Journal of Water and Health | 07.1 | 2009

A sea change ahead for recreational water quality criteria

Alexandria B. Boehm, Nicholas J. Ashbolt, John M. Colford Jr, Lee E. Dunbar, Lora E. Fleming, Mark A. Gold, Joel A. Hansel, Paul R. Hunter, Audrey M. Ichida, Charles D. McGee, Jeffrey A. Soller and Stephen B. Weisberg

ABSTRACT

The United States Environmental Protection Agency is committed to developing new recreational water quality criteria for coastal waters by 2012 to provide increased protection to swimmers. We review the uncertainties and shortcomings of the current recreational water quality criteria, describe critical research needs for the development of new criteria, as well as recommend a path forward for new criteria development. We believe that among the most needed research needs are the completion of epidemiology studies in tropical waters and in waters adversely impacted by urban runoff and animal feces, as well as studies aimed to validate the use of models for indicator and pathogen concentration and health risk predictions.

Key words | epidemiology, indicators, pathogens, risk, swimming, water criteria

Alexandria B. Boehm (corresponding author)*
Department of Civil and Environmental Engineering,
Stanford University, Stanford, CA, USA
Tel.: 650-724-9128
Fax: 650-725-3164
E-mail: *aboehm@stanford.edu*

Nicholas J. Ashbolt
National Exposure Research Laboratory, Office of Research and Development, United States,
Environmental Protection Agency,
Cincinnati, OH, USA

John M. Colford Jr
Division of Epidemiology, School of Public Health University of California, Berkeley, CA, USA

Lee E. Dunbar
Connecticut Department of Environmental Protection, Hartford, CT, USA

Lora E. Fleming
Departments of Epidemiology & Public Health and Marine Biology & Fisheries, Miller School of Medicine and Rosenstiel School of Marine and Atmospheric Sciences, NSF NIEHS Oceans and Human Health Center, Miami, FL USA

Mark A. Gold
Heal the Bay, Monica, CA, USA

Joel A. Hansel
United States Environmental Protection Agency Region 4, Atlanta, GA, USA

Paul R. Hunter
Medical School, University of East Anglia,
Anglia, UK

Audrey M. Ichida
ICF International, Fairfax, VA, USA

Charles D. McGee
Orange County Sanitation District, Fountain Valley, CA, USA

Jeffrey A. Soller
Soller Environmental, 3022 King St, Berkeley, CA, USA

Stephen B. Weisberg
Southern California Coastal Water Research Project, Costa Mesa, CA, USA

*All authors contributed equally to this manuscript. Authors are listed in alphabetical order with the exception of the first author.

doi: 10.2166/wh.2009.122

INTRODUCTION

Recreational swimming is a popular activity in the United States (US) (Leeworthy & Wiley 2001)–Americans make an estimated 928 million trips to the beach each year (NOAA 2005). Because coastal waters are susceptible to microbial contamination and can serve as a vehicle for transmission of microbial pathogens (NRC 2004), considerable resources are expended to measure microbial water quality at recreational beaches. Nearly 3,000 beaches in the US are tested at least weekly for fecal indicator bacteria (FIB) (Dorfman & Stoner 2007). The requirement for such monitoring was formalized in the Clean Water Act and the Beaches Environmental Assessment and Coastal Health (BEACH) Act (2000) which require coastal states to monitor beach water quality and warn the public when levels of FIB exceed concentrations considered unacceptable for recreational contact. These monitoring programs have identified many beaches of concern and have resulted in some 25,000 days of closures or advisories issued for recreational beaches in 2006 (Dorfman & Stoner 2007) (Figure 1).

Monitoring programs measure FIB using culture-based laboratory techniques, some of which were originally developed over a century ago. The United States Environmental Protection Agency (USEPA) is now poised to revise the decades old recreational water quality criteria. There are new information, technologies and approaches that should be considered in updates to the old criteria and existing monitoring programs.

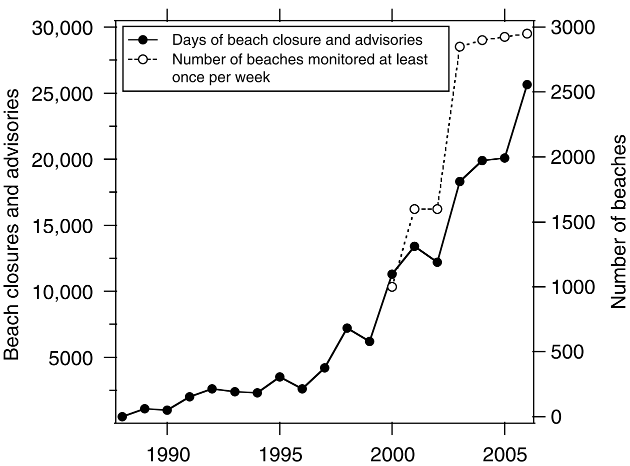

Figure 1 | Beach closures and advisories and the number of beaches monitored in the US as a function of time (Dorfman & Stoner 2007).

The advent of molecular measurement techniques provides the opportunity to greatly expand and improve monitoring programs. Methods which allow measurement of FIB in two hours are in late stages of development, greatly improving upon the 24 hours presently needed for laboratory analysis (Haugland *et al.* 2005; Noble & Weisberg 2005). Many of the same molecular technologies which allow for rapid measurement also provide opportunities for measuring new indicators or pathogens which are presently difficult to measure using laboratory culture techniques. In addition, a number of researchers have identified genetic markers which distinguish between microbial pollution originating from human or nonhuman fecal sources (reviewed by Stoeckel & Harwood 2007). Source identification techniques potentially allow for establishment of source-dependent criteria, as human fecal material is thought to present a greater health risk to humans (NRC 2004).

There are numerous regulatory hurdles and associated research needs which must be met before newly developed technologies can be incorporated into criteria and adopted in routine monitoring programs. Foremost among these is the need for epidemiology studies which quantify the relationship between the density of new indicators and health risk to swimmers. In March 2007, the USEPA gathered 43 experts from around the world to conceptualize the best approaches for criteria development and to identify research priorities which would assist them in developing criteria and transitioning new methods from the development to the implementation phase (USEPA 2007). This article presents a summary of the findings from that workshop. We describe the current US recreational ambient water quality criteria and their shortcomings, introduce alternative approaches to new criteria development, critical research needs, and a path forward for new criteria development.

