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State of Science

New recreational water testing alternatives

By Kurt Kesteloot, Azliyati Azizan, Richard Whitman, and Meredith Nevers

Abstract: Each year recreational water users descend on national parks by the millions. U.S. Environmental Protection Agency (EPA) regulations require monitoring waters for fecal indicator bacteria in order to safeguard human health, and obtaining results using the culturing method takes 18 hours or more of analytical time. Thus, under this surveillance regime swimmers can be exposed to waterborne disease organisms before health advisories can be issued. To address the need for timelier notification of recreational water quality, the EPA has evaluated and approved new and faster testing methods as of November 2012. This article discusses new recreational water testing methodologies such as qPCR, empirical predictive modeling, rainfall threshold levels, and advanced notification options for park managers to consider and tailor to their needs.

Key Words: advanced notification, empirical predictive modeling, qPCR, rainfall threshold levels, recreational water testing, water-quality testing

Introduction

Elevated levels of fecal indicator bacteria (FIB) such as Escherichia coli (E. coli) and enterococci can indicate the presence of pathogenic microorganisms, leading to health risk concerns for recreational areas along lakes, rivers, and oceans. These pathogens can cause a variety of illnesses in humans, including gastrointestinal illnesses, rashes, and eye infections. The U.S. Environmental Protection Agency (EPA) regulations provide standards for FIB levels in recreational waters that guide health advisory decisions. Until they were revised in November 2012, EPA-approved methodologies for monitoring FIB were relatively slow in providing results to health officials and recreational water users, typically 18–24 hours after sampling (Brady et al. 2009). According to the USEPA (2012), there is no scientific evidence supporting beach water quality determinations based on, at best, day-old (culture-based) data. Thus, health advisories or beach closures are usually issued many hours after visitors may have been exposed to potential pathogens and have since left the area.

USGS/Meredith Nevers

A technician samples water from a swimming area adjacent to Indiana Dunes National Lakeshore. New analytical methods allow for near–real time test results of water quality and better protection of public health.

Since the EPA recreational water FIB limits were established in 1986, faster methods have been developed; however, until recently, they were prohibitively expensive, complicated, unproven, and pending approval for protecting public health (USEPA Office of Water 2003; USEPA 2006). The National Park Service (NPS) monitors recreational water quality according to the EPA standards and for more than a decade, along with federal and other scientists and public health officials, has raised concerns that the lag time of standard reporting methods places water recreators at unacceptable levels of risk for waterborne disease outbreaks. However, in November 2012 the EPA revised its recreation water quality testing standards, allowing park and recreation area managers to begin to incorporate some of the newer, more effective testing methods that we review in this article into their operations.

Background

Congress enacted the BEACH (Beaches Environmental Assessment and Coastal Health) Act in 2000, amending and strengthening the Clean Water Act with respect to recreational water quality. Section 304 stated that within five years of the BEACH Act enactment, new or revised water quality standards for pathogens and pathogen indicators should be developed to better protect human health in coastal recreational waters. It also stipulated that within three years of revision to Clean Water Act section 304, states and tribes with coastal waters must adopt new or revised water quality standards applicable to changes in section 304 pathogen reporting. It further encouraged the continuing development of accurate, timely, and cost-effective methods for modeling and analyzing recreational water for pathogens harmful to human health (USEPA Office of Water and Office of Research and Development 2007).

Prompted by BEACH Act provisions, the EPA, Centers for Disease Control, local health departments, and many others collaborated on the National Epidemiological and Environmental Assessment of Recreational Water (NEEAR) and other studies to evaluate real-time recreational water testing techniques. Microbiological methods were tested for enterococci, Bacteroides, and alternate fecal indicator organisms. The methods were further assessed for specificity and sensitivity, their ability to reduce detection levels below the 1986 EPA enterococci limit, and the validity of data derived from samples that have endured long holding times. Alternate monitoring approaches were also explored, such as determining which hydrometeorological or chemical factors could predict FIB concentrations in swimming water. Among these, empirical predictive models (statistical models) were identified as especially promising (USEPA Office of Water 2011).

This article highlights the current developments and needs for a cost-effective, timely monitoring technique to protect swimmers' health in coastal waters. We review the recently revised federal criteria for safe swimming and discuss approaches the beach manager can use to combine or adapt methods for more accurate, site-specific application. We analyze and summarize four methodologies (see table 1) because they appear to be the most viable options that are now available for testing recreational water in a timelier fashion.

