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Validation and Application of the Second Generation Three Dimensional Hydrodynamic Model of Chesapeake Bay

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Abstract

The validation and subsequent application of the current three dimensional numerical hydrodynamic model of Chesapeake Bay is presented. The numerical model solves conservation equations for water mass, momentum, salinity, and heat on a boundary-fitted grid in the horizontal plane. The vertical grid is Cartesian. A finite-difference solution scheme is employed such that vertically-averaged equations are first solved to yield the water surface elevations. These are then utilized in the computation of the barotropic portion of the horizontal pressure gradient in the internal mode. Model validation was accomplished by demonstrating the model's ability to reproduce observed data over time scales ranging from tidal to seasonal periods. After validation, the model was applied to simulate bay hydrodynamics for the 10 years of 1985-94. These results were used to drive the three-dimensional water quality model of Chesapeake Bay, which is discussed in a companion paper.

Introduction

The Chesapeake Bay (Figure 1), located on the eastern coast of the United States, is one of the largest estuaries in the world, and historically has been one of the most productive in terms of wildlife, fin fish, and shell fish. However, as a result of the decline in many of the Chesapeake Bay's resources due to the introduction of excess nutrients, the Chesapeake Bay Program (CBP), a partnership that includes the states of Maryland, Virginia, Pennsylvania, the District of Columbia, the Chesapeake Bay Commission, and the U.S. Environmental Protection Agency (EPA), was created in 1983 to restore the bay. An integral part of the CBP's strategy was the development of numerical models to predict the impact of various nutrient control measures before the implementation of those controls.

In the late 1980's, an agreement was reached in which the EPA and the U.S. Army Corps of Engineers jointly funded the development of fully dynamic three-dimensional (3D) hydrodynamic and water quality models of the Bay. Results from that effort are published in Johnson et al. (1991; 1993) and Cerco and Cole (1994). Although that effort was considered a great success by the bay community, it was recognized that to adequately address issues in the bay connected with the release and transport of nutrients from within the tributaries, a new study was needed in which the focus would be on the tributaries, as well as the bay proper. This effort included grid refinements, enhancement of the turbulence scheme, extending the computational domain onto the shelf, additions to the water quality model such as living resources, improvements to the hydrologic model of the bay's watershed, and the development of a numerical model of the bay's airshed to provide estimates of atmospheric nutrient loadings.

The 3D hydrodynamic model of Chesapeake Bay that provides transport to the 3D water quality model is called CH3D (Curvilinear Hydrodynamics in 3 Dimensions). Validation of the second generation model was accomplished by demonstrating the model's ability to reproduce the hydrodynamics due to processes covering a wide range of temporal scales. These include tidal time scales, meteorological time scales of 2-4 days, the neap – spring tidal cycle, and longer-term seasonal time scales.

After validation, the 3D Chesapeake Bay hydrodynamic model was applied to generate a 10-year record of transport for input to the 3D water quality model. The years simulated (1985-94) covered a wide range of environmental forcings. Hydrologically, 1985, 1988 and 1992 are considered dry years; 1986, 1987, 1990 and 1991 are considered average years; and 1989, 1993 and 1994 are considered wet years. Validation results, along with salinity and temperature results from the 10-year simulation are presented.

The Numerical Model

Theoretical Aspects: As its name implies, CH3D makes computations on a generalized curvilinear or boundary-fitted horizontal grid. However, to ensure that long-term stratification in the deep channels is maintained, the vertical grid is Cartesian. Boundary-fitted grids in the horizontal directions allow for a better representation of the bay's boundary as well as internal features such as channels and islands.

All physics impacting circulation and mixing in water bodies such as Chesapeake Bay are included. These include the impact of freshwater inflows, tides, wind forcing, the impact of the earth's rotation, surface heat exchange, and the effect of turbulence on the mean circulation. The vertical turbulence closure model computes the eddy viscosity and diffusivity from the kinetic energy and dissipation of the turbulence. This type of closure model is known as a k-e turbulence model. The production of turbulence occurs due to wind stress at the surface, velocity shear in the water column, and bottom friction. Density effects due to salinity and temperature are fully coupled with the developing flow field. Thus, advection/diffusion equations for the salinity and temperature are solved along with the conservation of mass and momentum equations for the flow field. An equation of state relates the water density to the salinity and temperature fields. Surface heat exchange is modeled through the Edinger et al. (1974) concept of an equilibrium temperature.

The numerical algorithm consists of an external and an internal mode. The two-dimensional (2D) water surface field and vertically-averaged velocities are computed in the external mode, with the water surface elevations then employed in the computation of the horizontal pressure gradient in the internal mode. Terms such as the vertically-averaged advection in the external mode are computed by summing up the 3D computations over the water column. The 3D velocities, salinity, and temperature are computed in the internal mode. The 3D velocities are adjusted to ensure that water flux over the water column is consistent between the external and internal modes. The computational scheme is such that the speed of a free-surface gravity wave is removed from the stability criteria controlling the size of the computational time step. However, other criteria remain (e.g., the advective speed of the water). Model details can be found in Sheng (1986); Johnson et al. (1991, 1993); Johnson et al. (In Preparation); and Kim and Johnson (1998).

