EPA 823-R-07-006

REPORT OF THE EXPERTS SCIENTIFIC WORKSHOP ON CRITICAL RESEARCH NEEDS FOR THE DEVELOPMENT OF NEW OR REVISED RECREATIONAL WATER QUALITY CRITERIA

Airlie Center
Warrenton, Virginia
March 26-30, 2007

U.S. Environmental Protection Agency
Office of Water
Office of Research and Development

June 15, 2007

CHAPTER 6
MODELING APPLICATIONS FOR CRITERIA AND IMPLEMENTATION

Alexandria Boehm, Chair, Stanford University, California
Donna Francy, U.S. Geological Survey
Mark Pfister, Lake County Health Department, Illinois
John Wathen, USEPA
Richard Zepp, USEPA

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6.1 Introduction

The Modeling workgroup was charged with determining how models might be incorporated into future recreational water criteria development and implementation. Workgroup members did not explicitly consider total maximum daily loads (TMDLs) in the discussion because models are already being used in TMDLs for pathogens throughout the United States. The discussion focused on what was generally felt to be the most important novel applications of models in new or revised recreational ambient water quality criteria.

In the context of recreational water quality criteria, a perfect model would allow prediction of fecal indicators, pathogens, or risk as a function of source presence and strength relative to physical, chemical, biological, and human variables.

There is limited understanding regarding the sources of microorganisms and their fate and transport in the aquatic environment, so the use of deterministic, process-based models (see Appendix G) in criteria development and implementation is not practical for most U.S. water quality managers within the next five years (2012). Rather, **simple heuristic, statistical models that do not necessarily require an understanding of processes and mechanisms are more realistic for criteria development and implementation within the next 5 years.** This is not to say that substantial research should not go into refining understanding of sources, fate, and transport of pathogens and pathogen indicators and their spatial and temporal variability in water and sediments. Thus, workgroup members suggested that a substantial research effort go into understanding these processes in watersheds and near-shore waters as this will have profound impacts of development of future ("next generation") recreational water quality criteria (see Section 6.5).

Workgroup members saw two roles for models in the development and implementation of near-term (five years) new or revised criteria: (1) recreational water quality notification models and (2) models to support sanitary investigations (hereafter referred to as "sanitary investigation models" for simplicity). Recreational water quality notification models are already in use in the Great Lakes and have proven to be effective and popular with the public (Francy and Lis, 2007; Olyphant, 2004; Whitman, 2007). There are a handful of sanitary investigation tools and models that are accessible to recreational water managers throughout the country (e.g., DigitalWatershed, the BASINS3 system). The main focus of this chapter is water quality notification models because these are easily accessible to a wide range of recreational water managers in the near-term. However, because workgroup members viewed the sanitary investigation model as an area of near-term research activities and investigation, with possible applications in the near-term development of new or revised criteria and/or implementation, discussion of sanitary investigation models was included as well.

6.1.1 Water Quality Notification

Numerous research studies in the peer reviewed literature show that a single sample standard implemented in conjunction with assays that require incubation longer than a few hours results in less accurate management decisions (Francy and Darner, 2006; Hou et al., 2006; Kim and Grant 2004). That is, by the time results from analysis of a water sample are available and a water quality notification is issued, the microbial water quality may have changed. This is due to the inherent variability in indicator bacteria levels over timescales shorter than a day (see Figures 4a and 4b), as measured by culture-based assay, both with selective membrane-filtration media and

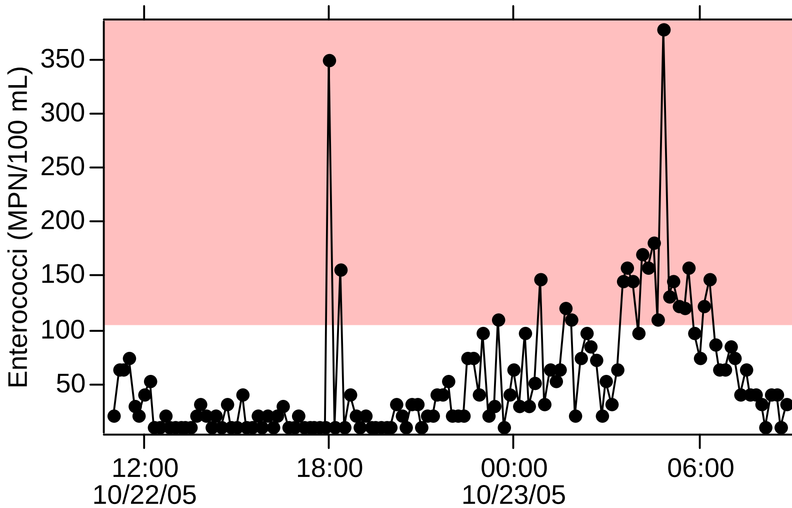

Figure 4a. Enterococci (MPN/100 mL) Sampled Every 10 Minutes at a Beach in California. (The reference background denotes the range of single sample exceedance.) SOURCE: A.B. Boehm, unpublished data (ENTEROLERT assay).

