Chapter 6. Modeling Efforts (Miles A. Sundermeyer & Yalin Fan)

1. Introduction

A number of hydrodynamic, water quality, and fish modeling studies of Mt. Hope Bay have been conducted to assess the impact of the Brayton Point Power Station (BPPS) thermal plume on local fish populations. To date, much of the hydrodynamic modeling has been performed by Applied Science Associates (ASA), using a three-dimensional boundary-fitted hydrodynamic model, WQMAP (Water Quality Mapping and Analysis Program). In addition, a second embedded hydrodynamic model, CORMIX (the Cornell Mixing Zone Expert System) has been used to simulate the near-field dynamics of the BPPS thermal plume. Results from the above hydrodynamics models have been used to force box models of water quality and dissolved oxygen as well as a fish metapopulation model, the RAMAS GIS/Metapop model. The ultimate purpose of these modeling studies has been to address the following questions:

1) What is the overall impact of BBPS on the hydrodynamics and property distributions (temperature, salinity, DO, BOD, and optionally carbonaceous and nitrogenous biochemical oxygen demand, ammonia, nitrate, and organic nitrogen) of Mt. Hope Bay?

Simulations have been run for pre- and post BPPS conditions, i.e., with and without the thermal plume present. The difference between solutions for these two cases represents the impact of the power station. According to available reports, to date this analysis has been done for temperature, salinity, and horizontal velocity.

2) What is the rate of impingement of fish eggs and larvae (i.e., how many are drawn into the cooling intakes) as a function of flow rate and position in the estuary?

This analysis was suggested by N. Fennessey (memo to W.L. Bridges, dated June 11, 1997). It was suggested that eggs and larvae could be represented by Lagrangian particles in the model. Using an initially uniform distribution of particles in the model, and tracking particle positions for a many tidal cycles, entrainment rates into the BPPS intake could be assessed as a function of location in the estuary. An additional question raised earlier by N. Fennessey (memo to G. Szal, Feb 7, 1997) was whether discharge of dead, entrained larvae could cause a local rise in BOD near the outfall? Finally, a January 1998 memo to EPA (memo from A.H. Aitken, January, 1998) cited evidence that the assumption of 100% larval mortality in water circulating through the power station was likely an overestimate; a 1997 study indicated that survivability of larvae may be 50% or more.

3) How does the extent of the plume (in terms of area and volume encompassed) vary by season and as a function of cooling water discharge rate and temperature?

The impact of the plume is assessed in terms of the percent area and volume of Mt. Hope Bay that experiences (a) a rise in temperature greater than or equal to 0.8^{o}C, or (b) an absolute temperature greater than or equal to some critical temperature. The latter critical temperature is species-specific, and has been a subject of ongoing debate (see, e.g., Meetings Notes of TAC Fisheries Subcommittee, November 5, 1997). In a memo to J. Parr from July 1998, it was further suggested that a "mixing zone" be defined in terms of whether the area influenced by the plume interferes with normal migration of fish, i.e., whether it impairs the passage and free movement of migratory species. Related issues are the temporal rate of change in temperature, and the extent to which fish can detect gradients.

4) What would be the largest possible size/extent that the thermal plume might attain in the "worst-case" scenario?

Numerical simulations were run by Applied Science Associates, using background conditions from summer 1994, which was characterized by cooler than average temperatures, and from summer 1996, which was characterized by warmer than average temperatures in Mt. Hope Bay. In these runs, they describe the area and volume that experienced a 0.8^{o}C rise in temperature with the plant operating at its maximum allowable discharge temperature of 95^{o}F. The 1994 simulation yielded the largest plume in terms of absolute temperature (percent area with temperature >26^{o}C), while the 1996 simulation yielded the largest in terms of rise in temperature (>0.8^{o}C).

5) Scenario testing for different discharge rates and temperatures.

Additional simulations were run for summer 1994 and 1996 conditions, but with varying discharge temperatures (number of cooling cells active) and with actual loading based on 1996 power plant data.

History of Hydrodynamic Modeling in Mt. Hope Bay

Early modeling studies of Mt. Hope Bay were conducted by ASA (Huang and Spaulding 1995a) in the context of a combined sewage outfall (CSO) plume study. These studies used an earlier version of ASA's three-dimensional hydrodynamic and pollutant transport model to simulate the dispersal of a passive tracer released on the eastern side of Mt. Hope Bay, specifically, River View and City Pier. ASA validated the model results using field data from a dye-release experiment (also by ASA) conducted during storm conditions from September 22-25, 1990 (Turner et al. 1990).

