SECTION 5: DETERMINING POLLUTANT LOADS

Section 5 Contents

This section is included for those interested in the technical information used to determine the dynamics of water flow and water quality variations. Although numerical models provide an effective approach to evaluate design parameters, marina developers may use their own discretion in employing modeling techniques.

The use of an area for a marina might infringe on or preclude other uses of the resources, and it is this potential conflict that can be evaluated by using of water quality modeling. Marina basins can contain pollutants ranging from sanitary wastes to toxic metals leached from hulls and petroleum products discharged in engine exhaust. These wastes pose a variety of potential problems for water quality, including microbiological contamination of adjacent shellfish and swimming areas, depletion of dissolved oxygen in the water column or sediments, and toxic effects on estuarine biological resources. Water quality monitoring can be used before marina construction or expansion to determine the design (including basin shape and entrance locations and runoff controls) that will be the least disturbing to the surrounding aquatic environment. It can be used after marina construction to determine compliance with water quality criteria and what, if any, changes in design are necessary to meet any water quality criteria that have been violated.

Water quality criteria are based on pollutant concentrations. Concentrations of water quality constituents (such as dissolved oxygen [DO] or petroleum hydrocarbons) can be used to assess instantaneous conditions (water quality when the sample is taken) and conditions over time (samples taken daily for a week or a month). Concentrations of pollutants in water can be measured in storm water runoff before the runoff reaches a waterbody or in the waterbody of interest. If concentrations are measured in runoff, the timing is important. Pollutant concentrations usually vary widely during a rainstorm, typically being higher during the first wave or “first flush” of storm water, when pollutants accumulated since the previous storm are washed away, and lower later in the storm.

Concentrations also vary from storm to storm. Longer periods between storms allow more pollutants to accumulate on surfaces, whereas a storm that occurs shortly after a previous storm might carry very few pollutants in its runoff.

Time of year is also important. A storm that occurs during a week of peak boat maintenance activity is likely to carry more pollutants than a storm that occurs in the spring before the boating season begins. If nothing else, the pollutants carried by the storm runoff will be different. A storm in spring might carry more sediment and salt from winter road treatments, whereas one in summer might have more oil and debris from hull maintenance activities.

Pollutant loads in a marina basin can be measured by collecting samples at various times, depths, and places in the basin. For a simple assessment of water quality, samples of dissolved oxygen, fecal coliform bacteria, and perhaps water clarity (using a Secchi disk) might be performed. If sampling for assessment of meeting state water quality standards, samples for the constituents required by the state have to be taken and the samples might have to be analyzed by a state-approved laboratory.

Samples can be taken once for an indication of instantaneous water quality or over a period of time to assess average water quality conditions or trends in water quality (for example, whether water quality is worse over busy boating weekends or in particular seasons, or just after a storm and for how long after a storm has occurred). Comparison of samples of storm water runoff and samples of marina basin water quality might be used to determine whether degraded water quality during and shortly after storms is due to runoff from the marina property or from surrounding properties.

General water quality monitoring is discussed under the Water Quality Assessment management measure in Section 4. A discussion of models and monitoring, which supports their use for in-depth analyses of water quality and water quality changes that might occur from changes in marina configuration or marina construction, follows. The discussion is somewhat technical because it is anticipated that if these models are applied, they will be applied by persons trained in their use and familiar with their implementation. Those without a background in modeling can still benefit from reading the discussion to gain a general understanding of what modeling involves and to help decide whether modeling is appropriate for a particular marina and situation.

Example Models for Marina Flushing Assessment

Selection Criteria

To understand what is needed to apply a model, it is essential to focus on the physical, chemical, and biological processes that move water into and out of the marina area, control mixing with adjacent waters, regulate chemical reactions in the water and sediments, and facilitate biological growth and decay (die-off). A variable combination of winds, tides, currents, and density differences is responsible for the physical movement of water volumes and pollutants. The geometry of a site can also have a major effect on flushing and dispersion and is an important issue in selecting the model, collecting the data, and attaining the required water quality standards.

