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Efficacy of monitoring and empirical predictive modeling at improving public health protection at Chicago beaches

Meredith B. Nevers, Richard L. Whitman*

U.S. Geological Survey, Great Lakes Science Center, Lake Michigan Ecological Research Station, 1100 N. Mineral Springs Road, Porter, IN 46304, USA

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ABSTRACT

Efforts to improve public health protection in recreational swimming waters have focused on obtaining real-time estimates of water quality. Current monitoring techniques rely on the time-intensive culturing of fecal indicator bacteria (FIB) from water samples, but rapidly changing FIB concentrations result in management errors that lead to the public being exposed to high FIB concentrations (type II error) or beaches being closed despite acceptable water quality (type I error). Empirical predictive models may provide a rapid solution, but their effectiveness at improving health protection has not been adequately assessed. We sought to determine if emerging monitoring approaches could effectively reduce risk of illness exposure by minimizing management errors. We examined four monitoring approaches (inactive, current protocol, a single predictive model for all beaches, and individual models for each beach) with increasing refinement at 14 Chicago beaches using historical monitoring and hydrometeorological data and compared management outcomes using different standards for decision-making. Predictability (R^2) of FIB concentration improved with model refinement at all beaches but one. Predictive models did not always reduce the number of management errors and therefore the overall illness burden. Use of a Chicago-specific single-sample standard—rather than the default 235 *E. coli* CFU/100 ml widely used—together with predictive modeling resulted in the greatest number of open beach days without any increase in public health risk. These results emphasize that emerging monitoring approaches such as empirical models are not equally applicable at all beaches, and combining monitoring approaches may expand beach access.

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1. Introduction

In recent years, efforts to improve public health protection in recreational swimming waters have focused on obtaining real-time estimates of water quality. Current monitoring techniques rely on the culturing of fecal indicator bacteria (FIB)—such as *Escherichia coli* or enterococci—from water samples, a process that requires an incubation time often in excess of the rate of change of bacteria concentrations in the water (Boehm et al., 2002; Whitman et al., 1999). Because of the lapse in results availability, the public are often either unknowingly swimming in contaminated beach water or are prohibited from

Abbreviations: FIB, fecal indicator bacteria; CFU, colony-forming units; MPN, most probable number; IA, inactive monitoring program model; CM, current model; RM, regional predictive model for all study beaches; IM, individual beach predictive model.

* *Corresponding author*. Tel.: +1 219 926 8336x425; fax: +1 219 929 5792.
E-mail address: mnevers@usgs.gov (M.B. Nevers).

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swimming in water that meets the public health criteria. Efforts have been focused on two means of correcting this shortcoming: shorten the analytical time for the current indicator or find an alternate, faster way to assess water quality. To accomplish the latter, empirical predictive models have been attempted with various levels of success and application.

Predictive models have been suggested by numerous authors as a potential means for minimizing errors in beach closings (Hou et al., 2006; Kim and Grant, 2004; Nevers and Whitman, 2005). These models range from simple models that associate weather conditions with direct bacteria loadings—such as rainfall and associated runoff (McPhail and Stidson, 2009) – to more advanced models that integrate multiple hydrometeorological variables (Kim and Grant, 2004). Model accuracy at predicting FIB concentration depends on beach location, instrument accuracy, wealth of available data, and level of effort, but predictive models can be successfully incorporated into beach management (Nevers and Whitman, 2005). Beaches at which models have been attempted tend to be high profile beaches with heavy visitor use (Boehm, 2007; Hou et al., 2006), directly or strongly impacted by a large point source (He and He, 2008), or having frequent swimming advisories (Olyphant and Whitman, 2004).

The accuracy or success of a given modeling approach has typically been assessed by analyzing the amount of variation in the target FIB explained by the model, the error explained by the model, or the specificity (the percent of false negatives, or type II errors) and sensitivity (the percent of false positives, or type I errors) of the model. The first two calculations determine the accuracy of the model at predicting all FIB concentrations. The third, error-based calculation is used due to the use of a binary approach in beach management policies: beaches are either open or closed to swimming, depending on where the FIB concentration falls relative to a designated standard (acceptable health risk); errors occur when the predicted concentration is not equal to actual concentration. Errors result in either inadvertent exposure of the public to high concentrations of FIB (type II error) or exclusion of swimmers from water that meets the exposure standard (type I error). More type II errors result in more swimmers exposed to high concentrations of FIB and therefore a higher public health risk; decreasing the instances of type II errors is necessary to increase public health protection.

Current water quality standards for freshwater were developed using epidemiological studies and based on historical acceptable illness rate (Prüss, 1998, US EPA, 1986). Within the monitoring guidance, however, some measure of flexibility was provided for beach managers, including choice of application of two mathematical estimates of illness risk, based on the concentration of indicator bacteria (US EPA, 1986). Generally, beach managers have applied the single-sample maximum for an individual water sample because of its ease of use and interpretation (Nevers and Whitman, 2010, US EPA, 1986), but others use the 5-day geometric mean, both of which should theoretically provide equal levels of health protection.

In this paper, we examine four potential monitoring approaches with increasing refinement at 14 Chicago beaches: inactive, current monitoring model, use of one predictive model for all beaches, and use of individual predictive models for each beach. Further, we examine alternate applications of monitoring standards under these four approaches to assess the health and management outcome possibilities. Using historical monitoring and beach attendance data we compare the accuracy of each model with several calculations and also the relative public health protection provided by each of these models. Specifically, we sought to determine whether predictive modeling at Chicago beaches could be used as a monitoring tool to increase public health protection over traditional monitoring practices.

2. Materials and methods

2.1. Study site

Chicago beaches in general are not impacted by a major point source of contamination. Urban sewage is regularly discharged through the Chicago River and a series of man-made or modified canals to the Mississippi River. In events of extreme precipitation, the system override leads to sewage being directed to Lake Michigan (<1 per year); all beaches are then preemptively closed to swimming. Sources of FIB at the Chicago beaches are unknown but likely include beach sand, birds, and algae (Whitman and Nevers, 2003; Whitman et al., 2003). Beaches included in the current study were (from north to south) Loyola, Albion, Hollywood, Foster, Montrose, North Avenue, Oak, 12th Street, 31st Street, 57th Street, 63rd Street, South Shore, Rainbow, and Calumet.

2.2. Beach monitoring data

E. coli monitoring data, measured as most probable number (MPN)/100 ml of water, were obtained from the Chicago Park District for 2000–2004. Beaches were sampled at least five days a week; replicate samples (up to three) were averaged. *E. coli* concentrations above or below detection limits were set at detection limits after determining that occurrences were rare (Boehm et al., 2002; Whitman and Nevers, 2008). Missing data points for individual beaches were calculated; values were estimated from the nearest 6 values (average of three previous and three subsequent readings).

Beach management is a binary decision: if *E. coli* concentration <235 MPN/100 ml, the beach is open for swimming; if *E. coli* >235 a swimming advisory is issued. This model assumes that *E. coli* concentration today = *E. coli* concentration yesterday. Inaccurate predictions, therefore, result in a type I or type II error (Table 1). Type I errors occur when the model predicts an *E. coli* concentration >235 when the actual concentration is <235, resulting in an unnecessary swimming advisory. A type II error occurs when the model predicts *E. coli* concentration <235 when the actual concentration is >235, resulting in swimmers being exposed to high concentrations of indicator bacteria and associated pathogens. A simple characterization is that type I errors are associated with economic losses because swimmers are denied access and type II errors are associated with greater public health risk, as swimming occurs in the presence of excessive FIB concentrations (Rabinovici et al., 2004).