The present-day ASA hydrodynamic model, WQMAP (described in detail in Spaulding et al. 1999b) is a three-dimensional hydrodynamic model combined with three separate water quality or pollutant transport and fate models. The model solves the conservation of momentum, mass, salt and energy equations on a spherical, non-orthogonal, boundary-conforming, sigma-coordinate grid (Figure

6.1). The grid is staggered in the horizontal, and non-staggered in the vertical. The model employs a split mode solution methodology, with the exterior mode solved semi-implicitly, and the internal mode solved explicitly by finite difference, except for vertical diffusion term, which is also handled implicitly. Eddy viscosities are specified either by the user, or through a simple turbulent kinetic energy model. The WQMAP model is described in further detail in Appendix A.

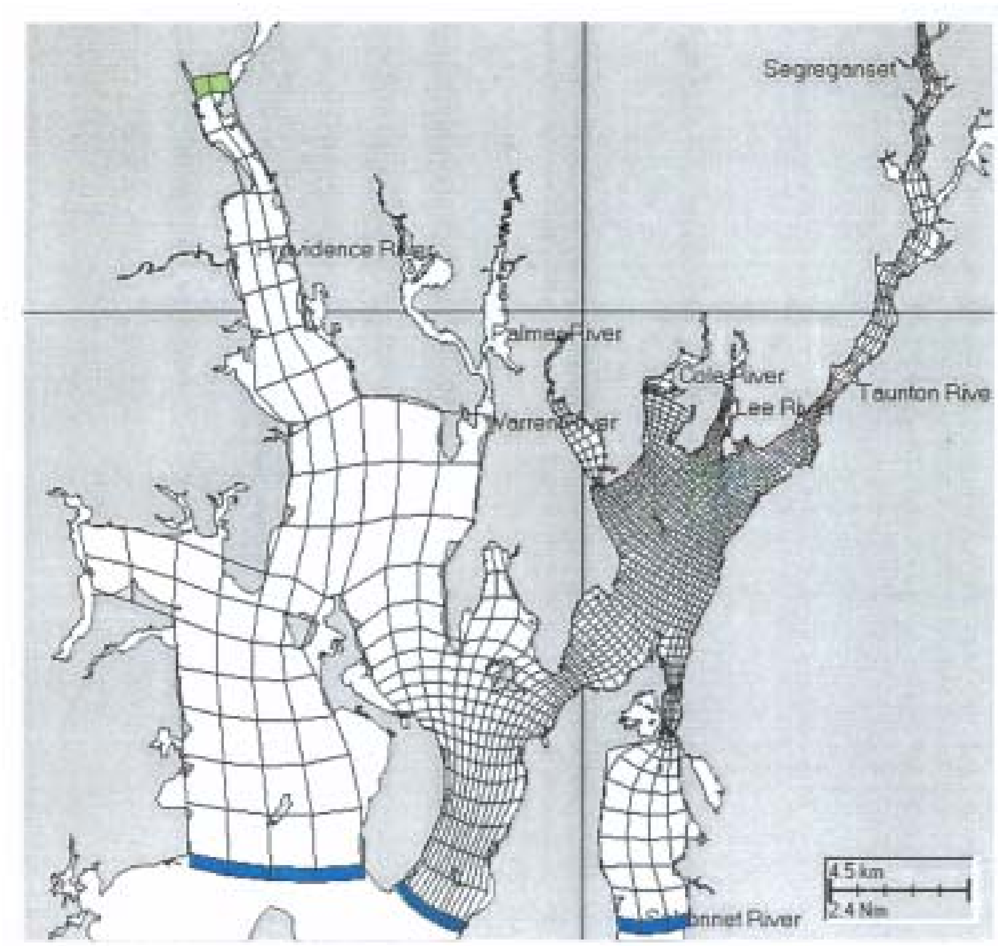

Figure 6.1. Model grid used for simulations in Mt. Hope Bay. The gridded area extends into substantial portions of Narragansett Bay to more accurately reflect conditions at the entrance to Mt. Hope Bay.

WQMAP Model Applications

In the context of the present study, WQMAP was used to hindcast the three-dimensional circulation and thermal dynamics of Mt. Hope Bay, which are subject to the discharge from the Brayton Point Station once-through cooling system. In these simulations, the model grid of 3300 cells extended from mid Narragansett Bay and Sakonnet River north to the upper reaches of the Providence and Taunton Rivers (Figure 6.1). Grid size in Mt. Hope Bay ranged from 50-100 m in the vicinity of the power plant to 200-300 m in other parts of the bay, and to greater than 1 km in parts of Narragansett Bay. Eleven layers were used to resolve the vertical structure.

The model was driven by presumed tidal sea level, temperatures and salinities at the southern boundaries, river flows scaled from gauge data at the northern boundaries, and meteorological forcing (winds, air temperature, solar radiation) from the weather station at T.F. Green State Airport in Warwick, RI. Cooling water intake and discharge conditions were based on Brayton Point Station measurements.

The model was initially calibrated and verified with field data acquired during summer 1996, spring 1997, summer 1997, and winter 1999. Model hindcasts of velocities, temperature, and salinity were found to be in good statistical agreement with the data in terms of relative error, root mean square error, linear regression analysis, and error coefficient of variation. The model was further optimized to the thermistor data acquired near the Brayton Point Station discharge (at approximately 2km) for both summer and winter conditions.

