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Modeling the Hydraulic Zone of Influence of Connecticut Yankee Nuclear Power Plant's Cooling Water Intake Structure

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Abstract.—Ecological studies performed in the late 1960s and throughout the 1970s sought to identify the impact of the Connecticut Yankee nuclear power plant (CY) located on the banks of the Connecticut River. These original studies relied on intensive biological sampling, hydrography, and inference based on observations. Numerical modeling was, at that time, in its infancy, and comprehensive dynamic simulations of river, lake, and estuarine systems required computer resources beyond the reach of most individuals and institutions. Today, detailed hydraulic analyses over large scales are practical, and unified approaches can now be used to study complex flow problems involving different near-field and far-field dynamics. For example, where scale models would have been used to study the dispersion of effluents from a heated water discharge in the past, today, this kind of analysis can be done on the computer using computational fluid dynamics (CFD) techniques. This paper demonstrates how the hydraulic zone of influence (HZI) of the CY cooling water intake structure (CWIS) can be determined from the results of CFD investigation. The analysis procedures are general and can be used for HZI or intake area of influence determination on other water body types (e.g., lakes, rivers, salt wedge estuaries, and open coastal locations).

Introduction

Ecological studies performed in the late 1960s and throughout the 1970s sought to identify the impact of the Connecticut Yankee nuclear power plant (CY) located on the banks of the Connecticut River (Merriman 1970; Merriman and Thorpe 2004 [1976], this volume). These original studies relied on intensive biological sampling, hydrography, and inference based on observations. Numerical modeling was, at that time, in its infancy, and comprehensive dynamic simulations of river, lake, and estuarine systems required computer resources beyond the reach of most individuals and institutions.

Recent developments in computer technology are providing new ways to integrate different kinds of data and to promote informed decision making (e.g., this is the emphasis of *Hydroinformatics*—an expression coined in the 1980s by Michael Abbott, former director of the Danish Hydraulic Institute). As a result, initiatives like the EPA's Total Daily Maximum Load (TMDL) Program are being devised and a new generation of analysis tools are being implemented (e.g., Chen et al. 2004, this volume). Hydraulic modeling has developed similarly since the original Connecticut Yankee Ecological Study was performed.

Today, detailed hydraulic analyses over large scales are practical, and unified approaches can now be used to study complex flow problems involving different near-field and far-field dynamics. For example, where scale models would have been used to study the dispersion of effluents from a heated water discharge in the past, today, this kind of analysis can be done on the computer using computational fluid dynamics (CFD) techniques.

Emerging hydraulic modeling techniques,

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like CFD, coupled with biological and hydrologic information, can be used to estimate the entrainment of organisms passing by cooling water intake structure (CWIS) from far-field locations (i.e., to determine the hydraulic zone of influence [HZI] or "area of influence" of a CWIS). State-of-the-art techniques such as those described herein will contribute to future ecological studies by reducing costs (e.g., to optimally design field programs that minimize data collection and clarify data needs), improving the interpretation of data, and promoting insight (e.g., what-if scenarios can be used to establish cause and effect relationships).

The analysis presented in this paper demonstrates the use of *FLOW-3D* (Flow Science 2003) to determine the HZI of the CY CWIS. The simulation was conducted as a case study for an EPRI sponsored project designed to demonstrate the use of commercially available CFD programs applied to the problem of HZI determination (EPRI 2004). In this analysis, *FLOW-3D* was used to estimate the entrainment of passive organisms originating at locations upstream of the CY CWIS. As part of the EPRI study, the HZI was determined for power plant CWIS located at five other water body type locations (i.e., main-stem reservoir, tidal estuary, river, coastal ocean station, and Great Lake station) in addition to CY. Results from additional EPRI case studies (discussed later) illustrate other ways in which the HZI for CWIS can be visualized.

Study Area

The Connecticut Yankee nuclear power plant is located on the eastern bank of the Connecticut River at river kilometer 25.7. The study area (and domain of the numerical model) extends about 1.6 km upstream from the CWIS and about 5.0 km downstream from the CWIS. These are the approximate limits of the thermal plume produced by the power plant (Merriman 1970; Merriman and Thorpe 2004 [1976]). The flow in this portion of the river is affected by the tide; however, saline water from Long Island Sound do not intrude into the study area.

The Connecticut Yankee nuclear power plant withdraws approximately 25.5 m^3/s of water from the river and raises its temperature to a maximum of 12.5°C above ambient before returning it to the river. This diversion amounts to as much as 6% of the river flow during low-flow conditions (Massengill 2004 [1976], this volume).

Cooling water is withdrawn from a shoreline location through a single structure containing four inlet bays (Jacobson et al. 2004, this volume). While not demonstrated in this study, CFD models that include intake details such as the bar grids and fish screens, and extend into the far field can be developed through the use of grid nesting techniques, multiblock gridding procedures, or unstructured grids.

Heated water is discharged from the power plant into a channel that carries the effluent back to the river. The passage of water through the plant and down the discharge canal is described by Merriman and Thorpe (2004 [1976]), Merriman (1970), and Jacobson et al. (2004).

