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Review of Potential Modeling Tools and Approaches to Support the BEACH Program

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Abstract

The objective of EPA’s Beach Environmental Assessment, Closure and Health (BEACH) Program is to significantly reduce the risk of infection to users of the nation’s recreational waters. Waterborne pathogens reaching recreational areas can originate from various sources located either within the proximity of the beach or at upstream locations within the drainage area or watershed. These sources can be grouped into three categories: (1) nonpoint source-dominated systems, where pathogen contamination is governed by rainfall events; (2) point source-dominated systems, where pathogen impact is due to either continuous or intermittent discharges; and (3) episodic releases of untreated wastewater due to uncontrolled discharges and accidental spills.

States and local agencies that operate recreational beaches rely on monitoring of water quality for the presence of pathogens to support their beach advisory decisions. When pathogen concentrations exceed the water quality standard or local action level, beach advisories or closures are issued. To further support beach advisory decisions and to optimize water quality monitoring and testing activities, several agencies use mathematical models to predict increased pathogen concentrations. This document reviews predictive models currently used by beach operators as management tools to minimize exposure to pathogens. It also reviews available techniques that potentially can be used to further enhance pathogen prediction capabilities. This review is based first on the results of the 1998 National Health Protection Survey of Beaches, which asked respondents about predictive tools to support beach closure decisions. Available models developed and used to support other water quality-related programs are also reviewed, and their applicability to real-time prediction of pathogen concentrations is evaluated.

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Part I. Identification of Methods Currently Used to Predict Beach Advisories

1. Introduction

The objective of the EPA Beach Environmental Assessment, Closure and Health (BEACH) Program is to significantly reduce the risk of infection to users of the nation's recreational waters. Users of recreational waters are exposed to waterborne pathogens because of inadequate monitoring or delayed notification during periods of poor water quality. Currently, most notifications are based on monitoring of the beach water quality. Local government agencies test for the presence of increased levels of pathogens that may pose a threat to the health of beachgoers. The current laboratory methods used to detect potentially harmful microorganisms take up to 48 hours. During these 48 hours of water sample processing, beachgoers might be exposed to harmful pathogens.

To reduce exposure to pathogens, local government agencies need tools that can provide a quick and reliable indication of the water quality conditions. EPA Method 1600 for enterococcus is one such tool. This laboratory method reduces the test time to 24 hours. Another tool is the use of computer models or other information that can give an indication of the water quality conditions. The overall goal is to provide local governments with a range of predictive tools to determine the water quality conditions so that based on this information, decision makers can determine the need for beach advisories or closures.

In spring of 1998, EPA conducted the first annual National Health Protection Survey of Beaches. The objective was to collect information on beach health activities. Information on about 1,000 beaches was collected as result of the 350 questionnaires distributed by EPA to beach health agencies. A summary of the information from the 159 respondents was put on the Internet to enable public access. It is located at EPA's "Beach Watch" web site at www.epa.gov/ost/beaches.

The objective of this study is to inventory predictive models or tools currently in use by agencies responsible for evaluating the need for closing beaches or issuing advisories and warnings. A description of the predictive tools currently in use and their attributes is provided, as well as a discussion of the limitations, input data requirements, and availability for each of the predictive tools.

2. Waterborne Pathogens

Microorganisms are rampant in both the aquatic and the terrestrial environment, and many perform important functions. The survival of ecosystems is impossible without the decomposers. These microorganisms are responsible for converting organic matter to inorganic nutrients that can be used by other plants and animals. Also, microorganisms are an essential component of the nitrogen cycle and other biogeochemical cycles. In humans and animals high on the food chain, microorganisms resident in the digestive tract aid in the digestion process and are excreted in high numbers. A small group of microorganisms have been identified and linked with diseases and death. These pathogens can infect the body through skin contact or ingestion of contaminated water or food.

Pathogens are small in size, and once released to the environment they are easily transported by water. These characteristics are a primary concern of water resources managers, whose goal is to protect the public from coming into contact with pathogens through ingestion or swimming. Illnesses such as respiratory illness, fever, cryptosporidiosis, gastroenteritis, and hepatitis have been associated with waterborne microorganisms. These pathogens have been grouped into three subcategories—bacteria, protozoa, and viruses. Table 2.1 shows some of the waterborne diseases associated with each category.

Bacteria are microscopic, unicellular organisms that reproduce by binary fission (Chapra, 1997). Not all bacteria are pathogenic. Table 2.1 shows some of the major pathogenic waterborne bacteria of concern. Pathogenic bacteria found in surface water are often attributed to excretions from the bodies of warm-blooded animals. The coliform group, *Streptococcus, Lactobacillus, Staphylococcus,* and *Clostridium* are some of the pathogenic bacteria excreted.

Protozoans are also unicellular organisms that reproduce by binary fission. Pathogenic protozoans exist in the environment as cysts to protect themselves from harsh conditions of temperature and salinity. Once ingested, the cysts hatch, grow, and multiply, manifesting the associated disease. *Giardia lamblia* and *Cryptosporidium* are the two major groups of pathogenic protozoans associated with waterborne diseases in the United States. A cryptosporidiosis outbreak in Milwaukee in 1993 was caused by *Cryptosporidium* contamination of drinking water.

Viruses are submicroscopic infectious agents that require a host to live. The nucleic acid core is protected by a protein or lipoprotein shell that determines the surface to which a virus can adhere. Once inside the host, the virus reproduces, manifesting the associated illness. Viruses such as hepatitis A, rotaviruses, and Norwalk-type viruses are then excreted in the feces of infected individuals. These enteric viruses present a major threat to human health.

2.1 Indicator Organisms

Waterborne pathogens pose a threat to human health when people come into contact with contaminated water through ingestion of water, ingestion of fish or shellfish harvested from contaminated water, or skin contact (swimming). Identification and enumeration of pathogens such as viruses in water is a difficult process. Instead, laboratory methods have been developed to test for the presence and density of indicator organisms. The presence of the indicator organisms shows that a water body might be contaminated, and the concentration of the indicator organisms can be correlated to the concentration of the pathogen to give an indication of the extent of pollution (Thomann and Mueller, 1987). The coliform bacteria group is found in the intestines and feces of warm-blooded animals. Therefore, their presence indicates that pathogens from untreated or partially treated sewage or contaminated runoff may be present in the water. Bacteria in the coliform group, which includes total coliform, fecal coliform, and fecal streptococci bacteria, are used as indicators because (1) they are easily detected by simple laboratory methods, (2) they are not usually present in unpolluted waters, and (3) they appear in concentrations that can be correlated with the extent of contamination.

Table 2.1 *Waterborne pathogens*

Pathogen		**Disease**	**Effects**
Bacteria	*Escherichia coli* (enteropathogenic)	Gastroenteritis	Vomiting, diarrhea, death in susceptible populations
	Legionella pneumophila	Legionellosis	Acute respiratory illness
	Leptospira	Leptospirosis	Jaundice, fever (Weil's disease)
	Salmonella typhi	Typhoid fever	High fever, diarrhea, ulceration of the small intestine
	Salmonella	Salmonellosis	Diarrhea, dehydration
	Shigella	Shigellosis	Bacillary dysentery
	Vibrio cholerae	Cholera	Extremely heavy diarrhea, dehydration
	Yersinia enterolitica	Yersinosis	Diarrhea
Protozoans	*Balantidium coli*	Balantidiasis	Diarrhea, dysentery
	Cryptosporidium	Cryptosporidiosis	Diarrhea
	Entamoeba histolytica	Amedbiasis (amoebic dysentery)	Prolonged diarrhea with bleeding, abscesses of the liver and small intestine
	Giardia lamblia	Giardiasis	Mild to severe diarrhea, nausea, indigestion
	Naegleria fowleri	Amoebic meningoencephalitis	Fatal disease; inflammation of the brain
Viruses	Adenovirus (31 types)	Respiratory disease	
	Enterovirus (67 types, e.g., polio, echo, and Coxsackie viruses)	Gastroenteritis	Heart anomalies, meningitis
	Hepatitis A	Infectious hepatitis	Jaundice, fever
	Norwalk agent	Gastroenteritis	Vomiting, diarrhea
	Reovirus	Gastroenteritis	Vomiting, diarrhea
	Rotavirus	Gastroenteritis	Vomiting, diarrhea

2.2 Water Quality Standards

In response to widespread public concern about the condition of our nation's waters, the United States Congress enacted landmark legislation in 1972. This statute, the Federal Water Pollution Control Act Amendments of 1972 (referred to as the Clean Water Act of 1972, or CWA), expanded and built upon existing laws designed to control and prevent water pollution. Successive amendments to the 1972 CWA (the Clean Water Act of 1977 and the Water Quality Act of 1987) have continued to strengthen the law to better protect our nation's waters.

Water quality standards are the cornerstone of a state's water quality management program. States, territories, and Indian tribes set water quality standards for waters within their jurisdictions. Water quality standards define a use for a water body and describe the specific water quality criteria to achieve that use. The water quality standards also contain antidegradation policies to protect existing water quality. These are the goals by which success is ultimately gauged for a given water body or watershed.

The water quality standards program is administered by the U.S. Environmental Protection Agency (EPA). Congress has mandated that EPA is responsible for providing water quality criteria recommendations, approving state-adopted standards for interstate waters, evaluating adherence to the standards, and overseeing enforcement of standards compliance. Guidance for the development of standards by individual states, tribes, and territories is contained in the EPA documents *Water Quality Standards Handbook*, second edition (1983) and *Ambient Water Quality Criteria for Bacteria* (1986).

However, because of the difficulties in analyzing for and detecting the many possible pathogens or parasites, concentrations of fecal bacteria, including fecal coliforms, enterococci, and *Escherichia coli*, are used as the primary indicators of fecal contamination. The latter two indicators are considered to have a higher degree of association with outbreaks of certain diseases than fecal coliforms and were recommended as the basis for bacterial water quality standards in the 1986 *Ambient Water Quality Criteria for Bacteria* document (both for fresh waters, enterococci for marine waters). The standards are defined as a concentration of the indicator above which the health risk from waterborne disease is unacceptably high.

Prior to the 1986 revision to the national critera, recommendations were made by the National Technical Advisory Committee to the Secretary of the Interior in *Water Quality Criteria* (1967) and by EPA in *Quality Criteria for Water* (1976). In both of these documents criteria were based on fecal coliforms, and both recommended that maximum densities not exceed geometric means of 200 organisms per 100 ml in recreational waters (USEPA, 1998).

The 1986 criteria statement for bacteriological criteria follows:

EPA Criteria for Bathing (Full Body Contact)
Recreational Waters

Freshwater

Based on a statistically sufficient number of samples (generally not less than 5 samples equally spaced over a 30-day period), the geometric mean of the indicated bacterial densities should not exceed one or the other of the following:[1]

E. coli	126 per 100 mL; or
Enterococci	33 per 100 mL.

No sample should exceed a one sided confidence limit (C.L.) calculated using the following as guidance:

Designated bathing beach	75% C.L.
Moderate use for bathing	82% C.L.
Light use for bathing	90% C.L.
Infrequent use for bathing	95% C.L.

based on a site-specific log standard deviation, or if site data are insufficient to establish a log standard deviation, then using 0.4 as the log standard deviation for both indicators.

Marine Water

Based on a statistically sufficient number of samples (generally not less than 5 samples equally spaced over a 30-day period), the geometric mean of the enterococci densities should not exceed 35 per 100 mL.

No sample should exceed a one sided confidence limit using the following as guidance:

Designated bathing beach	75% C.L.
Moderate use for bathing	82% C.L.
Light use for bathing	90% C.L.
Infrequent use for bathing	95% C.L.

based on a site specific log standard deviation, or if site data are insufficient to establish a log standard deviation, then using 0.7 as the log standard deviation.