Once the model was calibrated and verified, it was used to simulate conditions in Mt. Hope Bay subjected to a series of historical and hypothetical plant loads. The purpose of the hindcast simulations was to determine the size of the thermal plume generated by the plant during previous years for the purpose of assessing potential effects on fish habitat. A series of scenario-testing simulations were also run using reduced power plant load conditions in order to evaluate potential benefits of new cooling technologies and operations.

CORMIX Model Applications

The near-field dynamics of the BPPS thermal plume were simulated using a second embedded numerical model, CORMIX (Cornell Mixing Zone Expert System)–a commercially available, USEPA-approved, near-field model that simulates temperature distributions within a discharge plume. CORMIX is a length-scale-based model that simulates the dilution of effluent from a submerged or surface discharge (Jirka et al. 1996). The CORMIX model was used to determine the extent of the Brayton Point Station's cooling water discharge plume in the near-field region (within approximately 500 meters = 1,640 ft) of the BPPS venturi. CORMIX3 (Jones et al. 1996)–a subcomponent of CORMIX–was used to estimate near-field surface plume temperatures. The results of CORMIX3 were used to determine biological effects from the thermal plume.

First, the CORMIX model was used to calculate a set of non-dimensional parameters based on ambient conditions, effluent data, and discharge geometry. The discharge flow was then classified according to a variety of defined flow regimes. Next, CORMIX3 was used to determine the location of the BPPS plume centerline, plume width and depth, and centerline concentration and attenuation as the plume moved through the receiving water body. From these results, the volume and exposure time as a function of temperature rise and plume velocities were calculated.

To ensure consistent results in the application of the CORMIX and CORMIX3 components of the model to Brayton Point Station, CORMIX3 was assessed for sensitivity to variations in certain model input parameters. This was accomplished by running a series of simulations for various discharge flows and discharge temperatures under both summer and winter conditions. Model results were then compared in terms of the resultant temperature and velocity in the near-field region of the discharge venturi.

Combined WQMAP and CORMIX Model Results

CORMIX near-field results were integrated with larger-scale WQMAP results in order to determine the impacts of the Brayton Point Station thermal discharge in terms of the volume of water affected by the thermal plume. Results generally showed modest temperature increases (1°C) over significant portions of the bay (up to 62%), with higher temperature increases (5°C) in the very near field (less than 0.002% of the Bay). Estimates of the exposure times of near-field biota were also estimated with CORMIX. Exposure times were generally less than 15 minutes for temperature increases of 3°C, and less than 3 minutes for increases of 5°C. Exposure times in summer were significantly less than in winter, because the plume-induced increase in water temperature was generally less in summer.

The blended WQMAP/CORMIX outputs were used to assess the extent of the temperature plume during flood and ebb tides. Results suggest that within a given season, the volume of the plume does not vary significantly over a tidal cycle. Furthermore, for a given discharge, the volume of water in the Bay that undergoes a given increase in temperature is greater in winter than in summer. This is because discharge temperatures are higher, relative to the ambient temperature of the bay, in winter than in summer. For a given discharge, the percent of water in Mt. Hope bay that exceeds a given threshold temperature value is greater in summer than in winter. Again, this is due to the higher ambient water temperatures in summer compared to winter.

Other WQMAP Model Applications in the Narragansett/Mt. Hope Bay Region

WQMAP was also applied to the Providence River/upper bay as part of a combined sewer overflow (CSO) facilities planning effort for the Narragansett Bay Commission. Here model results were compared using both dry and wet weather conditions, and the model was tuned to provide the best overall comparison with observations.

WQMAP has also been to address the issue of total maximum daily loading (TMDL) for nutrient reduction. The hydrodynamic model was configured to run in a three-dimensional mode, with prognostic calculation of density-induced flow. Forcing included tidal sea level, winds, river flows, and density distributions.

Finally, the WQMAP hydrodynamic and pollutant transport model has been used in dredging impact studies in the Providence River and upper Narragansett Bay. Again, the three-dimensional, time-dependent, boundary-fitted calculation used 11 layers to simulate the vertical structure of currents that resulted from tidal sea level, wind, density and river flow forcing.

2. Model Validation and Verification

The WQMAP hydrodynamic model of ASA is calibrated by adjusting model parameters to optimize the match between model predictions and observed data. Adjustment parameters include bottom and surface friction, bathymetric resolution, vertical and horizontal diffusivities, and parameterization of surface heat transfer rates. For the water quality portion of the model (i.e., DO), parameters include reaeration rate, deoxygenation rates, nitrogen mineralization and nitrification rates, photosynthesis and perspiration rates.