Flow in the Connecticut River changes direction at the location of the CY CWIS during periods of low discharge. For this reason, low river flow conditions were chosen for this study to demonstrate the ability of a fully three-dimensional CFD model to simulate tidally influenced river flows affected by the discharge of heated water from a power plant. Table 1 identifies the simulation conditions considered in the analysis.

Methods

Computational Model

All of the simulation results presented in this paper were developed within the framework of the *FLOW-3D* computer software system (Flow Science 2003; version 8.1.1). *FLOW-3D* is a CFD software package developed by Flow Science, Inc. located in Santa Fe, New Mexico. *FLOW-3D* has been commercially available for about 20 years. Originally used to investigate fuel sloshing by the aerospace industry, today the program is used extensively by engineers and scientists engaged in the study of free-surface flows. In fact, *FLOW-3D* is the only commercially available CFD

Table 1. Simulation conditions.

Parameter	Value
Mean river flow rate	425 m^3/s
Water temperature	30°C
Tidal range	1.5 m
Intake/discharge flow rate	25.5 m^3/s
Discharge water temperature	41°C

program that fully implements Hirt and Nichols' (1981) volume-of-fluid (VOF) method for the computation of free-surface flows.

The roots of *FLOW-3D* may be traced back to original developments at the Los Alamos National Laboratory (LANL) beginning in the early 1960s. Many basic numerical techniques originated there for the solution of compressible and incompressible flow problems. Of particular interest are techniques for describing the behavior of free surface flows, a technique for solving both compressible and incompressible flow problems with a single solution method and with new types of grid and geometry models. Variations of these basic algorithms are, today, resident in the *FLOW-3D* software system.

At the time the original CY ecological study was performed, numerical simulations of the kind discussed in this research could not be carried out due to limitations in computing speed and data storage. Today, the typical personal computer (PC) provides enough resources to solve all but the most demanding problems.

Numerical Approximations

Numerical analysis of the kind used in this study involves the solution of governing equations for fluid motion, mass/volume conservation, turbulence (production, advection, and dissipation), energy conservation, and thermal buoyancy. In this study, the Reynolds-averaged Navier-Stokes equations were used as the governing equations for fluid motion. Therefore, the computed results provide estimates of fluid velocities in three-dimensions. Connecticut River water was also assumed to be incompressible (a standard assumption).

The Renormalized-Group (RNG) method was used for turbulence closure (Yakhot and Orszag 1986; Yakhot and Smith 1992). This approach applies statistical methods for a derivation of the averaged equations for turbulence quantities, such as turbulent kinetic energy and its dissipation rate. RNG-based models have wider applicability than the standard two equation k - e model. In particular, the RNG model is known to describe more accurately low intensity turbulence flows and flows having strong shear regions.

An equation for energy conservation was used to account for the transfer of heat from the discharge water to the receiving water, and the influence of buoyant forces associated with density variations in the flow were approximated with a linearized model for buoyant flow (i.e., one that neglects the thermal expansion of the water). All of these features are part of the commercial *FLOW-3D* program.

Analysis

The procedure used to set up the numerical model and to calculate tidally influenced flows in the Connecticut River consists of four basic operations: (1) model setup, (2) definition of boundary conditions, (3) flow simulation, and (4) visualization and analysis. The data required for the analysis is typically available and of no more detail than the data required to carry out more simplified studies (except for the fact that more topographic/bathymetric information will be used, if available).

In this study, topographic/bathymetric data describing the Connecticut River in the vicinity of the CY CWIS were taken from USGS topographic maps, NOAA navigational charts, and detailed bathymetric data provided by Dominion Nuclear Connecticut (DNC). This digital information was imported directly into the CFD program, which transformed the data into a three-dimensional surface model (Figure 1). In the final preprocessing operation a structured, rectangular, grid was superimposed over the surface model and intersections between the grid and the surface model were calculated. A FAVOR method was then used to assign blockages to cells occupied in full or in part by "solid ground" (Hirt and Sicilian 1985). The completed mesh consisted of about 260,000 control volumes with horizontal dimensions of 30 m and vertical dimensions of 0.6 m (in the main body of the river).

Conditions on the flow entering and leaving the model domain (i.e., the computational mesh) were assigned at open boundary locations. These included the up and downstream limits of the modeled region, the location of the CWIS, and the location of the heated water discharge. Table 2 provides a list of conditions specified at each open boundary.

Parameter values, required for the specification of boundary conditions, are normally provided by plant operating records (CWIS and discharge flow rates and temperature), in situ flow measurements (e.g., USGS gauging station data), or the results of other larger scale flow calcula-