[1] Only one indicator should be used. The regulatory agency should select the appropriate indicator for its conditions.

Source: USEPA, 1998.

3. Predictive Methods Currently Used in the BEACH Program

The process of identifying predictive tools currently in use by local agencies responsible for beach advisories was based on three approaches. First, using the 1998 National Health Protection Survey of Beaches (or beach survey), agencies that are currently basing their beach advisories on water quality model prediction were identified. The agencies were then contacted regarding the types of models being used and information about extent of use, who developed the model, and the model's availability.

The second approach was a review of literature and information from related EPA programs. This approach included a review of the models and guidelines provided in the Clean Water Act (CWA) 301(h) program, identification of tools used in the Total Maximum Daily Load (TMDL) program, and review of other EPA publications that relate to water quality modeling.

The third approach in the process was networking within the modeling community. Model developers were queried about their models' availability and applicability to the BEACH Program. This approach was the most fruitful.

3.1 Model Categories

The overall objective of all beach advisory predictive tools is to reduce the risk of illness due to exposure to elevated levels of pathogens. The tools currently in use by responsible agencies vary in their complexity and approach to minimizing exposure. In the case of the City of Milwaukee, City of Stamford, and Delaware Department of Natural Resources and Environmental Control (DNREC), the approach taken was regression analysis to relate rainfall to pathogen concentration. Models developed based on this approach are site-specific since they are derived from locally observed relationships between water quality and rainfall data.

Simulation of water quality conditions under a variety of scenarios of untreated or partially treated wastewater can also be used. Comparison of the resulting water quality conditions to the established action level, such as the water quality standard, can serve as the basis for the beach advisory or closure. For the New York-New Jersey Harbor, a model was developed to predict water quality conditions that result from the bypassing of sewage at preselected locations. Beaches surrounding the discharge location are closed whenever the predicted pathogen concentrations exceed a locally specified threshold level.

Water quality models are used to establish closure zones in the shellfish sanitation programs of several states. Although the models used differ in their description of the dominant mixing and transport processes and their applicability to local conditions, the same basic approach is followed. The models are used to predict pathogen concentration in the waters surrounding a pathogen source, such as a wastewater treatment plant outfall. The boundary of the closure zone is then delineated based on these predicted pathogen concentrations. Dye studies may also be conducted in conjunction with the water quality modeling to refine the closure zone boundaries.

3.2 Use of Predictive Tools

Review of the 1998 beach survey results indicated that few local agencies are currently using models for beach closure. Some of the models used are based on simple relationships between the observed rainfall and pathogen concentration, and others are based on complex modeling of the dominant mixing and transport processes. The objective of either approach is to reduce the risk of illness due to exposure to water high in pathogen concentrations. It is important to note that in most cases predictive tools are not used alone; they are usually combined with real-time monitoring of water quality conditions. These two processes are dependent on one another. The frequency of water quality sampling might be reduced in the future once a reliable modeling approach is in place. Detailed descriptions and analyses of models now in use are provided in the next section.

3.3 Overview of Predictive Tools

3.3.1 Rainfall-based Alert Curves

The objective of rainfall-based alert curve models is to establish a statistical relationship between rainfall events and pathogen concentrations. This relationship can then serve as a management tool for developing operating guidelines or predicting pathogen concentrations requiring a beach advisory or closure. Several agencies have developed beach operating rules based on analysis of site-specific relationships between rainfall and water quality monitoring data. Examples from Delaware (DNREC, 1997), Wisconsin (City of Milwaukee Health Department, 1998), and Connecticut (Kuntz, 1998) are presented in this section to illustrate the development and application of this approach. These types of models are based on simple regression and frequency of exceedance analysis of simultaneous observations of pathogen concentration at representative monitoring stations located near the beach and rainfall events at one or several locations in the upstream watershed. The development of rainfall-based models consists of three phases, as described in the following box. These phases include data collection, data analysis and development of predictive tool(s), and development of operating rules.

For relatively small watersheds, it is common to use a single rainfall station selected to be representative of storm conditions of the upstream drainage area. The selection of a representative rainfall station takes into consideration its location within the watershed and its ability to capture the most dominant rainfall events (magnitude and duration) that generate relatively high storm runoff volumes and transport high pathogen loadings to the beach. For example, DNREC selected a rainfall station based on its central location in the watershed and strong statistical correlation with observed pathogen concentrations at the beach site of interest (DNREC, 1998). The city of Milwaukee compared rainfall data from various stations and elected to use a NOAA rainfall database that consistently provided a relatively better correlation with observed levels of pathogens. The city is currently performing further data collection and analysis to refine rainfall station selection for use in prediction of pathogen levels at three beach sites (City of Milwaukee Health Department, 1998).

Development of Rainfall-based Models

1. Data Collection

- Define pathogen species to serve as an indicator
- Define applicable standards and their expression
- Identify all rainfall monitoring stations within and surrounding the contributing watershed. (Define stations as hourly or daily stations. Hourly stations are preferred especially when dealing with small to medium-sized watersheds.)
- Define season of concern and collect corresponding rainfall data concurrently with pathogen data

2. Development of Predictive Tool

- Analyze rainfall data by storm events and identify representative data set and storm characteristics to consider in tool development (i.e., rain station, storm duration, intensity, interevent duration, etc.)
- Test various prediction relationships between storm characteristics and pathogen concentration at beach locations of concerns
- Perform statistical and validation tests to select most appropriate prediction model(s)

3. Development of Beach Advising Operating Rules

- Use the selected prediction model(s) to develop a set of beach operating rules
- Operating rules may range from warning and increased water testing frequency to beach advisory or closure

Key rainfall characteristics considered in the development of these rainfall-based alert curve models include (1) amount of rainfall expressed in inches, (2) storm duration expressed in hours, (3) interevent periods expressed in dry days, (4) lag time between rainfall record event and receiving beach response, and (5) the season(s) of high usage of the beach resources. When dealing with nonpoint source-dominated systems, antecedent rainfall conditions can be very significant factors in explaining the relationship between the rainfall and pathogen concentrations. Kuntz (1998) found higher pathogen concentrations during periods of low rainfall or near-drought conditions than during seasons of normal rainfall. Storm event duration is also a key factor in explaining rainfall-water quality relationships. For a watershed in Delaware, examination of the relationship between the cumulative rainfall obtained based on two durations (24 hours and 3 days) and pathogen concentrations showed that the 24-hour cumulative rainfall data yielded a statistically stronger relationship than the 3-day cumulative rainfall data (DNREC, 1997).

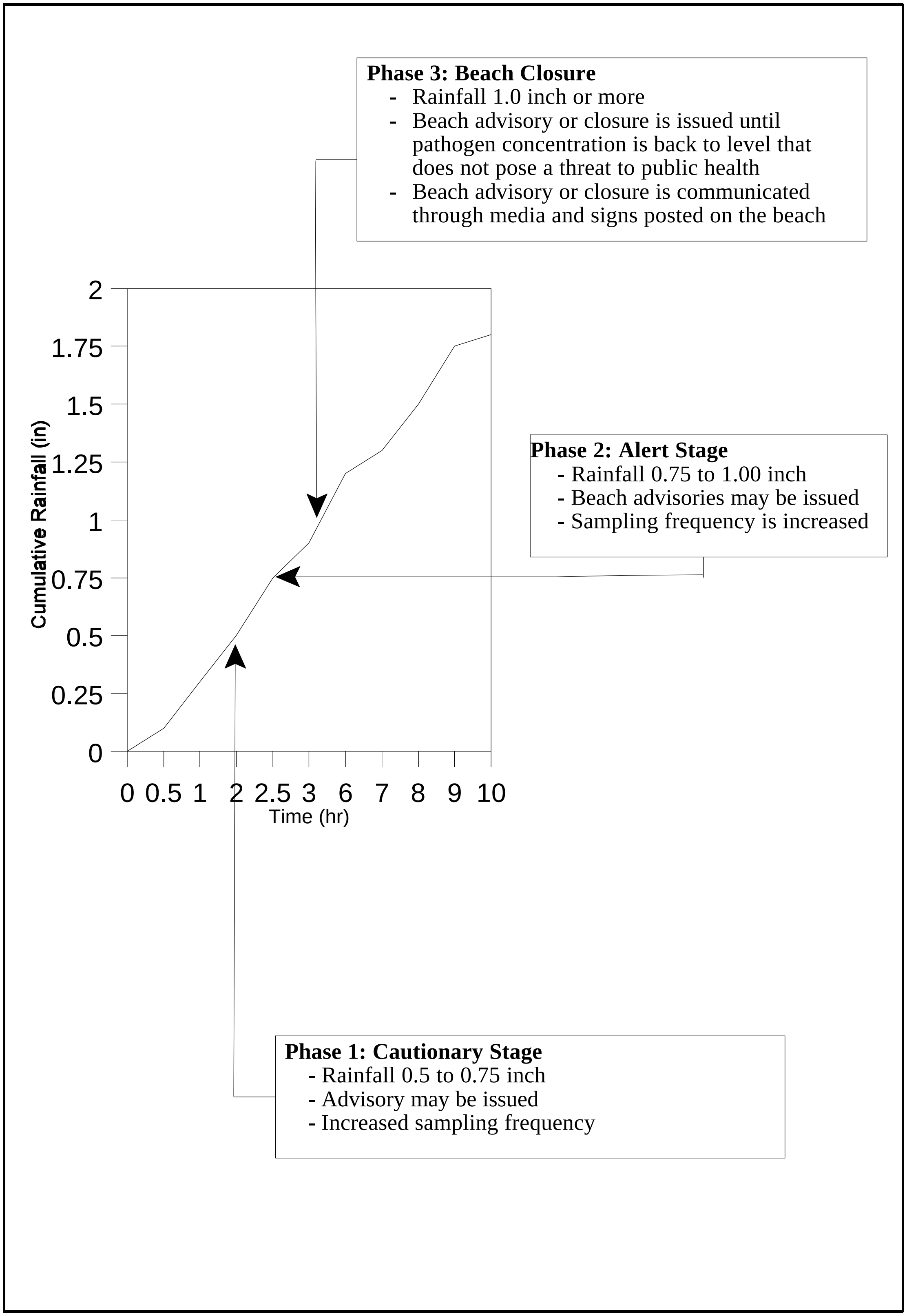
Pathogen data supporting the development of rainfall-based models are generated from water column concentrations obtained from ambient or targeted monitoring programs. Pathogen concentrations can be used in the regression model or frequency of exceedance analyses as direct observations or can be transformed to a set of geometric mean values of a defined step. Transformation of pathogen observations prior to development of regression models can allow direct comparison to state water quality standards for recreational uses, which are usually expressed as limits on geometric mean values of observed concentrations. The regression model can be developed for one or several pathogen species. Fecal coliform, *E. coli*, and enterococcus bacteria are common indicator species used in these models. The city of Milwaukee uses *E. coli* and fecal coliform in the regression analysis, whereas the city of Stamford uses the geometric mean of enterococcus bacteria (City of Milwaukee Health Department, 1998; Kuntz, 1998).

Because of the seasonality of recreation activities, as well as of rainstorm characteristics, rainfall-pathogen models can be developed for targeted seasons. In addition, developing predictive tools for various seasons can significantly enhance the predictive capability of the tool. The city of Milwaukee developed beach closure rules based on analysis of *fecal coliform* and *E. coli* concentrations collected daily (Monday-Friday) during the June-September season (City of Milwaukee Health Department, 1998).