Model results are evaluated both qualitatively and quantitatively (ASA 1997b). Qualitative evaluations generally rely on visual comparisons of data and model results presented as time series, spatial maps, and power spectra. Quantitative comparisons are based on the following statistical measures applied to any number of model/observable variables:

a) Relative mean absolute error

$$e = \frac{|\overline{x} - \overline{c}|}{\overline{x}}$$

b) Relative mean error

$$e = \frac{\bar{x} - \bar{c}}{\bar{x}}$$

c) Mean relative error

$$e = \frac{\overline{|x - c|}}{\bar{x}}$$

d) Root mean square (rms) error

$$r = \frac{\sqrt{\sum (x_i - c_i)^2}}{N}$$

e) Linear regression: slope and intercept (including significance tests), r^2, standard error

f) Comparisons of means based on t-test

g) Coherence analysis

where x_i are the observed values, c_i are the model-predicted values, and the overbar denotes the mean. Finally, model parameter sensitivity is examined to determine which model parameters are most important.

An EPA report (Martin et al. 1990) provides some guidelines as to the acceptable values of the above statistical measures (see Table 6.1). Note that the above qualitative and quantitative criteria are that they focus on comparing model results to data collected during specific time periods and specific locations in the bay. However, they do not address the larger issue of what is the inherent variability of the system, and hence what is the uncertainty associated with model results (see: Meeting Notes from TAC Fisheries Subcommittee, November 5, 1997; and Comments by Christian Krahforst, December, 1997).

Table 6.1. EPA model calibration guidelines (McCutcheon et al. 1990).

Analysis	Property	Value
Relative Error	Hydrodynamic (velocity)	<30%
	Transport (salinity, temperature)	<25%
	Dissolved Oxygen	<15%
Coefficient of Variation (std/mean)	Hydrodynamic (velocity)	<10%
	Transport (salinity, temperature)	<45%
	Dissolved Oxygen	<1.7%
Correlation Coefficients	Hydrodynamic (velocity)	<0.94
	Transport (salinity, temperature)	<0.84
	Dissolved Oxygen	<0.80

Model Performance

WQMAP has been used to simulate Mt. Hope Bay conditions for a variety of BPPS discharge scenarios. Model validation was generally performed using an array of temperature strings situated around BPPS, with each station containing sensors at 0.25, 0.5, 1, 2, and 4 m below the surface. Deeper stations had an additional sensor at 6 m. Two current meter stations were also used, one at BPPS and one at Borden Flats. Water temperature and tidal height from an NOAA/NOS station at Newport were used to force the model’s open boundary, while river flow rates for the Taunton and Three Mile River were obtained from USGS.

Analysis presented in Spaulding et al. (1999a) for a one-month simulation in winter 1996 shows that while the model generally captures heating and cooling trends due to atmospheric forcing, it underpredicts temperatures in Mt. Hope Bay during the coolest periods. Spaulding et al. (1999a) further find that (1) the relative mean error (*rme*) varies from 0.00 to 0.22, averaging 0.07; (2) the root mean square error (*rms* error) varies from 0.40 to 1.75 ^{o}C; (3) the correlation coefficient (*r*) ranges from 0.40 to 0.97, averaging 0.80; and (4) the *ecv* ranges from 0.09 to 0.39, averaging 0.17. Plan view maps of *rme* and *rms* temperature error across the Bay (Figure 6.2) show that in general the highest *rme*

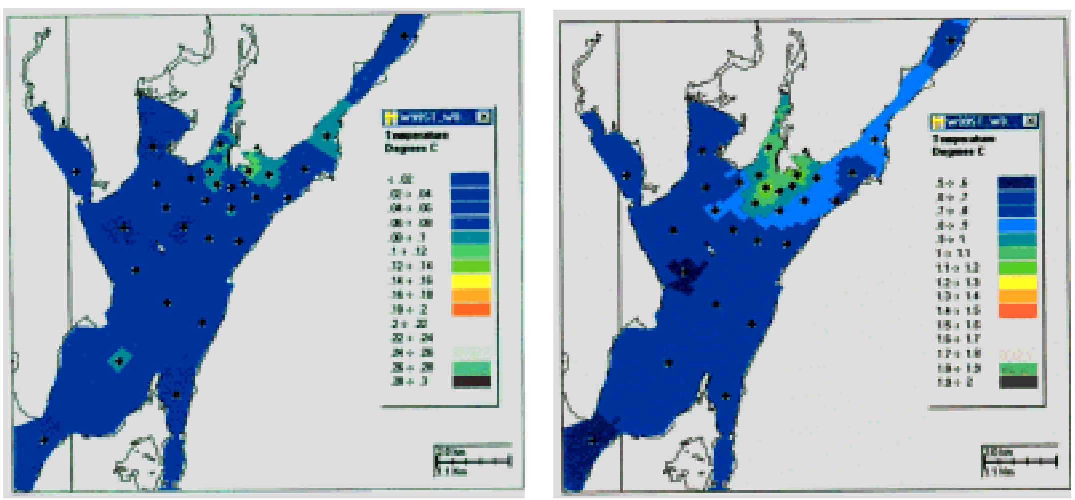

Figure 6.2. ASA WQMAP model error for Mt. Hope Bay simulations: (left panel) relative mean error (rme) and (right panel) root mean square error (rms) between model predictions and observations for the surface (0.25 m) thermister locations. (From Spaulding et al. 1999b; permission pending).