Numerical Grid: The numerical grid for the second generation Chesapeake Bay hydrodynamic and water quality models is shown in Figure 2. As can be seen, the modeled domain includes a portion of the Atlantic Ocean out to depths of about 100 ft (30.49 m). The extension of the grid onto the continental shelf moves water quality boundary conditions away from the bay mouth and allows for a better computation of the exchange of flow between the bay and the shelf.

There are 2,129 computational cells in the horizontal plane of the numerical grid with cell lengths varying from about 1 km (in tributaries) to 5 km (in continental shelf). In the vertical direction there is a maximum of 20 layers with each layer being 5 ft (1.52 m) thick, except for the top layer, which varies with the tide. Thus, the total number of computational cells is 10,657. With the numerical algorithm employed in CH3D, a one-year simulation with a time step of 5 minutes requires about 15 hours on a Dec-Alpha 500 MHz work station.

Boundary Conditions

Many data are required to numerically simulate the 3D hydrodynamics of water bodies such as Chesapeake Bay. These include water surface elevations, salinity, and temperature on the open ocean portion of the numerical grid shown in Figure 2. The water surface elevations were computed for the period of 1985-94 from a vertically-averaged global model of the Caribbean, Gulf of Mexico, and eastern coast of the United States. This model is called ADCIRC and was developed by Westerink et al. (1992). In the ADCIRC computations, historical wind fields were applied over the modeled domain shown in Figure 3. Near-surface and near-bottom salinity and temperature data were specified on the open ocean grid at the locations shown in Figure 4. Both the near-surface and near-bottom values at locations A, C, and D are monthly climatological data taken from Lavitus (1982). The near-surface values at location B are observed data from the Field Research Facility at Duck, N.C. Near-bottom values at location B were also taken from Lavitus (1982).

During model validation it was observed that the computed and observed near-bottom salinities at the bay mouth often did not match well (Figure 5). An analysis of freshwater discharges at Trenton, N.J. on the Delaware River and observed salinity data south of the mouth of Delaware Bay revealed that the coastal salinities and the freshwater flow at Trenton correlated well with a lag of several weeks. Thus, it was decided to modify the climatological monthly salinity specified at location D (Figure 4) based on the freshwater flow released at Trenton, N.J. three months earlier. With this modification to the open-ocean salinity boundary condition, Figure 6 shows the improved calculation of the near-bottom salinity at the bay mouth over that shown in Figure 5.

In addition to the open-ocean boundary conditions, freshwater inflows at the fall line or head of tide are specified on each of the Chesapeake Bay tributaries. Approximately 50% of the total freshwater flow into Chesapeake Bay comes from the Susquehanna River. The tributary fall line flows are daily-averaged discharges published by the U.S. Geological Survey. Freshwater inflows below the fall line were taken from the CBP watershed model (Donigian et al. 1994; Linker, 1996). These were distributed over the computational cells that border land along the tributaries as well as the bay proper. Figure 7 illustrates the importance of including below-fall-line flows in the computation of salinities up the bay tributaries.

The remaining boundary condition data are the wind and surface heat exchange at the bay surface. Hourly values of wind data were taken from the Norfolk Airport (NFA), the Patuxent Naval Station (PAS), and the Baltimore-Washington International Airport (BWI) (Figure 1). Values for the components of the wind velocity specified at each grid point were determined by interpolating between the three sets of wind data. All of the wind data were collected over land; however, it is well known that values of the wind over the bay are different from data collected at land stations. Based on work by Goodrich (1985) and Sanford (1997), the north-south and east-west components of the wind at each of the three data stations were multiplied by the following factors to reflect over water winds:

Station	N-S Component	E-W Component
Norfolk	1.37	1.25
Patuxent	2.05	1.43
BWI	1.50	1.00

Daily-averaged surface heat exchange coefficients and equilibrium temperatures for input to the hydrodynamic model were computed using meteorological data collected at the Patuxent Naval Station. These values were assumed to be constant over the entire bay.
One additional note concerning model boundary conditions relates to how the Chesapeake and Delaware Canal (C&D Canal) is treated in the model. Based on information provided by Dr. William Boicourt of the University of Maryland (personal communication), a long-term average flow of 750 cfs (21.24 $m^3 s^{-1}$) was specified at the eastern end of the C&D Canal. The direction of the flow was from the Chesapeake Bay toward the Delaware Bay. Thus, the C&D Canal was treated as a river boundary with a constant outflow. In reality, time varying flows in excess of 100,000 cfs (2831.6 $m^3 s^{-1}$) can occur through the canal. Normally the flow reverses direction every 6 hours or so as the tide changes. However, during episodic events related to large set ups and set downs in the surface waters of the two bays, large flows can continue in the same direction for 2-3 days. Thus, the treatment of the C&D Canal as a river with a constant outflow in the 3D Chesapeake Bay hydrodynamic model is a simplification.