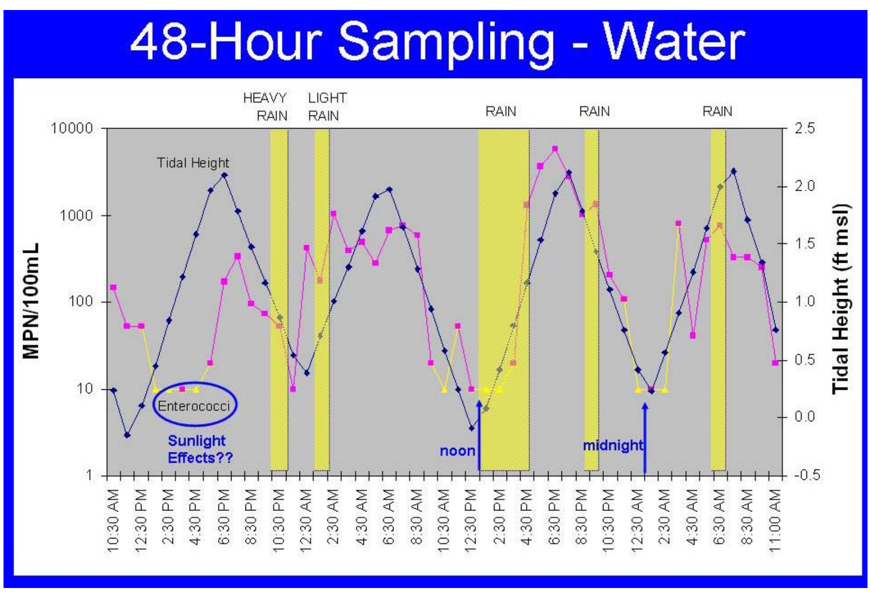

Figure 4b. Subtropical Marine Beach (Miami, Florida): 48 hours Sampling. SOURCE: Amir Abdelzaher, Samir Elmir, Lora Fleming, Kelly Goodwin, Helena Solo-Gabriele, John Wang, Mary Wright, University of Miami, personal communication, 2007.

defined substrate technologies such as Quanti-Tray (IDEXX, Westbrook, Maine). Note, variability in indicator levels as measured by nucleic acid-based assays (like quantitative polymerase chain reaction [qPCR]) has not been well characterized in the peer reviewed literature. The variability in Figures 4a and 4b is not unusual in environmental waters because "patchiness" is an inherently natural phenomena. **A water quality notification model can be used to augment monitoring data and provide more timely and accurate recreational water quality notification to better protect the public from exposure to waters not in compliance with water quality criteria or standards.**

Summary of near-term research needs (i.e., the next 2 to 3 years) specific to **water quality notification** include (see Section 6.5 for further information) the following:

1. Day-to-day water quality notifications should not be issued using a single sample standard in conjunction with a microbial assay that takes longer than a few hours due to time-lag notification errors as discussed above. Simple, heuristic or statistical water quality notification models are one way to improve water quality notification accuracy.
2. Immediate research needs include the following:
    a. Testing whether models can be used to predict health outcomes during upcoming epidemiological studies in California and in Alabama and Rhode Island and retrospectively for the Great Lake epidemiology study in the Great Lakes (Wade et al., 2006) (that is, risk = f[temperature, tides, waves, etc.]);
    b. Developing and testing simple notification models on different recreational water types with a wide range of sources and geographical locals;
    c. Exploring the feasibility of developing regional models that apply to more than one recreational water;
    d. Training recreational water managers; and
    e. Creating a user-friendly portable package for developing local models.

6.1.2 Sanitary Investigation

Quantitatively determining the potential for a waterbody to be impaired with human pathogens is essential if the European Union (EU; EP/CEU, 2006) or World Health Organization (WHO, 2003) approach to criteria development is undertaken (i.e., sanitary investigation is integrated into the criteria). This potential could be determined using a "toolbox approach" in conjunction with water quality notification models or sanitary investigation models. In the first case, the water quality notification model results can be used to learn about the factors that influence water quality in recreation waters; for example, high rainfall and wave action from a given direction and of a given height might lead to greatest impairment. The occurrence of these environmental conditions can be used to trigger sampling for "toolbox" approaches such as analyses for human-specific or bird-specific markers and human pathogens to "rule in" or "rule out" high probability of human pathogen presence. In the second case (sanitary investigation models), simple, quantitative sanitary investigation models that relate watershed attributes to probability of human pathogen impairment may be developed.

Summary near-term research needs (i.e., the next 2 to 3 years) specific to **sanitary investigation models** include (see Section 6.5 for further information) the following:

1. Simple, heuristic or statistical models that correlate watershed activities (presence of wastewater/sewage treatment plant effluents, agricultural activities, and domesticated animals) and attributes (slope, soil type, climate, soil moisture) can be used to determine the susceptibility of a waterbody to pathogen impairment.
2. Research should be conducted to better understand how watershed activities and attributes relate to pathogen presence in streams and receiving waters and include the following:
    a. factors that modulate septic tank impact on waterbodies;
    b. factors that modulate contributions of animal wastes to pathogen and pathogen loads to waterbodies;
    c. sources in urban landscapes (e.g., broken/leaky sewer pipes, combined sewer overflows [CSOs], runoff); and
    d. effect of meterological factors (e.g., rainfall, evapotranspiration, etc.) on non-point sources.

6.2 How Models are Currently Being Used

6.2.1 Sanitary Investigation Models

Sanitary investigation models that explore the relationship between land use, watershed attributes, and water quality are already in place and have been used in TMDL implementation (criteria implementation); however, they have not been specifically applied to criteria development. Creating a TMDL-like model for a waterbody prior to impairment may be viewed as proactive rather than reactive. Such models in use include deterministic models like Hydrological Simulation Program-Fortran (HSPF) and Storm Water Management Model (SWMM) for watershed loading, and CE-QUAL models for pathogen fate and transport (US EPA, 2002). Feedback from some environmental engineers and consultants who apply these models to pathogen and fecal indicator transport suggests they provide highly uncertain predictions for pathogen and indicator concentrations and fluxes (Ali Boehm, Stanford University, personal communication, 2007).

If sanitary investigation models are to be used for criteria development (i.e., prioritizing or discounting procedure for various type of sources), then models that are quantitative yet simple must be available to managers who do not have the resources to run full-scale simulations. These quantitative simple models need to relate land use activities and patterns to the likelihood of human pathogen presence. The ability to rule in or rule out the presence of human pathogen sources in a watershed would be useful to recreational water managers—especially if the EU or WHO approach to criteria development is undertaken. The relationship between land use patterns and microbial water quality has been investigated quantitatively along the California coast (Handler et al., 2006), lakes of South Carolina (Siewicki et al., 2007), North Carolina (Mallin et al., 2000), and Georgia (Fong et al., 2005; Vereen et al., 2007). In Australia, the relationship between land use and watershed attributes and pathogens and pathogen indicators has been applied to numerous catchments using what is termed "pathogen catchment budgets (PCBs)" (Ferguson and Croke, 2005; Ferguson et al., 2007). A sanitary investigation model, for example, might indicate that a completely undeveloped watershed with no agriculture has very low probability of producing runoff containing human pathogens and could potentially place a water body in a "low concern" tier in criteria similar to the EU or WHO approaches (see Tables 1 and 2, Chapter 1). Such models are being developed and used in the U.K. for criteria implementation and development (David Kay, University of Wales, U.K., personal communication, 2007; Kay et al., 2005, 2007).