temperatures occur in the lower Taunton River, the Lee River near the discharge, and just south of Mt. Hope. Similarly, the highest *rms* error temperatures error occur in the Taunton River and near BPPS. Thus the modeling results satisfy the EPA guidelines (McCutcheon et al. 1990). The latter was also true for salinity, sea surface elevation, and currents. Model-data comparisons were poorest for currents (C. Turner, memo dated May 26, 1998).

Model-data comparisons for winter 1997, and summer 1996 and 1997 calibration runs yielded similar results. Again temperature, salinity, sea surface elevation and currents were compared to standards described in McCutcheon et al.(1990). Model-data comparison statistics for these three sets of runs are described in detail in Swanson et al. (1998).

The criteria outlined by McCutcheon et al. (1990) for model validation and verification provide a variety of measures of performance based on mean properties of the system and at specific locations in the study region. However, it is important to note that the use of only one or two of these criteria alone, and/or the presence of spatial variations in these statistics, may make it difficult to assess model accuracy. For example, in an October 1997 memo to EPA from BBPS, ASA argued–on the basis of relative error statistics of current speed, salinity, and temperature at the surface and bottom at two stations–that the ranges of these statistics were "well within the guidance" set forth by EPA, and that "using this measure, the model is clearly calibrated." Note, however, that the relative error is a measure only of whether the model reproduces mean property values, and says nothing about how well it simulates variations in time. In short, the complete suite of statistics outlined by EPA, both qualitative and quantitative, are required to give a complete assessment of model performance. As discussed above, a report by Spaulding et al. (1999a) further shows that even when multiple statistics are used together, spatial variations in these statistics may indicate good model performance in some parts of the domain, while still leaving poor performance in other parts.

3. Water / Habitat Quality Modeling and Changes in Fish Abundance

Beyond the hydrodynamic modeling efforts described in the previous sections, there has been a strong consensus among state and federal agency biologists that the ASA model should be linked to both a water quality model and a fish population model in order to assess effect of BPPS's on issues such as nutrient and dissolved oxygen (DO) levels, benthic habitat, phyto- and zoo-plankton community structure, natural mortality and fishing impacts, habitat modification/avoidance, entrainment, and impingement (e.g., Meeting Notes TAC Fisheries Subcommittee, November, 1997). However, there is also much debate as to whether sufficient information is available to constrain such models of Mt. Hope Bay, particularly since it is an open system with respect to fish populations, and since much of the life history of the local fish populations occurs outside the bay (e.g., Review of Mt. Hope Bay Modeling Proposal by Steve Cadrin, July, 1998, unpublished memo; Coutant et al. 1998).

A review by Coutant et al. (1998) further emphasized that from a modeling perspective uncertainties in a few key variables limit the accuracy of predicted impacts. For example, the following variables are considered the most important for controlling predictions in assessments to estimate the population-level consequences of entrainment and impingement:

1. Size and geographic extent of source adult population
2. Size of source population of early life stages from which losses occur
3. Number of early life stages killed by entrainment and impingement (especially the probability of through-plant survival
4. Natural mortality rates (especially those for early life stages) used to extrapolate losses of early life stages to equivalent adults, production foregone, or reproductive potential or used to simulate population trajectories or estimate risk of extinction
5. Density-dependent effects

Coutant et al.(1998) further concluded that since all but one or two of these variables (numbers 1 and 3) are extremely difficult to constrain from field data, the expectation or hope that better or different models per se will lead to better predictions of population-level effects is not realistic. The above considerations suggest that a more thorough examination of whether our understanding of the Mt. Hope Bay ecosystem is model- or data-limited is thus advisable in the early developmental stages of the proposed Mt. Hope Bay Natural Laboratory.

Water Quality/DO Modeling

The water quality/DO component of ASA's WQMAP is based on the EPA WASP5 model (Ambrose et al. 1992). It is intended to be able to run at any of six levels of complexity ranging from a simple balance between biochemical oxygen demand and dissolved oxygen (BOD-DO) to increasing levels of nutrient, phytoplankton, BOD and DO representation, up to full eutrophication kinetics including the benthos. The different levels of complexity are as follows:

1. Streeter-Phelps, a simple BOD-DO balance;
2. Modified Streeter-Phelps, BOD-DO balance with BOD compartmentalized into carbonaceous and nitrogenous BOD (CBOD and NBOD);
3. Full linear DO balance, which adds the effects of photosynthesis, respiration, and more complex nitrogen kinetics;
4. Simple eutrophication kinetics, including phytoplankton kinetics and more complex nutrient interactions;
5. Intermediate eutrophication kinetics, with full nutrient cycles including nonlinear feedbacks;
6. Intermediate eutrophication kinetics with benthos, which includes the simulation of all stat variables in the benthic segments.