New methodologies

The qPCR Method

Quantitative polymerase chain reaction (qPCR) is used in recreational water applications to detect Bacteroides or enterococci in water samples by identifying a particular signature genetic marker. When testing for enterococci, qPCR is more than 85% accurate in correctly identifying EPA-approved FIB levels (SCCWRP 2010). Figure 1 illustrates the correlation between incidences of reported swimming-related gastrointestinal illnesses and the average daily enterococcus values as measured using qPCR. Results of analyses for enterococci using qPCR do not typically match culturable bacteria counts: qPCR enumerates both live and dead bacteria. Studies have shown high correlations between qPCR and culturable counts, however, and studies in both marine and freshwater have revealed that public health protection decisions would be similar if time were not a factor (SCCWRP 2010; Whitman et al. 2010). However, the largest difference between the analytical techniques is that qPCR results can be obtained in just three to four hours, making it far timelier than culturable counts. In extensive epidemiological studies conducted by the EPA (NEEAR study) to test the use of qPCR for predicting illness of swimmers potentially exposed to point sources such as wastewater effluent, there was a significant correlation between incidences of gastrointestinal illnesses in swimmers and enterococcus levels as identified through the qPCR testing method. One study location at Indiana Dunes National Lakeshore (West Beach) showed a significant relationship between qPCR and the number of illnesses contracted by visitors (USEPA Office of Water 2010a).

The initial cost of a qPCR system is $30,000–$50,000, and the cost of each individual test ranges from $8 to $15. Use of qPCR also requires training for lab personnel to process and analyze results. Expensive initially, use of qPCR testing becomes more cost-effective as more tests are performed. The EPA has developed and validated a molecular testing method with qPCR, which is a rapid analytical technique for the detection of enterococci in recreational water (EPA Method 1611). Accordingly, it encourages federal and state agencies responsible for water quality monitoring to perform site-specific condition assessments before adopting statewide standards for FIB recreational water quality monitoring via qPCR. Agencies interested in developing site-specific water quality standards using qPCR will find a detailed discussion of EPA recommendations at http://water.epa.gov/scitech/swguidance/standards/criteria/health/recreation/upload/factsheet2012.pdf.

Empirical predictive models

Commonly referred to as statistical models, empirical models can offer accurate and timely determinations of FIB levels in recreational waters. Physical, chemical, and meteorological conditions are commonly analyzed for statistical correlation with FIB and often include wind speed and direction, current magnitude and direction, tide or moon phase, river flow and stage, lake stage, groundwater levels, and physical location of the recreational area (USEPA Office of Water 2010b). Turbidity is a commonly used physical characteristic for approximating FIB, and can be measured instantaneously with a sensing probe. If an analysis of turbidity and bacteria levels reveals a statistically significant correlation between the two, then a single turbidity sensor reading can be used to signal unhealthy recreational water conditions. These empirical predictive models can be developed using single or multiple parameters, providing a robust prediction of real-time water quality (Nevers and Whitman 2005). Hydrodynamic models have been developed, but use and validation are trailing the traditional multiple linear regression models currently in use.

Since 2002 the National Park Service has based its health advisories for the Chattahoochee River National Recreation Area (NRA), Georgia, on empirical predictive models that correlate turbidity with E. coli and total coliform counts (USGS 2002). As shown in figure 2, some locations have a stronger correlation (r value) of turbidity to bacteria than others. At Chattahoochee River NRA, the r value between turbidity and E. coli ranged from 0.12 to 0.88, while the r value between turbidity and total coliform ranged from 0.28 to 0.76. An r value nearing 1.0 indicates a strong relationship between the data, while a value at or near 0.0 indicates little or no relationship between the sets of data compared. Therefore, in some locations at Chattahoochee NRA, turbidity levels provide a better indication of the amount of E. coli in the water than does total coliform.