6.2.2 Water Quality Notification Models

Water quality notification models that are most commonly used are simple heuristic models that relate rainfall to water quality. More complex models currently in use for informing advisory and closure decisions are exclusively statistical models that are used in conjunction with historical water quality data. The models draw on a body of past recreational water monitoring water quality data and temporally-associated physical parameters. The models are developed by assessing and exploring data for parameters that correlate most strongly with variations in water quality detected over the course of monitoring for pathogen indicators. Promising variables are selected, regression models are tested, and the models are refined on the basis of the results obtained using single variables and/or sets of variables.

Another type of "model" for water quality notification is the Heal the Bay Beach Report Card grading system (http://www.healthebay.org/brc/statemap.asp), which provides grades for water quality that are updated daily and formulated using more than one water quality measurement. Given the major uncertainty and variability in measured microbial water quality (e.g., Figures 4a and 4b), this is highly preferable compared to using a single sample to drive public water quality notifications.

One workshop participant (not from the Modeling workgroup) suggested that neural network models be used to model water quality for notification. Neural networks relate independent variables to a dependent variable non-linearly and have been used to model fecal coliforms in some waterbodies (Kumar and Jain, 2006; Neelakantan et al., 2002). However, the Modeling workgroup members agreed that neural network models would not be accessible to the majority of U.S. recreational water quality managers and public health officials in the near-term (5 years). In addition, neural network models have not been used previously for water quality notification, so they are probably not going to be useful in the near-term. They are, however, worth examining in the future.

Simple statistical models have been developed for Great Lakes and West Coast recreational waters that link fecal indicator concentration with meteorological and water quality data/information, and include the following:

- water quality and dynamic hydrologic variables (e.g., water temperature, turbidity, currents, wave height, tide level or range, lake height);
- optical property data (e.g., UV and visible irradiance, light scattering, cloud cover);
- meteorological parameters (air temperature, wind speed/direction, rainfall, pressure); and

- other factors (e.g., bird counts near a recreational water, number of swimmers in the water, video counts of swimmers and wildlife, flow/discharge from a storm drain or nearby creek).

These models have been used very successfully in three states in the Great Lakes to predict the likelihood of exceedance of the current (US EPA, 1986) indicator bacteria criteria for public water quality notification. The models have been shown to be effective in predicting indicator concentrations for compliance and for making timely public health decisions relative to recreational water advisories and beach closures.

The short-term predictions derived from these statistical models have been referred to as "nowcasting." Nowcasting has been described in the peer reviewed literature (Boehm et al., 2007; Francy et al., 2002, 2003; Hou et al., 2006; Nevers et al., 2005). The variables that are used to correlate with indicator concentrations vary depending on the type of setting of the recreational water. Among the descriptive variables assessed to date, turbidity, rainfall, tides, and wave height have been found to be among the most highly-correlated. The success of these models has been evaluated by their effectiveness in predicting days when current EPA limits have been exceeded and comparing predictions with bacteria concentrations from monitoring on a given day.

Statistical tools such as Swimming Advisory Forecast Estimate (SAFE) and SwimCast (http://www.earth911.org/waterquality/) for Lake Michigan and nowcasting models for Lake Erie are being used to warn the public about potentially unhealthy conditions in recreational waters. Project SAFE is a statistical model used for the five recreational waters in Lake and Porter Counties that extend to the west of the Burns Ditch outfall (Ogden Dunes, West, Wells Street, Lake Street, and Marquette Beaches). These beaches are directly affected by contaminants in the Burns Ditch outfall, particularly during prevailing north wind conditions. Project SAFE models provide a far better real-time estimate of *E. coli* counts than advisories based on single sample monitoring, and are generated for the five beaches simultaneously. Similar applications are being developed for other Great Lakes recreational waters. Another instance of statistical model use is the Ohio Nowcast system. The U.S. Geological Survey (USGS) and Cuyahoga County Board of Health are implementing a pilot Nowcast project to test the use of a statistical model at Huntington Beach, Bay Village, Ohio (Francy and Lis, 2007). Nowcast was used as a tool for recreational water closure decisions for the first time in Ohio in 2006. If the testing goes well, the Nowcast model will be used in subsequent years at other Lake Erie recreational waters.

In all cases where models are being used in the Great Lakes, the modeling is being used to augment microbial water quality monitoring that is being continued as required by the *National Beach Guidance and Required Performance Criteria for Grants* (US EPA, 2002). In Lake County Illinois (SwimCast) all recreational waters are monitored each day in the morning and 5 days per week in the afternoon at locations used for obtaining data for statistical modeling. In Indiana (SAFE model) recreational waters are monitored once a week. In Ohio (Nowcast) monitoring occurs 4 days per week at most Lake Erie recreational waters; and at Huntington Beach, monitoring was increased to 7 days per week during 2006 to provide a large data set to test the accuracy of the Nowcast system.

Hou et al. (2006) and Frick and Ge (submitted) have taken other important steps in developing useful statistical tools for use in recreational water quality notifications. Currently used models are based on long time-series records because models developed from large data sets are generally considered better than models developed from smaller data sets. However, large data sets are developed over time, so this approach is "static." Because conditions at recreational waters are highly dynamic and change from year-to-year and as the season progresses, these authors' models use a dynamic approach in which the descriptive variables are updated periodically.

6.2.1 Communication of Modeled Information to the Public and Recreational Water Managers

Information on modeled projections of water quality has been communicated to the public through the use of a range of communication media and in a variety of information formats. Internet postings, radio spots, and local signs have all been employed in communicating the output of regression model-based advisories. Model outputs intrinsically include an estimate of error. This is expressed in the Nowcast program in a manner similar to the familiar weather forecast probability of precipitation (POP). That is, the likelihood of an exceedance of water quality standards for a given day is expressed as a percentage. In SwimCast, the modeled estimate of fecal indicator concentrations is provided with the average prediction and the upper and lower bounds of the 99th percent confidence limit of the projected figure. Because the value of that number to the general public is limited, a risk explanation is reported based on this statistical prediction in terms of a text description (e.g., low risk if entire confidence interval is below the single sample maximum criteria).