The DO balance in the WQMAP eutrophication model is determined by five state variables: phytoplankton carbon, ammonia, nitrate, carbonaceous biochemical oxygen demand, and DO. Sources and sinks include reaeration and phytoplankton growth (both of which are sources), phytoplankton respiration, oxidation of carbonaceous material, (including semdiment demand) and nitrification (all of which are sinks); plus transport terms.

Calibration of the DO model is described in detail in Swanson et al. (1999). The initial model process rates are based on values obtained from the literature and then adjusted once the hydrodynamic model has been fully calibrated. Calibration of the DO model is based on how well the model reproduces (a) BOD and nitrification process distributions and (2) constituents affected by other processes. The DO balance is calibrated after the BOD, nitrification, and photosynthesis sub-models are calibrated. In addition, quantitative evaluations of DO model-data comparisons (based on the error statistics similar to those used in the hydrodynamic model described above) are compared to EPA-recommended levels.

Preliminary ASA-model simulations of dissolved oxygen (DO) in Mt. Hope Bay are summarized in Isaji and Rines (1998). According to Swanson et al. (1998), initial model runs "successfully" simulated mean DO conditions for summer 1996 but did not achieve the dynamic range of DO seen in the field data. Hence the WASP5 model was replaced by a much simpler box model which employed the same set of governing equations but could not resolve spatial distributions of WASP5. The replacement model included reaeration, BOD oxidation, nitrification, sediment oxygen demand, phytoplankton growth and respiration (a single daily net value), horizontal exchange, and vertical exchange. Three stations were chosen to evaluate how DO can be expected to vary with temperature. Rather than attempting to simulate time series of DO at the specified stations, the runs focused on determining how each term in the DO balance effects the variability observed at each station. In this way, the relative importance of temperature at each station could be compared to that of the other variables, and the impact of different levels of thermal discharge could be determined.

Eutrophication Modeling of Mt. Hope Bay

The purpose of eutrophication or water quality modeling is to provide a tool for evaluating the linkages to watershed nutrient loading. A properly parameterized and validated eutrophication model can be used to identify: (1) the nutrient sources controlling water quality, both within and external to the Bay; (2) the critical factors and physical conditions which control bottom water oxygen levels; (3) the relationship of oxygen conditions to organic matter production within the Bay versus that entering the Bay from the watershed or via adjacent marine waters; (4) areas where additional field data collection is needed; and (5) the potential for improvements in the health of Mt. Hope Bay through reduction of nitrogen sources or other key parameters.

Typical eutrophication models consist of eight water quality variables: (1) ammonia (NH_3); (2) nitrate and nitrite (NO_2 and NO_3); (3) inorganic phosphorus (OPO_4); (4) organic nitrogen (ON); (5) organic phosphorus (OP); (6) phytoplankton (PHYT); (7) carbonaceous biochemical oxygen demand (CBOD); and (8) dissolved oxygen (DO). In addition, a prerequisite for any water quality or eutrophication model is a good hydrodynamic model that provides information on 1) river discharges (spring and early summer), 2) water exchange between the bay and surrounding area, 3) seasonal development of stratification and sediment resuspension and 4) tidal- and wind-induced mixing. Benthic and sediment resuspension processes may also be incorporated into water quality models via a benthic layer and/or a sediment pool on the bed of the estuary. Such biological/chemical models are useful for simulating basic transformation processes including photosynthesis, respiration, nitrification, denitrification, sediment suspension, and nutrient release to overlying waters from bottom sediments. As a result, water quality models are useful for understanding the critical parameters controlling eutrophication within a specific embayment and for evaluating options for system management. In addition, eutrophication models can be linked to fish population dynamics through a zooplankton component, which may have application to the Mt. Hope Bay Natural Laboratory Program. The most practical approach for configuring an eutrophication model in a new bay system is to begin with the simplest possible dynamics in the model, and then proceed to incrementally increasing levels of complexity by stages.