Cuyahoga Valley National Park (Ohio) has also evaluated a similar model comparing turbidity and E. coli levels in the water. The model delivered promising results in 2009 at the Jaite site on the Cuyahoga River by correctly identifying unsafe levels of E. coli 81% of the time compared with traditional culture-based EPA testing methods. At a nearby river location called Independence, this same model also correctly identified unsafe E. coli levels 91% of the time, as opposed to 88% using the traditional method. However, results for other locations were not as accurate, with percentages in the low 70s for the model and low 80s for traditional methods (Brady et al. 2009). In 2011, one application of the turbidity-based model deemed the water safe when actually it tested poor using traditional methods (USGS Ohio Water Science Center 2011). The big advantage of the turbidity-based model, of course, is that it provided results within one hour, making it timelier than traditional monitoring methods. The EPA looks at empirical predictive models as a support tool for notifying recreational water users, thus there is no official r, R^2, or percentage comparison that is accepted that allows sole use of an empirical model for notifying and legally monitoring recreational waters.

Likewise, Indiana Dunes National Lakeshore uses predictive models developed by the U.S. Geological Survey (USGS) that assist with determining FIB levels at West Beach in the park and nearby Burns Ditch (Olyphant and Whitman 2004; Nevers and Whitman 2005). Based on the research of Nevers and Whitman (2011), the use of water quality standards specific to a location, combined with empirical predictive models, resulted in the greatest beach access without compromising health protection. However, they found that beach-specific models often incur greater costs than regional models that incorporate multiple beaches (Nevers and Whitman 2008). USGS scientists refined their model by including turbidity results along with many other hydrometeorological variables, such as rainfall, wind speed and direction, wave height, lake stage, air and water temperature, nearby stream discharge, and E. coli loading from nearby streams (Nevers and Whitman 2005). They also correlated their results with qPCR analyses of enterococci levels and found that the revised model more accurately closed beaches than the traditional method, with 95% accuracy in correctly issuing beach advisories. In areas where turbidity models do not work well, qPCR and those models linked to other water quality characteristics or hydro-meteorological variables may prove timelier and more cost-effective. Current models for Portage Lakefront Beach, Indiana Dunes National Lakeshore, yielded highly reliable results (R^2 of 0.7) as opposed to an R^2 of 0.1 using culturing techniques. One of the most current and sophisticated programs of public notification of beach conditions was developed by Nevers and Whitman in collaboration with the Chicago Park District. Three weather stations and seven water quality monitoring buoys gather data and predict swimming conditions continuously, feeding the information to the Internet, smartphones, and managers, keeping everyone abreast of swimming conditions in real time (Hazlett 2011).

The chief disadvantage of modeling is the degree of expertise in modern statistics needed to develop and optimize the performance. To address this problem, the EPA developed software that is highly user-friendly. Virtual Beach 2.0 is a computer program that develops, tests, and ranks multiple linear regression models based on user-specified selection criteria. This allows users to settle on the best model for their application. More information about the program can be found in Zepp et al. 2010 and at http://www.epa.gov/ceampubl/swater/vb2/.

Rain threshold levels

Runoff from rainfall often contains harmful pollutants that may include elevated levels of fecal indicator bacteria. Rainfall thresholds, for example inches of rain in a 24-hour period, are useful indicators of FIB levels at beaches impacted by a river or stream outfall; thresholds can serve as the primary method for identifying when FIB levels are likely to exceed recreational water quality standards. Rain threshold levels are a form of empirical predictive model. The rainfall threshold level is related to the amount and intensity of a rainfall event in a watershed that drains to a specific recreational water area under monitoring. Thresholds are relatively easily determined by analysis of a statistical association between FIB and rainfall levels. California, Delaware, Hawaii, New Jersey, Wisconsin, New York, and Scotland are a few locations that use rainfall thresholds to determine when to post beach advisories (reviewed in USEPA Office of Water 2010b). These alerts often need to remain in effect for 24 hours after the rain event to ensure that water quality returns to acceptable levels for water recreation. The rainfall threshold advisory method has proven effective when rainfall occurs during periods of normal weather or drought, as contaminants build up on land. It is highlighted separately here because it is a cost-effective method for national park units to consider. However, beaches and recreational areas cannot rely solely on this method.