Biodegradation of organic material, growth and decay of bacteria and other organisms, nutrient uptake, and chemical transformations of various kinds are typical of the biochemical processes that affect contaminants. Physical, chemical, and biological processes should be combined to form a conceptual model of the site and its consequent contaminant assimilation potential. After the site in question has been conceptualized, the next step is to choose a model that incorporates the appropriate physical processes and biochemistry to predict water quality. Depending on the level of sophistication at which the assessment is taking place, the model selected might be a simple screening calculation (e.g., Tidal Prism Analysis) or a multidimensional numerical model (e.g., WASP4, DEM, WQM2D, or EFDC Hydrodynamic Model).

The models discussed here have been selected for the following reasons:

- They are in the public domain.

- They are available at a minimal cost from various public agencies.
- They are supported to a varying extent by federal or state agencies. The form of support is usually telephone contact with a staff of engineers and programmers who have experience with the model and can provide guidance (usually free of charge).
- They have been used extensively for various purposes and are generally accepted within the modeling profession.
- Together they form a sequence of increasingly more technically complex models; that is, each model takes additional phenomena into account in a more detailed manner than the preceding model.

Selection from among these models should be made on the basis of the model capabilities needed.

In addition to model capabilities, the two most important factors in the selection of a model are the adequacy of the documentation and the adequacy of the support available. The documentation should state the theory and assumptions in adequate detail, describe the program organization, and clearly present the input data requirements and format. A well-organized data scheme is essential. The support provided should include user access via telephone to programmers and engineers familiar with the model. Special support (including short courses or informational or personnel exchanges) might be available under existing intra-agency or interagency agreements or can be made available to the potential user. The support agency might also be able to provide the potential user with a list of local users who could be contacted for information regarding their past or current experience with the computer program. Table 5-1 presents documentation and user's support available for some of the models discussed in this section.

In addition to having adequate documentation and user's support, the selected model should address all marina water quality problems of concern.

The following section provides an overview of the best-qualified marina water quality model in each of the selected categories. These models are listed in Table 5-1, which provides information related to the operational features of the models. This information is provided to help in evaluating the estimated cost associated with and the ease of acquiring the model, getting the model running on the user's system, calibrating the model, and finally applying the model. Table 5-2 lists the level of effort involved in applying the models.

Models Selected

The most rigorous tools that can be used for assessing marina impacts on water quality are numerical models. Models range in complexity from simple desktop calculations to full three-dimensional models that simulate physical and chemical processes by solving equations of motion and rate equations for chemical processes.

The complexity of the model used and the quality of the input data determine the degree of resolution in the results. For example, in an early part of a study, the Tidal Prism Analysis strategy is used to obtain a general understanding of potential impacts caused by pollutant discharged from a proposed marina. It is likely that the simplified strategy will predict substantial impacts on the environment. Therefore, an advanced model is needed to conduct further detailed analyses. A mid-range model is used in situations where steady-state conditions may be assumed and tidal flushing is the predominant mode of flushing. A complex model is used in dynamic environments subject to complex circulation patterns and full biochemical kinetics, with sources and sinks for all dissolved constituents and for proposed marinas.

Simple Model

The methods listed here include desktop screening methodologies that calculate seasonal or annual mean pollutant concentrations based on steady-state conditions and simplified flushing time estimates. These models are designed to examine and isolate trouble spots for more detailed analyses. They should be used to highlight major water quality issues and important data gaps in the early stage of a study.

Methods presented in this section, particularly some of the mathematical descriptions, are

Table 5-1. Ease of application: Sources, support, and documentation.