Rainfall-based models are site-specific, and their development requires relatively large monitoring data sets of both rainfall and water quality. The overall relationship can be described by a statistical regression/estimation model. Depending on the number of rainfall stations considered and the number of rainfall characteristics (amount, duration, lag time, etc.), the relationship may require a more complex multiple-regression model. Because of their statistical nature, these types of models do not distinguish between point sources or nonpoint sources of pathogens and do not explicitly incorporate the advection, transport, and decay processes. Since their use is also limited to assisting in the development of beach operating guidelines, they do not attempt to provide the spatial and vertical distribution of pathogens.

Frequency of exceedance analysis is another rainfall-based method that can be used to develop rainfall-based alert curvers. An exceedance is defined as any time the observed pathogen concentration exceeds the action level, such as the state water quality standard specified by the responsible agencies. The objective of this method is to determine the minimum amount of rainfall that causes the pathogen concentration to exceed the action level. This determination can be accomplished by dividing cumulative rainfall amounts over a 24-hour period or more into segments that range from no rainfall to an upper limit that is representative of the rainfall record, types of storms, and season. For each rainfall amount category, either the observed pathogen concentration or the geometric mean is compared to the action level. A guideline is developed based on the least amount of rainfall that would result in a violation of the action level. This method applies to situations where historical rainfall data and water quality records exist. Guidelines or closure rules should also be developed to include seasonal variation in rainfall data.

After establishing a relationship between rainfall amounts and pathogen concentrations, developing guidelines or decision rules for beach advisory and closure is the next step. The process can be developed in three phases, which are explained here for the hypothetical cumulative rainfall data shown in Figure 3.1.



Phase 3: Beach Closure
- Rainfall 1.0 inch or more
- Beach advisory or closure is issued until pathogen concentration is back to level that does not pose a threat to public health
- Beach advisory or closure is communicated through media and signs posted on the beach

Phase 2: Alert Stage
- Rainfall 0.75 to 1.00 inch
- Beach advisories may be issued
- Sampling frequency is increased

Phase 1: Cautionary Stage
- Rainfall 0.5 to 0.75 inch
- Advisory may be issued
- Increased sampling frequency

Figure 3.1 *Example steps illustrating development and use of guidelines or decision rules for beach closure based on real-time rainfall observations*

For this example the exceedance criterion is 1 inch of rainfall in a 24-hour period. Phase 1 is the cautionary stage, which starts when cumulative rainfall exceeds 0.5 inch. At this point sampling frequency is increased and an advisory may be issued to notify the public of potential health risks associated with an increase in pathogen concentration.

Phase 2 is the alert stage, which begins at cumulative rainfall of 0.75 inch. Beach water quality samples are taken at a higher frequency, and a beach advisory may be issued if not issued during the cautionary stage. The advisory to the public should stress the potential health risks associated with recreation in pathogen-contaminated waters.

Phase 3 is beach advisory or closure. This stage is reached when the cumulative rainfall is 1 or more inches. The public is notified about the risk and strongly advised not to recreate. Also, water quality samples are collected and analyzed at a higher frequency. Rainfall-pathogen data collected following this approach can then be entered into the existing database and can be used in future regression analysis. This process would keep the database up-to-date and help to strengthen the rainfall-pathogen relationship.

3.3.1.1 State of Delaware Closure Guidelines

The state of Delaware’s Department of Natural Resources and Environmental Control (DNREC) investigated the effect of rainfall on bacteria levels in natural waterways (DNREC, 1997). The objective was to establish rainfall conditions that lead to increased levels of pathogens in water that might result in beach advisory or closure. The DNREC obtained rainfall data from two gaging stations, the Georgetown station and the Lewes station. Twelve freshwater sites were selected in Sussex County, Delaware. These sites were selected based on watershed characteristics such as implementation of nonpoint source best management practice (BMP) conditions (good or poor) and land use (DNREC, 1997). Eighteen sets of 12 water samples were collected and analyzed for enterococcus bacteria.

Linear regression methods were used to evaluate the relationship between the observed enterococcus bacteria concentrations at the 12 sites. The Georgetown rainfall data were selected over the Lewes station data since the Georgetown station was centrally located to the 12 sampling sites and regression analysis yielded a positive and more statistically significant relationship. Three-day and 24-hour cumulative rainfall data prior to sampling were correlated with pathogen concentrations at the 12 sampling sites. The relationship between water quality and rainfall was positive for cumulative 3 days and 24 hours prior to sampling. A stronger positive relationship was found for cumulative rainfall 24 hours prior to sampling.

Antecedent conditions prior to sampling were defined as wet weather conditions (rainfall event of 0.15 inch in 24 hours or less or 0.25 inch of rain in a 3-day period prior to sampling) (DNREC, 1997). Eleven of the eighteen sample sets collected were taken during wet weather conditions. Correlation coefficients describing the relationship between total enterococcus level and rainfall data ranged from 0.0232 to 0.7299 (DNREC, 1997). Five sites did not meet the DNREC freshwater primary contact geometric mean standard of 193 enterococcus/100 mL.

The DNREC used a similar approach to evaluate water quality conditions at marine and fresh water beach areas after rainfall events. Using regression methods, the DNREC determined the level of rainfall above which a beach advisory will be issued. For marine water, e.g., Rehoboth Beach, a beach advisory for 12 hours may be issued following 3.5 inches of rain or more in 24 hours or 3 inches of rain in 12 hours at one or more rainfall observation sites. A freshwater beach advisory may be issued at Lums Pond following 2.5 inches of rain in a 24-hour period or less and at Lake Como, Silver Lake, and Trap Pond following a rainfall event of 1.5 inches in a 24-hour period. The duration of freshwater advisories is 24 hours (DNREC, 1998).

3.3.1.2 City of Milwaukee Closure Guidelines

A rainfall model for beach closure in the city of Milwaukee was developed in the early 1970s. Recently, the City of Milwaukee Health Department in collaboration with the Milwaukee Metropolitan

Sewerage District investigated the predictive accuracy of the model and planned to update the model to reflect changes in the land use in the Milwaukee River basin. The observed fecal coliform concentrations were compared at different sites and at the wastewater treatment plant outfall using regression methods. The objective of these correlations was to determine whether the wastewater treatment plant significantly contributes to observed pathogen concentrations at the beach area, as well as to investigate the relationships between rainfall and poor water quality due to high bacteria (*E. coli* and fecal coliform) concentrations.

Two sources of rainfall data, General Mitchell Field and the river watershed monitoring stations, were used to investigate the relationship between rainfall and fecal coliform concentrations at South Shore beach. Analysis of rainfall data, fecal coliform data, and dates of beach closings and openings for the period from 1991 to 1993 indicated that insufficient data were available to establish a statistically significant relationship. Therefore, one of the conclusions was to increase the frequency of bacterial sampling during 1995.

Analysis of the 1995 single-sample data collected by the City of Milwaukee Health Department indicated that 55 percent of water quality samples exceeded the fecal coliform criterion (235 colonies/100 mL) following 0.1 inch of rain. In addition, after 0.3 inch of rainfall, 30 percent of *E. coli* single samples and 15 percent of fecal coliform single samples violated the water quality criteria. The model was not validated since violations in the water quality standards occurred following a rainfall event of 0.1 inch instead of 0.3 inch.

To understand the increased pathogen concentrations during low rainfall, the effects of the antecedent moisture condition, lag time, number of dry days, individual and cumulative river flow, wastewater treatment outfalls, and day of the week the violation occurred were investigated. Based on correlation analysis, the increased fecal coliform concentrations were explained by total river flow, Menomonee River flow, or total rain at General Mitchell Field.

The General Mitchell Field total rainfall (NOAA data) was selected as the best indicator of the water quality conditions at South Shore beach. Guidelines for beach closure for the period from June 1 to September 30, 1998, were established as follows:

- 48-hours closure after 0.3 to 0.69 inch of rainfall
- 72-hour closure following 0.7 to 1.49 inches of rainfall
- 96-hour closure following 1.5 inches of rain or more
- 96-hour closure in cases where a 48-hour or a 72-hour advisory was already in effect

3.3.1.3 City of Stamford Closure Guidelines

The state of Connecticut adopted enterococcus bacteria as an indicator of beach water quality in 1990. The established limit for beach closure is based on a geometric mean of 33 colonies/100 mL enterococcus bacteria. Water quality data collected between 1989 to 1996 at Stamford beaches on Long Island Sound indicated that enterococcus bacteria concentrations were directly related to rainfall and that this correlation was statistically significant (Kuntz, 1998). Rainfall levels at or greater than 1 inch could result in an enterococcus bacteria count that would exceed the standard.

The effect of rainfall on water quality was evaluated at Cove Island Beach, Cummings Beach, West Beach, and Southfield Beach. Rainfall amount data were divided into five increments, and the geometric mean was calculated for each increment. Rainfall data and enterococcus bacteria counts collected by the City of Stamford Health Department indicate that in cases where there were no rainfall events, the geometric mean of enterococcus bacteria at the five beaches did not exceed 7 counts/100 mL. Exceedance of the 33 counts/100 mL at four of the five beaches was observed following a rainfall event of 1 inch or more. Southfield Beach was the site most sensitive to rainfall; enterococcus exceeded the standard following a rainfall event of 0.25 inch or more (Kuntz, 1998).

Beach closure due to elevated levels of enterococcus bacteria following rainfall events was also influenced by periods of low rainfall or drought conditions. The City of Stamford Health Department observed that during drought conditions, enterococcus exceeded the standard following 0.7 inch of rain and in some cases 0.5 inch of rain (Kuntz, 1998). The geometric mean of enterococcus bacteria during periods of low rainfall exceeded the standard at four beaches following a rainfall event in the range of 0.5 to 0.99 inch.

Based on the above information, the current policy of the city of Stamford is to close beaches for 24 hours following a rainfall event of 1 inch or more under normal conditions. During periods of low rainfall or drought conditions, advisories are issued following a rainfall event greater than or equal to 0.5 inch (Kuntz, 1998).

3.3.1.4 Preemptive Closure

Several agencies are using closure guidelines based on rainfall amounts. The agencies listed in Table 3.1 indicated that beach advisories or closure may be posted based on rainfall events. These guidelines are used by local health agencies to minimize beach users exposure pathogens. No analytical methods were used in developing these guideline; they are based on the responsible agency's observations and expertise.

3.3.2 Point-Source-Dominated Steady-State Predictive Tools

3.3.2.1 Simple Mixing and Transport Model

The Simple Mixing and Transport Model (SMTM) was developed in 1989 for the Virginia Bureau of Shellfish Sanitation by the Virginia Institute of Marine Science, Gloucester Point, Virginia (Hamrick and Neilson, 1989). This model was designed to assist in the determination of marina buffer zones, as well as buffer zones for other point source discharges. The potential for pathogenic contamination of shellfish beds in areas around marinas and other point discharges is determined based on the concentration of total or fecal coliform in the water column. Although SMTM was developed for determining marina buffer zones, it can be applied to evaluate the impacts of point source discharges or prolonged accidental spills on other recreational activities such as swimming.

Table 3.1 *Rainfall-based beach advisory*

Agency	Rainfall Amounts	Beach Advisory Duration
City of St. Petersburg, Leisure Services Department, Florida Maximo Beach North Shore Beach	 0.8 in./24 hr 1 in./24 hr	Until samples indicate low bacterial count
Darien Health Department, Connecticut	>1 in./24 hr	24 hr
Orange County Environmental Health Division, California	0.2 in. /24 hr	72 hr
Town of Fairfield, Connecticut	1 in. /24 hr	24 hr
Monroe County Department of Health, New York	0.3 to 0.7 in./24 hr 0.7 to 1.5 in./24 hr ≥ 1.5 in./24 hr	24 hr[a] 24 hr 48 hr
Village of Shorewood Health Department, Wisconsin	1-2 in. /24 hr with strong easterly winds	Until samples indicate low bacterial count

[a] A 24-hour closure if the lake shore current is west or there is a northwest wind. No beach advisories are issued under other conditions.