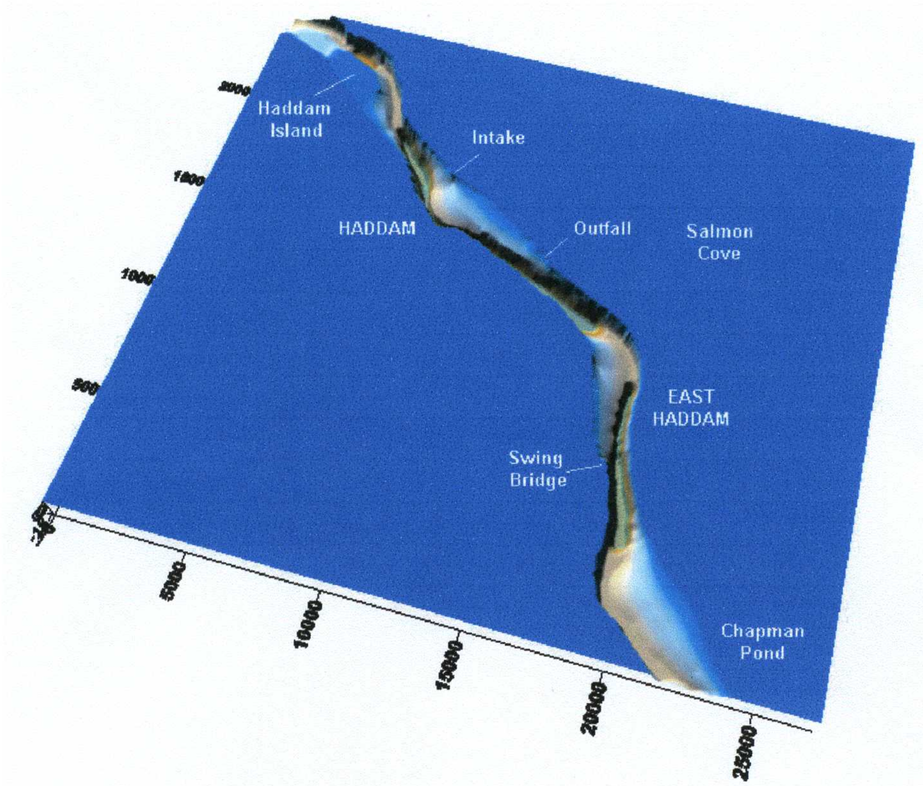


Figure 1. Digital terrain model (grid not shown for clarity).

tion (e.g., more detailed simulation grids can be nested within larger more coarsely defined two- or three-dimensional grids—this is referred to as grid nesting). In this study, conditions at the upstream and downstream river cross sections were derived from the results of two-dimensional tidal flow simulations. That is, time-series of water surface elevations and velocities at locations corresponding to the upstream and downstream river cross-sections were determined from the results of the two-dimensional flow calculations and used to "force" the flow through the three-dimensional model.

With the computational mesh constructed and

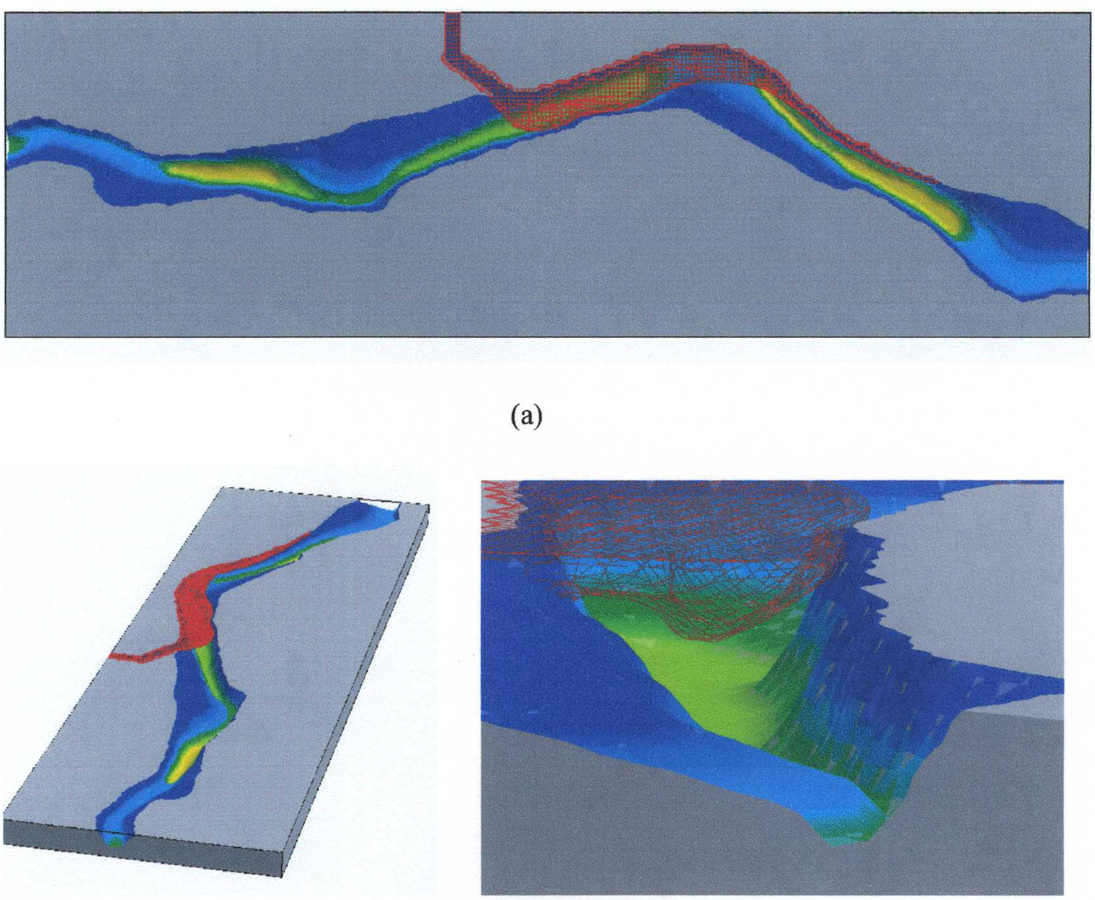
Table 2. Boundary conditions.