THE 1986 CRITERIA: A ONE-SIZE FITS ALL APPROACH

USEPA developed ambient water quality criteria in 1986 (USEPA 1986), hereafter referred to as the "1986 criteria".

The 1986 criteria are based on the outcomes of epidemiology studies conducted at recreational beaches impacted by point discharges of municipal wastewater in the late 1970s at the Great Lakes, Oklahoma, Boston, New York, and Lake Ponchartrain in New Orleans (Cabelli *et al.* 1982; Cabelli 1983; Dufour 1984). The studies aimed to identify relationships between FIB concentrations and the rates of recreational waterborne illness (RWI) (including gastroenteritis and fever) in swimmers. Geometric mean and single-sample standards were developed for enterococci and *E. coli* for freshwater, and enterococci for marine waters since these indicators best correlated to gastroenteritis in swimmers in the respective environments. The numerical standards were derived based on historically accepted swimming-associated gastroenteritis rates in freshwater and marine water of 8 and 19 out of 1,000 swimmers, respectively (USEPA 2004*a*). As the BEACH Act (2000) required coastal states to adopt the 1986 or more stringent criteria prior to 2005, the FIB-gastroenteritis relationships at beaches in the Great Lakes, Oklahoma, Boston, New York, and New Orleans became the bases of water quality standards in recreational waters around the country, from Hawaii to Michigan to Florida.

Exceedances of water quality standards trigger actions aimed at protecting the health of the public and the environment. If measured FIB concentrations exceed state regulatory thresholds, health officials warn the public of potential risk of illnesses or close the beach to swimming. Exceedances of the standards may result in a state listing the waterbody as "impaired" in accordance with Section 303(d) of the Clean Water Act. Listing a waterbody as impaired initiates the total maximum daily load (TMDL) process which ultimately leads to implementing remediative actions so that water quality standards can be met and designated uses, such as recreational water contact, can be attained.

RESEARCH REVEALS SHORTCOMINGS OF THE 1986 CRITERIA

Over the last few decades, the understanding of the ecology of FIB in the environment and their relation to RWI has advanced. Numerous shortcomings of the 1986 criteria have become evident.

E. coli and enterococci are not just found in human sewage

Although *E. coli* and enterococci are found in high concentrations in human sewage (Maier *et al.* 1999), they are also highly prevalent in the environment. They are excreted in the feces of numerous warm blood animals (Parveen *et al.* 1999; Harwood *et al.* 2000; Ashbolt *et al.* 2001). There is strong evidence that some genotypes of *E. coli* are naturalized–meaning they are adapted to persisting and even growing in extra-enteric environments like lakes, soils and sediments (Davies *et al.* 1995; Desmarais *et al.* 2002; Ishii *et al.* 2006). *E. coli* and enterococci can be found in a number of environmental reservoirs including soils and sands in tropical, subtropical and temperate climates (Fujioka *et al.* 1999; Byappanahalli *et al.* 2006; Yamahara *et al.* 2007). Enterococci can be found on terrestrial grasses (Ott *et al.* 2001) and aquatic plants (Whitman *et al.* 2003). If *E. coli* and enterococci measured at a beach during water quality monitoring emanate from these sources rather than municipal wastewater, then the FIB-gastroenteritis relationship upon which the 1986 criteria is based might not hold.

The FIB-gastroenteritis relationship may not be appropriate at many beaches

The epidemiology studies conducted by the USEPA in the 1970s at beaches impacted point source discharges of municipal wastewater are the cornerstones of the 1986 criteria. Since then, many municipal sewage discharges have been upgraded and become well regulated. While there are still point sources of wastewater contributing to poor water quality, urban runoff, stormwater, confined animal feeding operations, agricultural runoff, septic systems, and animal feces are now believed to represent major sources of FIB to most recreational waterbodies (e.g., Ahn *et al.* 2005). Some studies have investigated the FIB-RWI relationship at beaches impacted by sources other than municipal wastewater, but the results have been mixed. In California, Haile *et al.* (1999) found swimming in close proximity to urban drains discharging FIB led to significant risks of RWI. In this case, positive, correlative relationships between FIB and numerous RWI were apparent. A New Zealand study showed that RWI was correlated with enterococci at beaches adversely impact by both rural and urban runoff (McBride *et al.* 1998). In contrast, Colford *et al.* (2007) examined the risk associated with exposure to non-point FIB sources in a beach without runoff sources in California, and found no statistical association between FIB and 14 different human health outcomes. Similarly, a study of risk and exposure to enterococci and *E. coli* from non-point animal sources in a lake in Connecticut showed no correlation between RWI and FIB densities (Calderon *et al.* 1991). The diverse findings regarding the relationship between RWI and FIB from sources other than municipal wastewater illustrate the potential inappropriateness of applying the FIB-RWI relationships which are the bases of the 1986 criteria to all US waterbodies. If the risks associated with exposure to these other sources are less than those endured during exposure to municipal wastewater, application of 1986 criteria could be overprotective.

The missing causative link between FIB and RWI

A positive, correlative relationship between FIB and human pathogen concentrations (for example, human enteric viruses) has remained elusive. In fact, most studies show a striking lack of correlation between the two (e.g., Noble & Fuhrman 2001; Boehm *et al.* 2003; Jiang & Chu 2004; Pusch *et al.* 2005). Ultimately, the lack of strong, positive relationships between FIB and pathogens in ambient waters casts doubt on the appropriateness of extrapolating the 1986 criteria to conditions and sites which were not included in the original epidemiological studies used for criteria development.