SMTM is a computerized steady-state/tidally averaged simulation model based on a simple analytical mixing and transport formulation. Because of its analytical solution, it requires readily available site data from tidal tables and navigation charts. Pathogen kinetics are represented by a first-order decay function. Model simulation algorithms predict the horizontal distribution of pathogen concentrations and assume that the concentration in the vertical direction is uniformly distributed. SMTM consists of three modeling options developed to address various physical characteristics of the marina sites. The three modeling options are described below.

Wide river module. This module addresses marinas located along a shoreline of a wide channel with measurable net freshwater discharge in addition to tidally driven flow. Wide channels are described as channels wider than 100 meters in which the water depth changes are assumed to be negligible during tidal cycles. The pathogen concentration is set constant across the water column, and the channel-end effects are neglected based on the assumption that the contaminant will decay or die off before it reaches either end of the channel. The longitudinal and lateral dispersion coefficients are based on a flow rate that is tidally dominated; however, the advection of pathogen organisms is dominated by the freshwater flow in the channel (Hamrick and Neilson, 1989).

Narrow channel module. This module addresses marinas located within narrow channels with insignificant net freshwater discharge. An example of this type would be a tidal creek. Since the net freshwater flow is negligible, both advection and dispersion processes are dominated by the tidal flow. The model formulation uses a one-dimensional advection-dispersion equation to estimate the horizontal distribution of pathogen concentration along the channel. In cases where the distinction between wide and narrow sites is not clear, it is recommended that the analyst apply both the wide and narrow module and select the most conservative results.

Semi-enclosed bays and basins. This module addresses marinas located in semi-enclosed bays characterized by narrow entrances. Contaminant mixing and transport in semi-enclosed systems assumes that mixing of pathogens is complete and that change in depth due to tidal flow is negligible. If the predicted concentration in the entire basin exceeds the water quality standard, use of the one- or two-dimensional advection-dispersion module is suggested (Hamrick and Neilson, 1989).

Parameters required for use of these modules are simple and can often be easily obtained. Input parameters include the following:

Site characterization

- Mean water depth (meters).
- Upstream distance to closed end (meters), applicable to narrow channel and semi-enclosed bays or basins.
- Downstream distance to open end (meters), applicable to narrow channel and semi-enclosed bays or basins.
- Channel width (meters).
- Entrance channel cross-sectional area (square meters), applicable to narrow channel and semi-enclosed bays or basins.
- Basin surface area (square meters).
- Maximum tidal velocity magnitude (meters/second).
- Tidally averaged mean discharge velocity (meters/second)
- Tidal elevation range (meters) change in depth between high and low water.
- Tidal period (44712 seconds).

Discharge characterization

- Loading rate (organisms/second). Constant loading rate can be estimated from discharge flow rate and the fecal coliform concentration.

Kinetics

- Decay rate coefficient (1/second); first-order microbial death or decay rate that is applicable to water body conditions (fresh or marine water).

Model parameters required to characterize the site are obtained from navigation or topographic charts and tidal tables. The pathogen loading rate can be estimated based on the size and occupancy of the marina, discharge monitoring data, or permit information. The model uses a constant discharge/loading rate for each simulation run.

The Virginia Department of Health, Division of Shellfish Sanitation uses SMTM to determine the size of the required buffer zone surrounding marinas or wastewater discharge locations. The objective is to minimize potential pathogenic contamination of shellfish harvested in these areas. Therefore, direct shellfish harvesting is banned from waters where fecal coliform concentrations are 14 organisms/100 mL surrounding any source of fecal material (e.g., waste from boats). These criteria are used to delineate the buffer zone boundaries. Two examples of model application to a marina site and a wastewater treatment site are presented below for illustration purposes.

3.3.3 Point Source-Dominated Dynamic Predictive Tools

3.3.3.1 Regional Bypass Model

The Regional Bypass Model (RBM) was developed for USEPA Region 2 and part of USEPA Region 1 to determine the impact of bacterial discharge on beaches and shellfish beds due to untreated wastewater bypass in the New York-New Jersey Harbor, including the Hudson River, East River, New York Bay, Raritan Bay, and Apex of New York Bight. In addition, Long Island Sound beaches and shellfish beds in Westchester and Nassau County, New York, as well as southwest Connecticut, are included in the model grid. The objective of the model is to allow a rapid evaluation of water quality condition and determine impact areas where either increased monitoring frequency or temporary closure of beach recreational activities and shellfish harvesting is needed.

The model simulates a discharge of a known quantity of bacteria at a specified location and calculates the water quality response at sensitive areas including existing and potential beaches and shellfish harvesting areas. Application to the New York-New Jersey-Connecticut metropolitan area included 29 discharge location points and 53 beaches/shellfish areas distributed throughout the tristate metropolitan area. The bacteria selected for the modeling analysis are total coliform. However, other bacteria such as fecal coliform bacteria or enterococci can be approximated using proportionality ratios (HydroQual, Inc., 1998).

The RBM is based on a modified version of the System-Wide Eutrophication Model (SWEM) developed for the New York City Department of Environmental Protection. The hydrodynamics were represented using an existing three-dimensional SWEM developed under a previous eutrophication study of the harbor. The hydrodynamic conditions for various temperature scenarios were generated to serve as input to the water quality model. Temperature was considered a significant factor affecting the bacterial kinetics. However, for the purpose of developing a quick-reference tool, the effects of wind, which were estimated to have negligible influence compared to tidal influences, were not considered a key variable in the model. The water quality representation includes a first-order kinetic model for total coliform.

Example Illustrating the Use of SMTM

Buffer Zone for Mythical Marina

Mythical Marina is located on the south shoreline of the Nice River in Great County, Wonderland. The marina is located on a major estuarine channel and has 40 boat slips.

Input data are:

M = loading rate = 1.2 x10^6 organisms/second
K_d = decay coefficient = 10^{-5} /second
q_m = maximum tidal velocity magnitude = 0.57 meter/second
h = mean water depth = 3.3 meters
B = channel width = 3550 meters
u = tidally averaged mean discharge velocity = 0.0002 meter/second

The steps taken to estimate the buffer zone for Mythical Marina are:

(1) Make initial estimate of the dispersion coefficients.
The dispersion coefficients are calculated assuming uniform channel conditions (γ_x=1) and using the following equations:

$$D_x = \frac{h}{8} q_m \gamma_x \quad and \quad D_y = \frac{h}{60} q_m$$

D_x = 0.23 square meters/second
D_y = 0.03 square meters/second

(2) Run the model based on the initial estimates of the dispersion coefficients.
The model was run using the above dispersion coefficients. The boundaries of the buffer zone are selected from the tabular output of the model and based on an action level concentration of fecal coliform of 14 organisms /100 mL. The across the channel mixing zone width, Y_m, is 43 meters and the channel nonuniformity factor γ_x is 100.

(3) Estimate D_x based on the new γ_x value.
Using the above equation and *a* γ_x value of 100, the calculated new D_x is 23 m^2 /s.

(4) Perform final iteration.
Finally the model was run while setting the velocity equal to zero to ensure a conservative prediction of the upstream buffer zone and D_x = 23 m^2 /s.

The model predicts that the boundary of the 14 organisms/100 mL buffer zone is 852 meters along the channel and 142 meters across the channel. This corresponds to a buffer zone area of 47 acres surrounding Mythical Marina.

The discharge characteristics considered to have a significant influence on the modeling results include (1) discharge quantity and quality represented by discharge flow rate and corresponding coliform concentrations and (2) spill duration expressed in hours. Because of the significant influence of the timing of the spill (flood tide vs. ebb tide), the minimum spill duration was assumed to extend over a full tidal cycle. This assumption provides a conservative bound on the modeling results.

Because of the linear relationship between the discharge flux and the resulting concentration at receptor sites, the modified SWEM model was applied to simulate various discharge and temperature scenarios. The results were processed to develop a quick-reference tool that allows estimation of total coliform concentration (MPN/100 mL) at the 53 beaches/shellfish areas as a result of a spill at 1 of the 29 discharge points. The scenarios used to develop the RBM include the following:

- ***Bypassing of untreated wastewater*** at a rate of 100 million gallons per day and a fecal coliform concentration of 20×10^6 MPN/100 mL. Assuming a linear relationship between the discharge and resulting concentration, model results can be used to calculate other flow rates using a direct proportionality calculation. The discharge rate of 100 MGD serves as a reference value that allows users to scale down to specifically fit the actual wastewater bypass flow rate while preserving a significant number of digits.
- ***Three different bypass durations*** (12 hr, 24 hr, and 96 hr). Each duration represents a multiple number of tidal cycles. The range of discharge durations considered represents the most likely spill scenarios.
- ***Three different temperatures*** (-4 ^{o}C, 12 ^{o}C, and 22 ^{o}C). Temperature values were selected to represent winter, spring/fall, and summer conditions, respectively.

The RBM package consists of a computer program that uses the results of presimulated scenarios and performs all the necessary interpolation to adjust for the actual flux rate and temperature conditions and calculate the bacterial concentration response at the specified receptor sites. The user does not actually run SWEM.

Key input data required by the model include:

- Discharge location
- Receptor site location
- Water temperature
- Volume of discharges (million gallons)
- Discharge concentration (most probable number, MPN $\times 10^6$)
- Bacteria type to analyze (total coliform is the default)

The program output can be viewed in a tabular or graphical form. In either case the results given are maximum bacteria concentrations for 12-hour intervals beginning at the start of the discharge. Also, the results are displayed for 12-, 24-, and 96-hour discharge durations. If a threshold concentration were selected, the program would highlight receptor site locations to allow a visual screening of the receptor site locations exceeding the threshold. The principle of super position applies to multiple untreated wastewater bypasses.

3.3.4 Hydrodynamic Mixing Zone Models

3.3.4.1 CORMIX

CORMIX is a microcomputer-based hydrodynamic mixing zone modeling and decision support system that is widely used for near-field water quality studies. The current version of CORMIX (Jirka et al., 1996) includes three submodels—CORMIX1 for submerged single-port discharges, CORMIX2 for submerged multi-port discharges, and CORMIX3 for surface discharges. The CORMIX system also includes a number of utility programs: CORJECT is a single-port buoyant jet model, FFLOCATR is a far-field plume locator model, and CMXGRAPH is a graphical utility for displaying CORMIX submodel predictions. The three primary CORMIX submodels are based on integral solutions of the Eulerian momentum and transport equations. The CORMIX1 and CORMIX2 submodels can be used to analyze steady-state buoyant submerged discharges from single-port outfalls and multi-port diffusers, respectively, into flowing, density stratified ambient environments. The CORMIX3 submodel can be used to analyze steady-state buoyant surface discharge from a discharge canal or pipe into a flowing, homogeneous, density-stratified environment.

Use of CORMIX1 requires the specification of an idealized rectangular cross section to characterize the geometry of the receiving water, a steady and uniform ambient flow normal to the cross-section plane, and a piecewise linear vertical density structure to characterize the ambient flow environment. The discharge is specified by its position and orientation (angles with respect to the horizontal and vertical), volume flow rate, and discharge velocity, the density of the discharged water, and the contaminant concentration in the discharged water. To simulate coastal discharges, the width of the rectangular cross section is set to a large value such that the plume trajectory does not reach the far bank. For nonconservative contaminants, a first-order decay rate can be specified. From 35 possible classes, the decision support system implemented in CORMIX1 selects the solution class most representative of the specified situation and provides the user with graphical and tabular summaries of the solution results that are used to define the mixing zone. The major advantage of CORMIX1 is its ease of use. The primary disadvantages or limitations of CORMIX1 are related to its use of idealized receiving water geometry and spatially and temporally uniform ambient conditions. For example, the use of a constant depth precludes accurate representation of discharges offshore from sloping beaches. The constant ambient flow condition, including flow direction alignment parallel to the lateral boundary, precludes modeling the effects of vertical and horizontal spatial variations in ambient current speed and direction associated with wind-, wave-, and tide induced currents in coastal regions. Because the ambient current and stratification are time-invariant, multiple analyses must be conducted for tidal receiving waters to identify variations in mixing boundaries at different tidal phases.