Upstream/downstream river cross sections	• Velocity • Water surface elevation • Water temperature
CWIS	• Flow rate (sink)
Discharge canal	• Flow rate (source • Water temperature

boundary conditions defined, numerical simulations of river flows and the movement of passive organisms through the modeled region were performed. In this study, three-dimensional velocities in a 6.5-km reach that surrounds CY were calculated over a period of seven successive tidal cycles (about 3.5 d). To determine the HZI of the CY CWIS, scalar quantities, representing concentrations of passive organisms, were released into the flow from different locations upstream of the power plant. An advection/dispersion algorithm was used to calculate the movement of the "numerical surrogates" past the CWIS towards the open ocean. The concentration of organisms in the intake flow was monitored during the simulations. At the conclusion of the simulations, the percentage of organisms entrained by the CWIS could be calculated since the total organism population at the beginning of the simulations was known. In some respects, this type of analysis is similar to that used to determine the movement and extent of thermal plumes, only in reverse. That is, scalar quantities are released from remote locations far from the CWIS and the amount of material entering the CWIS is calculated. This is in contrast to a thermal plume analysis, where a scalar quantity (heated water) is released from a single discharge point and the evolution of the thermal plume in surrounding waters is estimated.

The results of the studies were postprocessed after the computer calculations were complete and used to promote subsequent analyses. One of CFD's greatest strengths relates to its ability to provide detailed datasets that can later be "visualized." Figure 2 shows a view of the Connecticut River from above. In this figure, the bathymetry of the river is colored by elevation, and red "wire-meshing" is used to delineate the extent of the thermal plume defined as a surface of constant temperature (both, the temperature used to define the plume and the color scheme used to color bed were arbitrarily chosen). Visual renderings, such as the ones shown in Figure 2, can be used to explain complex flow phenomena and to aid in the interpretation of field data. Standard plot types include vector diagrams, streamline plots, and contour plots colored by scalar quantities such as speed, temperature, and concentration.

The quantitative data produced by the simulations was used to determine where the source water that enters the CWIS comes from and to determine the likelihood of entrainment of passive organisms coming from remote locations. Additional what-if scenarios could also be performed



(a)

(b) (c)

Figure 2. Thermal plume, low tide slack water: (a) plan-view, (b) oblique-view, and (c) close-up showing area of cold water beneath the thermal plume (river bottom colored by depth, thermal plume is red)

to determine how entrainment responds to changes in CWIS location and design.

Results

Hydraulics

To demonstrate the ability of a commercial CFD program to simulate time-varying flows in the Connecticut River, a low-flow condition was chosen to accentuate the effect of the tide on local flow conditions (see Table 1). At this location, the effects of the thermal plume must be accounted for, since the presence of the thermal plume affects flow patterns in the vicinity of the CY CWIS during flood tides for this low-flow condition. Figure 3 shows the extent of the thermal plume at low slack water.

The size, shape, and location of the thermal plume compares closely with infrared photographs provided by Merriman (1970). The results of CFD analyses can also be compared to other more detailed information. For example, velocity distributions measured with the latest generation of acoustic Doppler current profilers (ADCP) data can be used to develop boundary conditions for CFD analyses.

The results of CFD analyses can be shown in a form similar to that used to present data collected with modern field equipment. Figure 4 shows calculated time histories of organism concentration, water temperature, and local velocities near the CWIS. These time series are similar to those that can be produced by measurements made with velocimeters, thermometers, and fluorometers. It is relatively easy to compare the results of CFD analysis with field data since many measured quantities and computed explicitly in the numerical simulations.