Model Validation

In the validation of the second generation 3D Chesapeake Bay hydrodynamic model it was considered crucial to demonstrate the model's ability to reproduce the hydrodynamics produced by processes occurring over a wide range of temporal scales, e.g., the tidal time scale to seasonal periods. Thus, the following model results were compared with observed data:

- Tides / water surface elevations
- Intra-tidal velocity
- Intra-tidal variation of salinity and temperature
- Wind mixing
- Neap – spring stratification
- Flux through the bay mouth
- Residual currents
- Impact of spring runoff on salinity
- Seasonally-averaged salinity transects and vertical profiles

Tides / Water Surface Elevations: Figures 8-10 show a comparison of computed times to both low and high water, along with the mean tide range, up the York River with data extracted from NOAA tide tables. As can be seen, model results compare extremely favorably with the tables. Phasing differences on the order of a few minutes and differences in the mean tide range of 5-10 cm are computed. Figure 11 shows a comparison of the computed and observed water surface elevations at Fort Eustis on the James River at a distance of 40 km above the mouth of the James (Figure 12). It can be seen that the neap–spring tidal cycle, as well as the impact of meteorological forcing that results in set ups and set downs of the water surface are reproduced well by the model.

Intra-tidal Velocity: Velocity data were collected by the Virginia Institute of Marine Sciences (VIMS) during May 27 - June 18, 1985 on the James River at Ft Eustis and during Oct. 20 – Nov. 20, 1986 at a location about 20 km above the mouth of the York River (Figure 13). Figure 14 illustrates the comparison of the computed and observed component along the estuary of the tidal velocity at Ft Eustis. A similar comparison is given in Figure 15 on the York River. The phasing of the tidal velocities is reproduced well at both locations with magnitudes generally computed to within about 10-15% of the observed values.

Intra-tidal Salinities and Temperatures: Both salinity and water temperature were measured during 1986 at the York River station shown on Figure 13. Results presented in Figure 16 show that during this period both the computed and observed salinity ranged from about 22 – 24 ppt with the normal tidal fluctuation being about 1 ppt. As can be seen in Figure 17, computed temperatures also agree with the observed data. This is to be expected if the surface heat exchange data are accurate since water temperature is primarily a function of the surface heat exchange. Note that there is much more fluctuation in the observed data than in the model results. However, the surface heat exchange data input to the model are daily-averaged values. Thus, one would expect to see more fluctuation in the observed temperature than in the computed.

Wind Mixing: Wind forcing accounts for much of the energy in Chesapeake Bay. Mixing of the surface waters into the water column occurs often and is an important process that must be captured in the hydrodynamics provided to the water quality model of Chesapeake Bay. NOAA collected data at several stations in September 1983 that captured such a mixing event. As can be seen in Figure 18, a wind event that occurred around the 20^{th} of the month resulted in the near surface and near bottom salinity at the mid-bay station CCA (see Figure 23) off from the mouth of the Patuxent River becoming almost uniform. It is likely that the temperature inversion that occurred a few days earlier aided the mixing process. Figure 19 shows results from the numerical model. It can be seen that the mixing event is captured well.

Neap – Spring Stratification: It has been observed that a neap – spring stratification pattern develops on the tributaries of Chesapeake Bay. During more energetic spring tides, greater turbulence is created, resulting in more mixing in the water column and less stratification. Figure 20 shows plots of the vertical structure of the salinity along the York River during both a neap and a spring tide. Note that during the spring tide, the water column is indeed less stratified due to increased mixing.

Flux through the Bay Mouth: No data existed on the magnitude of the water flux through the bay mouth during the simulation periods of the model; namely, September 1983 and 1985-94. However, Boicourt (1973) presents values for the net flux into and out of the bay mouth averaged over July and November 1971. A comparison of the net flux (m^3/s) in and out of the bay mouth computed for July and November 1988 with Boicourt's data is given below:

July	Flux In	Flux Out
Boicourt	6100	8400
Computed	6400	8300
Nov		
Boicourt	5800	6800
Computed	7100	7900

Obviously, since the observed data were not collected during the simulation period an exact comparison can not be made. However, since meteorological conditions are generally similar for the same month during different years, the above comparison tends to increase confidence in the ability of the Chesapeake Bay hydrodynamic model to compute the proper exchange between the bay and the ocean.

Residual Currents: Chesapeake Bay is classified as a partially-stratified estuary. Thus, if the flow velocity is averaged over a few days the surface velocity is directed toward the ocean with the bottom waters moving up estuary. This circulation pattern is referred to as gravitational circulation and occurs because of the baroclinic contribution to the horizontal pressure gradient. It is important that a hydrodynamic model being used to provide transport to a water quality model reproduce the residual circulation of an estuary since these currents reflect the net transport experienced by the water quality variables.