Another confounding factor in the search for the FIB-pathogen relationship is our glaring lack of knowledge regarding the etiologies of RWI. RWI are typically self-limiting, requiring no medical visit, therefore there is a paucity of medical and epidemiologic data describing them. While it is widely believed that enteric viruses are the main cause of RWI (WHO 2003), epidemiology studies have largely not incorporated methods to confirm etiology (such as serology or other biological sampling from ill participants) nor enumerated enteric viruses. Until we know which pathogens are causing illness and the infectious doses and potential sources of these pathogens, it will be difficult to know which pathogens to measure in order to elucidate the FIB-pathogen relationship.

The 1986 criteria do not address non-gastrointestinal illnesses

The 1986 criteria purport to protect swimmers from unacceptable rates of gastroenteritis, but do not necessarily protect swimmers from other RWI. Individuals may experience respiratory illnesses, eye irritation, skin rash or infection, and *otitis externa* (“swimmers ear”) (Prüss 1998; Wade *et al.* 2003) from swimming. At least two studies have illustrated increased risk of respiratory illness in waters with elevated FIB levels (Fleisher *et al.* 1996; Haile *et al.* 1999). However, the USEPA found no relationship between FIB and respiratory illness in their epidemiology studies (Cabelli 1983; Dufour 1984) and therefore non-gastrointestinal illnesses were not addressed in the 1986 criteria. The 1986 criteria do not address risks associated with exposure to free-living water-based pathogens (e.g., *Vibrio*, *Aeromonas* spp., and *Staphylococcus aureus*) and cyanobacteria which are of concern in some geographic regions (Charoenca & Fujioka 1995; Dziuban *et al.* 2006).

Water quality characterization

The effectiveness of water quality criteria should be measured by an ability to correctly identify conditions when water exposure will lead to unacceptable disease levels. There is concern that the 1986 criteria do not accomplish this (Kim & Grant 2004).

E. coli and enterococci emanating from naturalized or non-fecal sources may result in the water body being incorrectly classified as impaired when the risk of illness is actually not above what had been determined to be acceptable. The development of best management practices and treatment technologies for removing FIB from waters where there are no obvious fecal inputs could be costly, destructive to natural ecosystems, and not substantively reduce the health risk of those using the water for recreation.

FIB concentrations in surface water are variable over time scales from minutes to years owing to variation in mixing, sunlight induced inactivation, infrastructure upgrades, and seasonal cycles of rainfall (Boehm *et al.* 2002; Whitman *et al.* 2004; Roser & Ashbolt 2007). Spatial variability has also been documented over scales of 10 m and more (Boehm *et al.* 2002; Whitman & Nevers 2004). It is particularly concerning that FIB concentrations vary more quickly than monitoring results can be obtained using USEPA-approved or other culture-based methods (typically 24 h). This means that waters may be left open to swimming when they should be closed and vice versa. In situations where FIB are truly reflective of recreational illness rates, there may be serious health implications to permitting access during times of heightened risk, especially if a waterbody is contaminated with human sewage. In the opposite scenario, limiting access to beaches when there is minimal health risk results in unnecessary loss of the economic resource to the local economy and unnecessarily restricting the public use of a recreational site (Rabinovici *et al.* 2004; Hou *et al.* 2006).

Intra-day variation of indicators due to sunlight, tides, and mixing presents a challenge to the utility of the 1986 criteria which rely, in part, on a single-sample exceedance standard as a management tool. Evidence is mounting that a single-sample of water reveals little about the water quality of an entire recreational site (Boehm 2007).

Acceptable risk

The USEPA used different levels of public health protection for setting the 1986 criteria in fresh and marine waters, 8 and 19 illnesses per 1000 swimmers, respectively (USEPA 2004*a*). These "acceptable risk" levels correspond to the estimated level of public health protection afforded by the old fecal coliform criteria of 200 organisms/100 ml (USEPA 2004*a*) and, thus, to some degree represent a historical precedent. However, it is apparent that the public has never been formally interviewed about its knowledge of or willingness to accept risks during swimming. There is neither scientific nor social justification for providing more stringent protection for swimming in freshwater than marine water (USEPA 2004*b*).

The selection of health endpoints for the general population (Cabelli *et al.* 1982) for the 1986 criteria is somewhat concerning because there are specific life-stages when individuals may either be more highly exposed or more susceptible to RWI. In particular, children may face higher risks than the general population because they can have increased exposures (Dufour *et al.* 2006) and naïve immune systems. Preliminary analysis of epidemiology data from a recent USEPA study of RWI in the Great Lakes suggests that children experience higher rates of illness than adults (Timothy Wade, personal communication 2007). Health endpoints for swimmers with multiple exposures and varying degrees of exposure have not been considered in criteria development either.

A SEA CHANGE AHEAD: EXAMPLE FROM THE WORLD HEALTH ORGANIZATION

Many water quality managers find themselves constrained by the 1986 criteria. In some situations, managers find themselves spending valuable resources issuing swimming advisories, establishing TMDLs, and developing implementation strategies to address perceived pollution problems at a beach where no real threat to public health exists to recreational swimmers. The time has come to apply new information and technologies to design modern criteria that are defensible for a broader range of scenarios, which ultimately should provide increased protection to swimmers.

We suggest that policy makers consider the water quality criteria framework developed by the World Health Organization (hereafter referred to as "WHO approach") as a starting point for new criteria, following Australia, New Zealand, and the European Union (WHO 1999; WHO 2003; NZME 2003; EP/CEU 2006; Roser *et al.* 2007). Below, we describe the WHO approach, as well as 7 key requirements we believe the US criteria should meet.

The WHO approach

The WHO approach (WHO 2003) provides a basis for standard setting in light of local and regional circumstances. It is based on the perspective that recreational water quality and protection of public health are best described by a combination of sanitary inspection and microbial water quality assessments. The WHO approach considers the probability of human fecal pollution in a recreational water (sanitary investigation category in Table 1), as well as observed levels of fecal pollution (microbial assessment of water quality category in Table 1), and combines them into

Table 1 | World Health Organization annual classification matrix for integrating microbial water quality, as measured by enterococci density with sanitary investigation category. The enterococci concentrations represent the 95th percentile of enterococci measured at the target beach.