Model	Source(s) of Model	Nature of Support	Adequacy of Documentation	Cost
Tidal Prism Analysis	USEPA, Region 4, Atlanta, GA. 1985. Chapter 4 of *Coastal Marinas Assessment Handbook*.	N/A	Excellent documentation with example application	Low
Flushing Characteristics Diagram	Christensen, B.A. 1989. Canal and marina flushing characteristics. *The Environmental Professional* 11:241-255.	N/A	Good illustrations with numerical example application	Low
NCDEM DO Model	North Carolina Dept. of Environmental Health and Natural Resources, Division of Environmental Management (919) 733-6510	Telephone contact	Good documentation with several applications	Medium
Tidal Prism Model	Virginia Institute of Marine Science, Gloucester Point, VA 23062 (804) 642-7212	Telephone contact	Excellent documentation of theory and assumptions; excellent user's guide with input and output information	Medium
WASP4	Center for Exposure Assessment Modeling, U.S. Environmental Protection Agency, Athens, GA 30613 (404) 546-3585	Software maintenance, workshop technical assistance through EPA channels	Excellent documentation of theory and assumptions; excellent user's guide with input and output information	High
EFDC Hydrodynamic Model	Virginia Institute of Marine Science, Gloucester Point, VA 23062 (804) 642-7212	Telephone contact	Excellent documentation of theoretical and computational aspects; excellent user's manual with input and output information; numerous papers written describing capabilities of the model	High

simplifications of more sophisticated techniques. These techniques, as presented, can provide reasonable approximations for screening potential impact problems when site-specific data are not available. The Tidal Prism Analysis was selected as the method of choice in this category. This method is capable of addressing all marina water quality issues of concern (e.g., dissolved oxygen and fecal coliform bacteria) and comes with excellent documentation. The primary strengths and advantages of the screening procedures are as follows:

- Excellent user documentation and guidance.

Table 5-2. Level of effort for best models.

Complexity	Model	Water Quality Problem	Approximate Level of Effort
Simple	Tidal Prism Analysis	DO, fecal coliform bacteria	1-2 Days
Mid-range	Tidal Prism Model	DO, BOD, nutrients, phytoplankton, fecal coliform	3-7 Days
Mid-range	NCDEM DO	DO	1-2 Days
Complex	WASP4	DO, BOD, nutrients, phytoplankton, toxics, fecal coliform	3-4 Weeks
Complex	EFDC Hydrodynamic	DO, BOD, temperature, salinity, nutrients, sediment, finfish, phytoplankton, shellfish, toxics, fecal coliform, eutrophication	4-6 weeks

Note: DO = dissolved oxygen, BOD = biological oxygen demand

- No computer is necessary because the procedures can be performed on hand calculators.
- Relatively simple procedures with minimal data requirements that can be satisfied from the user's manual when site-specific data are lacking.

The Tidal Prism Analysis procedures can be easily implemented in a computer program. This allows the user to test model sensitivity and determine the range of potential water quality impacts from a proposed marina quickly and efficiently.

Mid-Range Models

The recommended marina mid-range models are the Tidal Prism Model and the NCDEM DO Model. Both models are in the public domain, are easy to apply, and are supported with good documentation.

Tidal Prism Model

The Tidal Prism Model is a steady-state model capable of simulating up to 10 water quality variables, including dissolved oxygen and fecal coliform bacteria. The user's manual is well written and includes input/output examples, as well as guidance on how to calibrate and apply the model. Based on constituents modeled, the Tidal Prism Model is recommended as the best-qualified marina mid-range model. The primary strengths and advantages of the Tidal Prism Model are as follows:

- Excellent user documentation and guidance.
- Minimal computer storage requirements.
- Relatively simple procedures with data requirements that can be satisfied from existing data when site-specific time series data are lacking.

The Tidal Prism Model is applicable only to marinas where tidal forces are predominant with oscillating flow (e.g., an estuary or a tidal river). Therefore, the Tidal Prism Model can't be applied to marinas located on a sound, an open sea, or a lake or reservoir. Because the Tidal Prism Model is not applicable to most marina situations, the NCDEM DO model is recommended as an alternative best-qualified model for mid-range applications where the Tidal Prism Model isn't applicable.

NCDEM DO Model

The NCDEM DO model is a steady-state program that is capable of predicting only DO concentrations. The NCDEM DO model is applicable to one-, two-, and three-segment marinas. Model theory, assumptions, and input parameters are presented in adequate detail. Model documentation includes input and output examples of several applications as well as a listing of the model code. The model code is written in BASIC.

