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Research article

Implementation of an automated beach water quality nowcast system at ten California oceanic beaches

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ABSTRACT

Fecal indicator bacteria like *Escherichia coli* and enterococci are monitored at beaches around the world to reduce incidence of recreational waterborne illness. Measurements are usually made weekly, but FIB concentrations can exhibit extreme variability, fluctuating at shorter periods. The result is that water quality has likely changed by the time data are provided to beachgoers. Here, we present an automated water quality prediction system (called the nowcast system) that is capable of providing daily predictions of water quality for numerous beaches. We created nowcast models for 10 California beaches using weather, oceanographic, and other environmental variables as input to tuned regression models to predict if FIB concentrations were above single sample water quality standards. Rainfall was used as a variable in nearly every model. The models were calibrated and validated using historical data. Subsequently, models were implemented during the 2017 swim season in collaboration with local beach managers. During the 2017 swim season, the median sensitivity of the nowcast models was 0.5 compared to 0 for the current method of using day-to-week old measurements to make beach posting decisions. Model specificity was also high (median of 0.87). During the implementation phase, nowcast models provided an average of 140 additional days per beach of updated water quality information to managers when water quality measurements were not made. The work presented herein emphasizes that a one-size-fits all approach to nowcast modeling, even when beaches are in close proximity, is infeasible. Flexibility in modeling approaches and adaptive responses to modeling and data challenges are required when implementing nowcast models for beach management.

1. Introduction

Beach water quality is measured around the world to protect beachgoers from exposure to waterborne pathogens. Total and fecal coliforms, *Escherichia coli* and enterococci are fecal indicator bacteria (FIB) that are typically used to assess water quality. Epidemiology studies show that exposure to recreational waters contaminated with FIB from wastewater and urban runoff correlates with risk of diarrheal illness, respiratory disease, and skin ailments (Arnold et al., 2016; Colford et al., 2007; Haile et al., 1999; Wade et al., 2003; Yau et al., 2009, 2014). In the United States, 3943 beaches are monitored for FIB each year (USEPA, 2018). If concentrations exceed regulatory guidelines, then the beaches are posted as unfit for swimming or closed. Poor beach water quality not only affects the health of beachgoers, it also has large economic costs to surrounding communities (Rabinovici et al., 2004). In Southern California, Given et al. (2006) estimate that there are up to 1.5 million illnesses each year attributed to poor water quality at beaches costing as much as $51 million. Nationally, DeFlorio-Barker et al. (2018) estimate 90 million illnesses and costs of $2.2- $3.7 billion annually.

Analytical methods for detecting FIB require growing bacteria using selective microbiological media (USEPA, 2006, 2002). The methods take approximately 24 h in order to allow the bacteria to grow. Therefore, there is at least a 1 day lag between the time a water quality sample is collected and the result is obtained. Beach management decisions (posting or closing a beach) and public notification of water quality is therefore based on at least a 1 day old measurement (Kim and Grant, 2004). At most beaches, water samples are collected approximately weekly so that management decisions and public notification are based on even older measurements. It is well understood that FIB concentrations vary at periods smaller than a week, and smaller than a day (Boehm et al., 2002). Day-to-day changes in FIB sources, wind, tides, solar intensity, and rain, for example, may affect beach FIB concentrations (Hou et al., 2006; Jennings et al., 2018; Jovanovic et al.,

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2017; Laureano-Rosario et al., 2017; Nevers and Whitman, 2005; Thoe et al., 2015). Studies at marine beaches along the California coast have shown that FIB concentrations can even vary from minute-to-minute due to mixing processes in the coastal ocean, and the resultant patchiness of FIB contamination (Boehm, 2007).

Molecular methods such as quantitative PCR (QPCR) can be used to measure FIB concentrations at beaches (Haugland et al., 2005; Shanks et al., 2012) and have been proposed as a means to overcome the 1 day lag associated with culture-based method. QPCR methods can take a few hours to obtain results, however, when water sample collection and transport from the field to the laboratory is included, the total time is longer. US ambient water quality criteria allow for measurements of FIB by QPCR to complement measurements made by culture-based methods (USEPA, 2012). Although QPCR may provide water quality data for the same day the water is sampled, its not clear whether the data would be available in time for public notification that day. Additionally, as water samples are typically collected weekly, QPCR cannot provide information on water quality on days when a sample is not collected. On the other hand, FIB models can be used to provide predictions of water quality, even on days when a water sample is not collected.