		Microbial water quality assessment category (95th percentile intestinal enterococci/100 mL) A	B	C	D	
		<40	41–200	201–00	>500	Exceptional circumstances
Sanitary investigation category (susceptibility to fecal influence)	Very Low	Very good	Very good	Follow up[*]	Follow up[*]	Action
	Low	Very good	Good	Fair	Follow up[*]	
	Moderate	Good[#]	Good	Fair	Poor	
	High	Good[#]	Fair[#]	Poor	Very poor	
	Very High	Follow up[#]	Fair[#]	Poor	Very poor	
	Exceptional circumstances	Action				

[*] denotes that non-fecal source of enterococci may be influencing measurement and this should be verified.
[#] indicates that there is a possible discontinuous source of enterococci (for example, driven by rainfall) and that these results should be confirmed and analytical results reviewed. Exceptional circumstances relate to periods with known higher risk, such as during an outbreak from a waterborne pathogen, sewer spills, etc. Under these circumstances, the matrix may not apply and actions should be taken. This table is adapted from WHO (2003).

a five-level classification scheme for recreational water environments. The microbial assessment criteria set risk ranges for acquiring gastroenteritis, while the sanitary investigation category describes the probability that human waste is contributing to poor water quality. The sanitary investigation category could be modified to include other sources of microbial pollution deemed to be a health threat (e.g., Ashbolt & Bruno 2003), and the risk ranges can be altered to account for other RWI.

New criteria must meet seven requirements

We believe the new criteria should meet seven requirements (Table 2). First, criteria must be health-based; that is, they must be anchored by results from epidemiology studies. Second, they must be compatible with all Clean Water Act needs (including BEACH Act updates), including water quality assessment for public notification at beaches and impaired water listings, development of TMDLs and their implementation, and National Pollutant Discharge Elimination System (NPDES) compliance monitoring and other permitting. Third, new criteria need to be scientifically defensible for application in a wide variety of geographical locations including fresh and marine waters, and temperate, subtropical, and tropical waters. Fourth, they need to be robust and flexible so that they can be configured to protect the public health of those exposed to recreational water impacted by all sorts of pathogen sources including animal feces, stormwater, and sewage. Fifth, criteria should be protective of children as a more exposed and susceptible life-stage. Sixth, they need to based on indicators that can be quantified reliably, robustly, and reproducibly. Seventh, they should be equally protective of all swimmers including those using freshwater and saltwater, regardless of geographic

Table 2 | The new criteria should meet these seven requirements

	Requirements of new criteria
1	Health based, anchored in results from epidemiology studies.
2	Compatible with all Clean Water Act needs including beach advisories and closures, TMDL development, and NPDES permitting.
3	Scientifically defensible for application in a wide variety of geographical locations and water types.
4	Protective of individuals exposed to recreational waters impacted by all sorts of pathogen sources including animal feces, stormwater, and sewage.
5	Protective of children as a more exposed and susceptible life-stage.
6	Based on indicators that can be quantified reliably, robustly, and reproducibly.
7	Equally protective of all recreation users including those using freshwater and saltwater, regardless of geographic locale.

locale, and those swimming in waters contaminated with microbial pollutants from diverse sources.

KNOWLEDGE GAPS AND RESEARCH NEEDS

We have identified four areas where research is needed before criteria that fulfills the requirements can be developed: 1) elucidation of human health risks from exposure to different sources of fecal contamination, 2) identification of new fecal indicators and methods for their measurement, 3) determination of appropriate indicators and means of coping with their variability, and 4) determination of appropriate risk levels and strategies for risk communication.

Elucidation of human health risks from exposure to different sources of fecal contamination

There is a strong need for including in the new criteria provisions to protect against RWI risks associated with human and nonhuman sources of fecal contamination, as well as point and non-point sources in a range of climates and water types. Differences between animal and human waste associated risks are not well characterized, and may vary greatly geographically and temporally, and even between animal types. Point sources and non-point sources of fecal contamination may also differ in risk, and those differences are not well characterized. To fully understand these risks, additional epidemiology studies are needed at different locales and with varying microbial pollution sources. In particular, the need for additional epidemiological studies at non-point source, confined animal feeding operations, and runoff impacted beaches is viewed as essential. Epidemiology studies should be augmented with quantitative microbial risk assessments (QMRA) (particularly for non-enteric pathogens and rare diseases (Soller *et al.* 2003; Seto *et al.* 2007)), quantitative sanitary investigations (that quantitatively identify potential microbial pollutant and pathogen sources within a watershed), and models (that relate watershed and beach attributes and characteristics to water quality and risk of RWI) to help characterize risks and to provide a basis to better extrapolate information to different recreational settings. The complete range of RWI needs to be considered in the epidemiology studies.

Identification of new fecal indicators and methods for their measurement

In the short term, we believe that new recreational criteria should be based on fecal indicators rather than pathogens because the levels of occurrence and the types of pathogens in municipal wastewater and other pathogen sources may vary greatly both temporally and spatially (Harwood *et al.* 2005). In the long-term, however, detection and enumeration of pathogens or groups of pathogens will be key for identifying dangerous conditions as our understanding of their occurrence, and fate and transport in the environment increases. New and improved methods for measuring fecal indicators and specific pathogens are needed so that they can be tested for correlation to RWI in epidemiology studies and used in QMRA simulations. At the present time, spores of *Clostridium perfringens*, various coliphages, and *Bacteroidales* bacteria are promising candidates for inclusion in the new criteria. Regardless of which indicators are used to set criteria, USEPA standard methods should be published for enumerating the indicators in ambient waters as well as wastewater and other relevant sources. In addition, research must continue to develop affordable and reliable source tracking targets which aid in identification and management of pathogen and indicator sources (Field & Samadpour 2007) including fecal shedding by bathers (Gerba 2000).

