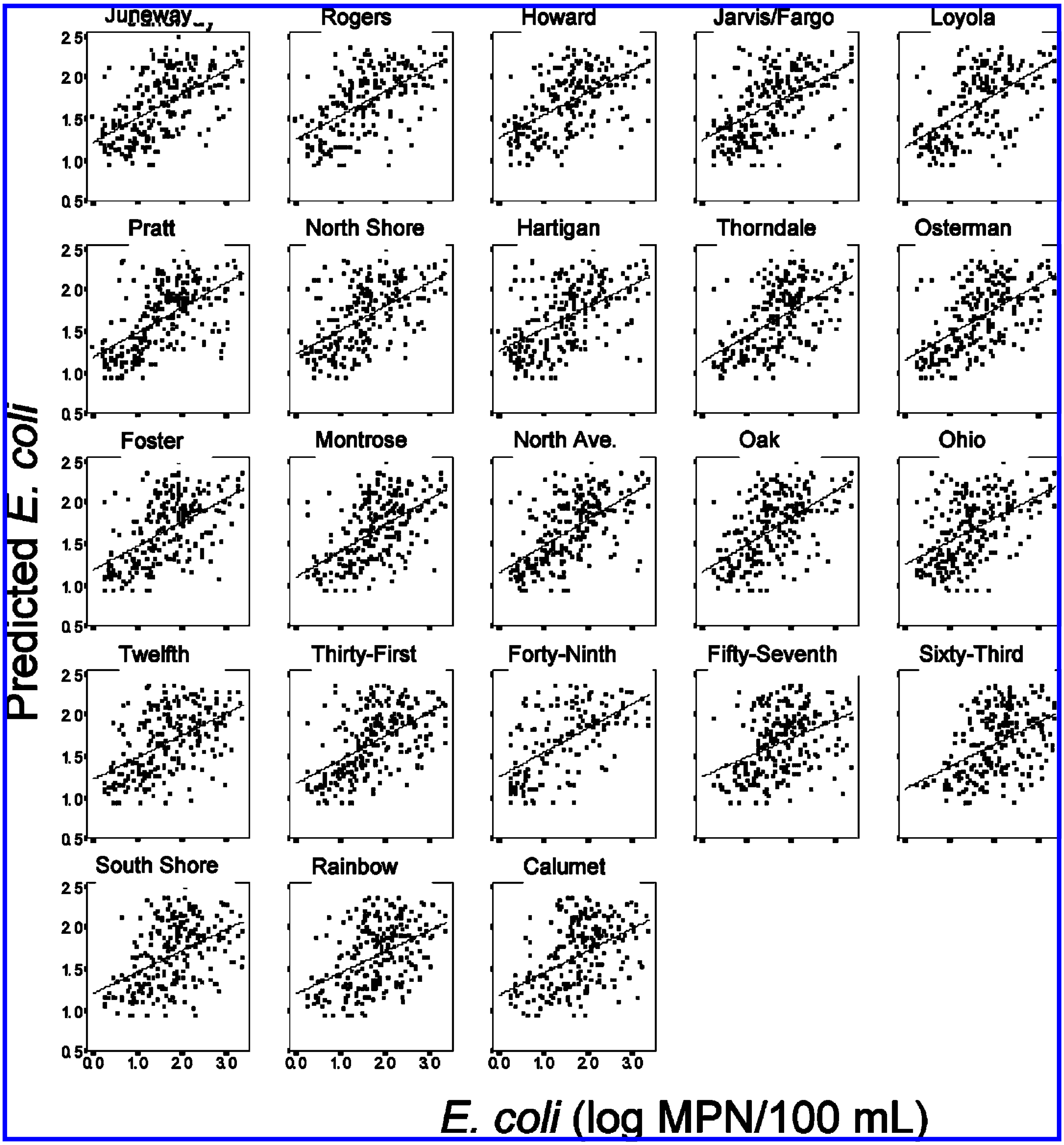

FIGURE 4. Measured *E. coli* concentration (log MPN/100 mL) vs *E. coli* concentration as predicted by regression model. Regression model used Julian day, barometric pressure, and wave height to predict *E. coli* concentration for a given beach on a given day.

shipping, drinking water, and recreational opportunities. During the summer, Chicago's lakefront beaches provide a recreational outlet for thousands of tourists and residents, so management of these beaches is a high priority for the city. Of recent and primary concern is maintaining recreational water quality conditions to protect public health.

A large portion of the waterfront in Chicago has been reserved for beach use, but because of the prevailing longshore current and heavy urban development, sand must be retained by a series of breakwaters, which generally face north, to prevent erosion of the beaches. In some instances, most notably 63rd Street and Montrose, the breakwaters may effectively trap contamination that is moving along the coast with the current or they may help retain contamination at the swimming beaches that originates from terrestrial sources (e.g., beach sand, runoff) (*20*).