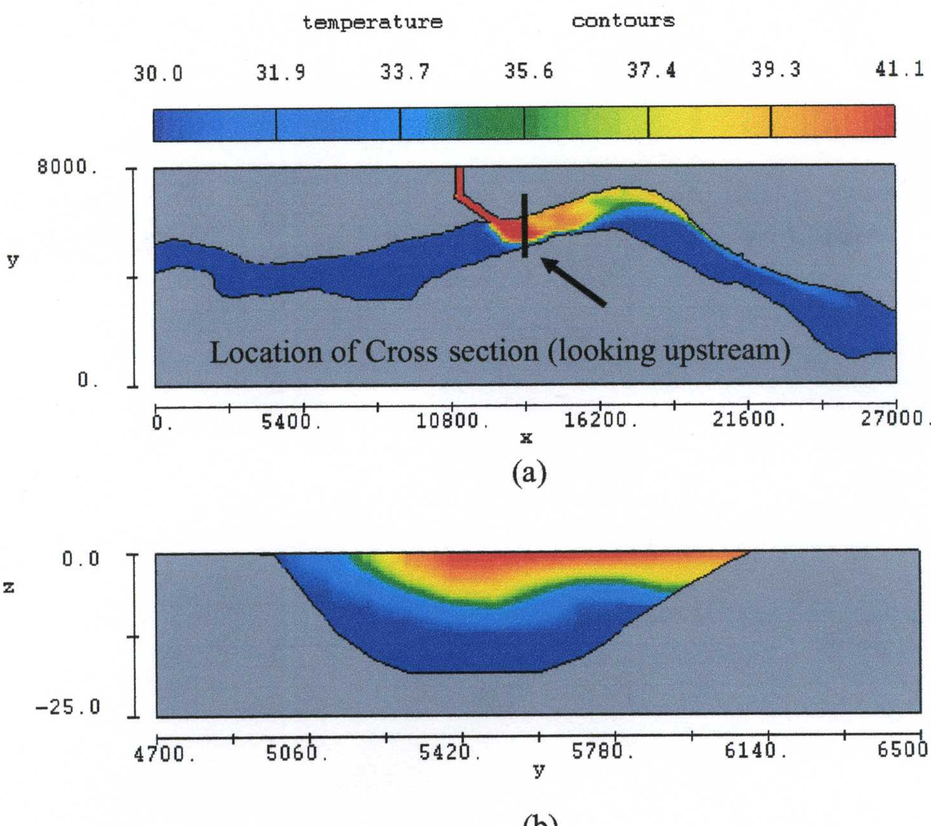


Figure 3. Temperature distribution at low slack water: (a) plan-view, (b) cross-sectional view (looking upstream; colored by temperature—degrees Celsius, length units—feet)