Understanding fate and transport differences between new and current indicators and pathogens in treated effluents and in recreational waters will better inform the use of those indicators for TMDL development and NPDES permitting. There is evidence that nucleic-acid based detection of indicators will be problematic for NPDES permitting (He & Jiang 2005). For example, in some preliminary experiments a 2 ppm chlorine residual in secondary treated sewage destroyed culturable enterococci within minutes. However, there was no reduction or loss of either RNA or DNA targets of enterococci after eight hours of exposure to the disinfectant (Griffith *et al.* 2007). If this preliminary work is confirmed, these methods may not have utility for determining appropriate concentrations of microbial pollutants in permitted discharges of treated wastewater.

Determination of appropriate indicators and means of coping with their variability

Enterococci and *E. coli* may not be appropriate indicators in all locations since they may be naturalized or present in sediments (Fujioka *et al.* 1999).The potential for regrowth and survival of these and other indicators in the environment needs to be further studied and verified, specifically to clarify the absence of other animal fecal inputs. Appropriate indicators that correlate with RWI in locations where indicators are naturalized, such as tropical, subtropical, and temperate climates, as well as in flowing waters where sediment/microbe resuspension occurs, are needed and should be determined by conducting epidemiology studies in these locales.

The spatial and temporal variability evident in FIB data sets as well as the delay in obtaining analytical results render a single sample standard (USEPA 1986) impractical for routine water quality notification purposes. Rapid methods, such as quantitative polymerase chain reaction, may help address this issue, particularly in identifying beaches impacted by an undetected sewage spill. However, rapid detection technologies are not likely to be appropriate for all management situations due to equipment costs, skill level of technicians in small agencies, and other logistical aspects.

Simple statistical models that do not necessarily require an understanding of processes and mechanisms controlling indicator fate and transport have the potential to be incorporated into the new criteria, particularly for daily water quality assessment and public notification of water quality. Such "now-casting" models relate environmental factors to water quality at a particular beach in real time and allow early warnings to be issued by managers (Nevers & Whitman 2005; Francy *et al.* 2006; Roser *et al.* 2007).

Determination of appropriate risk levels and strategies for risk communication

Risks for children should be considered as the basis for the new criteria due to their potential for elevated exposure and increased susceptibility. To accomplish this, research should be done to understand risks to children more completely. Of note, although immunocompromised individuals may experience even greater risk than children, their risks may be managed using public health messages targeted at these individuals.

We suggest that the beach-going public should have a voice in identifying the appropriate level of risk used for setting water quality standards, and which types of RWI new criteria should protect against. Future epidemiology studies could incorporate questions to help inform what levels of risk might be appropriate. Providing information to the public on background illness rates for gastroenteritis, skin rash, upper respiratory infections and other RWI could help frame the appropriate risk determination effort. In addition, studies can be initiated to assess how impacted groups understand and perceive risks associated with recreational water use and what level of voluntary risk would be appropriate.

Social science research should inform RWI risk communication strategies. A precedent for such research has been set by the USEPA for air quality warnings (Johnson 2003) and beach notifications in Sydney, Australia and California where beach signage, daily newspapers, radio broadcasts, and informative websites are effectively used (Heal the Bay 2007; NSWEPA 2007).

A PATH FORWARD

The new criteria will need to balance flexibility and scientific robustness with the realities of implementation and USEPA's commitment to develop new criteria by 2012 (USEPA 2007). New criteria will not only need to strengthen public health protection compared to the 1986 criteria, but will also need to provide a mechanism to ensure that the various Clean Water Act needs (NPDES permitting, TMDLs, and water quality assessment) can be met, as outlined in Table 2.

The WHO approach (Table 1), provides valuable perspectives from which new criteria could be developed within a context that is consistent with the Clean Water Act, the BEACH Act of 2000, and criteria requirements (Table 2). In particular, the sanitary investigation component of the WHO approach provides a mechanism to consider the relative risks associated with contamination from different sources in diverse waters. In the short term, however, it does not seem feasible to derive criteria based on multiple risk levels (columns in Table 1).

Separate criteria could be developed corresponding to different sources of contamination (as determined by a sanitary investigation) for different waterbody classes (such as standing temperate fresh waters, flowing temperate fresh waters, temperate marine waters, tropical marine waters). The resultant criteria could be represented in a table, similar to the WHO approach (Table 1). Rows would correspond to different sources of contamination and columns, different classes of waterbodies. Values in the table would represent standards that provide the same level of public health protection for each source/waterbody combination. Development of this type of criteria would require research to elucidate relevant pathogens and their relation to pathogen indicators from various sources (including point and non-point), a way of quantifying sources, and an understanding of how these sources vary over time within watersheds. In each waterbody class, a relationship between a measure of water quality appropriate for the particular sources and associated health effects would need to be determined. For each indicator that is used to characterize the water quality for a waterbody type/source combination, linkages would need to be developed within and between the various uses of water in each state to ensure that all Clean Water Act programmatic needs can be harmonized, attained and reliably demonstrated.

The creation of separate criteria for all types of waterbodies and contamination sources may not be feasible within the next five years. For example, if criteria for five pathogen sources and four waterbody types were desired, twenty different waterbody type/source combinations would need to be investigated and characterized. While QMRA may represent one alternative for determining risk for some source-waterbody combinations where there is no epidemiology data, there are still many unknowns regarding the appropriate inputs to these models including etiologic agents and concentrations, dose-response curves, and relationships between pathogens and indicators.

Therefore, we recommend that in the short term, USEPA should give priority to conducting epidemiology studies in tropical/subtropical waters and during exposure to urban runoff and animal feces. The studies should include concurrent environmental data collection so that forecasting models can be developed for indicator and pathogen concentrations, as well as health risk, and their utility as early warning tools explored. Results will facilitate expansion of the criteria to three different source types (urban runoff, animal feces, and treated municipal wastewater) in four types of waterbodies (temperate fresh, temperate marine, tropical fresh, tropical marine) compared to the current criteria which account for one source (treated municipal wastewater) and two types of waterbodies (fresh and marine).

All seven criteria requirements (Table 2) must be met for the 2012 criteria and this will require substantial effort. Thus, we believe it is imperative that the USEPA partner with various academic, state, and other federal agencies to pursue the needed research objectives. The time has come to renew our commitment to the protection of swimmable waters in the US. New criteria should reflect over 25 years of new research in order to better protect the public health of the hundreds of millions of people who swim in US waters every year.