To date, eutrophication modeling within Mt. Hope Bay has focused upon simulating dissolved oxygen conditions. Preliminary simulations of dissolved oxygen (DO) in Mt. Hope Bay have been performed by ASA using the EPA WASP5 model (Isaji and Rines 1998; see also Ambrose et al. 1992). However, as reported by Swanson et al. (1998), while initial runs showed that the model was able to simulate mean DO conditions for summer 1996, it could not achieve the dynamic range of DO seen the field data. It was thus proposed by ASA that the model be replaced by a much simpler box model which uses the same set of governing equations as WASP5, but which does not contain any information on spatial distributions. The proposed model included reaeration, BOD oxidation, nitrification, sediment oxygen demand, phytoplankton growth and respiration (a single daily net value), horizontal exchange, and vertical exchange. Three stations were chosen to evaluate how DO can be expected to vary with temperature. Rather than attempting to simulate time series of DO at the specified stations, the runs focused on determining how each term in the DO balance effects the variability observed at each station. In this way, the relative importance of temperature at each station could be compared to that of the other variables, and the impact of different levels of thermal discharge could be determined. Reports describing the results from the above box model simulations have not yet been obtained by SMAST and have not yet been reviewed at this time.

To adequately understand the role of various inputs of nutrients and freshwater to Mt. Hope Bay relative to habitat health and stress to animal communities, eutrophication modeling needs to be undertaken. In its simplest form, the model needs to integrate watershed inputs with respiration and regeneration within the Bay, inputs from greater Narragansett Bay, and distribution of water quality as determined by hydrodynamics. After this is accomplished, the addition of primary production, dissolved oxygen or animal (fish) components will be addressed.

Fish Modeling

As discussed in Chapters 4 and 5, dissolved oxygen concentration and benthic prey abundance and type play an important role in determining distributions of key fish species in Mt. Hope Bay, including winter flounder. Furthermore, in a January 1999 workshop held at the URI Coastal Institute to discuss factors that may have affected winter flounder in Narragansett Bay, it was concluded that stressors for that species also include natural variability, pollution, habitat change, power plant effects, predators, regime shifts in community structure, and fishing mortality (Collie and DeLong 2001). Table 6.2 provides a list of detailed factors and the life stages that are believed to be affected.

Table 6.2. Factors potentially affecting the survival of winter flounder in Narragansett Bay (from Collie and DeLong 2001).

Stressors	Spawning	Egg	Larvae	0-Group	Juveniles	Adults
Natural Variability						
Temperature	x	x	x	X	x	
Precipitation/runoff				X		
Pollution						
Organics	x	?		X		
Metals	?	?		X		
Sewage	?	?	?	X		
Chlorine			?	X	?	
Habitat Loss	?	?		X	?	
Power Plant						
Entrainment			x			
Heating	x	x	x	X	x	x
Predators	x	x	x	X	x	x
Regime Shift in Community Structure						x
Fishery					x	x

Notes: x: Scientific evidence to support

Although discussions during the aforementioned workshop focused on winter flounder, it is not unreasonable to assume that similar factors affect other species as well, although the exact details may differ. Indeed, the simplest explanation for the decline in fish populations in Mt. Hope Bay is that the large change in coolant flow at BPPS has modified environmental conditions in MHB to the detriment of the fish populations living there (Coutant et al. 1998). Fluctuations in Narragansett Bay winter flounder abundances have been linked to fluctuations in winter water temperatures; the available data suggest a temperature- and/or oxygen-mediated effect, although causality cannot be demonstrated based on available monitoring data (Coutant et al. 1998). In addition, as discussed in Chapter 4 and 5, increases in winter zooplankton abundance and feeding activity, and corresponding declines in winter-spring chlorophyll concentration in lower Narragansett Bay, occur partially in response to warming (winter) water temperatures. However, as also discussed in Chapter 5, the variations (on the order of ± 2-3 ^{o}C) are well within the physiological thermal tolerance of winter flounder, suggesting secondary rather than direct temperature effects.

Other correlations between the decline of fish stocks and habitat changes in Mt. Hope Bay are also evident. For example, it is known that winter founder prefer relatively open sand/silt barren bottom, as well as such areas that are adjacent to eelgrass beds. Furthermore, as discussed in Chapter 5, there has been a recorded decline in the extent of coverage of eelgrass beds in Narragansett Bay. Again, causality cannot be demonstrated. However, the coincidence of these trends suggests that the decline of eelgrass beds (which may be due directly or indirectly to the thermal effects of BBPS discharge, or to changes in stratification, circulation, or nutrient and/or DO levels) may be contributing to the decline in the populations of winter flounder and other fish species in the bay.

To date, there have been two attempts to assess the effects of BPPS on fish populations in Mt. Hope Bay. The first, by Collie and DeLong (2001), used empirically based correlation models to determine whether timing and/or magnitude of winter flounder migrations have changed due to BPPS, to look for time trends and density-dependence in mortality rates, and to look for changes in spatial distributions of winter flounder within the Bay. The latter was used to infer changes in habitat suitability, under the assumption that mobile organisms will distribute themselves in accordance with the relative suitabilities of the regions in which they reside. This study confirmed that catches of larger female winter flounder in Narragansett Bay have declined more than they have in areas immediately outside the bay, and that one of the key factors in this decline may be higher mortality rates prior to recruitment (age-1 fall to age-2 spring). Furthermore, spatial analysis suggested that changes in habitat quality within Narragansett Bay may have affected the population.