Advanced notification and emerging technologies

The National Oceanic and Atmospheric Administration (NOAA) maintains forecasting models, such as Nowcast, that aid in predicting recreational water quality up to 120 hours in advance. The Nowcast cycle uses surface meteorological data gathered from the National Ocean Service (NOS) Operation Data Acquisition and Archive System (ODAAS). The National Weather Service (NWS), National Centers for Environmental Prediction (NCEP), and National Coastal Ocean Program (NCOP) provide meteorological data to ODAAS from the NCEP's central computer system two times per hour to assist in developing forecasting models (Kelley et al. 2007). Based on models, NOAA's Great Lakes Environmental Research Laboratory has been working to develop specific forecasting methods for Grand River, Michigan (near Grand Rapids), and Burns Ditch, adjacent to Indiana Dunes National Lakeshore. More information on these techniques can be found at
http://www.glerl.noaa.gov/res/glcfs/gh/,
http://www.glerl.noaa.gov/pubs/fulltext/2007/2007tmNOS_CS8.pdf, and
http://www.glerl.noaa.gov/res/glcfs/bd/ (USEPA Office of Water 2010b).

The NOAA Human Health Initiative is developing prototypic beach-closure forecasting models. NOAA is attempting to forecast E. coli and enterococci concentrations throughout the Great Lakes using three-dimensional hydrodynamic modeling. Staff compares model results with field data and evaluates the ecological consequences of model simulations under varied weather and FIB loading conditions (NOAA CEGLHH 2012). Development of predictive and empirical predictive models along with rainfall threshold levels will help provide for minimal to low-risk recreational water access, and combinations of various types of testing will aid further in the development of real-time, cost-effective notification for recreational water users.

Summary

Development of real-time water quality testing methodologies is an important step toward decreasing health risks for water recreators. The culture-based EPA recreational water testing methodologies in place from 1986 to 2012 determined FIB levels in 18 hours or more, whereas the new FIB testing methods, released by the EPA in November 2012, return results in three hours or less and result in fewer beach closures than traditional methods, without increasing health risks. These new methods and models incur significant start-up costs and greater complexity but provide a means to notify recreators of the public health risks associated with recreational water activities in near–real time, which in itself provides economic benefits as well as health advantages (Rabinovici et al. 2004; USEPA Office of Water 2012). They also give managers more flexibility to tailor their recreational water quality monitoring to best meet their needs.

The array of techniques now available for recreational water quality analysis are a boon to public health safety, but evaluating the trade-offs in cost and other factors creates challenging decisions. Managers may need guidance from scientists and experienced regulators to help choose and implement appropriate management and monitoring strategies. Fortunately, veteran scientists and public health professionals at the Department of the Interior, the EPA, the state level, and universities can provide managers with good information to optimize solutions that protect swimmers and park resources alike and address programmatic feasibility. Organizations such as the Great Lakes Beach Association are another great resource for further information.

The field of recreational water quality monitoring technology has been evolving rapidly, and here we have covered only a few techniques recommended by the EPA. However, several additional methods are now in development and will continue to advance the state of the art. For example, new in situ devices that measure pathogens directly, the use of anthropogenic chemical tracers, molecular markers and arrays, sophisticated computer modeling, dynamic modeling, and longer-scale forecasting are emerging techniques that hold promise. The best news is that technology for evaluating recreational water quality is quickly improving, providing managers with the promise of higher confidence in making the best decisions for the safe, healthy enjoyment of recreational aquatic resources in the National Park System.