The NCDEM DO model incrementally mixes the ambient and marina waters as a function of the average lunar tides. The tidal variation is assumed to follow a sinusoidal distribution. For simplicity, a 12-hour tidal cycle is used. If this time-variable model is run through a sufficient number of tidal cycles, the average marina basin DO value approaches a steady-state value.

Complex Models

Complex models consist of two components—hydrodynamics and water quality. In this model category, hydrodynamics may be represented by numerical solution of the one-dimensional or the full two-dimensional equations of motion and continuity. Water quality conservation-of-mass equations are executed using the hydrodynamic output of water volumes and flows. The water quality component of the models calculates pollutant dispersion and transformation or decay, giving resultant concentrations over time. These models are very complex and require an extensive effort for specific applications.

Water Quality Analysis Simulation Program (WASP4)

The Water Quality Analysis Simulation Program, WASP4, is a dynamic compartment modeling system that can be used to analyze a variety of water quality problems in one, two, or three dimensions. WASP4 simulates the transport and transformation of conventional and toxic pollutants in the water column and benthos of ponds, streams, lakes, reservoirs, rivers, estuaries, and coastal waters. The WASP4 modeling system covers four major subjects—hydrodynamics, conservative mass transport, eutrophication-dissolved oxygen kinetics, and toxic chemical-sediment dynamics. The modeling system also includes a stand-alone hydrodynamic program called DYNHYD4, which simulates the movement of water. DYNHYD4 is a link-node model that can be driven by either constantly repetitive or variable tides. Unsteady inflows can be specified, as well as wind that varies in speed and direction. DYNHYD4 produces an output file of flows and volumes that can be read by WASP4 during the water quality simulation. WASP4 contains two separate kinetic submodels, EUTRO4 and TOXI4. EUTRO4 is a simplified version of the Potomac Eutrophication Model (PEM) and is designed to simulate most conventional pollutant problems. EUTRO4 can simulate up to eight state variables, including dissolved oxygen and fecal coliform. TOXI4 simulates organic chemicals, metals, and sediment in the water column and underlying bed.

The WASP4 model system is supported by the EPA's Center for Exposure Assessment Modeling (CEAM) in Athens, Georgia, and has been applied to many aquatic environments. The WASP4 model can be obtained from the CEAM web page (www.epa.gov/ceampubl/softwdos.htm). The water quality component is set up for a wide range of pollutants, and the model is the most versatile and most widely applicable of all models considered here. For these reasons WASP4 is the model of choice in this category. The primary strengths and advantages of the WASP4 model are as follows:

- *Documentation*: WASP4 has excellent user documentation and guidance. Theory and assumptions are presented in adequate detail; program organization and input data requirements and format are clearly presented.
- *Support*: User access is available by telephone to programmers and engineers familiar with the model. Occasional workshops, sponsored by CEAM, are available. The support agency (CEAM) can provide the potential user with a list of local users who could be contacted for information regarding their past or current experience with the computer program.

- *Flexibility*: Model users can add their own subroutines to model other constituents that might be more important to the specific application with minimal or virtually no programming effort required. The user can operate WASP4 at various levels of complexity to simulate some or all of these variables and interactions.

CEAM maintains and updates software for WASP4 and the associated programs. Continuing model development and testing within the CEAM community will likely lead to further enhancements and developments of the WASP4 modeling system. In fact, CEAM is currently supporting the development of a 3-dimensional (3-D) hydrodynamic model that will be linked to the WASP4 model.