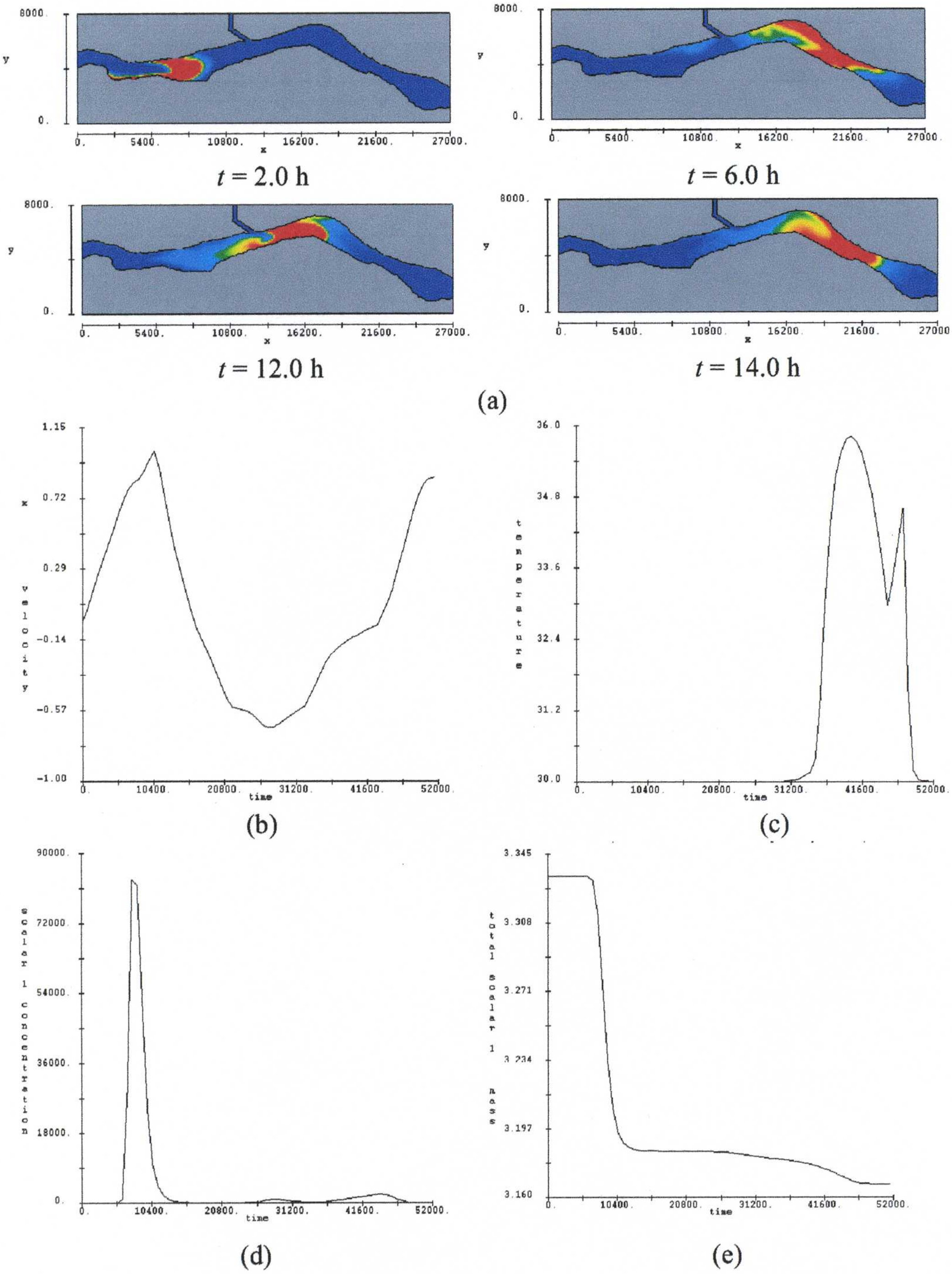


Figure 4. Computed movement of organisms past CY – CWIS: (a) concentration of organisms, (b) velocity in direction of flow near intake, t = s, (c) water temperature near intake, degrees Celsius, (d) concentration of organisms near intake, and (e) total mass of organisms in computed region (units of concentration and total mass are arbitrary).

Hydraulic Zone of Influence

The HZI of a CWIS is defined as the region in a water body where the probability of entrainment (i.e., passage of a passive or somewhat passive particle, such as fish eggs and larvae, into and through the power plant cooling water condenser system) is high. For a condition where the flow does not change with time, the HZI is defined by the area from which the CWIS withdraws water directly. For example, if a CWIS is located on a river where the flow is steady, then the HZI can be shown by identifying streamlines of flow that enter the CWIS. Figure 5 shows the HZI for the Tennessee Valley Authority Browns Ferry Nuclear Power Plant Case Study delineated for a steady-flow condition (EPRI 2004). In this figure, streamlines that enter the CWIS are colored red and the volume of water occupied by the streamlines is, in fact, the HZI of the CWIS for this flow condition.

When a CWIS is located on a water body where the direction of flow changes with time, the HZI of the CWIS can no longer be visualized with streamlines. Entrainment percentages for the Dominion Millstone nuclear power plant (Waterford, Connecticut on Long Island Sound) are shown in Figure 6 (EPRI 2004). To identify the HZI of the CWIS at this coastal location, known concentrations of scalar quantities (tracer material) were released into the flow at 25 different locations. The amount of tracer material that entered the CWIS (located on the eastern shore of Niantic Bay near Millstone Point) was calculated for each release. The entrainment percentage was then expressed as a ratio between the amount of material that entered the intakes and the total amount of material released at each location. The results in Figure 6 show that majority of flow entering the CWIS at Millstone originates in Niantic Bay rather than Long Island Sound.

Since the direction of flow in the river changes twice a day, for the modeled conditions, the HZI for Connecticut Yankee's CWIS could

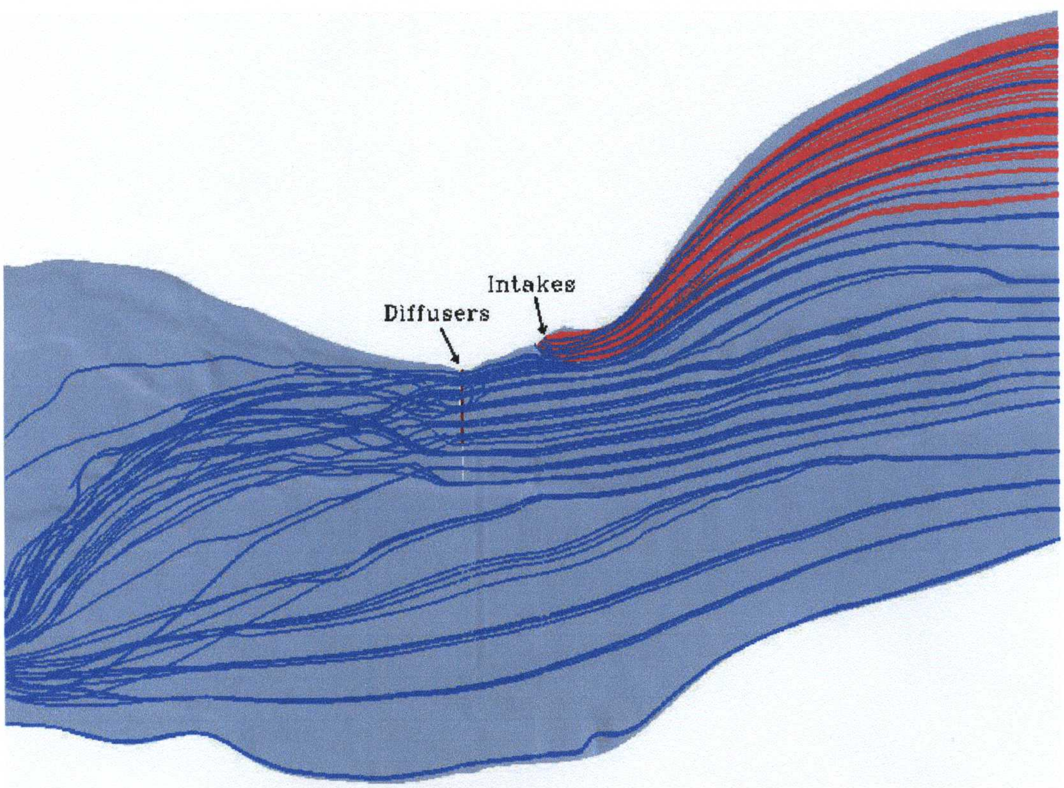


Figure 5. Hydraulic zone of influence, Tennessee Valley Authority Browns Ferry nuclear power plant on Lake Wheeler, an impounded portion of the Tennessee River (EPRI 2004)