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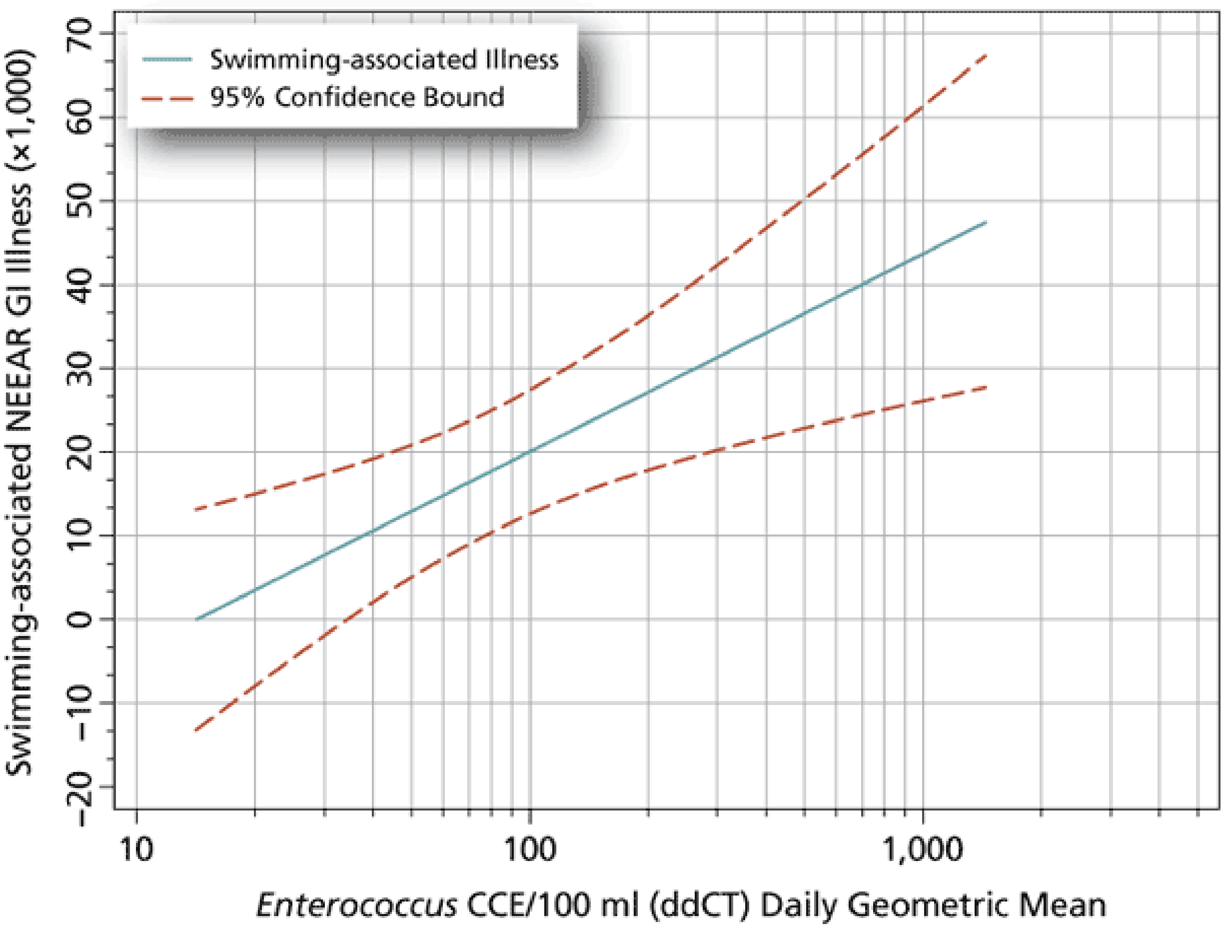


Figure 1. This graph relates the number of swimming-related gastrointestinal illnesses as defined by the National Epidemiological and Environmental Assessment of Recreational Water (NEEAR) study program to the average daily enterococcus qPCR calibrator cell equivalents (USEPA 2012), one of the promising new surveillance methods we review in this article.