EFDC Hydrodynamic Model

The environmental fluid dynamics code (EFDC) model was originally developed at the Virginia Institute of Marine Science (VIMS) for estuarine and coastal applications and is considered public domain software. It is a general-purpose modeling package for simulating three-dimensional flow, transport, and biogeochemical processes in surface water systems, including rivers, lakes, estuaries, reservoirs, wetlands, and coastal regions. In addition to hydrodynamic and salinity and temperature transport simulation capabilities, EFDC can simulate cohesive and noncohesive sediment transport, near-field and far-field discharge dilution from multiple sources, eutrophication processes, the transport and fate of toxic contaminants in the water and sediment phases, and the transport and fate of various life stages of finfish and shellfish. Special enhancements to the hydrodynamic portion of the code, including vegetation resistance, drying and wetting, hydraulic structure representation, wave-current boundary layer interaction, and wave-induced currents, allow refined modeling of wetland marsh systems, controlled flow systems, and nearshore wave-induced currents and sediment transport. The EFDC model has been extensively tested and documented for more than 20 modeling studies. The model is currently being used by a number of organizations, including universities, governmental organizations, and environmental consulting firms.

The structure of the EFDC model includes four major modules: (1) a hydrodynamics model, (2) a water quality model, (3) a sediment transport model, and (4) a toxics model (see Figure 5-1). The EFDC hydrodynamic model itself is composed of six transport modules—dynamics, dye, temperature, salinity, near-field plume, and drifter. Various products of the dynamics module (water depth, velocity, and mixing) are directly coupled to the water quality, sediment transport, and toxic models.

- *Documentation*: Extensive documentation of the EFDC model is available. Theoretical and computational aspects of the model are described by Hamrick (1992a). An excellent user's manual (Hamrick, 1996) is available and includes input file templates. A number of papers describe model applications and capabilities (Hamrick, 1992b, 1994; Hamrick and Wu, 1996; Moustafa and Hamrick, 1994; and Wu et al., 1996).

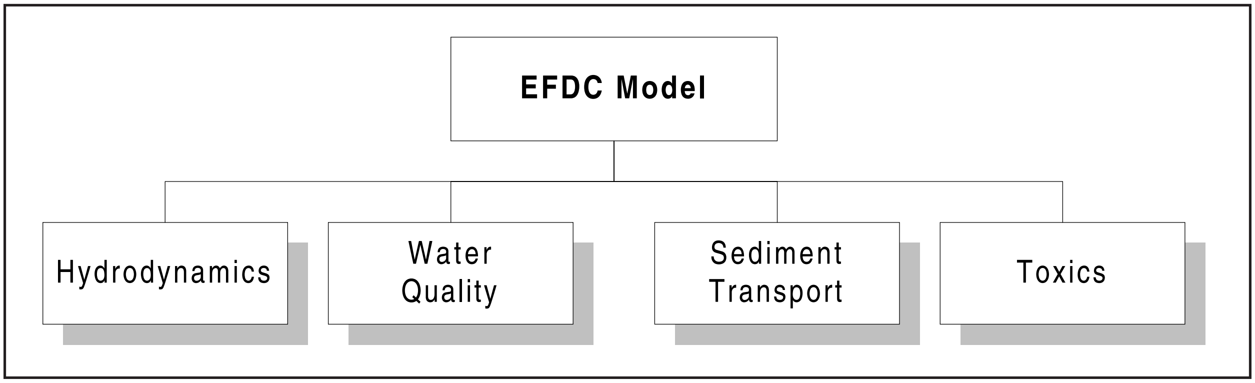

Figure 5-1. Structure of and modules associated with the EFDC model.

- *Support*: User access is available by telephone to programmers and engineers familiar with the model. VIMS can provide the potential user with a list of local users who could be contacted for model information.
- *Flexibility*: The EFDC model can be configured to execute all or a portion of a model application in reduced spatial dimension mode, including two-dimension depth or width averaged and one-dimension cross section averaged. The number of layers used in the three-dimension mode or two-dimension width averaged mode is readily changed by one line of model input. Model grid sections specified as two-dimension width-averaged are allowed to have depth-varying widths to provide representations equivalent to those of two-dimension width-averaged estuarine and reservoir models, such a CE-QUAL-W2.