The CORMIX2 submodel idealizes a multi-port diffuser as a finite-length, buoyant slot jet with the slot width and orientation chosen to give volume, momentum, and buoyancy fluxes equivalent to the vector sums of the corresponding port fluxes. The ambient flow environment is specified by an idealized rectangular cross section, a steady and uniform ambient flow, and a piece-wise linear vertical density structure, consistent with CORMIX1. The discharge is specified by its position and orientation (angles with respect to the horizontal and vertical), the slot equivalent volume flow rate and discharge velocity, and the density of the discharged water and its contaminant concentration. From 24 possible classes, the decision support system implemented in CORMIX2 can select the solution class most representative of the specified situation and provide graphical and tabular summaries of the solution results for dilution and near-field the mixing zone definition. The major advantage of CORMIX2 is its ease of use. The primary disadvantages or limitations of CORMIX2 are the same as those discussed for CORMIX1 and are related to the use of idealized receiving water geometry and spatially and temporally uniform ambient conditions.

The CORMIX3 submodel simulates a surface discharge from a canal or pipe into a semi-infinite ambient environment. The ambient flow environment is represented by a constant shoreline depth and bottom sloping downward away from the shoreline. The spatially and temporally constant ambient current is aligned parallel to the shoreline. The discharge is specified by its orientation (angle with respect to the shoreline), canal width or pipe diameter, and volume flow rate and discharge velocity, and the density of the discharged water and its contaminant concentration. CORMIX3 is particularly suited for the analysis of thermal discharges and includes a wind speed-dependent atmospheric heat exchange formulation. From nine possible classes the decision support system implemented in CORMIX3 can select the solution class most representative of the specified situation and provide graphical and tabular summaries of the solution results for dilution and near-field mixing zone definition. The major advantage of CORMIX3 is its ease of use. The primary disadvantages or limitations of CORMIX3 are similar to those of the other two CORMIX submodels and are related to the use of idealized receiving water geometry and spatially and temporally uniform ambient conditions.

All three of the CORMIX models include limited far-field capabilities, in that when the discharge plume mixing characteristics are no longer described by the appropriate solution classes, additional mixing and dilution can occur by user-specified ambient turbulent diffusion in the horizontal and vertical as appropriate.

The utility program CORJET complements the CORMIX1 and CORMIX2 submodels, allowing the user to simulate greater details of the discharge's dynamic behavior in the immediate vicinity of the discharge point. CORJET allows arbitrary specification of vertical variations in ambient current speed and ambient density. However, since CORJET is designed to investigate the immediate vicinity of the discharge, the ambient environment is assumed to be of infinite extent in the horizontal and of constant depth. For single-port discharges, CORJET can be used to investigate anomalous discharges and ambient conditions identified by the CORMIX1 decision support system and as well as the effects of the idealizations inherent in ORMIX1’s representation of ambient current and stratification conditions. For multiple port discharges, CORJET can be used to analyze the discharge and mixing characteristics of individual ports and to verify the appropriateness of CORMIX2’s representation of multi-port discharges by line jets. The utility program FFLOATR uses a superposition procedure to extend the results of CORMIX submodels to more complex flow environments such as meandering rivers or sloping beaches.

The CORMIX system is characterized by a user-friendly interface and a variety of output options including graphical display. The user interface allows the CORMIX system to be efficiently used by relatively inexperienced users, with the built-in decision support capability providing ample warnings if further detailed analysis or interpretation is required. The version 3 user’s manual (Jirka et al., 1996) includes a variety of documented examples for each submodel and appropriate references to research reports and papers providing greater technical details regarding the submodel’s underlying formulations.

The major limitations of the CORMIX submodels are related to the use of idealized representations of ambient geometry, currents, and stratification. To further illustrate these limitations, consider a submerged single- or multi-port discharge offshore from a recreational beach and the necessity of predicting the risk of bathers being exposed to contaminants issuing from the discharge. Under such conditions, the ambient flow could include tidal, wind- and wave-driven components having significant horizontal and vertical variations, and not aligned parallel to the shoreline in contrast to CORMIX's idealization of a spatially uniform, shore-parallel current. Current magnitudes and direction could also change significantly over the course of a few hours due to tidal phase, sea breeze effects, and incident wave direction changes in contrast to CORMIX’s assumption of steady current. The nearshore bathymetry profile would likely be characterized by increasing depth in the offshore direction, but could include isolated features such as bars and depressions in contrast to CORMIX’s spatially uniform bathymetry. A continuous discharge would also contribute to the establishment of time and spatial variations in ambient contaminant concentrations in contrast to CORMIX’s assumption of no existing ambient contaminant levels. Under these realistic conditions, the use of the CORMIX models to determine probable distributions of discharged contaminants is subject to a high degree of uncertainty and would at best require that a user having considerable knowledge of nearshore dynamics evaluate a variety of conditions to estimate the risk of exposure.

Input data required to use CORMIX are divided into four groups, which include ambient data, discharge port data, effluent characteristics, and mixing zone data.

Ambient data

- Water body depth (meters)
- Water body depth at discharge (meters)
- Ambient flow rate if steady (cubic meters/second)
- Water body width if bounded (meters)

- Tidal period (hours)
- Maximum tidal velocity (meters/second)
- Manning’s *n* or Darcy-Weisback *f*
- Wind speed (meters/second)
- Density of water body (fresh or marine water)
- Units of density
- Stratification data: pycnocline height (meters)
- Density/temp at surface
- Density/temp at bottom

Discharge data

- Single port discharge: CORMIX1
    - \- Location of nearest bank
    - \- Distance to nearest bank (meters)
    - \- Vertical angle (degrees)
    - \- Horizontal angle (degrees)
    - \- Port diameter (meters)
    - \- Port height (meters)
    - \- Port area (square meters)
- Submerged multi-port discharge: CORMIX2
    - \- Nearest bank orientation
    - \- Distance to endpoints
    - \- Diffuser length
    - \- Total number of openings
    - \- Port diameter
    - \- Port height
    - \- Concentration ratio
    - \- Diffuser arrangement type
    - \- Alignment angle
    - \- Horizontal angle
    - \- Vertical angle
    - \- Relative orientation
- Buoyant surface discharge: CORMIX3
    - \- Discharge location
    - \- Discharge configuration
    - \- Horizontal angle
    - \- Distance form bank
    - \- Depth at discharge
    - \- Bottom slope
    - \- Discharge width and channel depth if rectangular
    - \- Discharge diameter and bottom invert pie if circular

Effluent Characteristics

- Flow rate (cubic meters/second)
- Effluent velocity (meters/second)
- Effluent temperature (^{o}C)
- Heat loss coefficient in cases of heated discharge
- Effluent concentration and units
- Decay rate coefficient in case of nonconservative substances

Mixing zone data

- Value of water quality standard
- Toxicity of pollutant
- CMC and CCC for toxic pollutants
- Distance, width, or area of mixing zone in case specified.

The state of Washington's Department of Health, Shellfish Program, is currently using the CORMIX model to estimate shellfish closure areas around wastewater treatment plant outfalls (Meriwether, 1998). Shellfish harvesting is banned in water bodies that contains fecal coliform bacteria equal to or greater than 14 organisms/100 mL. This criterion is used to delineate the boundaries of the closure area. In addition, the Washington State Department of Health uses a conservative approach in estimating the closure zone by setting the input parameters to reflect maximum fecal coliform concentration in the plume. The assumptions used in estimation of the closure zone include the following:

- Use of the larger of treatment plant average monthly flow or design flow.
- Use of maximum fecal coliform concentration. This can be obtained from sampling the wastewater treatment plant effluent prior to disinfection, or from plant DMR.
- No fecal coliform decay.
- Use of ambient adverse water conditions, usually based on the winter season conditions, since most treatment plant upsets occur during the winter months.

3.3.4.2 PLUMES

PLUMES (Baumgartner et al., 1994) is a microcomputer-based hydrodynamic mixing zone modeling system that has many functional features similar to those of the CORMIX system. The PLUMES system has five main components: the PLUMES interface, which allows interactive construction of input files describing the discharge and ambient conditions and visualization of model predictions; the RSB model, which is appropriate for submerged multi-port discharges, and the UM model, which is appropriate for both single- and multi-port submerged discharges; a far-field mixing modeling that automatically extends the dilution calculates of RSB and UM; and a discharge classification system based on the CORMIX1 and CORMIX2 classification systems. From a functional perspective, the UM model includes capabilities similar to those of CORMIX1 and CORMIX2, whereas the RSB model is similar to CORMIX2. For multi-port discharges, the RSB and UM model complement each other in that their theoretical bases and formulations represent two entirely different approaches to near-field mixing zone analysis.

The RSB and UM models in the PLUMES system use identical input data to define discharge and ambient conditions. The ambient flow environment is assumed to be of infinite horizontal extent and constant depth. The ambient current is steady and unidirectional but can vary arbitrarily in the vertical over the depth of the water column. The ambient density and background contaminant concentrations are steady but can vary arbitrarily in the vertical. The assumption of infinite or unbounded conditions in the horizontal generally precludes the use of these models for rivers and narrow estuaries. The discharge is specified by its position and orientation (angles with respect to the horizontal and vertical), volume flow rate, and number of ports and port spacing, and the density of the discharged water and its contaminant concentration. The UM model also allows inclusion of ambient concentration levels of discharged contaminants.

The RSB (Roberts, Snyder and Baumgartner, 1989a, 1989b, 1989c) model is a semi-empirical model based on the principles of dynamic similitude and dimensional analysis applied to an extensive set of laboratory and field observations of multi-port discharge behavior. Input parameters specifying discharge and ambient conditions are used to calculate a set of dimensionaless parameters, which are in turn used to evaluate observational data correlation functions and predicted plume trajectory and dilution characteristics. The RSB model is recommended primarily for large-volume freshwater discharges into marine environments.

The UM model is the latest in a family of plume models that includes OUTPLM, MERGE, UOUTPLM, and UMERGE. The UM model is based on a Lagrangian formulation incorporating the projected area entrainment hypothesis. The UM model is applicable to both single- and multi-port discharges. For multi-port discharges, UM simulates each individual port discharge and merging of plumes from adjacent discharges. In contrast to CORMIX1, CORMIX2, and RSB, the UM model can be executed in batch mode with multiple input files to facilitate the automatic analysis of mixing and dilution under a range of ambient conditions. The UM model is appropriate for both marine and freshwater environments, but due to its infinite horizontal extent formulation it is not recommended for narrow rivers and estuaries.

The PLUMES system is characterized by a graphical user interface and a variety of output options including graphical display. The inclusion of the CORMIX classification system allows diagnostics of unusual plume conditions to be made and provides a means of cross checking PLUMES analyses using the CORMIX system. The user’s manual includes background information, a tutorial on use of the interfaces, and a variety of documented examples for each submodel, as well as appropriate references to research reports and papers providing greater technical details regarding the submodels’ underlying formulations. The major limitations of the PLUMES system are similar to those previously discussed for the CORMIX system and are related to the use of idealized representations of ambient geometry, currents, and stratification. A notable exception is the UM model’s arbitrary specification of vertically varying current and density. However, the UM assumption of constant depth and infinite horizontal extent limits its applications to discharges not influenced by shorelines. The batch mode capability of UM does allow for investigation of a range of ambient conditions for a specific discharge in a more efficient manner than does the CORMIX system.