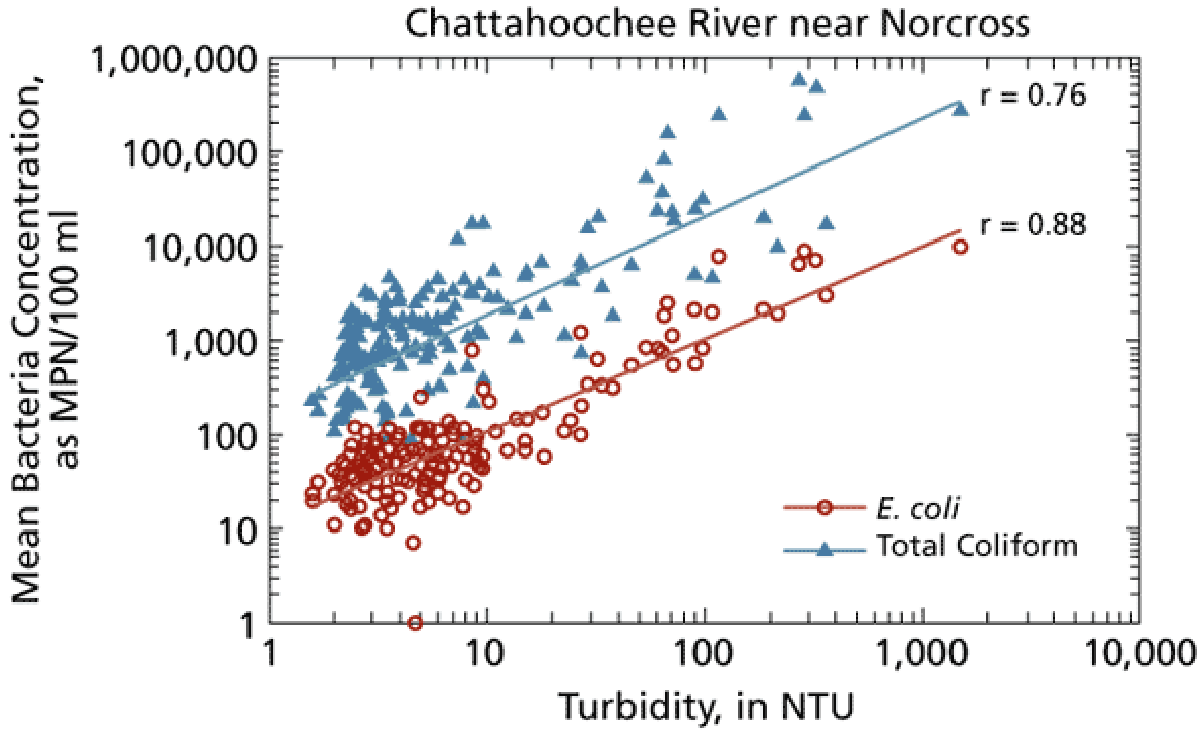
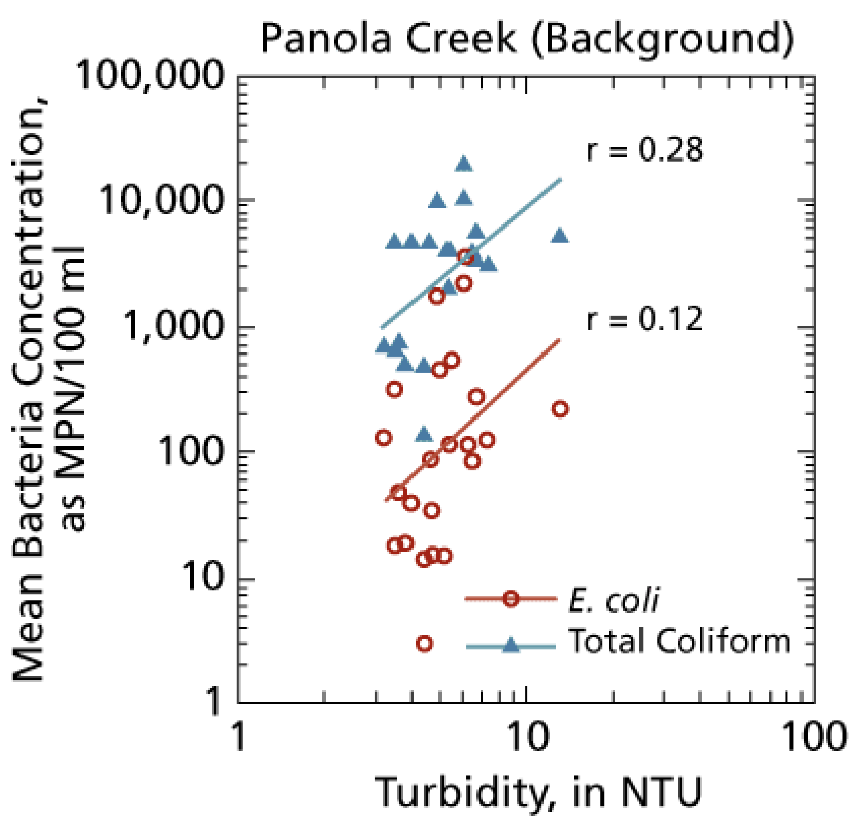


Figure 2. The graphs correlate bacterial counts of E. coli and total coliform at three sites in or near Chattahoochee River National Recreation Area, Georgia, with turbidity levels. The use of water quality standards specific to a location, combined with empirical predictive models, resulted in the greatest beach access without compromising health protection.