Water Quality Monitoring in Marinas (for modeling applications)

Sampling Guidelines for Existing Marinas

General guidance is presented to develop the framework for a site-specific water quality sampling program suitable for an existing marina. A monitoring study at an existing marina may be requested by regulatory agencies if it is suspected that the marina is causing degradation of water quality standards. An overall monitoring program can consist of three phases or levels. In Level 1, preliminary screening is conducted to gather baseline information on the marina. If historical data on the marina are available, this level might not be needed or the quantity of data needed might be reduced. Based on the historical or Level 1 data, if it is established that the marina may be causing impacts on water quality, Level 2 sampling, which incorporates additional sampling of the receiving waters, would commence. If evaluation of Level 2 data also indicates that the marina is affecting water quality, marina design changes may be recommended and eventually implemented. Level 3 sampling would be initiated to evaluate the performance of any implemented marina design changes. Examples of potential marina design changes include removal of sills, which tend to trap water in the lower depths of a marina, and improvement of flushing by altering sharp corners within the marina or by enlarging the marina entrance.

Spatial Coverage

An intensive spatial coverage of the marina and the adjacent waterbody for some indicator or surrogate water quality parameter, such as salinity or turbidity, is generally needed to estimate spatial variability and to determine the model type and the segmentation required.

Generally, the spatial coverage of the modeled marina should extend away from the marina site to the extent that normal background levels for DO are encountered. At this location, model boundary conditions (i.e., surface elevations or current velocities) can be established. In this manner the total effect of the marina can be measured.

The preceding approach is appropriate when using complex models. Sampling stations for complex models should be spaced throughout the model grid system, with the spatial coverage being governed by the gradients in velocities and water quality constituents. For existing marinas, adjacent waterbodies are divided into a series of reaches for complex model application, with each reach described by a specific set of channel geometry dimensions (cross-sectional dimensions) and flow characteristics (flow rates, tidal range, velocities, and biochemical processes). The models assume that these conditions are uniform within each reach. Each reach is in turn divided into a series of model segments or computational elements to provide spatial variation for the water quality analysis. Each segment is represented by a grid point in the model where all water quality variables are computed. For the WASP4 model, the segment length is dependent on the degree of resolution desired and the natural variability in the system. Enough detail should be provided to characterize anticipated spatial variation in water quality.

The hydrodynamics of the Tidal Prism Model are based on the tidal prism volume at each segment. Therefore, the spatial coverage of a marina, using the Tidal Prism Model, includes the entire estuary/river where the marina is located. The length of each segment is defined by the tidal excursion, the average distance traveled by a water particle on the flood tide, because this is the maximum length over which complete mixing can be assumed.

A sampling station for each model segment is the minimum requirement to calibrate the returning ratios of the Tidal Prism Model. Sampling stations should generally be located along the length of the estuary and in the main channel. The returning ratio is defined as the percentage of tidal prism that was previously flushed from the marina on the outgoing tide.

Constituents Sampled

The specific constituents that must be sampled, as well as the sampling frequency, depend to some extent on the particular modeling framework to be used in the analysis. The selected model should include all of the processes that are significant in the area under investigation without the unnecessary complexity of processes that are insignificant. A few preliminary measurements might be useful to define which processes are important.

The minimum sampling requirements for all dissolved oxygen studies should include dissolved oxygen, temperature, carbonaceous biochemical oxygen demand (CBOD), and total Kjeldahl nitrogen (TKN), because these parameters are fundamental to any dissolved oxygen analysis. Biochemical oxygen demand (BOD) is typically measured as 5-day BOD, but a few measurements of long-term BOD are also necessary. The Tidal Prism Model considers only the CBOD component, and therefore the model should be used only in situations where the nitrogenous components are known to be unimportant.

In addition to TKN, ammonia (NH_3) and nitrate (NO_{3G}) (or nitrite [NO_{2G}] plus nitrate) should be measured for dissolved oxygen investigations for both the Tidal Prism and WASP4 models. Even if ammonia, nitrate, and nitrite are not modeled, the data are useful for estimating the nitrogenous BOD decay rate or ammonia oxidation rate.

Concentrations of algal dry weight biomass or chlorophyll *a* should be measured because both the complex models and the Tidal Prism Model simulate algae growth for dissolved oxygen analysis. Light extinction coefficients (or Secchi depths) are also needed for the algal growth computations in dissolved oxygen analysis if the complex models are used.