Figure 21 was generated by Dr. Alan Blumberg of HydroQual, Inc in Mawah, N.J. (Goodrich and Blumberg, 1991). Data on water currents collected by NOAA at several locations from 1977-83 were used to generate the near-surface and near-bottom residual velocity vectors shown. Only data records at least 15 days in length were utilized. From Figure 21, it can be seen that the maximum residual velocities are on the order of 10 cm/s for both near-surface and near-bottom flow. Figure 22 contains similar plots of the computed residual currents. Figures 21 and 22 provide a qualitative assessment of the model's ability to reproduce the residual transport in Chesapeake Bay. Actual values of residual currents in cm/s computed from the observed data were compared with model results from 1985 at several locations shown on Figure 23. These are given below:

Station	Surface		Bottom	
	Data	Model	Data	Model
Bay Mouth	-10.7	-10.1	8.2	6.1
Eastern Shore	-8.5	-7.6	5.3	4.1
Potomac Mouth	-8.5	-8.0	3.2	4.5
Patuxent Mouth	-9.2	-7.8	5.1	2.6

Although the above does not constitute a direct comparison between observed data and model results, these results imply that the 3D Chesapeake Bay hydrodynamic model does compute the proper residual transport in Chesapeake Bay. Further confirmation of this is provided in Figure

24 showing low pass model results compared with data collected by Boicourt in September 1996 at the Station CCA shown on Figure 23. It can be seen that there is excellent comparison between the data and computed results for both the near-surface and near-bottom velocities.

Impact of Spring Runoff on Salinity: As illustrated in Figure 25, during the spring of 1993, flows from the Susquehanna River reached almost 500,000 cfs. This runoff event is one of the top ten flows ever recorded on the Susquehanna River. With such a large freshwater flow event, one would expect that much of the upper Chesapeake Bay would become almost fresh. Figure 26 shows a comparison of computed and recorded salinity at a location, CB3.3C, near the Bay Bridge at Annapolis, MD. It can be seen that surface waters in the entire upper bay were indeed virtually fresh. Bottom salinities are also reproduced well except for one data point. It may be that this data point was collected in a deep hole not represented within the schematization shown in Figure 2.

Seasonal Salinity Transects and Vertical Profiles: Long-term salinity patterns in the Chesapeake Bay are determined primarily by freshwater inflows into the bay, which generally have a seasonal variation. For example, summer months tend to be dry, resulting in more salt intrusion up the bay, whereas, spring months tend to be wetter, resulting in the salt being pushed down the bay. During large spring freshwater flows, stratification of the water column is greater. Since changes in water quality tend to occur over seasonal time scales, it is important that the 3D Chesapeake Bay hydrodynamic model compute seasonally-averaged salinities well. Figures 27 and 28 are near-surface and near-bottom transects of salinity along the deep channel in the bay averaged over the spring and summer seasons for 1985-88. Note that although the absolute values of the computed salinities can differ by 2-3 ppt at some locations the computed stratification generally agrees with the observed data. This is further substantiated in Figures 29-30 showing seasonally-averaged vertical profiles of salinity at several locations shown on Figure 23.

All of the results presented above demonstrate that the second generation 3D Chesapeake Bay hydrodynamic model is a good representation of the bay. It has been shown that the model accurately computes bay hydrodynamics resulting from processes that occur over a wide range of temporal scales.

Hydrodynamic Simulation for 1985-94

With the hydrodynamic model having been demonstrated to be a good representation of the Chesapeake Bay, it was then applied to provide 10 years of flow fields and diffusion coefficients to the water quality model. As previously noted, the years of 1985-94 were simulated. During this period, the CBP collected salinity and temperature data at two- to four-week intervals at multiple locations throughout the bay and its tributaries. Figures 31-32 show a comparison of computed salinities for the ten-year simulation at Stations CB3.3C near the Bay Bridge and at CB5.2 in the mid-bay (Figure 23). The computed salinities plotted are 10-day averages. Thus, high frequency events associated with meteorological forcing on a 2-4 day time scale tend to be averaged out. Still, it can be seen that salinities computed over the 10-year simulation match the observed data collected every two weeks quite well. Figure 33 illustrates that the model accurately computes water temperature over the 10-year simulation.

Summary and Conclusions

A second generation 3D numerical hydrodynamic model of Chesapeake Bay and its tributaries has been developed to provide flow fields and diffusion coefficients to drive a 3D water quality model of Chesapeake Bay. The numerical grid is boundary-fitted in the horizontal and Cartesian in the vertical. The grid contains in excess of 10,000 computational cells with a maximum of 20 vertical layers representing a maximum depth of 100 ft (30.49 m).