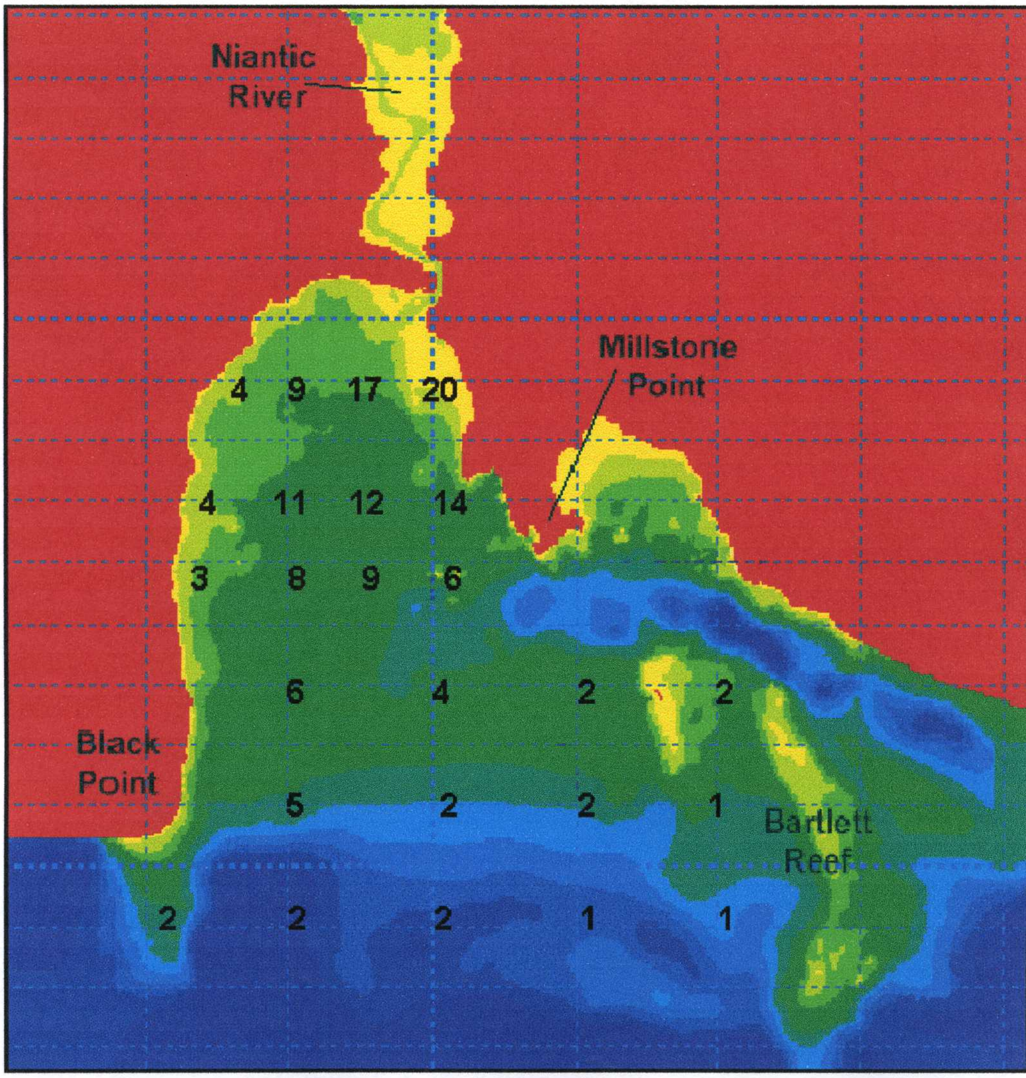


Figure 6. Hydraulic zone of influence, Dominion Millstone nuclear power plant, Waterford, Connecticut on Niantic Bay and Long Island Sound (entrainment percentage calculated 6d after release) (EPRI 2004).

not be effectively visualized with streamlines. For this reason, the HZI for Connecticut Yankee is better illustrated as a mapping of entrainment percentages similar to the one developed for Millstone.

Figure 7 shows the HZI of the CY CWIS. To identify the HZI at these two river cross sections, known concentrations of scalar quantities were released into the river at 19 different locations. The amount of "material" that entered the plant intakes from each location was calculated. Entrainment percentages were then expressed as the ratio between the amount of material that entered the intakes and the total amount of material released at each location.