Among all beaches, *E. coli* concentrations exhibited similar fluctuations over time, with extreme high concentrations often associated with considerable rain events and similar decreases following peaks. The similarity in responses indicates that most beaches are likely not impacted by discrete and acute contamination sources (e.g., failing infrastructure, point sources). The lack of common response at 63rd Street, Montrose, and Thorndale may be a result of beach orientation, physical structures, or circulation patterns. *E. coli* concentrations at 63rd Street beach in particular are greatly influenced by the presence of breakwaters that enclose the swimming area and cause embayment conditions (*10*). Montrose has a similar substantial breakwater system. The prevailing long current carries suspended materials south, and the breakwaters likely trap these materials in the near-beach areas; this scenario may be amplified at 63rd Street

Beach where runoff from the rest of the city can accumulate in this shallow beach system.

The division between north and south beaches was characterized by higher concentrations of *E. coli* that were associated with south Chicago beaches. The Chicago River outlet and locks are situated between these two groups of beaches, along with an extensive series of associated breakwaters and a large pier (Navy Pier). Without flow from the Chicago River to the lake, it seems that point-source plume dynamics cannot be used to explain the north−south divide.

Despite the absence of a major river point source, individual beaches in Chicago are subject to presumably significant amounts of surface runoff, which is directed to drains emptying into the nearshore beach water, as witnessed by the authors. Surface runoff from impervious surface areas has been identified as a potential significant source of indicator bacteria to receiving waters in other locations (*21, 22*). During rain events, stormwater typically contains significantly higher concentrations of indicator bacteria (*2*), so despite the absence of contributions from sewer overflows, but for extraordinary circumstances when the locks are opened, nonpoint stormwater likely is a significant contributor of bacteria to Chicago's beach water.

Hydrometeorological Factors. Among the three variables included in the resulting empirical model, wave height is often included in predictive models for the Great Lakes (*11, 13, 23, 24*). High waves often result in higher concentrations of *E. coli* in the water because they resuspend bacteria-laden beach sand (*4, 25, 26*), stranded algae (*5, 6*), and fecal material from shorebirds and other wildlife (*27*). This effect is magnified during seiches, when additional swash area may be included in resuspension. Two predictive models were previously developed for Chicago's 63rd Street beach, one of which included wave height using both conventional multiple regression (*28*) and another that did not include it (*29*). Accounting for differences due to time of day and depth of water distinguished the two models, with wave height included in the model that used *E. coli* data collected at 1300 h in 90 cm of water when wave action had increased for the day. The model that excluded wave height combined *E. coli* and wave data collected at 0700 h and 1300 h and samples collected in 45 and 90 cm of water. Increased wave heights may occur in association with storm conditions, which are often related to a shift in barometric pressure. While winds are closely associated with wave height, they are only one of the factors that affect very near shore wave height. Fetch, bottom contours, internal waves, cross currents, vertical wind components, and antecedent conditions also play into wave characterization. Although wind speed, direction, wave height, and barometric pressure are interrelated, these variables were not critically collinear (variance inflation factor = 1.04−1.06), providing further support for wave height's usefulness in predictions.

The inclusion of day of year as a variable is likely the result of the increase in mean *E. coli* counts as the summer progresses, a characteristic also seen at other locations (*30*) but as yet unexplained. Noble et al. (*31*) and Wait and Sobsey (*32*) have demonstrated that fecal indicators survive longer in cooler water temperatures. In contrast, our data show a positive relationship between culturable *E. coli* counts and temperature. Seasonal changes may be due to decreasing solar intensity or changes in rainfall but remain unexplained in this analysis.

Previous research has shown the large variability in *E. coli* concentrations over the course of days (*23*), hours (*10*), or minutes (*33*), so the autocorrelation between days might seem counterintuitive. Certain beaches, however, can exhibit some "memory" where *E. coli* concentrations fluctuate more gradually. For Chicago beaches, it may be that in the event of extreme high *E. coli* concentrations, it takes more time to return to baseline conditions. Similarly, low concentrations may be maintained for long periods of time.

In geographic comparisons, regression coefficients for northern beaches tended to have higher coefficients (slope) for both day of year and pressure; coefficients for wave height were highly variable between beaches, and the pattern was not as geographically defined. The higher coefficients at northern beaches may indicate beaches that are more reactive to storm events (pressure) or seasonal changes (day of year). Many northern beaches are situated at the ends of streets and have few obstacles for the longshore current, which may result in abrupt increases in *E. coli* followed by equally rapid decreases. South Chicago beaches have numerous breakwaters, and they are also situated where the coastline begins to curve more sharply to the east, which may promote bacterial settling and slower return to baseline levels after an extreme weather or bacteria event. The scatter of actual vs predicted *E. coli* concentrations supports this theory in that higher overall concentrations are apparent at the southern beaches. Points were generally more tightly grouped for the south beaches, with the exception of 49th Street. This indicates that variation was lower at the southern beaches, consistent with more gradual fluctuations.