Validation of the Chesapeake Bay 3D hydrodynamic model was conducted by demonstrating that the model accurately reproduces the bay hydrodynamics due to processes occurring over a wide range of temporal scales. For example, it was shown that the propagation of tides up the tributaries is accurately computed, along with the set ups and set downs in the water surface occurring due to meteorological events resulting from both local wind forcing as well as wind forcing over the continental shelf. Tidal velocities and salinities over the neap-spring cycle were shown to be accurately computed, along with the neap-spring stratification that occurs on bay tributaries such as the York River. Results from a simulation of September 1983 demonstrated the model's ability to capture wind mixing events. Using data collected by Boicourt (1973), it was shown that the model accurately computes the exchange between the bay and the shelf through the bay's mouth. Data collected by NOAA during 1977-83 were used to generate a picture of the residual transport in Chesapeake Bay. Model results agreed very well with these data. Finally, it was shown that seasonally-averaged stratification in Chesapeake Bay resulting from seasonal changes in freshwater inflows was reproduced well.

The validated 3D Chesapeake Bay hydrodynamic model was then applied to generate 10 years of hydrodynamics to drive the 3D Chesapeake Bay water quality model. These years were 1985-94 and covered a wide range of environmental forcings.

The basic conclusion is that the 3D model is an extremely good representation of Chesapeake Bay and accurately computes the hydrodynamics of the bay resulting from the different types of environmental forcings experienced by the bay over varying time scales. These include tides, meteorological forcing related to both local and non-local winds, turbulence generated by wind forcing, and freshwater inflows.

Further improvements planned for the model include additional grid refinement and improvements in the open ocean and C&D Canal boundary conditions.

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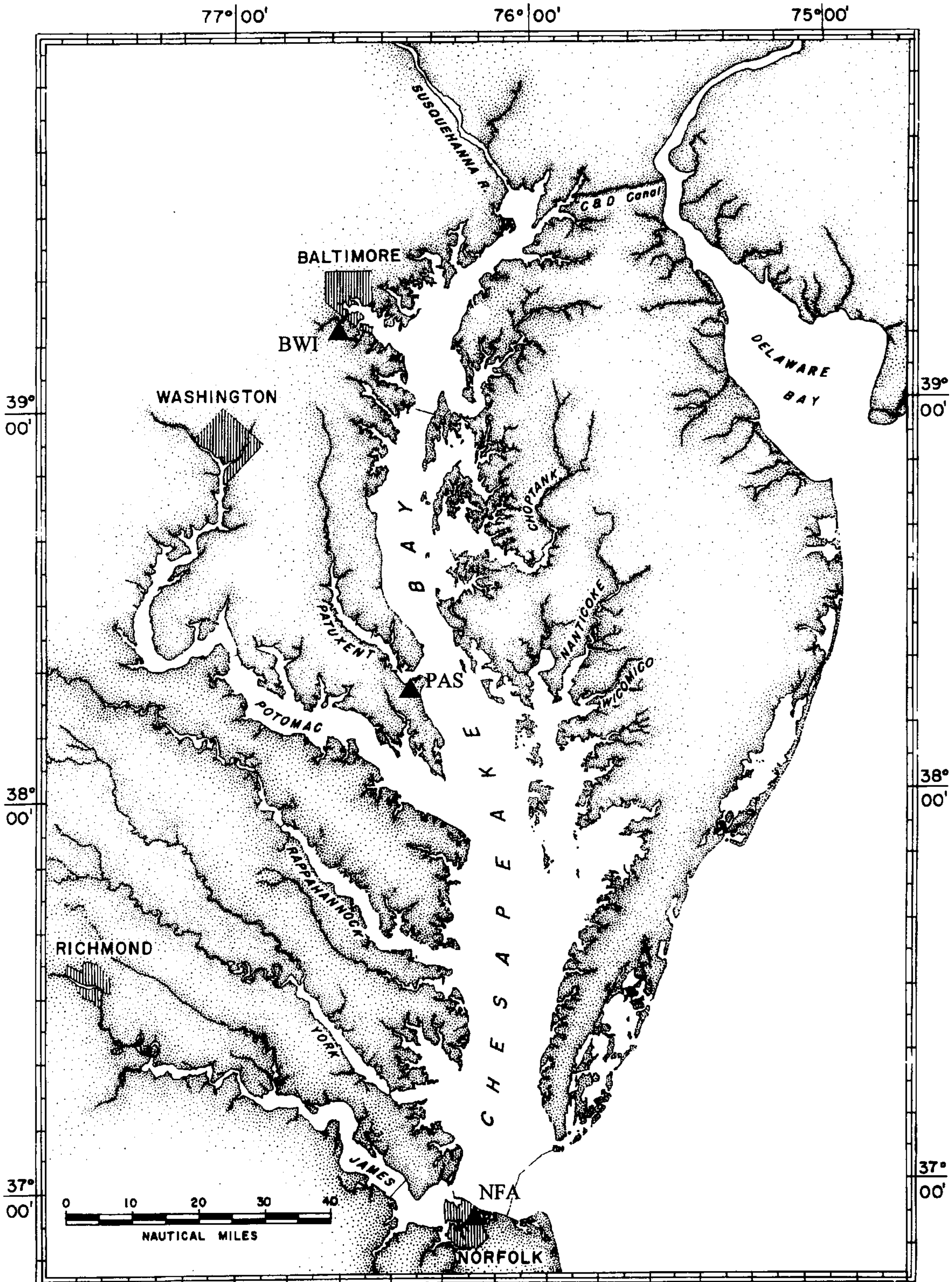