The data required to use PLUMES are listed below:

Ambient data

- Water body depth
- Far-field distance
- Far-field increment
- Current speed
- Density
- Salinity
- Temperature
- Ambient concentration
- Farfield dispersion coefficient
- Average current speed in the farfield

Outfall structure

- Total diffuser flow
- Number of ports in the diffuser
- Spacing between ports
- Port depth
- Port diameter
- Port elevation
- Vertical angle
- Contraction coefficient cell
- Horizontal diffuser angle

Effluent characteristics

- Effluent density
- Pollutant concentration
- Effluent salinity
- Effluent temperature
- First-order decay coefficient

The Rhode Island Department of Environmental Management (RIDEM) has used the PLUMES model to predict water quality conditions surrounding wastewater treatment plant outfalls (Goblick, 1995). In particular, RIDEM was interested in protecting shellfish growing areas in Narragansett Bay from the impacts of a potential 6-hour failure in the chlorination process at wastewater treatment plants. RIDEM needed to delineate buffer zones for the 12 wastewater treatment plants discharging into the bay within a short duration of time and thus chose PLUMES to determine initial buffer zones. RIDEM has since begun to refine the initial buffer zones through dye dilution studies of dye-tagged effluent.

PLUMES was set up to provide the most conservative estimate of pathogen concentrations by simulating chlorination failure occurring during the start of the ebb tide. Minimum mixing due to dispersion occurs during this stage because of the minimum velocity during the flood tide. The tidal current will sweep the plume the longest distance from the outfall beyond the near-field initial dilution.

The actual input parameters used in PLUMES were obtained from Rhode Island Pollutant Discharge Elimination System Permits, operation and maintenance records of wastewater treatment plants, and tidal charts. In addition, RIDEM developed *Assessment of Analytical Model PLUMES for Sizing Prohibitive Shellfish Closure Zones - A Technical Guidance Manual,* which includes a detailed sensitivity analysis of model parameters, application and limitations of the model, two case studies comparing modeling and dye study results, and derivation of wastefield width equations that were later incorporated into the model (Goblick, 1995).

3.3.4.3 JPEFDC Model

The JPEFDC (Jet, Plume-EFDC) is a buoyant jet near-field dilution and mixing zone submodel (Hamrick, 1998) that is incorporated directly into the EFDC (Environmental Fluid Dynamic Code) three-dimensional hydrodynamic and transport model (Hamrick and Wu, 1997). The JPEFDC model simulates single-port and merging multi-port discharges using a three-dimensional extension of the Lagrangian formulations used in the UM model (Baumgartner et al., 1994) and the JETLAG model (Lee and Cheung, 1990). The JPEFDC model is unique in its use of unsteady, fully three-dimensional ambient velocity density and concentration fields and realistic bathymetry for trajectory, entrainment, and dilution calculations. (See Table 3.2.) For multi-port discharges, the merging of individual port plumes into multiple coalesced plumes is simulated. In addition to simulating the near-field and far-field

Table 3.2 *Comparison of CORMIX and PLUMES submodels and JPEFDC model*

Model	Discharge	Ambient Geometry	Ambient Current	Ambient Density and Concentration
CORMIX1	single submerged	rectangular channel	constant	piecewise linear
CORMIX2	multi-port submerged	rectangular channel	constant	piecewise linear
CORMIX3	surface	rectangular channel	constant	constant
UM	single or multi-port submerged	infinite, constant depth	arbitrary vertical variations	arbitrary vertical variations
RSB	multi-port submerged	infinite constant depth	arbitrary vertical variations	arbitrary vertical variations
JPEFDC	single submerged (can be extended to multiple submerged)	arbitrary depth variations and lateral boundaries	arbitrary 3-D variations and time-variable	arbitrary 3-D variations and time-variable

concentration of dissolved contaminants, EFDC and JPEFDC simulate sediment transport and the transport and fate of sorptive contaminants, including the settling and bed exchange of the suspended and sorbed material.

Operating in the EFDC model, JPEFDC automatically updates multiple outfalls as ambient conditions and outfall discharges evolve in time. The near-field JPEFDC solution is automatically coupled to the EFDC model's far-field transport and fate simulation, allowing the ambient concentration field to represent the historical influences of all unsteady discharges.

The embedded JPEFDC near-field dilution model is currently being used to determine sediment contamination zones in the vicinity of wastewater treatment plant and combined sewer overflow discharges in Elliott Bay and Duwamish River, Washington. In this application, 15 unsteady outfalls are simulated at hourly intervals for one year to determine probability of exposure statistics. An attempt to do this type of analysis for 15 discharges over the course of one day would require 360 CORMIX simulations. The EFDC-JPEFDC model is particularly well suited to near-shore coastal simulations. The hydrodynamic component of the EFDC model is capable of simulating unsteady tide-, wind- and wave-driven currents including long-shore and across-shore currents associated with incident wave transformation and surf zone wave breaking. A graphical user interface and automated input file creation system are being developed for the EFDC model, including the JPEFDC submodel.

4. Review of Applicability and Key Characteristics

4.1 Evaluation of Models Currently Applied to Beach Advisory or Closure

The review of current beach closure techniques identified a wide variety of model types, complexities, and application protocols used across the country. The various model types employed can be summarized as shown in Figure 4.1. The models employed can be grouped into two broad categories— simple methods and deterministic models. Simple methods, as discussed previously, use statistical analysis to build relationships between indicators and closure actions. Deterministic models include a range of simple to complex modeling techniques. The range of model complexity can be evaluated based on the analytical framework, the calibration requirements, and the degree to which variability (i.e., dynamic loadings) is incorporated.

Several observations can be made regarding the choice of modeling tools currently used in beach advisories. One of the essential features is the short time frame under which decisions must be made. Real- time data collection efforts and meteorologic and/or pathogen sampling are usually the basis for supporting beach and shellfish closure decisions. Regardless of the computational or technical complexity of the approach, the application to day-to-day decision making must be very quick. The use of models to support advisories must therefore be adapted to this quick-turnaround requirement. Simple models are most often used because of the development procedures required and the relative ease of use. Mid-range or complex models are also used, although more typically in the development of decision rules, not for real-time application. The New York/New Jersey Harbor study is an illustration of the use of a complex model in the development of closure rules.

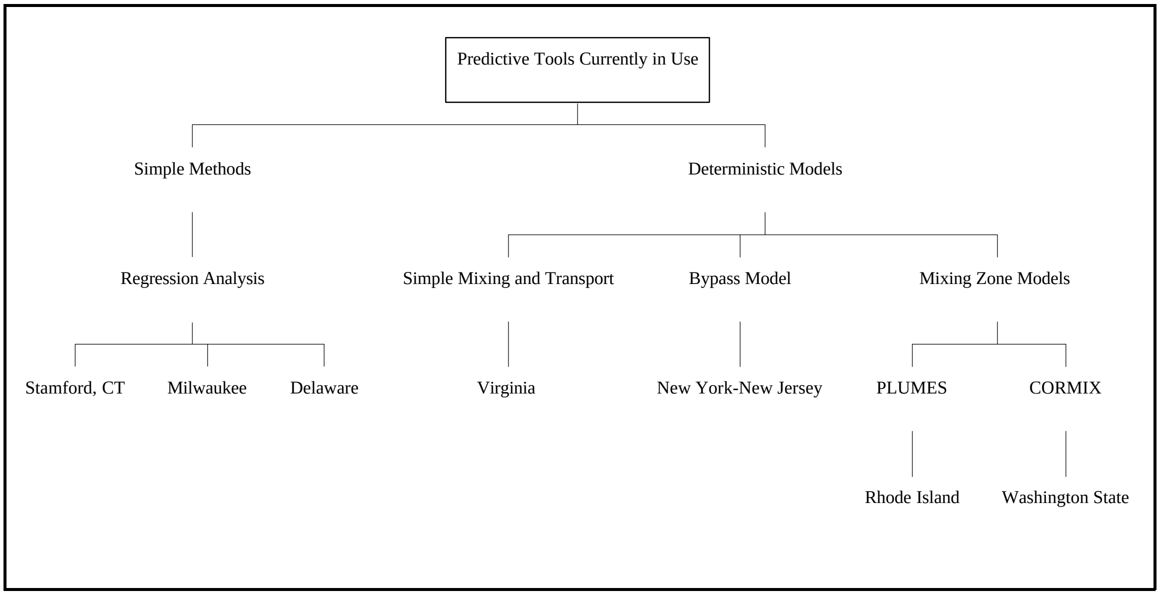


Figure 4.1 *Summary of pathogen predictive tools currently in use*

4.2 Criteria for the Evaluation of Potential Models

Selection of the appropriate model for beach advisories will depend on the site conditions of the water body of concern. Some of the site-specific considerations include the types of sources (point source/nonpoint source), water body types, transport and circulation patterns, severity of impairment, and frequency of exceedances. Other issues to consider are the modeling development and application cost, the accuracy required, the use of the system, training of staff, and public outreach and education requirements. Economies of scale may be identified when related analysis and modeling efforts have been initiated in the water body of concern. In some cases multiple models may be needed to address the various components of the system.

A wide range of models are available and could be adapted to support beach advisory decisions. Clearly, simple models for dilution and mixing zone evaluations are candidates for such analyses. More complex models should also be considered in light of their ability to assess dynamic loading and transport processes. Detailed models can be used in the development of a range of decision rules for categories of loading or environmental conditions. These decision rules can be used to address day-to-day operations in a cost-effective and timely manner.

In some cases objectives can best be met by using one model, and in others a combination of models is needed. Factors such as data needs, application cost, pollutant type, and required accuracy are important when considering the type of model to use. The selection of the appropriate model can be based on the following screening factors:

- *Combined point and nonpoint sources.* Combined point and nonpoint sources criteria relate to how the model handles the loadings from point and nonpoint sources. Models based on water quality data implicitly take into account the point and nonpoint sources, whereas models that use continuous simulation of the water quality directly account for the sources. Typically, the sources are part of the input parameters. For example, the rainfall-based alert curves discussed earlier are models based on the water quality conditions. Those models do not explicitly account for the point and nonpoint sources. Instead, the sources affect the water quality parameters used in the models. In the case of the CORMIX and PLUME models, point sources are a component of the model input; the flow and concentration must be included.
- *Pathogen source characterization*. Pathogens found at a beach site of interest might be from point sources (e.g., wastewater treatment plants, combined sewer overflows, etc.) or nonpoint sources. Accounting for the different sources of pathogens requires the use and integration of a variety of models. Once pathogen loads from point and nonpoint sources are determined, the next step is the routing of the pathogen through the system using a representative model of the dominant mixing and transport processes to estimate the pathogen concentration at the location of interest.
- *Dominant mixing and transport processes*. The water body type dictates the dominant mixing and transport processes of a pollutant. In rivers and streams, the dominant processes are advection and dispersion. In estuaries, these processes are influenced by tidal cycles and flows. Factors such as water body size and net freshwater flow are key in determining the dominant processes.
- *Pathogen concentration prediction*. This criterion evaluates the ability of the model to predict the likelihood that the pathogen concentration will exceed the action level in the receiving water at the location of interest, which in this case is a beach site. Transformation processes such as bacterial kinetics must also be accounted for in the model to allow for a realistic prediction.
- *Real-time analysis, decision making, and guideline development*. Real-time analysis is needed for timely closure. Models applied to predict water quality conditions can be used as a basis for decision making and as management tools. For example, beach authorities can use such tools as a basis for beach advisories following a rainfall event or accidental sewage spills.