Information on beach water quality can be provided to the public through a tiered approach. The first tier involves communicating a red or green light; that is, simply informing the public on whether or not the recreational water is currently posted with a water quality advisory. The second tier is to provide additional information for those who desire to be more informed and could include posting the measured water quality, environmental water quality data, and the resultant numerical prediction on a website. The third tier is to provide detailed information on the Nowcast system and explain how statistical models are developed and tested, which can also be provided on a website or summarized in fact sheets distributed to the public at the recreational water. A tiered system allows the recreational water user the ability to choose their desired level of information.

Effective communication to the recreational water manager and state and local public health agency representatives is essential for acceptance of a Nowcast or similar system. Presenting the science behind statistical modeling in a simple and concise manner at periodic workshops and meetings is the first step toward gaining acceptance. Because the Nowcast system is different from conventional water quality notification systems already in place (i.e., using the previous day's measured bacterial indicator concentration), local officials may be apprehensive in accepting the new technological approach. Thus, demonstrating to local agencies that the Nowcast system provides a more accurate assessment of water quality conditions may be required before acceptance and implementation is achieved.

6.3 Advantages and Disadvantages of Modeling

The main advantage of modeling for water quality notification is that modeling can provide accurate and timely notification of water quality, whereas day-to-day monitoring cannot. Such modeling may be as simple as a heuristic model or a letter grade for recreational water. More complex models, such as those already in place in the Great Lakes, use multiple regression modeling or similar tools.

An advantage of using a simple sanitary investigation model that relates land use activities and patterns to microbial water quality is that a manager may be able to rule in or rule out the presence of human pathogen sources in a watershed to relax criteria, as is proposed in the EU (EP/CEU, 2006) and WHO (2003) approaches to criteria development.

6.3.1 Advantages of Modeling

- Statistical/regression fecal indicator estimation models are relatively easy to create for an individual with knowledge of statistics and may in some cases only require one variable to adequately describe/predict the pathogen indicator. Several government or private entities currently maintain hydro-meteorological equipment and sensors (e.g., USGS, National Oceanic and Atmospheric Administration [NOAA]) with readily accessible real-time data via the Internet, which could be used at no cost to the recreational water quality manager if deemed appropriate for the specific recreational water. Collected descriptive variables can either be continuous or categorical. Once developed and put into place, statistical models are also easy to use with minimal training required for the recreational water managers and operators.
- Predictions from a sanitary investigation model may allow managers to rule in or rule out human pathogen sources in their watershed and hence relax water quality criteria using an EU or WHO criteria approach. Land use and watershed attributes may be readily available for incorporation into such a model (e.g., Digital Watershed, see http://www.iwr.msu.edu/dw/).
- Water quality notification predictions may be made "near" real-time if required data elements (input variables) exist. This alleviates the delay currently experienced by culturable methods (18 to 24 hours for *E. coli* or at least 24 hours for enterococci). Even with the advent of rapid qPCR (molecular-based) methods, there will continue to be time associated with collection, sample preparation, analysis, and results evaluation. For example, sample preparation adds an estimated minimum of 2 hours in addition to the analysis time. In addition, only the most intensively used waterbodies will likely be monitored with a frequency that will make the best use of the timely results from the use of these methods.
- Collection and analysis delays for both culture- and non culture-based methods currently have and potentially will continue to result in false negative (Type II) advisory/closure errors (e.g., contaminated recreational waters remain open). This is due to the inherent variability of fecal bacteria densities—even over time scales as short as every 10 minutes (see Figures 4a and 4b). Statistical models created for various recreational waters in the Great Lakes have been successfully used to correctly advise/notify the recreational water user of current fecal indicator conditions. Proper public notification should result in

improved public health outcomes and is the major benefit of statistical modeling. It has been well received (instills confidence) by the public and recreational water managers and operators at currently used recreational water locations.

- For recreational waters that have daily (or multiple day per week) monitoring of a fecal indicator and other hydro-meteorological data, costs for creating a statistical model will be low relative to other monitoring/advisory costs. For many recreational waters, initial model creation will require additional water quality monitoring for fecal indicators because it is imperative that the data set on which the model is based include a full range of fecal indicator concentrations for the specific location. However, once the statistical model is created and is validated, the need for daily or weekly monitoring could be reduced, potentially reducing monitoring costs.
- Once the statistical model has been created, both the data-element collection and actual prediction can be automated using current technologies. Although automation initially increases costs (i.e., equipment and programming), personnel costs should be reduced over time.
- Many recreational waters are monitored infrequently due to economic reasons or logistical issues (e.g., difficulty of sampling on weekends). Statistical modeling, if relatively automated, will improve water quality notification activities at these locations, often during highest use days.
- When associated variables become known during model development, a deeper understanding and knowledge of the potential reasons driving increased fecal indicator concentration should assist the recreational water operator (and other interested parties) with future assessments and sanitary investigation work. Simple linear relationships can help to identify potential sources of fecal indicator bacteria (i.e., waterfowl counts versus *E. coli* measurements) and can be used to help design monitoring and microbial source tracking studies.
- Currently used statistical models are based on recreational water quality criteria and thus meet Beaches Environmental Assessment and Coastal Health (BEACH) Act of 2000 and recommended Clean Water Act (CWA) §304(a) single sample maximum allowable fecal indicator density requirements. Because previous studies have demonstrated that the currently-used bacterial indicators are statistically associated with acute GI illness, predictions based on these pathogen indicators should be protective of public health.
- Statistical models could possibly be used to forecast poor conditions at recreational waters using forecasted descriptive variables available from NOAA.
- The statistical approach is flexible and could be applied to prediction of other criteria besides the current culturable *E. coli*- and enterococci-based criteria. However, new data would be required to calibrate the models if the criteria changes and this could be a disadvantage (see more below).