ACKNOWLEDGEMENTS

The authors acknowledge the USEPA Office of Water, Office of Science and Technology (OST, Health and Ecological Criteria Division (HECD) and Standards and Health Protection Division (SHPD)) and Office of Research and Development (ORD) for organizing and hosting the *Experts Scientific Workshop on Critical Research Needs for the Development of New or Revised Recreational Water Quality Criteria*. Thanks to Denise Keehner (workshop chairperson, SHPD), Ephraim King (OST), Suzanne Rudzinski (OST), and Kevin Teichman (ORD) for their attention and commitment to furthering both the science and the policy that support the development of criteria. Members of the USEPA workshop organizing committee, S. Barash, R. Calderon, E. Doyle, A. Dufour, S. Fontenelle, P. Harrigan, R. Hoffmann, B. Leamond, C. Noss, K. Oshima, J. Ravenscroft, G. Robiou, C. Roberts, S. Schaub, T. Wade, J. Wathen and L. Wisniewski, are also acknowledged. LEF acknowledges funding in part from grants from NIEHS (P50 ES12736) and NSF (OCE0432368). JMC was supported by grant NIH 1 R01

ES013519. ABB was supported by NOAA Oceans and Human Health Grant NA04OAR4600195 and acknowledges Sharyl Rabinovici who inspired some of the ideas presented in this paper. The views expressed in this paper are not necessarily those of the US EPA.

REFERENCES

Ahn, J. H., Grant, S. B., Surbeck, C. Q., DiGiacomo, P. M., Nezlin, N. P. & Jiang, S. 2005 Coastal water quality impact of stormwater runoff from an urban watershed in Southern California. *Environ. Sci. Technol.* **39**(16), 5940–5953.

Ashbolt, N. J. & Bruno, M. 2003 Application and refinement of the WHO risk framework for recreational waters in Sydney Australia. *J. Water Health* **1**(3), 125–131.

Ashbolt, N. J., Grabow, W. O. K. & Snozzi, M. 2001 Indicators of microbial water quality. In *Water Quality: Guidelines, Standards and Health. Risk Assessment and Management for Water-Related Infectious Disease* (ed. L. Fewtrell & J. Bartram), pp. 289–315. IWA Publishing, London, UK.

Beaches Environmental Assessment and Coastal Health Act (BEACH Act) of 2000. Public Law 106–284–OCT. 10, 2000 http://www.epa.gov/waterscience/beaches/rules/act.html

Boehm, A. B. 2007 Enterococci concentrations in diverse coastal environments exhibit extreme variability. *Environ. Sci. Technol.* **41**(24), 8227–8232.

Boehm, A. B., Grant, S. B., Kim, J.-H., Mowbray, S. L., McGee, C. D., Clark, C. D., Foley, D. M. & Wellman, D. E. 2002 Decadal and shorter period variability of surf zone water quality at Huntington Beach, California. *Environ. Sci. Technol.* **36**(18), 3885–3892.

Boehm, A. B., Fuhrman, J. A., Mrse, R. D. & Grant, S. B. 2003 A tiered approach for identification of a human fecal pollution source at a recreational beach: case study at Avalon Bay, Catalina Island, California, USA. *Environ. Sci. Technol.* **37**(4), 673–680.

Byappanahalli, M. N., Whitman, R. L., Shively, D. A., Ting, W. T., Tseng, C. C. & Nevers, M. B. 2006 Seasonal persistence and population characteristics of *Escherichia coli* and enterococci in deep backshore sand of two freshwater beaches. *J. Water Health* **4**(3), 313–320.

Cabelli, V. J. 1983 Health effects criteria for marine recreational waters. *U.S. Environmental Protection Agency* EPA-600/1-80-031. Cincinnati, OH. http://www.epa.gov/microbes/online.htm

Cabelli, V. J., Dufour, A. P., McCabe, L. J. & Levin, M. A. 1982 Swimming-associated gastroenteritis and water quality. *Am. J. Epidemiol.* **115**(4), 606–616.

Calderon, R. L., Mood, E. W. & Dufour, A. P. 1991 Health effects of swimmers and nonpoint sources of contaminated water. *Int. J. Environ. Health Res.* **1**(1), 21–31.

Charoenca, N. & Fujioka, R. S. 1995 Association of staphylococcal skin infections and swimming. *Water Sci. Technol.* **31**(5–6), 11–17.

Colford, J. M. Jr., Wade, T. J., Schiff, K. C., Wright, C. C., Griffith, J. F., Sandhu, S. K., Burns, S., Sobsey, M., Lovelace, G. & Weisberg, S. B. 2007 Water quality indicators and the risk of illness at beaches with nonpoint sources of fecal contamination. *Epidemiology* **18**(1), 27–35.

Davies, C. M., Long, J. A. H., Donald, M. & Ashbolt, N. J. 1995 Survival of fecal microorganisms in marine and freshwater sediments. *Appl. Environ. Microbiol.* **61**(5), 1888–1896.

Desmarais, T. R., Solo-Gabriele, H. M. & Palmer, C. J. 2002 Influence of soil on fecal indicator organisms in a tidally influenced subtropical environment. *Appl. Environ. Microbiol.* **68**(3), 1165–1172.

Dorfman, M. & Stoner, N. 2007 *Testing the Waters. A Guide to Water Quality at Vacation Beaches*. National Resources Defense Council, Washington DC, USA.

Dufour, A. P. 1984 Health Effects Criteria for Fresh Recreational Waters. U.S. Environmental Protection Agency. EPA-600/1-84-004. Cincinnati, OH. http://www.epa.gov/microbes/frc.pdf

Dufour, A. P., Evans, O., Behymer, T. D. & Cantú, R. 2006 Water ingestion during swimming activities in a pool: a pilot study. *J. Water Health* **4**(4), 425–430.

Dziuban, E. J., Liang, J. L., Craun, G. F., Hill, V., Yu, P. A., Painter, J., Moore, M. R., Calderon, R. L., Roy, S. L. & Beach, M. J. 2006 Surveillance for waterborne disease and outbreaks associated with recreational water–United States, 2003–2004. *MMWR Surveill. Summ.* **55**(12), 1–30.