In situ sediment oxygen demand (SOD) should be measured in situations where it is expected to be a significant component of the oxygen budget. This is most likely to occur in shallow areas where the organic content of the sediments is high or in deep marina basins where flushing is minimal. In developing a strategy for SOD measurement, it is logical to assume that those factors important in establishing model reaches or segments are also relevant to selecting SOD measurement sites. The more important of these factors are

- *Geometry*: depth and width.
- *Hydraulics*: velocity, slope, flow, and bottom roughness.
- *Water quality*: location of point sources, nonpoint source runoff, and abrupt changes in DO/SOD concentrations.

The most important factor for SOD is likely to be the location of abrupt changes in DO/BOD concentrations, such as areas surrounding the entrance channels of marinas and in the marina basin proper. The final point to consider is that SOD can vary with season. This observation is particularly relevant to marinas and adjacent areas dominated by algal activity and/or oxidation of organic and inorganic nutrients by benthic microorganisms, both of which can occur seasonally. The modeler should thus be aware of this potential concern and structure the SOD measurement times accordingly.

In addition to sampling for the constituents to be simulated, measurements are also necessary to help quantify the various coefficients and parameters included in the model equations. Coefficient values can be obtained in four ways: (1) direct measurement, (2) estimation from field data, (3) literature values, and (4) model calibration. Model calibration is usually required regardless of the selected approach. However, coefficients that tend to be site-specific or that can take on a wide range of values should be either measured directly or estimated from field samples. These could include the following parameters:

- CBOD decay rate
- CBOD settling rate
- NH_3 oxidation rate (nitrogenous BOD decay rate)
- SOD

In addition to the preceding model parameters, which are determined primarily from the results of field sampling surveys, several other rate coefficients can be measured in the field. For example, stream reaeration rates for the WASP4 model and returning ratios for the Tidal Prism Model can be measured using tracer techniques. WASP4 provides several options for the reaeration rate equation because many of the equations are applicable to only certain ranges of depth and velocity.

Sampling Locations

Water quality data should be collected at the downstream boundary of the study area for model calibration. Adjacent waters both upstream and downstream should also be sampled to determine background concentrations of water quality constituents. Although a single downstream station is the minimum requirement for short channel sections, additional sampling stations are desirable to provide more spatial data for calibrating the model. Logical locations for additional stations are sharp corners and dead end segments in the marina basin proper. If the marina is segmented for a complex model application, each segment should be sampled. However, water quality variations might be negligible at stations located upstream and downstream immediately outside marinas.

In the Tidal Prism Model, water quality is assumed to be well mixed and uniform over each segment of the stream. Therefore, samples taken immediately downstream of the marina would probably not match conditions in the model unless they were taken far enough downstream for complete cross-sectional mixing to occur. In general, increased sampling should be allocated to those areas of the marina and the adjacent water that have the most impact (along the shoreline). In general, all of the major water quality parameters of interest (DO, CBOD, TKN, NH_3, NO_3, fecal coliform bacteria, temperature, and so forth) should be measured at each station in the sampling network.

Rate coefficients and model parameters can be estimated from literature values before site-specific measurements are available. For important parameters such as the BOD decay rate, sensitivity analyses can be performed to evaluate the effects of different coefficient values in formulating DO concentrations. These analyses should provide enough information so that sampling stations can be located in critical areas.

Sampling Time and Frequency

The duration and frequency of water quality sampling depend to a large extent on whether the Tidal Prism Model or a complex model will be used. The Tidal Prism Model computes water quality conditions only at slack before ebb; thus, sampling at a higher rate is not necessary. The complex models have a user-specified time step, which means that sampling should be more frequent for shorter time steps.

Because the Tidal Prism Model assumes that conditions remain constant with time, it is important to conduct the sampling program during a period when this assumption is valid. Synoptic surveys (e.g., sampling all stations over 2 to 3 days) should be conducted to the extent possible so that water quality conditions at different locations are not affected significantly by changes in the weather or variations in the marina discharge that are not accounted for in the model. However, since temperature varies diurnally and temperature influences the process rates of most biological and chemical reactions, some variability in the sampling results will be inevitable. It should be noted that the Tidal Prism Model uses the first day of field data as initial and boundary condition input to the model. Field data from succeeding cycles are then used to compare the output simulations at the same cycle.