Empirical modeling has been used recently as a timelier means of monitoring water conditions for recreational swimming, and these models have incorporated a limited length of beach shoreline. Although the regional model developed in this exercise can explain a similar amount of variation in the *E. coli* population as models developed for individual beaches, the intention was not to develop an alternative monitoring tool but rather to highlight similarities in *E. coli* fluctuations among region-wide beaches. For Chicago, the proximity and the apparent similarity of responses to ambient conditions, and perhaps a common contaminant source, make it possible to include a long extent of shoreline.

Components of Variation. Earlier studies have highlighted the large variation inherent in fecal indicator bacteria concentrations at swimming beaches, even over very small distances (*34*) and short time periods (*35*). In a study at Chicago's 63rd Street Beach, estimates were made that for 80% precision, up to 54 samples would have to be collected to include the variation across the beach length (400 m) (*34*); that beach has noticeably high variation, and concentrations fluctuate widely. Studies at Huntington Beach in California have shown wide variation in fecal indicator bacteria over time periods of less than an hour (*35*). In the current study, the time and distance over which comparisons were made are orders of magnitude greater than the ones cited, and yet spatial and temporal patterns are evident and variation remains comparable among beaches. For spatial variation, correlation coefficients increase with decreasing distance between beaches (Figure 2). For temporal variation, there were similar fluctuations in *E. coli* concentrations (Figure 3), indicating that the variation at these beaches is similar and likely lower than seen at 63rd Street Beach in a previous study (*34*).

Using the data presented in this paper and additional papers that explored components of variation in indicator bacteria, we attempted to partition variation spatially and temporally. The empirical regression model developed in this paper was able to describe about 31% (between 20 and 40% for each beach) of the variation in *E. coli* concentrations using three variables. We performed a general linear model variance component analysis on data collected in 2004 using the Minque approach (*36*). Days (visits) were random effects while beaches were treated as fixed factors. Dates among beaches explained 36% of that remaining variation according to an assessment of variance components using standardized values. Effects of date of sampling were far more important than beach effects. An analysis of homogeneity of variance on the *E. coli* data resulted in a similar outcome, with no difference in variance among beaches. This result supports the pattern of similarity in daily fluctuations previously discussed (Figure 3) and strengthens the regional approach to characterizing *E. coli* concentrations. Smaller scale variation in *E. coli* counts attributable to effects within beaches was examined using a data set from 2000 for 63rd Street Beach, and the majority of error could again be explained by date (65%). With this data set, additional components were considered, including water depth and time of day, which contributed to 7 and 13% of the error when nested with date; these estimates incorporate the error associated with replicates from a single location.

Sources of *E. coli* variation within the Great Lakes basin are nested, and error decreases as time and space intervals converge. Hierarchically, the replicate error is nested within beach strata or intrabeach variation (*34*). This, in turn, is a component of interbeach comparisons of a given area. While the delineation of the terms "area" and "region" are relative, here we use region to describe a relatively large spatial expanse that has common landscape features such as the Chicago (the present paper) or Indiana (*14*) regions vs a smaller area such as eastern Lake County, Indiana (*23*), eastern Lake St. Clair (*37*), or central Cleveland (*13*). Temporal variation further superimposes itself on spatial variation and is obviously autocorrelated, at least within strata (*20, 35*). Coastline variation of *E. coli* across an entire lake is rarely studied and is beyond the scope of this paper, although data assemblages such as Rockwell (*38*) make these analyses feasible. In conclusion, day was the most important component of variation for this data set, more so than beach, depth, or time of day, all of which lends support to the concept of modeling on a regional scale.

Using Regional Models. Because beaches are defined geographically for recreational use, research approaches tend to be limited to characterizing a problem or issue at a beach of interest. This approach ignores the nearshore, lakewide, and meteorological influences that work on an individual beach only as part of a larger region of coastline. The limits to the size of the region that can be considered will depend on the question asked. For Chicago's beaches, their proximity to one another, the urban setting, and the absence of a major point source immediately create a beach grouping. However, these beaches are also part of a larger whole; recreational beaches just north of the Chicago city limits might have *E. coli* concentrations that fluctuate in ways similar to Chicago beaches. At a finer scale, the Chicago beaches vary by morphology; depth; configuration; orientation; debris loading; visitor impact; bird visitation; runoff; and offshore influences such as harbor mouths, offshore breakwalls, and algal mats. All of these factors likely add to the variation among beaches observed in this study, yet it is also clear that the 37 km stretch of coastline has much in common relative to *E. coli* fluctuations. Significant insight for potential contaminant sources, microbiological community composition, and beach management can be gained by considering a study beach relative to the longer coastline: potential sources can be eliminated, community comparisons can be made, and swimming advisories can take into account neighboring beaches.

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Supporting Information Available

Figure depicting multidimensional scaling of *E. coli* concentrations (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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