6.3.2 Disadvantages of Modeling

- Because water quality notification models are based on real-time data, prediction accuracy may be diminished by poorly collected or inappropriately maintained equipment. Quality assurance and quality control procedures must be in place for all required input data elements. Recreational water managers and operators (or other individuals) must be diligent in ensuring that proper collection and data management techniques are used.

- Because current water quality notification models utilize statistical techniques, a relatively large (n = 75) and rigorous data set is required to develop the model. Both dependent and assumed descriptive variables should be collected at least 3 to 4 days/week during the recreational water season (if possible). Additionally, the data set should contain a variety of sampling events to capture temporal variability (morning and afternoon) and under both wet and dry weather conditions. It is also necessary to attempt to sample and collect the full range of fecal indicator concentrations for a specific recreational water to help ensure accurate future predictions.
- Politicians, government officials, recreational water operators and managers, and the public may be apprehensive to accept the concept or the need for a modeling-based water quality notification system. Initial support may be difficult to obtain and a local "champion" would be beneficial to advance the concept. The workgroup members noted that once a model is created and accurate predictions are demonstrated, this apprehension would lessen substantially over time.
- Statistical water quality notification models are based on previously collected data and historical associations. Unanticipated events such as sewage spills, large increases in wildlife populations, changes in shoreline from extreme weather events, or new non-point sources of fecal contamination may reduce the predictive ability of the model. If numerous under- or over-predictions occur, additional data collection activities would be warranted to determine whether the model would need to be modified.
- Statistical water quality notification models appear to be most useful at recreational water locations that have occasional but infrequent exceedances of current bacterial water quality criteria. Recreational waters with consistently low or high fecal indicator concentrations may be very difficult to model. Additionally, the need for modeling will be harder to justify as currently accepted monitoring designs may be a preferable and cheaper method.
- Simple statistical models, whether for recreational water quality notification or sanitary investigations, are generally not sufficient for use as deterministic models (e.g., bacterial fate and transport) or to provide load estimates for use in developing TMDLs.
- Current statistical water quality notification models are based on recreational water criteria and thus meet BEACH Act and recommended CWA §304(a) single sample maximum allowable fecal indicator density requirements. However, if ambient water quality criteria for bacteria change, all currently used statistical models will need to be modified to reflect and predict the new criteria. This will result in new costs in the redevelopment and modification of an existing model to incorporate the changed relationships of predictive variables to indicator concentrations. In addition, because fecal indicators are used to predict health risk, the model is only as good as the indicator used.
- There is some confusion as to whether a model output should be measured against a single sample standard and/or a 30-day geometric mean standard. Input from workshop participants revealed that these criteria are used differently around the country with monitoring data. Output from water quality notification models should be used with the

single sample standard and not the 30-day geometric mean standard because it is not clear that model outputs should be averaged for comparison with the 30-day geometric mean standard. Guidance needs to be provided on this issue if new or revised recreational water quality criteria will support the use of models.

- Because water quality is inherently variable, even over a 10-minute scale (see Figures 4a and 4b), how to collect data to develop and validate models needs to be carefully considered. In the Great Lakes, composite sampling is conducted. Guidance for any new or revised criteria that recommend models would need to address this.
- There was some concern from the Implementation Realities workgroup that recreational water advisories or closures instigated by model output would count against them for CWA §303(d) listings or other CWA applications. Guidance for any new or revised criteria that recommend models would need to address this concern.
- Models are site-specific and must be developed for various recreational sites, the same way water quality monitoring must be conducted at specific sites.
- Sanitary investigation models have not been used before for water quality criteria development.

6.4 Model Development and Evaluation

6.4.1 Initiating Model Development for Water Quality Notification

Prior to initiating statistical model development at any recreational water site, a review of all past monitoring and watershed data should be completed. In some cases, enough data may exist to analyze associations between the environmental variables and indicator densities. For example, some states and local agencies collect data on air and water temperature, rainfall, amount of algae wrack, and/or tide level during compliance water monitoring. This type of ancillary data can be used to develop preliminary models and determine if any relationships between indicators and readily available environmental variables exist. This may guide additional monitoring needs and variables to be assessed. As always should be the case, strict quality assurance and quality control practices are to be followed to ensure that a high quality data set has been or will be collected. Additionally, a good understanding of the potential sources and extent of fecal contamination should be determined to aid in choosing sample locations and frequencies. This type of information can be obtained from recently conducted sanitary investigations, historical observations from local water resource managers, and/or visits to the recreational water site.

6.4.2 Model Development for Water Quality Notification

Statistical models have relatively easy to obtain data needs. Data collection should include observations that cover the range of hydrometerological conditions that are expected to impact the recreational water. Sampling should be conducted, at the very least, by collecting at least two recreational seasons of data. A minimum of one recreational season will be necessary for model creation, while the second is used to gather additional data and for model evaluation. Water should be collected four or five times each week and the data set should contain a variety of sampling events to capture temporal variability (morning and afternoon) under both wet and dry weather conditions. It is also necessary to attempt to sample and collect the full range of fecal indicator concentrations for a specific recreational water to ensure accurate future predictions. If current monitoring is conducted on a weekly or monthly basis, serious consideration should be given to increasing data collection requirements as it will take a much longer time period (i.e., 5 years) to develop the model. Generally, a relatively large (n = 75) and rigorous data set is required to develop a water quality notification model. Recreational locations that have consistent good or bad water quality are not good candidates for statistical models. Rather, sites with mixed water quality conditions are the best candidates for statistical models. A representative sample of the waterbody (multiple point grab samples or composite samples for larger recreational areas) should be analyzed for concentrations of fecal indicator bacteria, such as *E. coli* and enterococci, determined by use of an EPA-recommended method.

The descriptive variables for each recreational waterbody will differ from site-to-site. More precise and frequent measurements may lead to better statistical models but also lead to increased costs. However, increased equipment use does lead to automated processes, greater reliability of measurements, and reductions in personnel time.