At the cross section closest to the CWIS, the results in Figure 7 show that more water is withdrawn from the same side of the river as the intakes are located. Somewhat more water is also withdrawn from locations near the surface of the river. At the upstream cross section, the difference between the amount of water withdrawn from the surface and the amount of water withdrawn from the bottom is less (i.e., the results show vertical

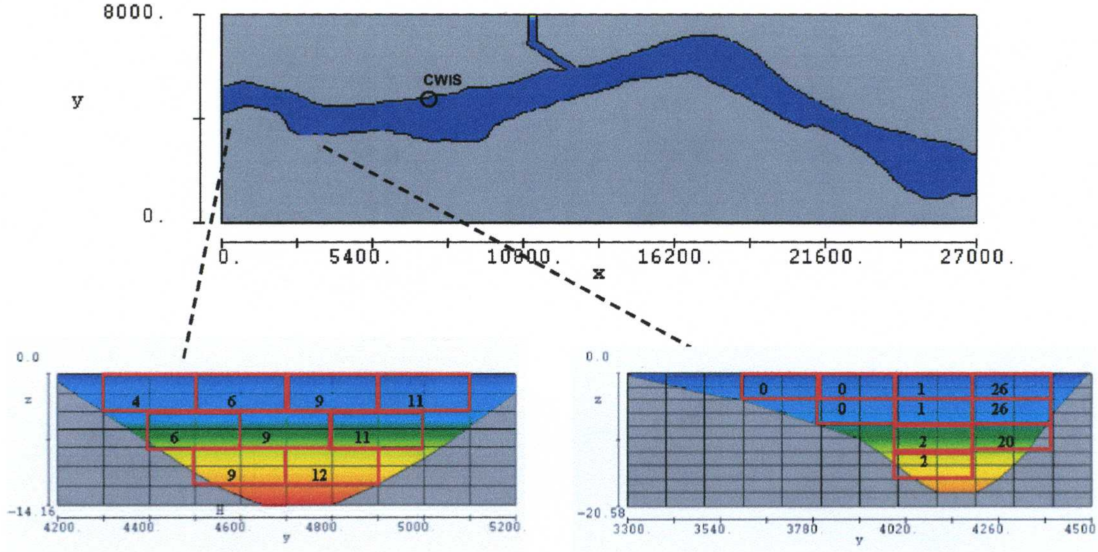


Figure 7. Hydraulic zone of influence, Connecticut Yankee nuclear power plant (entrainment percentage).

mixing). However, a difference in results across the channel still exists. If one were to produce similar results from far enough upstream, then even this lateral difference would disappear (i.e., at this new location the distance between the release point an the intakes would be great enough to mix the flow completely.

The techniques used to show the HZI of a CWIS can also be used to draw certain conclusions about the entrainment of organisms. For example, if a population of organisms was uniformly distributed in a body of water (and if they were neutrally buoyant and passive), then the entrainment of those organisms would be the same as the percentage of water removed by the CWIS. However, if a population of organisms was not uniformly distributed, then the entrainment of those organisms could be significantly different from the percentage of water removed by the CWIS. In the case of Connecticut Yankee, if a population of organisms spawned from a river location opposite the CWIS location and not far upstream of the plant, minimal numbers of these organisms would be entrained by the plant intakes (whereas, one might be inclined to be more concerned about the proximity of the spawning ground to the CWIS without the benefits of this type of study). It should also be noted that the results of this study compare well with Marcy (2004 [1976], this volume) and Massengill's (2004 [1976]) ecological sampling and entrainment studies conducted on the Connecticut River. Their results suggest that greater quantities of water are withdrawn from the side of the river where the CWIS is located—just as the numerical solutions do.

Discussion

Owing to continued advances in computer technology, detailed three-dimensional simulations of complex environmental flows can now be performed with desktop computing systems. The results of these analyses provide insights regarding the cause-and-effect relationships that govern the movement of water through natural systems and into CWIS. The programs that enable this type of study have a strong theoretical basis and many were, in fact, under development at the time of the original Connecticut River Ecological Study. Thirty years later, these programs are referred to commercially as CFD software packages.

CFD software packages are designed to be "general purpose" flow solvers and can be applied to the study of a great many different kinds of fluid dynamics problems. As applied to once-through cooling systems, a single CFD analysis can be used to determine the HZI of a CWIS and to study the behavior of discharge structures (i.e., thermal plume analysis) for power plants located on any type of water body.

If the Connecticut Yankee nuclear power plant were designed and sited today, CFD tools could be used to

a. *Perform what-if scenarios:* to site the intake and discharge structures and to assess differences in the performance and potential impact of different designs,
b. *Optimize field data collection programs:* to target important areas for baseline sampling within the HZI,
c. *Improve the interpretation of field-data:* CFD analysis can provide discrete time series information similar to field data and continuous time series information for the entire computed region,
d. *Evaluate the potential impact of plant operations on threatened or endangered species located near an intake,*
e. *Estimate the entrainment of organisms migrating from far-field locations*, and
f. *Augment TMDL studies:* to improve the quality of information required for effective decision-making (see Chen et al. 2004, this volume).

With the HZI of a CWIS defined, the next step in the evolution of this type of analysis will be to include environmental and behavioral realism (e.g., diurnal variations in organism abundance, swimming ability, and organism behavior).

In the next 30 years, the use of CFD to aid in the assessment of environmental impact should increase dramatically due to the still rapid improvements in microchip processing speeds, the ability to use the results of CFD studies to explain complex flow problems, the results of new biological research, and the continued development of the analysis tools by dedicated developers.

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