Complex models compute continuous changes that occur over time because of variations in stream flow, temperature, nonpoint and point source loadings, meteorology, and processes occurring within a marina and its adjacent waters. All of the factors that are assumed constant for a Tidal Prism analysis are free to vary continuously with time in a complex model. This feature allows an analysis of diurnal variations in temperature and water quality, as well as continuous prediction of daily variations or even seasonal variations in water quality.

Application of a complex model requires a much more detailed sampling program than that required by a mid-range model. Enough data should be collected to define the temporal variations in water quality throughout the simulation period at the model boundary conditions. Therefore, more frequent data collection should be conducted at the model boundary condition. Complex models investigate the temporal variations in dissolved oxygen and fecal coliform bacteria much better than mid-range models. To achieve this resolution, intensive surveys should be mixed with long-term trend monitoring. The significance of the temporal variations depends on the context of the problem. For example, if the daily average dissolved oxygen concentration is around 5 mg/L or less, a diurnal variation of less than 1 mg/L could be very important with respect to meeting water quality standards; if the average dissolved oxygen concentration is around 10 mg/L, diurnal variations are important and the sampling program should include 2 or 3 days of intensive sampling for dissolved oxygen and temperature at all of the key stations. As a minimum, these stations would include the stations designated as the model boundary, as well as the stations surrounding the marina and adjacent waters and stations within the marina. These locations satisfy the minimum requirements of defining the boundary and loading conditions, plus a few calibration stations in the critical areas for DO, SOD, and fecal coliform bacteria.

Long-term dynamic simulations of seasonal variations in stream water quality might be impractical. Where seasonal variation is of interest, the typical practice is to run the Tidal Prism Model or a complex model (with short-term simulations) several times for different sets of conditions that represent the full spectrum of conditions expected over the period of interest. Enough data should be collected to characterize the seasonal variations and to provide adequate data for calibrating and applying the model. If possible, enough data should be collected to cover the full range of conditions of the model analysis. As a minimum, these should include conditions during the critical season for the water quality variable of interest. For DO, for example, the critical season occurs during the hot summer months (July through September).

Two general types of studies can be defined—*intensive surveys*, which are those used to identify short-term variations in water quality, and *trend monitoring*, which is used to estimate trends or mean values. Intensive surveys are intended to identify intertidal variations or variations that occur because of a particular event in order to make short-term forecasts. Intensive surveys should encompass at least four full tidal cycles. They should usually be conducted regardless of the type of modeling study being conducted. Boundary conditions should be measured concurrently with the monitoring of the marina basin and the adjacent water. A record of all point source waste loads located near the marina site during the week before the survey is recommended. Variables that should be sampled during the intensive surveys include tide, current velocity, salinity, DO, fecal coliform bacteria, nitrogen, and phosphorus, measured hourly.

Trend monitoring is conducted to establish seasonal and long-term trends in water quality. Trend sampling may take place on a biweekly or monthly basis for a year at a time. Stations should be sampled at a consistent phase of the tide and time of day to minimize tidal and diurnal influences on water quality variations. Some stations may be selected for more detailed evaluation during the intensive survey. Long-term trend monitoring should also be considered as a way to track changes in water quality between the intensive surveys.

Most states have water quality standards for the 24-hour average concentration and the instantaneous minimum concentration of DO. Therefore, it is important to collect DO data throughout a complete cycle, that is, from the high value, which normally occurs at mid-afternoon, to the low value, which usually occurs at dawn. This approach will allow the DO range in the model to be calibrated to specific field conditions. If the waterbody is stratified, samples should be collected at the surface, mid-depth (above and below the thermocline and pycnocline, if possible), and bottom. In general, it is necessary to collect samples at a 2-hour frequency over a 24-hour period to adequately define the daily average and the minimum DO concentrations.