The second attempt to assess the effects of fisheries, power plant operations, and water quality on fish populations was proposed by Lawler, Matusky & Skelly Engineers, LLP (see Swanson et al. 1998). This study used the RAMAS GIS/Metapop model developed by Applied Mathematics to predict the effects of changes in fishing pressure and BPPS plant operations on selected fish populations within Mt. Hope Bay. To date, the model has been calibrated using available historical data on catch-per-unit-effort (CPUE) of winter flounder in Mt. Hope Bay. Once calibrated, the model was used to forecast changes in stock abundances that are likely over the next 30 years to result from different management, fishing mortality, and power plant operation scenarios.

In the context of Mt. Hope Bay fish populations, the RAMAS GIS/Metapop model was run as a single-box model in order to simulate trends in selected fish species within the Bay. For input, the model utilizes demographic data such as recruitment, growth rates, fecundity, and natural mortality, as well as anthropogenic influences such as fishing mortality and power plant entrainment and impingement loss. The model integrates these competing factors according to their respective rates until the overall biotic potential of the species in question is balanced by the carrying capacity of the system. The carrying capacity in turn is set by environmental as well as biological factors such as maximum critical temperatures, avoidance temperatures, minimum DO levels, and density dependent mortality. For Mt. Hope Bay, species such as winter flounder are modeled as an isolated population (i.e., metapopulation), possibly linked to a second meta-population representing those fish that migrate in and out of the bay and are hence subject to additional fishing pressures outside the bay.

Historical simulations using the RAMAS model indicated that trends in population abundance of winter flounder during the period 1958-1999 were very similar, regardless of whether the model was run with the plant operating or not. This suggests that the plant's intake and discharge have had negligible effects on winter founder population trends over the past 40 years. Simulations projecting population levels of the same species, but for the next 30 years, further suggest that proposed targeted fishing restrictions will lead to population recovery approaching historical levels (i.e., pre-BPPS) over approximately the next 10 years. The model predicts that this recovery level would be diminished by 13.9 % in the case where BPPS continues to operate under the MOA II conditions, compared to levels that would obtain if the plant were absent. Similarly, the recovery is predicted to be reduced by 10.4% under the new enhanced multi-mode operation scenario proposed by BPPS.

In addition to the above modeling studies, as discussed in Chapter 5, there are also exist a number of data sources that have hitherto been underutilized. There are approximately 30 years (1971 to present) of monthly to twice-monthly trawl data from various locations in Mt. Hope Bay that provide information on fish abundance and community composition. However, these do not appear to have been thoroughly analyzed in terms of comprehensive examinations of long-term trends in fish abundance and community structure. Dissolved oxygen data are also available from both the MRI data and the DEM juvenile beach seine survey; these would be very useful in calibrating and evaluating future DO modeling studies. Additional data sources, such as the database of chlorine discharges from wastewater treatment plants compiled by Collie and DeLong (2001), could also provide valuable input to the models.

Numerous other data sets also exist for nearby regions, including lower Narragansett Bay; unfortunately, available empirical information from other study areas cannot always be extrapolated directly to Mt. Hope Bay, and hence expected effects must be inferred. In particular, there is little information in the literature on chronic effects, although available data suggests that significant effects ranging from growth, reproduction, and various behavioral responses can result from temperatures that are sub-lethal (Coutant et al. 1998).

4. Summary of Modeling and Future Directions for the Mt. Hope Bay Natural Laboratory

Given the mixed successes of previous numerical modeling efforts in Mt. Hope Bay, the following questions need to be considered and addressed:

- What level of simulation do we attempt to pursue?
- What kinds of data are currently available for simulation and/or data simulation?
- What kinds of new data are expected from the future field measurements?

With these questions in mind, the following models appear to be viable candidates for Mt. Hope Bay Natural Laboratory modeling studies at SMAST:

1) ASA non-orthogonal coordinate model;
2) Finite-Volume Coastal Ocean Model (FVCOM–Dr. C. Chen, SMAST);
3) RMA11 (3-d finite element water quality model–Resource Management Associates and the Army Corps of Engineers);

4) ECOM-si (updated Princeton model);
5) POM (old version of the Princeton model);
6) Dartmouth Element Model.

Each of these models has strengths and weaknesses that will need to be considered during the next phase of the project. The question of how extensive a biological model should be incorporated as part of the Mt. Hope Bay Natural Laboratory depends on the ultimate goal of the modeling efforts. If the goal is to understand fish decline over the last decade, a water quality model is likely a better choice than a general ecosystem model (such as the PZND model). In either case, however, a good hydrodynamic model is a prerequisite in order to provide information on 1) river discharges (spring and early summer), 2) water exchange between the bay and surrounding area, 3) seasonal development of stratification and sediment resuspension and 4) tidal- and wind-induced mixing.