Water quality notification models use a variety of descriptive variables and all are based on statistical correlations between descriptive variables and indicator organisms. Wave height has been shown to have a positive association with fecal indicator bacteria at some beaches and thus is often included as an independent variable in water quality notification models. Wave height can be estimated visually, measured with a graduated rod, or with pressure transducers. Wave height estimates can also be obtained from an off-site external source, such as a NOAA buoy. Turbidity has also been proven to be a useful factor for use in predictive models. Turbidity can be measured with a field turbidimeter or in situ by use of a turbidity sensor. Models of marine recreational water sites may also include tides (Boehm and Weisberg, 2005; Hou et al., 2006). Insolation, a measure of solar radiation, has been shown to be a useful predictor for fecal indicator bacteria models, since fecal indicator bacteria are sensitive to sunlight (Boehm et al., 2002). Insolation can be measured using a pyranometer on site or provided by external sources (such as NOAA). Rainfall, as well as wind speed and direction, have been included in predictive models. These data can be measured in situ using a weather station or obtained from a reliable source such as operating meteorological stations, which are often located at airports (NOAA, 2007). Streamflow rates from nearby tributaries (USGS, 2007) and effluent discharge rate information from wastewater treatment plants may also be useful factors for inclusion in a predictive model. The number of birds at the recreational water might also prove useful factors for inclusion in a model. Some models presently in use in the Great Lakes for water quality notification use the amount of biological wrack or algal mats as model inputs. Overall, the factors/variables included in a model will be site-specific. A thorough review of factors that might be included in a water quality notification model is outlined in Boehm et al. (2007). Water quality notification models that are most commonly used are simple heuristic models that relate rainfall to water quality (Ashbolt and Bruno, 2003).

Two types of output may be produced by statistical models. The first and obvious output is the predicted microbial concentration and its associated confidence limits. A second output variable is the probability of exceeding an appropriate target value; for example, the probability of exceeding the single sample maximum recreational water quality criteria (Francy and Darner, 2006). Either output may be used to issue advisories or closings of a recreational water site.

6.4.3 Data Needs for Simple Sanitary Investigation Model Development

Because the sanitary investigation model has not been implemented previously for water quality criteria development, data needs are based on characteristics that are important to models used for TMDL implementation. A waterbody manager would need data on land use within a watershed, types and numbers of domesticated and wild animals, publicly (and privately) owned (wastewater) treatment works (POTW) discharges and their degree of treatment and effluent characteristics, number and types of on-site septic systems, type and age of sewage infrastructure, presence of CSO and sanitary sewer overflows (SSO) systems, soil characteristics, and watershed slope. At minimum, such a model could generate a quantitative score of "very likely" to "not probable at all" regarding the possibility of having human pathogens present.

6.4.4 Cost Estimates

There is a wide range of cost estimates for the development, validation, and maintenance of statistical model programs. For all programs, the assumption is that an indicator monitoring program is already in place for the recreational water and computer hardware and statistical software are available. The following are 3 examples of costs for statistical modeling programs for 2 recreational seasons (60 observations per season), starting from the least to most expensive programs.

1. Using existing data from other sources, such as meterological data from the National Weather Service (NWS) and wave height data from NOAA. Expenditures include data compilation and model development (200 hours of computer time).
2. Using existing meterological data from other sources, measuring turbidity, wave heights, and number of birds at the time of sample collection. Expenditures include the purchase of a turbidimeter and standards ($1,200), field measurements (30 hours), and data compilation and model development (200 hours).
3. Installing in situ site-specific instruments for measurements of wave heights, turbidity, wind direction and speed, and rainfall amounts. Expenditures include the purchase and installation of equipment (a one-time cost of $15,000 to $20,000), maintenance of equipment ($2,000/year for replacement and manufacturer calibration of equipment and 80 hours), and data compilation and model development (200 hours).

6.4.5 Understanding the Uncertainty and Measuring Success of Statistical Models

The natural complexity of environmental systems means that it is difficult to develop complete mathematical descriptions of relevant processes, including all of the intrinsic mechanisms that govern their behavior. Model evaluation is defined as the process used to generate information to determine whether a model and its analytical results are of sufficient quality to serve as the basis for decision making (CREM, 2003). Once a statistical model is constructed, it is important to describe its usefulness or success. A regression model is built using a "training" data set comprised of dependent and independent variables (Boehm et al., 2007). The ability of the model to predict the dependent variable using independent descriptive variable inputs within the training data set can be described by a root mean square error (RMSE). A coefficient of determination (R^2) can also be used and is interpreted as the percent of the variation of the independent data set described by the model. However, the workgroup members agreed that this was not the best metric for evaluating model performance. A third metric for testing the performance of a model is to examine the number of Type I and Type II errors that result. Assuming the null hypothesis is that a recreational water is in compliance with a water quality regulation and should be open to the public, a Type I error occurs when a recreational water is closed or posted with a warning when it should not be (i.e., false positive), while a Type II error occurs when a recreational water is not posted or closed when it should be based on the water quality regulation (i.e., false negative). These two types of errors can be summed to determine the total errors. The number of such errors is a function of the specific policy used by recreational water managers in making water quality notification and closure decisions.

Model evaluation must be conducted using a data set with which it was not trained before it can be applied as a predictive tool. Model evaluation is defined as the process used to generate information to determine whether a model and its analytical results are of a quality sufficient to serve as the basis for a decision (CREM, 2003). It can only be completed if an appropriate evaluation data set of independent and dependent variables not used to train the model is available. The success of a model during evaluation is described by the root mean square error of prediction, which has the same mathematical formation as the RMSE. The number of Type I and II errors, as well as the total error rate is also calculated. The model's performance is then compared with the current method for assessing recreational water quality (i.e., using the previous day's measured bacterial indicator concentration).

At a Lake Michigan recreational waterbody during 2004 (Olyphant, 2004; Pfister, 2007), swimmers were exposed to a health threat without warning on three occasions and kept out of the water when it was safe on only one occasion when a water quality model was used to make recreational water closure decisions. In contrast, swimmers would have been exposed to a health threat without warning on 19 occasions and kept out of the water when it was safe on 12 occasions if daily morning monitoring data alone had been used to notify the public of health risks.

Because every model contains simplifications, predictions derived from the model can never be completely accurate and the model can never correspond exactly to reality (CREM, 2003). After model validation (e.g., those that have been shown to correspond to field data), an additional year of data can be added to the model development process and a new model with another year of data is developed for use in subsequent years.