Figure 1. Chesapeake Bay

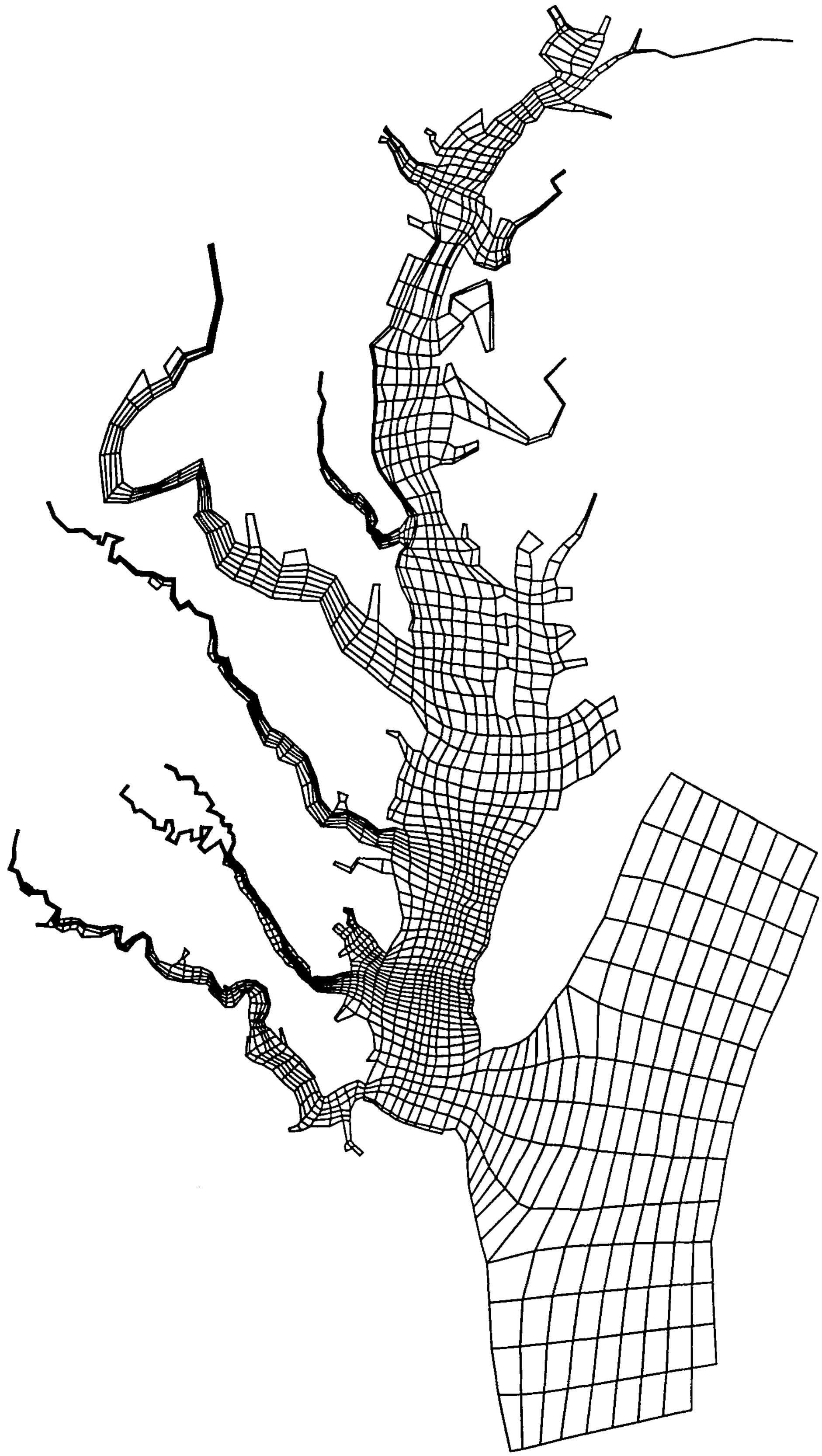


Figure 2. Planform numerical grid

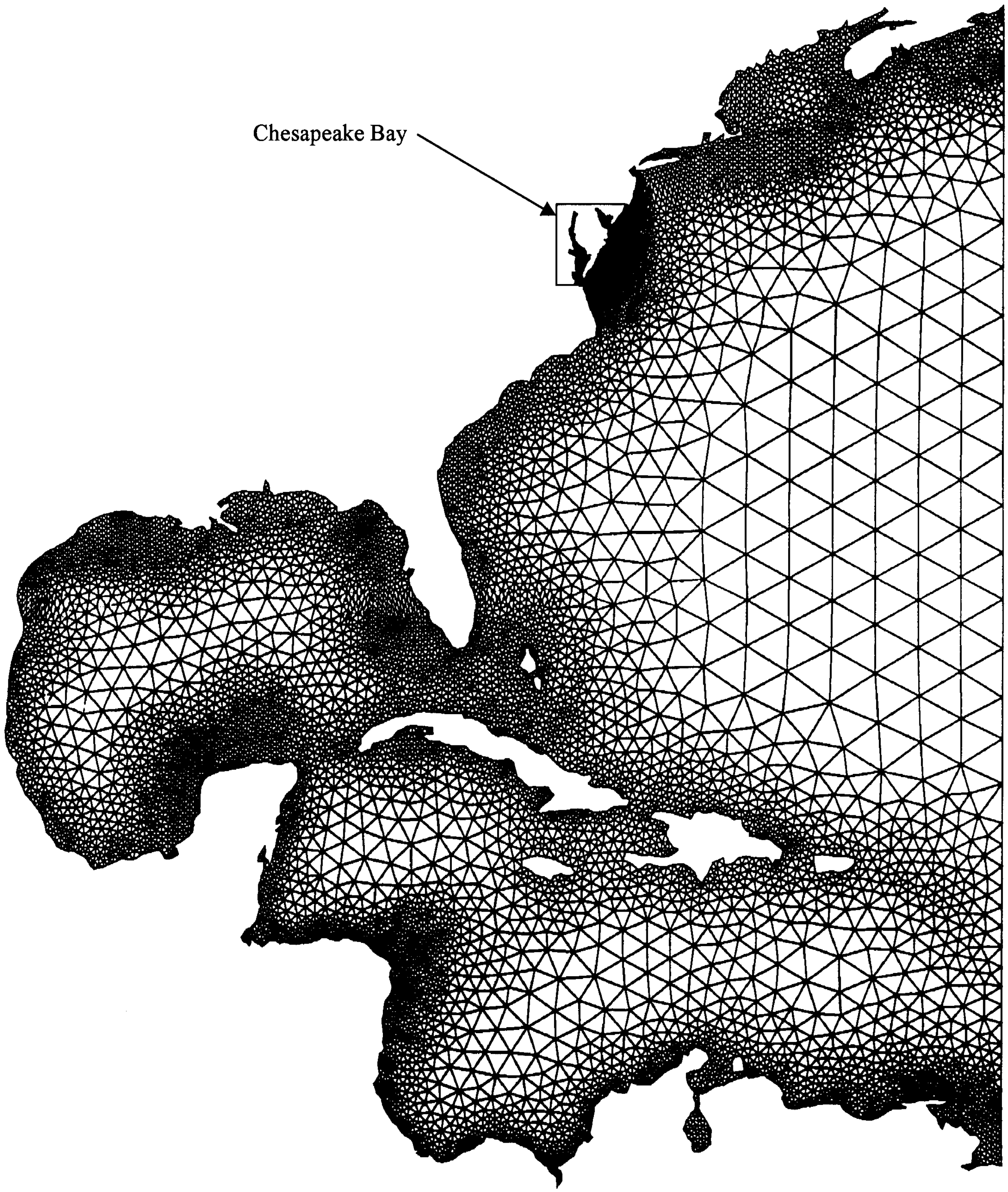