- *Real-time use.* Under this category the input data needed, processing time, and post processing abilities of the model are evaluated. Potential predictive tools for beach closure are required to predict pathogen concentration at the site of interest in a relatively short amount of time. This means that the data input requirements and processing time must be maintained to a minimum. Also crucial to the success of the predictive tool is the postprocessing of the output data. Tabular or graphical representation of the output data provides a quick and easy way to interpret the results and provides a basis for the decision making concerning beach closure.
- *Evaluation of unplanned and localized spills.* Spills or bypassing of a pollutant can be accidental due to equipment failure or rainfall. In either case, this criterion evaluates how the model handles the additional loading. Models that are based on water quality data do not account for this increased loading unless samples were collected during the rainfall or spill event, samples were analyzed, and data were entered into the model database. On the other hand, models that account for point sources can easily account for the increased loading by including the spill as an input parameter.
- *Documented application to beach and shellfish closure*. This criterion evaluates the applicability of the model to predict the water quality condition surrounding swimming and shellfish areas. Models can be used as water quality predictive tools and as a basis for decision making. In the previous section, rainfall models and the Regional Bypass model were shown to be effective tools to protect people from exposure to pathogens following rainfall events or sewage spills.
- *Ease of use.* The level of user experience is an important factor in determining whether a model is easy to use. Some complex models require a great deal of training and experience; simple methods require only a conceptual understanding of the processes.
- *Input data requirements.* Input data requirements are a function of a model’s complexity. In general, complex models require more specific and complex input data than simple models. Some of these data might not be readily available, and acquiring such data might require expenditure of resources. Therefore, the objective of the model application can be very important in this step to eliminate unnecessary expenditure of time resources.
- *Calibration requirements*. Decision making and management alternatives based on modeling results require that the model outcome be acceptable and reliable. Not all models can be calibrated. Models that simulate water quality conditions are calibrated against instream monitoring stations. Simple models such as the rainfall alert curves should be continuously updated to provide accurate results by continuously updating the model’s database.
- *Pollutant routing.* Pollutant routing addresses how a model deals with the fate and transport of pollutants. Simpler models may not include processes that describe pollutant transformation. More complex models vary in their description of the processes. The range can be from a gross or a net estimate of the process to a detailed mechanism of the process. The focus is on bacterial processes. In general, most environmental models use the first-order decay rate to represent the microbial death rate.
- *Kinetics of pathogen decay.* The survival of pathogens in the environment is influenced by many variables such as age of the fecal deposit, temperature, sunlight, pH, soil type, salinity, and moisture conditions. In general, the death rate of pathogens can be estimated as a first-order rate, which is incorporated into water quality models.

An evaluation of the models discussed in Section 3 based on the criteria above is summarized in Table 4.1.

Table 4.1 *Evaluation of model capabilities and applicability*

Model	**Combined PS/NPS**	**Real Time and Decision Making**	**Spills**	**Application to Beach or Shellfish Closure**	**Ease of Use**	**Input Data Requirements**	**Calib.**	**Developing Guidelines**	**Pollutant Routing**
Rainfall-Based Alert Curves	x x x	x x x	0	x x x	x x x	x	x x	x x	0
Bypass Model	x (PS)	x x x	x x x	x x x	x x x	x x x	x	x x	x x x
SMTM	x (PS)	x x	x x	x x	x x	x	x	0	x
PLUMES	x (PS)	x	x x	x x	x x	x	x	x	x
CORMIX	x (PS)	x	x	x	x x	x	x	x	x
JPEFDC	x x (NPS/PS)	x	x x x	x x x	x	x x x	x x	x	x x x

0	Not applicable
x	Low
x x	Medium
x x x	High

Part II. Review of Other Potential Modeling Tools Available for Beach Advisory or Closure

1. Introduction

The identified beach closure predictive tools were characterized based on their modeling or prediction application techniques and their modeling components. Rainfall-based alert curves, which are based on regression analysis, are simple, reliable tools that have been used in Milwaukee, Wisconsin, Stamford, Connecticut, and Delaware. Computer models that predict pathogen concentration by simulating the dominant mixing and transport processes in the receiving water range from simple to very complex. A simple mixing and transport model is used by the Virginia Department of Health to predict water quality conditions surrounding wastewater treatment plant outfalls. More complex models such as CORMIX and PLUMES are used by the states of Washington and Rhode Island, respectively, to predict water quality conditions surrounding wastewater treatment outfalls. Part I of this report provided a detailed description of these tools and their attributes, limitations, data requirements, and availability. The objective of Part II of this document is to identify water quality predictive tools that could be applied to beach advisories but are not currently in use by local agencies.

A description of the general process of modeling pathogens is presented in Figure 1.1. The first component in the process is characterizing the point and nonpoint sources of pathogens and establishing the loading rates. The second component is estimating the dominant fate and transport processes to estimate the pathogen distribution. The third component is interpreting the model output to find the pathogen concentration at the point of interest to determine the need for a beach advisory. This determination can be accomplished by comparing the model results with a preestablished action level, such as the state water quality standard for primary contact recreation. If the predicted pathogen concentration exceeds the action level, a beach advisory is issued. The advisory period depends on the length of time it takes for the pathogen levels to return to less than the established action level.

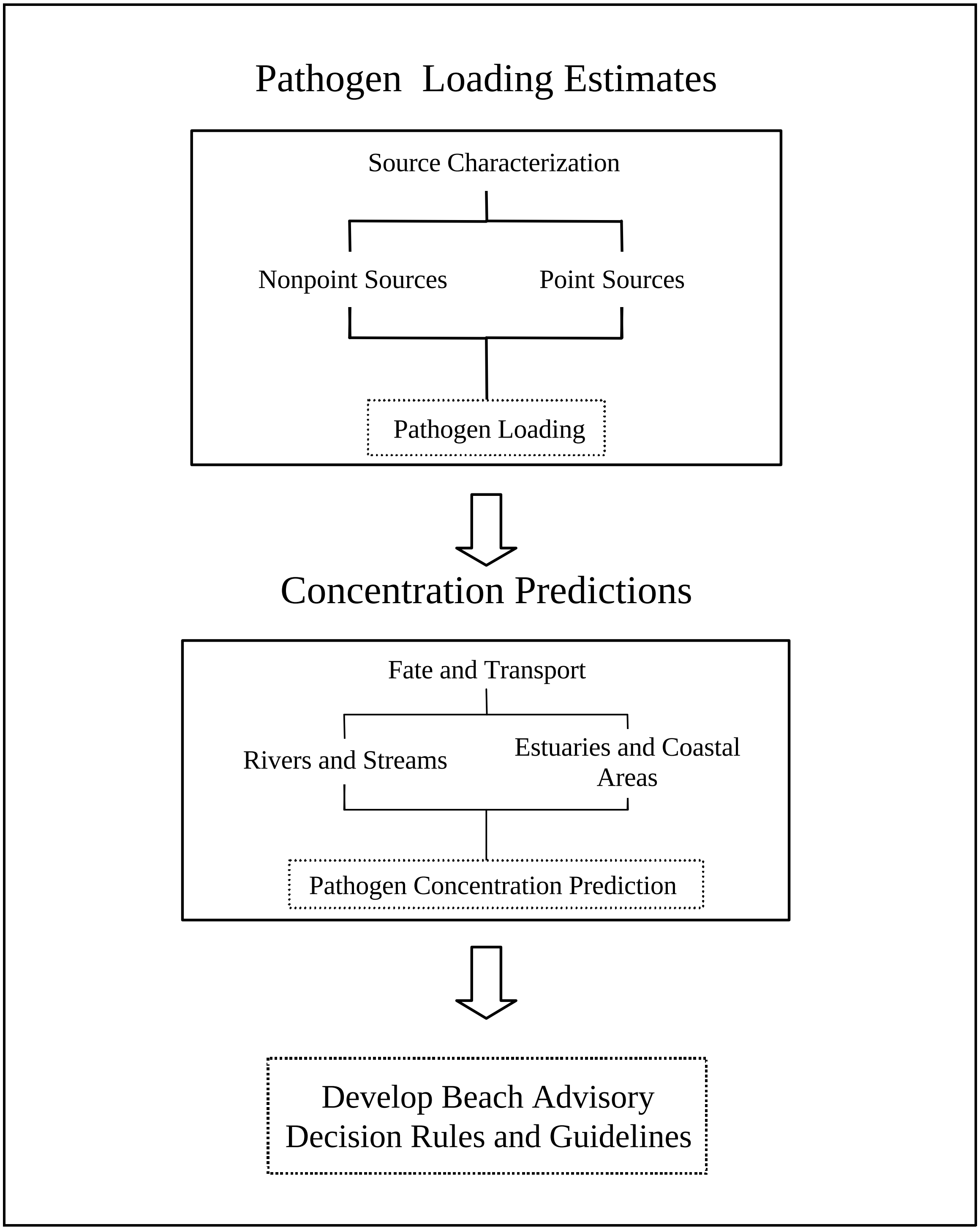


Figure 1.1 *Components of pathogen modeling*

2. Potential Models

The results of searching the literature and consulting with experts in the modeling field indicate that potential models for use as predictive tools to determine the need for beach advisories include the following modules:

- Pathogen loadings from point and nonpoint sources
- Pathogen fate and transport

Figure 2.1 shows potential predictive tools that can be used to determine the need for beach advisories. The listed models were divided into two categories: watershed-scale loading models and receiving water models. The latter category was divided into two additional groups to reflect the water body types—rivers and streams, and lakes and estuaries.

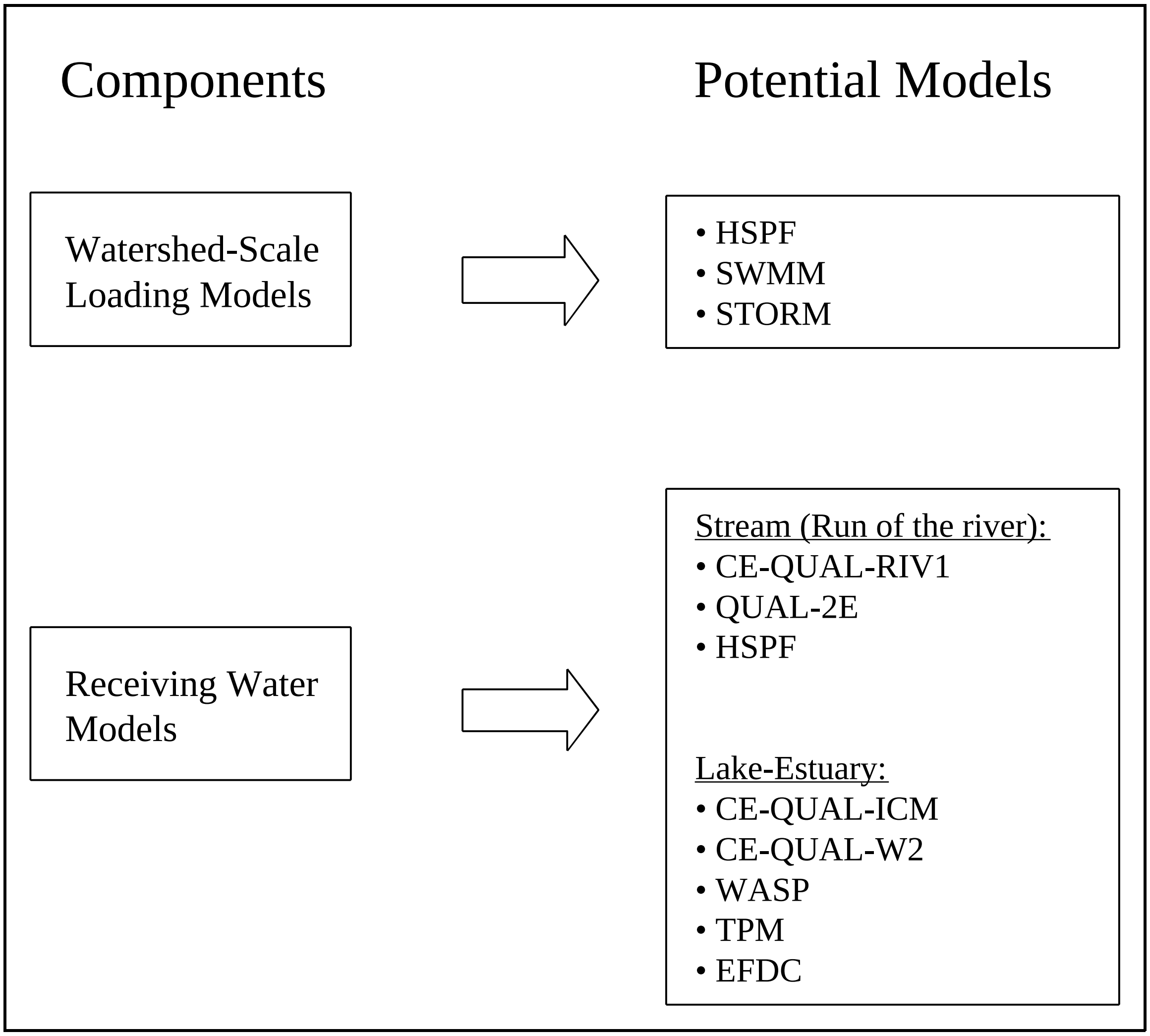


Figure 2.1 *Potential predictive tools applicable to pathogens*

2.1 Watershed-scale Loading Estimates

Potential watershed loading models that can be used to estimate pathogen loadings to receiving waters are presented in Table 2.1. Three considerations are taken into account in Table 2.1—real-time prediction, source types, and land use types.