EP/CEU (European Parliament/Council of the European Union) 2006 Directive 2006/7/EC of the European Parliament and of the Council of 15 February 2006 Concerning the Management of Bathing Water Quality and Repealing Directive 76/160/EEC. *Official J. Eur. Union* L64, 31–51.

Field, K. G. & Samadpour, M. 2007 Fecal source tracking, the indicator paradigm, and managing water quality. *Water Res.* **41**(16), 3517–3538.

Fleisher, J. M., Kay, D., Jones, F., Wyer, M. D. & Godfree, A. F. 1996 Marine waters contaminated with domestic sewage: nonenteric illness associated with bather exposure in the United Kingdom. *Am. J. Public Health* **86**(9), 1228–1234.

Francy, D. S., Darner, R. A. & Bertke, E. E. 2006 *Models for Predicting Recreational Water Quality at Lake Erie Beaches*. United States Geological Survey Scientific Investigations Rep. 2006–5192.

Fujioka, R. S., Sian-Denton, C., Borja, M., Castro, J. & Morphew, K. 1999 Soil: the environmental source of *Escherichia coli* and Enterococci in Guam's streams. *J. Appl. Microbiol. Symposium Suppl.* **85**(28), 83S–89S.

Gerba, C. P. 2000 Assessment of enteric pathogen shedding by bathers during recreational activity and its impact on water quality. *Quant. Microbiol.* **2**(1), 55–68.

Griffith, J. F., Moore, D., McGee, C. & Weisberg, S. B. 2007 *Beta Testing of Rapid Methods for Measuring Beach Water Quality*. Southern California Coastal Water Research Project Technical Report 506, Fountain Valley, California, USA.

Haile, R. W., Witte, J. S., Gold, M., Cressey, R., McGee, C., Millikan, R. C., Glasser, A., Harawa, N., Ervin, C., Harmon, P., Harper, J., Dermand, J., Alamillo, J., Barrett, K., Nides, M. & Wang, G. Y. 1999 The health effects of swimming in ocean water contaminated by storm drain runoff. *Epidemiology* **10**(4), 355–363.

Harwood, V. J., Whitlock, J. & Withington, V. 2000 Classification of antibiotic resistance patterns of indicator bacteria by discriminant analysis: use in predicting the source of fecal contamination in subtropical waters. *Appl. Environ. Microbiol.* **66**(9), 3698–3704.

Harwood, V. J., Levine, A. D., Scott, T. M., Chivukula, V., Lukasik, J., Farrah, S. R. & Rose, J. B. 2005 Validity of the indicator organism paradigm for pathogen reduction in reclaimed water and public health protection. *Appl. Environ. Microbiol.* **71**(6), 3163–3170.

Haugland, R. A., Siefring, S. C., Wymer, L. J., Brenner, K. P. & Dufour, A. P. 2005 Comparison of Enterococcus measurements in freshwater at two recreational beaches by quantitative polymerase chain reaction and membrane filter culture analysis. *Water Res.* **39**(4), 559–568.

He, J. & Jiang, S. 2005 Quantification of enterococci and human adenoviruses in environmental samples by real-time PCR. *Appl. Environ. Microbiol.* **71**(5), 2250–2255.

Heal the Bay 2007 Beach Report Card. http://www.healthebay.org/brc/

Hou, D., Rabinovici, S. J. M. & Boehm, A. B. 2006 Enterococci predictions from a partial least squares regression model can improve the efficacy of beach management advisories. *Environ. Sci. Technol.* **40**(6), 1737–1743.

Ishii, S., Ksoll, W. B., Hicks, R. E. & Sadowsky, M. J. 2006 Presence and growth of naturalized *Escherichia coli* in temperate soils from Lake Superior watersheds. *Appl. Environ. Microbiol.* **72**(1), 612–621.

Jiang, S. C. & Chu, W. 2004 PCR detection of pathogenic viruses in Southern California urban rivers. *J. Appl. Microbiol.* **97**(1), 17–28.

Johnson, B. B. 2003 Communicating air quality information: experimental tests of alternative formats. *Risk Anal.* **23**(1), 91–103.

Kim, J.-H. & Grant, S. B. 2004 Public mis-notification of coastal water quality: a probabilistic evaluation of posting errors at Huntington Beach, California. *Environ. Sci. Technol.* **38**(9), 2497–2504.

Leeworthy, V. R. & Wiley, P. C. 2001 *Marine Recreation Participation and Use, National Survey on Recreation and the Environment 2000*. National Oceanic and Atmospheric Administration, National Ocean Service, Special Projects Office, Silver Spring, MD, USA.

Maier, R. M., Pepper, I. L. & Gerba, C. P. 1999 *Environmental Microbiology*. Academic Press, New York, USA.

McBride, G. B., Salmond, C. E., Bandaranayake, D. R., Turner, S. J., Lewis, G. D. & Till, D. G. 1998 Health effects of marine bathing in New Zealand. *Int. J. Environ. Health Res.* **8**(2), 173–189.

National Oceanographic Atmospheric Association (NOAA) 2005 *Economic Statistics for NOAA 2005, Fourth Edition*. National Oceanic and Atmospheric Administration. Washington, DC, USA. www.publicaffairs.noaa.gov/pdf/economic-statistics2005.pdf

National Research Council (NRC) 2004 *Indicators for Waterborne Pathogens*. National Academies Press, Washington, DC, USA.

Nevers, M. B. & Whitman, R. L. 2005 Nowcast modeling of *Escherichia coli* concentrations at multiple urban beaches of southern Lake Michigan. *Water Res.* **39**(20), 5250–5260.

New South Wales Environmental Protection Agency (NSW EPA) 2007 *Beachwatch*. http://www.epa.nsw.gov.au/beach/about.htm

New Zealand Ministry of the Environment (NZME) 2003 *Microbiological Water Quality Guidelines for Marine and Freshwater Recreational Areas*. Ministry for the Environment, Wellington, New Zealand.