Figure 3. ADCIRC numerical model grid

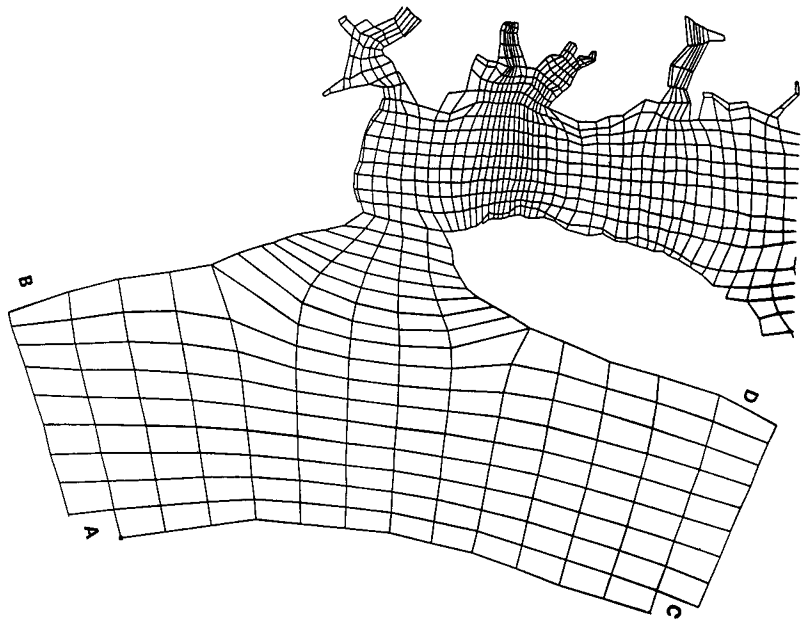


Figure 4. Location where open boundary salinity and temperature data are specified