FIB models can augment FIB measurements at beaches to overcome some of the problems associated with the use of FIB to make management decisions (Boehm et al., 2007; Frick et al., 2008; Hou et al., 2006; Nevers and Whitman, 2005; Thoe et al., 2015). Although process-based models that consider advection, dispersion, and non-conservative processes associated with FIB fate and transport have been developed and tested (Liu et al., 2006; Russell et al., 2013), they usually cannot provide the level of accuracy required for use in day-to-day beach management (Boehm et al., 2007). This is partly due to the uncertainties associated with FIB sources, lack of understanding of FIB fate in the environment, and difficulties parameterizing non-point FIB sources and fate processes within a model (Nevers and Boehm, 2010). Statistical models which take advantage of the correlative relationships between FIB and environmental variables, on the other hand, have been successfully used to develop FIB models that can accurately predict water quality standard exceedances (Avila et al., 2018; Boehm et al., 2007; Brooks et al., 2016; Francy, 2009; Frick et al., 2008; Gonzalez et al., 2012; Nevers and Whitman, 2005; Park et al., 2018). The USEPA supports the use of predictive models to supplement FIB measurements at beaches for public notification of water quality (USEPA, 2012).

Statistical FIB models have been used for beach management in the US (Great Lake beaches in Michigan, Ohio, and New York) (Francy, 2009; Francy et al., 2013), the UK (Crowther et al., 2001), and Hong Kong (Thoe and Lee, 2014). Multiple linear regression (MLR) models are used in these programs. Our previous work explored the ability of statistical FIB models to accurately predict beach water quality at California beaches (Thoe et al., 2014, 2015). We previously tested a variety of model types for their ability to accurately predict exceedances of the California single-sample standards for total coliform, fecal coliform, and enterococci at 25 California beaches. The results of those studies showed that the classification tree and tuned binary logistic regression (BLR-T) models best predicted whether beach water quality exceeded state single sample standards (SSS), and that these models' predictions were more accurate than the "current method" of using day-old or older measurements to make management decisions (referred to as the "persistence method" by some authors (Brooks et al., 2016; Francy et al., 2013)). Our previous work showed that accurate models could be created for most of the 25 beaches but that for a few, we could not find models that could be validated. Possible reasons for this include inter-annual trends in FIB concentrations that might result from changes in beach-specific infrastructure (installation of a new runoff diversion system for example), non-linear changes in climatic variables (for example, prolonged periods of rainfall, punctuated by drought or vice versa), or the stochastic, intermittent nature of FIB sources (Thoe et al., 2015).

In the present study, we develop and test an optimized variation of the MLR model– the tuned multiple linear regression model (MLR-T). This particular model type was not considered in our previous work. We also introduce a range of methods to partition historical data for model calibration and validation to create the best performing model. After identifying the best performing models, we created a custom Python code to actually implement the models for beach management during the 2017 summer swimming season at 10 California beaches, in collaboration with local beach managers. Model concentration predictions were compared against the California single sample FIB standards as outlined in the California Ocean Plan (10,000 most probable number (MPN)/100 ml total coliform, 400 MPN/100 ml fecal coliform, and 104 MPN/100 ml enterococci) to determine if a standard was exceeded and if a beach should be posted as unfit for swimming. During the implementation phase of the project, results were provided to beach managers and posted online before 10:00 h, 7 days a week. The three phases of the work (calibration, validation, and implementation) carried out with beach-specific MLR-T models set the present study apart from previous studies. We document the accuracy of the models and outline the successes and challenges to implementing a coast-wide California beach nowcast system. Overall, this study emphasizes that a one-size-fits all approach for creating nowcast models is infeasible, even when beaches are located in close proximity, and also that flexibility and adaptability is needed when implementing the models for beach management.

2. Methods

2.1. Overview

Ten beaches were chosen for the study. Historical FIB and environmental data were obtained for the beaches and divided into calibration and validation data. Models were calibrated and then validated using data to which they had not previously been exposed. The best performing models were chosen for each FIB at each beach and then used for actual beach management during the 2017 swimming season (referred to as the implementation phase). Model performance was evaluated using sensitivity and specificity metrics and compared to performance of the current method for beach management that uses day-to-week old measurements to estimate beach water quality. The modeling process is outlined in Fig. S1.

2.2. Beach selection

The 10 beaches were selected based upon their popularity among beachgoers and support for participation in the program among local beach managers (Fig. 1; each beach is denoted by a two letter abbreviation as shown in the figure). We included a variety of different beach types including those that were typically open ocean beaches, beaches with piers, and beaches with a drainage outlet. Nine of the beaches are located in Southern California; CB is located in Northern California. The 10 beaches are managed by 6 distinct local beach managers.

2.3. Historical data

Historical data collected between 2008 and 2016 during the swimming season (April through October) was used to calibrate and validate models. FIB concentrations (total coliform, fecal coliform, and enterococci), as well as the time of day and date the sample was collected, for the 10 beaches were obtained from the Heal the Bay database. Samples were collected on different days of the week including weekends, at all beaches. The database is constructed from data provided by local beach managers. If sample time was not available for a particular sample, the average sampling time at the beach (as stated by the beach manager or computed) was used. FIB data were measured using State-approved methods including IDEXX Coliert-18 and