Simulating the generation and movement of water and its pathogen content from the source area to the receiving water can be a continuous or single-event simulation. Single-event simulation requires defining and characterizing the antecedent moisture content before each simulation. Continuous simulation, on the other hand, provides a long time series of water and pathogen loading but requires a lot of input data and a long run time (USEPA, 1997).

The sources of pathogens can be point sources, nonpoint sources, and combined sewer overflows (CSOs). Models differ in their ability to account for these various source types. Models that simulate nonpoint sources are capable of describing the pathogen buildup processes during dry weather and washoff processes related to rainfall-generated runoff. Accounting for the various land uses is very important in estimating the nonpoint source loadings since the processes of buildup and washoff are land use-specific. In addition to land use, CSO loading is a function of the hydraulic routing and the facility's storage capacity and operations. Therefore, the model's ability to deal with the complex land uses in the watershed is an important factor in model selection and applicability. Key loading models suited for real-time prediction are briefly described below.

HSPF: Hydrological Simulation Program-Fortran. HSPF is a comprehensive watershed-scale model developed by EPA. The model uses continuous simulation of water balance and pollutant buildup and washoff processes to generate time series of runoff flow rate, as well as pollutant concentration at any given point in the watershed. Runoff from both urban and rural areas can be simulated using HSPF; however, simulation of CSOs is not possible. Because of the model's comprehensive nature, data requirements for HSPF are extensive and the model requires highly trained personnel (USEPA, 1997). The HSPF model has been integrated into BASINS as the Nonpoint Source Model, or NPSM (see Appendix B).

SWMM: Storm Water Management Model. SWMM is a comprehensive watershed-scale model developed by EPA. It can be used to model several types of pollutants on either a continuous or storm event basis. Simulation of mixed land uses is possible using SWMM, but the model's capabilities are limited for rural areas. Loadings from CSOs can be simulated using SWMM. The model requires intensive data input and requires a special effort for validation and calibration. The model output is time series of flow, storage, and contaminant concentration at any point in the watershed (USEPA, 1997).

Table 2.1 *Watershed-scale loading models*

Model Type	Model Name	Real-time Prediction		Source Type			Land Use Type	
		Data Needs	Processing Time	PS	NPS	CSO	Urban	Rural
Watershed-scale loading	HSPF: Hydrological Simulation Program-Fortran	x	x	xx	x	0	x	xxx
	SWMM: Storm Water Management Model	x	x	x	x	xx	xx	x
	STORM: Storage, Treatment, Overflow, Runoff Model	x	x	x	x	x	xx	0

0	Not applicable
x	Low
xx	Medium
xxx	High

STORM: Storage, Treatment, Overflow, Runoff Model. STORM is a watershed loading model that was developed by the US Army Corps of Engineers for continuous simulation of runoff quantity and quality. STORM was primarily designed for modeling storm water runoff from urban areas, but it can also simulate combined sewer systems. It requires relatively moderate to high calibration and input data. The simulation output is hourly hydrographs and pollutographs (USEPA, 1997).

2.2 Receiving Water Models

Loading models, depending on the simulation type, provide estimates of either the total water and pollutant loading or a time series loading of water and pollutants. Pathogen concentration prediction is the process of describing the response of the water body to pollutant loadings, flows, and ambient conditions. Since the response is specific to the water body type, different types of models are required for accurate simulation, as shown in Table 2.2. The models were divided into two categories—rivers and streams, and lakes and estuaries. The dominant processes for both types are briefly described here.

2.2.1 River and Streams

Prediction of pathogen concentration in rivers and streams is dominated by the processes of advection and dispersion and the death rate. One-, two-, and three-dimensional models have been developed to describe these processes, as shown in Table 2.2. Water body type and data availability are the two most important factors that determine model applicability. For most small and shallow rivers, one-dimensional models are sufficient to simulate the water body response to pathogen loading. However, for large and deep rivers and streams, the one-dimensional approach falls short of describing

Table 2.2 *Potential pathogen fate and transport models*

	Real-Time Prediction		**Water type**	
Model Name	**Data Needs**	**Processing Time**	**Rivers**	**Lakes & Estuaries**
HSPF: Hydrological Simulation Program-Fortran	xx	x	x	N/A
CE-QUAL-RIV1: Hydrodynamic and Water Quality Model for Streams	xx	xx	x	N/A
CE-QUAL-ICM: A Three-Dimensional Time-Variable Integrated-Compartment Eutrophication Model	xxx	xxx	x	xx
CE-QUAL-W2: A Two-Dimensional, Laterally Averaged Hydrodynamic and Water Quality Model	xxx	xx	xx	x
WASP5: Water Quality Analysis Simulation Program	xx	xx	xx	xx
EFDC: Environmental Fluid Dynamics Computer Code	xx	xx	xx	xx
QUAL2E: The Enhanced Stream Water Quality Model	x	x	x	N/A
TPM: Tidal Prism Model	x	x	N/A	x

x	Low
xx	Medium
xxx	High

the processes of advection and dispersion. Assumptions that the pathogen concentration is uniform both vertically and laterally are no longer valid. In such cases two- or three-dimensional models that include a description of the hydrodynamics are used.

HSPF: Hydrological Simulation Program-Fortran. HSPF is a comprehensive watershed-scale model developed by EPA. The receiving water component allows dynamic simulation of one-dimensional stream channels, with several hydrodynamic routing options available. The model output is time series of runoff flow rate, as well as pollutant concentration at any given point in the watershed. Because of the model's comprehensive nature, data requirements for HSPF are extensive and the model requires highly trained personnel (USEPA, 1997).

CE-QUAL-RIV1: Hydrodynamic and Water Quality Model for Streams. CE-QUAL-RIV1 is a dynamic, one-dimensional model for rivers and estuaries. The model consists of two codes—one for hydraulic routing and the other for dynamic water quality simulation. CE-QUAL-RIV1 allows simulation of unsteady flow of branched river systems. The input data requirements include the river geometry, boundary conditions, initial instream and inflow boundary water quality concentrations, and meteorological data. The model predicts time-varying concentration of water quality constituents (USEPA, 1997).

2.2.2 Lakes and Estuaries

Predicting the response of lakes and estuaries to pathogen loading requires an understanding of hydrodynamic processes. Shallow lakes can be simulated as a simplified, completely mixed system with an inflow stream and outflow stream. However, simulating deep lakes with multiple inflows and outflows that are affected by tidal cycles is not a simple task. Pathogen concentration prediction is dominated by the processes of advection and dispersion, but these processes are affected by the tidal flow. The size of the lake or the estuary, the net freshwater flow, and wind conditions are some of the factors that determine the applicability of the models (USEPA, 1997).

CE-QUAL-ICM: A Three-Dimensional Time-Variable Integrated-Compartment Eutrophication Model. CE-QUAL-ICM is a dynamic water quality model that can be applied to most water bodies in one, two, or three dimensions. The model can be coupled with three-dimensional hydrodynamic and benthic-sediment model components. CE-QUAL-ICM predicts time-varying concentrations of water quality constituents. The input requirements for the model include 140 parameters to specify the kinetic interactions, initial and boundary conditions, and geometric data to define the waterbody to be simulated. Model use may require significant expertise in aquatic biology and chemistry (USEPA, 1997).

CE-QUAL-W2: A Two-Dimensional, Laterally Averaged Hydrodynamic and Water Quality Model. CE-QUAL-W2 is a hydrodynamic water quality model that can be applied to most water bodies in one dimension or laterally averaged in two dimensions. The model is suited for simulating long and narrow water bodies like reservoirs and long estuaries where stratification may occur. The model application is flexible since the constituents are arranged in four levels of complexity. Also, the water quality and hydrodynamic routines are directly coupled, which allows for more frequent updating of the water quality routines. This can reduce the computational burden for complex systems. The input requirements for CE-QUAL-W2 include geometric data to define the water body, specific initial boundary conditions, and specification of approximately 60 coefficients for the simulation of water quality (USEPA, 1997).

WASP5: Water Quality Analysis Simulation Program. WASP5 is a general-purpose modeling system for assessing the fate and transport of pollutants in surface water. The model can be applied in one, two, or three dimensions and can be linked to other hydrodynamic models. WASP5 simulates the time- varying processes of advection and dispersion while considering point and nonpoint source loadings and boundary exchange. The water body to be simulated is divided into a series of completely mixed segments, and the loads, boundary concentrations, and initial concentrations must be specified for each state variable (USEPA, 1997).

EFDC: Environmental Fluid Dynamics Computer Code. EFDC is a general three-dimensional hydrodynamic model developed by Hamrick (1992). EFDC is applicable to rivers, lakes, reservoirs, estuaries, wetlands, and coastal regions where complex water circulation, mixing, and transport conditions exist. EFDC must be linked to water quality models to predict the receiving water quality conditions. HEM-3D is a three-dimensional hydrodynamic eutrophication model that was developed by integrating EFDC with a water quality model. Considerable technical expertise in hydrodynamics and eutrophication processes is required to use the EFDC model (USEPA, 1997).

QUAL2E: The Enhanced Stream Water Quality Model. QUAL2E is a steady-state receiving water model. The basic equation used in QUAL2E is the one-dimensional advective-dispersive mass transport equation. Although the model assumes a steady-state flow, it allows simulation of diel variations in meteorological inputs. QUAL2E input requirements include the stream reach physical representation and the chemical and biological properties for each reach (USEPA, 1997). QUAL2E has been fully integrated into BASINS (see Appendix B).

TPM: Tidal Prism Model. TPM is a steady-state receiving water quality model applicable only to small coastal basins. In such locations the mixing and transport of pollutants are dominated by the tidal cycles. The model assumes that the tide rises and falls simultaneously throughout the water body and that the system is in hydrodynamic equilibrium. Two types of input data are required to run TPM. The geometric data that define the system being simulated include the returning ratio, initial concentration, and boundary conditions. The physical data required include water temperature, reaction rate, point and nonpoint sources, and initial boundary conditions for water quality parameters modeled (USEPA, 1997).

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