The information about model evaluation presented above is an overview. The peer reviewed literature should always be examined for new ideas and thoughts about model evaluation.

6.5 Research Needs

Research needs for simple, statistical models are categorized below regarding near-term activities (2 to 3 year horizon) of immediate relevance to implementation and development of new or revised rcriteria in recreational waters to long-term research activities, such as elucidation of processes affecting pathogen/indicator fate and transport, development of non-point source models for catchments or watersheds, and deterministic models for TMDL development. There were differences of opinion among workgroup members about how important TMDL model development is for the long-term for criteria development and implementation.

6.5.1 Near-term Research Needs (2 to 3 years)

There is an immediate need to conduct research for development of models that can be used for water quality notification. Statistical (or empirical) models are most promising for this purpose because they are relatively cheap and simple, and readily accessible to most recreational water quality managers (see Chapter 7). Statistical models link microbial concentrations with meteorological and water quality data/information. Recent research has lead to the development of useful statistical models for some Great Lakes recreational beaches (Francy and Darner, 2006; Francy et al., 2003; Frick et al., 2005; Olyphant, 2005; Whitman and Nevers, 2004; Whitman et al., 2006) and marine coastal beaches (Hou et al., 2006). Although these statistical models have successfully predicted criteria exceedances under a variety of environmental conditions, statistical modeling studies must be extended to a variety of other recreational waters to evaluate fully the utility of this approach.

Near-term research needs for water quality notification include the following:

1. Day-to-day water quality notifications should not be issued using a single sample standard in conjunction with a microbial assay that takes longer than a few hours due to notification errors. Simple, heuristic or statistical water quality notification models can help avoid notification errors (**all 5 workgroup members [5/5] agree**).
2. Immediate research needs include the following:
    a. Testing whether models can be used to predict health outcomes during upcoming epidemiology studies at Doheny Beach (California) and in Alabama and Rhode Island, and as well as the already completed epidemiology studies done in the Great Lakes (described by Wade et al., 2006) (**high priority [5/5]**);
    b. Developing and testing simple notification models on different recreational water types with a wide range of sources and geographical locals (**high priority [5/5]**);
    c. Exploring the feasibility of developing regional models that apply to more than one recreational water (**low priority [5/5]**);
    d. Training recreational water managers (**high priority [3/5]**, **low priority [2/5]**, there was disagreement on whether this belonged on the research list);
    e. Creating an excellent user-friendly portable package for developing local models (**high priority [5/5]**); and
    f. Developing dynamic predictive modeling methods (refers to models where variables are constantly updated over time) (**high priority [2/5]**, **medium priority [2/5]**, **low priority [1/5]**).

1. Linking statistical models to health effects. One approach would be to concurrently conduct modeling studies along with planned epidemiological studies that will be conducted by EPA and the Southern California Coastal Water Research Project during the upcoming year in California, Alabama, and Rhode Island. In addition to measurements of microbial concentrations, appropriate data for model development should be collected during the epidemiological studies (e.g., turbidity, irradiance, wind speed/direction, wave height, tides, temperature).

Another approach would be to retrospectively develop statistical models for sites of past epidemiological studies in the Great Lakes, where appropriate data relevant to statistical modeling have already been collected (or can be obtained from existing meteorological data). For example, statistical models have been developed for Huntington Beach, Ohio, and West Beach, Indiana—both of which are sites of past NEEAR epidemiological studies (Haugland et al., 2005; Wade et al., 2006).

2. Developing statistical models for different types of recreational waters. To test the feasibility of the statistical modeling approach, research is needed in recreational waters that are impacted by different sources of biological contaminants (non-point or point sources such as POTWs) and that are described by a wide range of meteorological and water quality variables. Waters that are significantly impacted by POTWs or non-point agricultural sources will be accorded the highest priority in site selection because past studies have shown that these sources are most likely to adversely affect human health. Sites located in the following regions should be considered for this research:

- West Coast (open ocean and confined beach);
- East Coast (open ocean and confined beach);
- Gulf Coast;
- inland lakes/reservoirs;
- rivers with designated primary contact recreational use; and
- tropics and subtropics.

3. Dynamic approaches to statistical modeling. Currently used models are based on long time-series records that take at least 2 years to obtain. The regression constant and coefficients are held constant when the model is used to predict (generally Nowcast) conditions. Once established, the models are changed only at the end of season to incorporate new data. Other recent research suggests that model performance may be improved by using a dynamic approach in which the descriptive variables are updated periodically with data generated within a limited recent period—usually on the order of 30 to 60 days. Using the dynamic modeling approach, the predictions of bacterial concentrations have been significantly improved (Frick and Ge, submitted; Hou et al., 2006) and the time period for model development may be reduced. An alternative approach would be the development of a sliding seasonal band of data using multi-year data from the period surrounding the date of interest. Additional research is required to refine this approach, either though use of previously obtained data sets or data obtained at sites that will be used for the first two activities (i.e., linking statistical models to health effects and developing statistical models for different types of recreational waters).

4. Communicating and training modeling techniques. Various activities can improve the communication of modeling techniques and results to the public and training recreational water managers, including the following:

- creating a user-friendly portable package for developing local models;
- training for running statistical models for recreational water managers; and
- including recreational water managers on the decision process and polling them regarding their perception of its usefulness/feasibility.

Training is an important component towards acceptance and implementation of statistical models by recreational water managers and public health agencies. In a November 2003 workshop held as part of the Great Lakes Beach Association Annual Conference in Green Bay, Wisconsin, recreational water managers expressed as a high priority the need for informed training on statistical models and other recreational water monitoring activities. Similarly, training is being provided by EPA Region 5 on statistical model and sanitary survey (investigation) development in April 2007 at the request of recreational water managers.

5. Explore the feasibility of developing regional models (e.g., for southern Atlantic coast recreational waters). At present, simple water quality notification models are site-specific. The feasibility of using a regional scale model that predicts water quality regionally, within a large waterbody, for example, should be explored.