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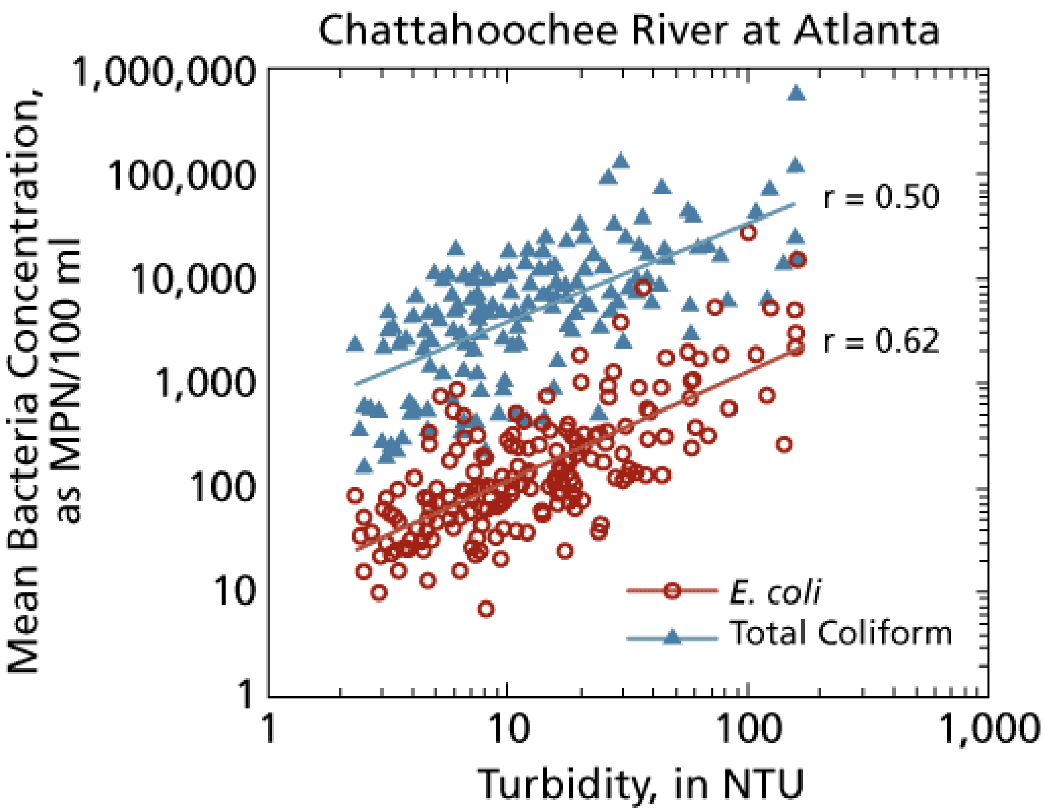

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Table 1. Characteristics of emerging testing methodologies for fecal indicator bacteria

qPCR	Empirical Predictive Models	Rainfall Threshold Levels	Advanced Notification
A rapid gene probe method used to quantify FIB levels; Cepheid Smart Cycler is an example	Tests various water and weather characteristics and develops relationships to FIB levels Resource managers select	Compares rainfall levels over specified durations from different floodplains that drain into recreational waters	Analyzes statistical models, rainfall threshold values, weather predictions, and other data Extrapolates FIB levels for future

of a device that provides means to speed up reactions. Significant setup cost Nominal single-test costs Need for skilled staff with training FIB levels determined in 3 hours or less Applicable to many sites Accepted by EPA with evidence of statistical significance for health effects	most costeffective and statistically representative hydrometeorological characteristic that relates to FIB levels Potential significant development cost Minimal cost for individual tests Need for skilled staff with limited training FIB levels in minutes to hours Typically site-specific Accepted by EPA with evidence of statistical significance	under investigation Relates FIB levels to rainfall Significant cost to develop thresholds Little to no cost for individual tests Staff with little to no training FIB levels in minutes to hours Site-specific Accepted by EPA with evidence of statistical significance	by combining model results Significant development costs for models and correlations Nominal to marginal cost for individual tests Need for skilled staff with limited training Predictive FIB levels Typically site-specific Accepted by EPA with evidence of statistical significance

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