Noble, R. T. & Fuhrman, J. A. 2001 Enteroviruses detected by reverse transcriptase polymerase chain reaction from the coastal waters of Santa Monica Bay, California: low correlation to bacterial indicator levels. *Hydrobiologia* **460**(1–3), 175–184.

Noble, R. T. & Weisberg, S. B. 2005 A review of technologies being developed for rapid detection of bacteria in recreational waters. *J. Water Health* **3**(4), 381–392.

Ott, E.-M., Muller, T., Muller, M., Franz, C. M. A. P., Ulrich, A., Gabel, M. & Seyfarth, W. 2001 Population dynamics and antagonistic potential of enterococci colonizing the phyllosphere of grasses. *J. Appl. Microbiol.* **91**(1), 54–66.

Parveen, S., Portier, K. M., Robinson, K., Edmiston, L. & Tamplin, M. L. 1999 Discriminant analysis of ribotype profiles of *Escherichia coli* for differentiating human and nonhuman sources of fecal pollution. 1999. *Appl. Environ. Microbiol.* **65**(7), 3142–3147.

Prüss, A. 1998 Review of epidemiological studies on health effects from exposure to recreational water. *Int. J. Epidemiol.* **27**(1), 1–9.

Pusch, D., Oh, D. Y., Wolf, S., Dumke, R., Schroter-Bobsin, U., Hohne, M., Roske, I. & Schreier, E. 2005 Detection of enteric viruses and bacterial indicators in German environmental waters. *Arch. Virol.* **150**(50), 929–947.

Rabinovici, S. J. M., Bernknopf, R. L., Wein, A. M., Coursey, D. L. & Whitman, R. L. 2004 Economic and health risk trade-offs of swim closures at a Lake Michigan beach. *Environ. Sci. Technol.* **38**(10), 2737–2745.

Roser, D. J. & Ashbolt, N. J. 2007 *Source Water Quality Assessment and the Management of Pathogens in Surface Catchments and Aquifers. Research Report 29*. CRC for Water Quality and Treatment, Bolivar.

Roser, D. J., Ashbolt, N. J., Davies, C. M., Glamore, W. C., Hawker, K. M. & Miller, B. M. 2007 Application of TMDL and risk assessment principles for pathogen management at an urban recreational lake. In *Watershed Management to Meet Water Quality Standards and TMDLS, 4th Conference Proceedings, March 10–14, 2007 San Antonio, Texas*. The American Society of Agricultural and Biological Engineers (ASABE), Stephenville, Texas, pp. 420–426.

Seto, E. Y. W., Soller, J. A. & Colford, J. M. Jr. 2007 Strategies to reduce person-to-person transmission during widespread

Escherichia coli O157:H7 outbreak. *Emerg. Infect. Dis.* **13**(6), 860–866. Available from http://www.cdc.gov/EID/content/13/6/860.htm.

Soller, J. A., Olivieri, A. W., Crook, J., Parkin, R., Tchobanoglous, G., Spear, R. C. & Eisenberg, J. N. S. 2003 A risked based approach to evaluate the public health benefit of additional wastewater treatment. *Environ. Sci. Technol.* **37**(9), 1882–1891.

Stoeckel, D. M. & Harwood, V. J. 2007 Performance, design, and analysis in microbial source tracking studies. *Appl. Environ. Microbiol.* **73**(8), 2405–2415.

United States Environmental Protection Agency (USEPA) 1986 *Ambient Water Quality Criteria for* Bacteria–1986. EPA440/5-84-002.

United States Environmental Protection Agency (USEPA) 2004*a* Water quality standards for coastal and Great Lakes Recreation Waters: proposed rule. *Fed. Regist.* **69**(131), 41720–41742.

United States Environmental Protection Agency (USEPA) 2004*b* Water quality standards for coastal and Great Lakes Recreation Waters: final rule. *Fed. Regist.* **69**(220), 67218–67243.

United States Environmental Protection Agency (USEPA) 2007 *Report of the Experts Scientific Workshop on Critical Research Needs for the Development of New or Revised Recreational Water Quality Criteria*. Washington, DC. EPA 823-R-07-006, http://www.epa.gov/waterscience/criteria/recreation/

Wade, T. J., Pai, N., Eisenberg, J. & Colford, J. M. Jr. 2003 Do US EPA water quality guidelines for recreational waters prevent gastrointestinal illness? A systematic review and meta-analysis. *Environ. Health Perspect.* **111**(8), 1102–1109.

Whitman, R. L. & Nevers, M. B. 2004 *Escherichia coli* sampling reliability at a frequently closed Chicago beach: monitoring and management implications. *Environ. Sci. Technol.* **38**(16), 4241–4246.

Whitman, R. L., Shively, D. A., Pawlik, H., Nevers, M. B. & Byappanahalli, M. N. 2003 Occurrence of *Escherichia coli* and enterococci in Cladophora (Chlorophyta) in nearshore water and beach sand of Lake Michigan. *Appl. Environ. Microbiol.* **69**(8), 4714–4719.

Whitman, R. L., Nevers, M. B., Korinek, G. C. & Byappanahalli, M. N. 2004 Solar and temporal effects on *Escherichia coli* concentration at a Lake Michigan swimming beach. *Appl. Environ. Microbiol.* **70**(7), 4276–4285.

WHO (World Health Organization) 1999 *Health Based Monitoring of Recreational Waters: The Feasibility of a New Approach (The "Annapolis Protocol")*. Organization Report No. WHO/SDE/WSH/99.1. Geneva, Switzerland.

WHO (World Health Organization) 2003 *Guidelines for Safe Recreational Water Environments. Volume 1 Coastal and Fresh Waters*. WHO, Geneva, Switzerland.

Yamahara, K. M., Layton, B. A., Santoro, A. E. & Boehm, A. B. 2007 Beach sands along the California coast are diffuse sources of fecal bacteria to coastal waters. *Environ. Sci. Technol.* **41**(13), 4515–4521.

First received 1 October 2007; accepted in revised form 11 February 2008. Available online October 2008.