Near-term research needs (next 2 to 3 years) for sanitary investigation models include the following:

1. Simple, heuristic, statistical/conceptual models that correlate watershed activities (e.g., presence of treatment plant effluents, agricultural activities, domesticated animals) and attributes (e.g., slope, soil type, climate, soil moisture) can be used to determine the probability of a waterbody having inputs of human pathogens (**all [5/5] agree**).
2. Research in the near-term should be carried out to better understand how watershed activities and attributes relate to pathogen presence in streams and receiving waters, including the following:
    a. factors that modulate septic tank impact on waterbodies (**high priority [1/5] medium priority [1/5]**, **low priority [3/5]**);
    b. factors that modulate contributions of animal wastes to pathogen and pathogen loads to waterbodies (**high priority [5/5]**);
    c. sources in urban landscapes such as broken/leaky sewer pipes, CSOs, stormwater and urban runoff (**high priority [5/5]**); and
    d. effect of geographical and climatic setting on non-point source delivery (**high priority [5/5]**).

6.5.2 Longer-term Research Needs (8 to 10 years)

A variety of research needs are required to be able to develop an excellent model that would allow prediction of fecal indicators or human pathogens. Additionally, important sources, and fate and transport processes will need to be elucidated. These research needs will require a longer time horizon for completion and are summarized below.

1. **Processes that affect fate and transport of pathogens and fecal indicators for incorporation into deterministic models and improving statistical models indicators.** This long-term research effort involves the development of data and descriptors of processes that are required in deterministic models that predict fate and transport effects on pathogen concentrations in recreational waters. Process information can also be used to help define appropriate variables to use in statistical models. Such research would focus on partitioning of microorganisms to suspended and bottom sediments and sands, mortality of pathogens and indicators, zooplankton grazing on fecal indicators and pathogens, and the possibility of bacteria proliferation in the environment. Some of these processes are shown in Figure 5. In addition to these processes, a better understanding of mobilization of pathogens and pathogen indicators from sources within a watershed (i.e., from animal feces) and source strength from POTWs and CSOs are needed (**high priority[5/5]**).

2. **Research on GIS layers relevant to modeling.** In order to develop viable models, recent and relevant GIS data need to be readily available and usable for models (e.g., POTW locations, recent land use categories, storm sewer locations). Digital Watershed

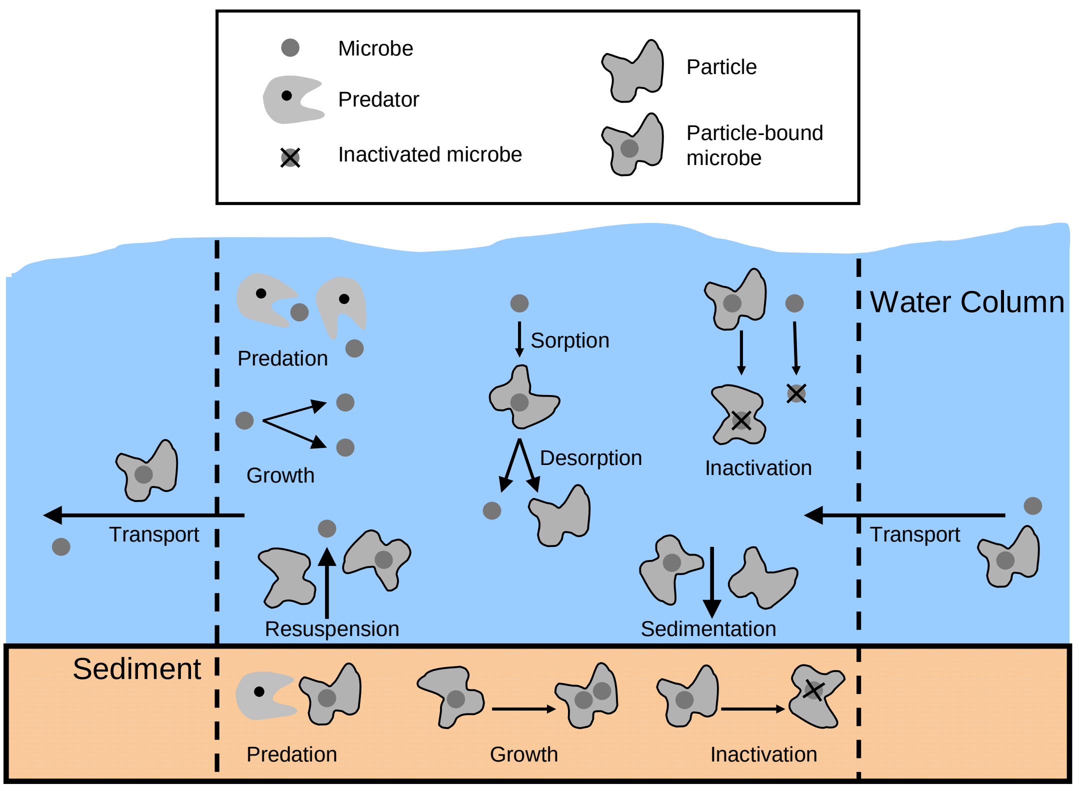

Figure 5. The Possible Fates of Microbes (Fecal Indicators and Pathogens) in Environmental Water and Sediment (the fate of nucleic acids may be different; this figure does not include those sources). SOURCE: Adapted from Olivieri et al. (2007).

is one example of a GIS-based software that can be used to provide inputs for deterministic models such as L-THIA (**high priority [1/5]**, **medium priority [4/5]**, **[1/5]** does not think this is a research need).

3. **Combining deterministic models with statistical models.** This research involves using outputs from deterministic models as inputs for statistical models that would be used for water quality notification and sanitary investigation purposes (**high priority [0/5], medium priority [5/5]**).

4. **Forecasting using statistical models.** This research will seek to expand current efforts (e.g., by Frick and Ge, submitted) to use forecasted variables (such as wind speed and direction, precipitation, wave height, and turbidity, if available) to forecast concentrations of biological contaminants in recreational waters (**high priority [2/5]**, **medium priority [1/5]**, **low priority [2/5]**).

5. **Development of deterministic models of pathogen and fecal indicators for criteria implementation and development** (**high priority [3/5]**, **medium priority [2/5]** there was concern that these would not be really used by recreational water managers and that this is already being done if resources permit).

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