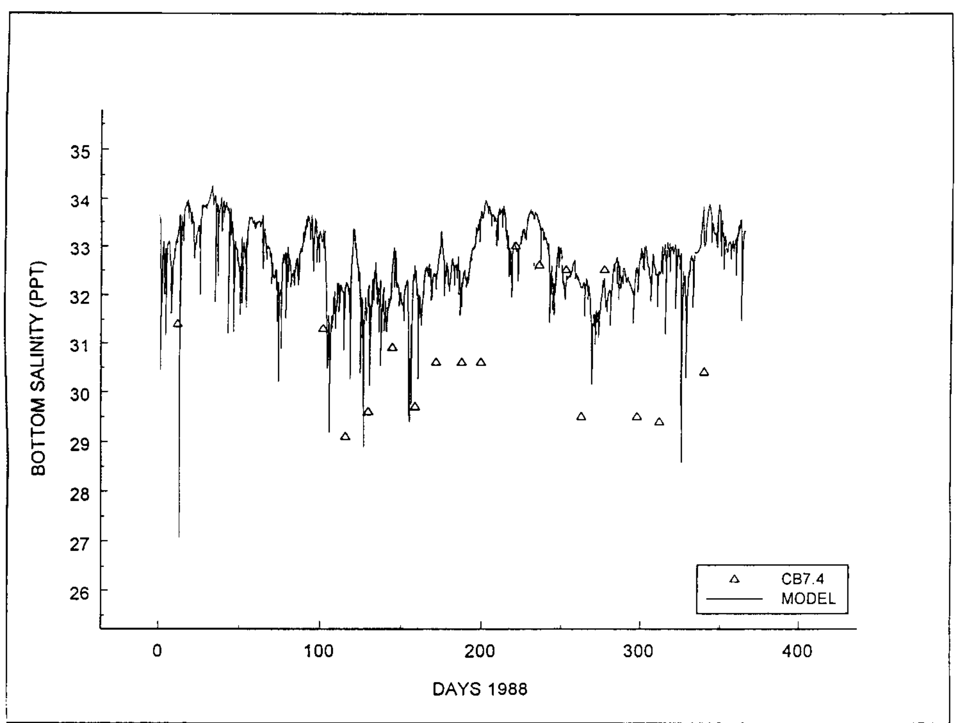


Figure 5. Near-bottom salinity at bay mouth with original salinity boundary condition

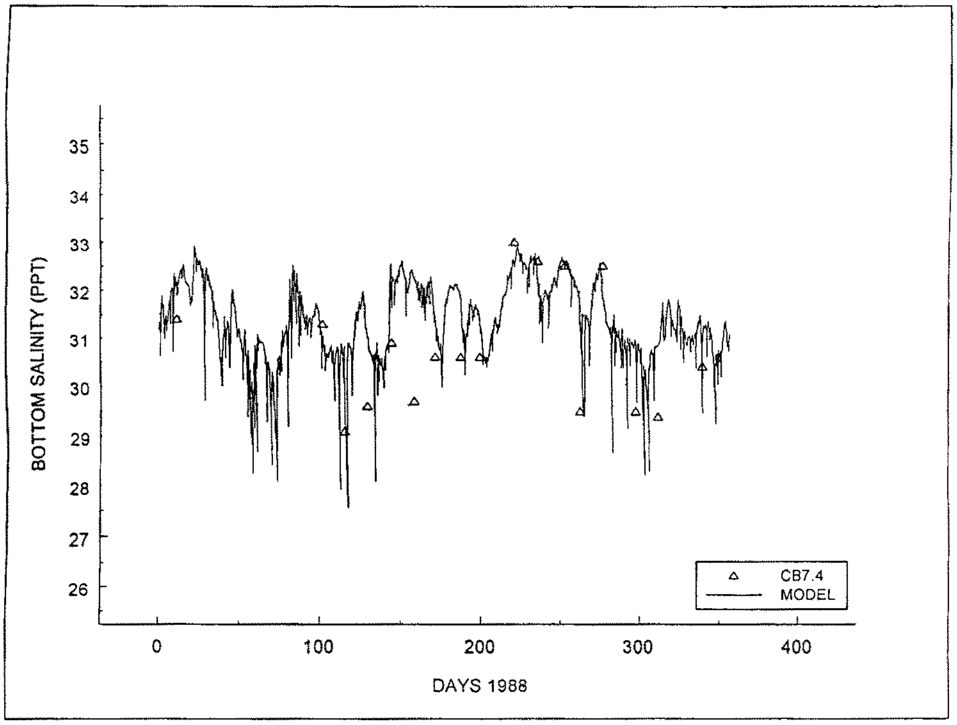


Figure 6. Near-bottom salinity at bay mouth with modified salinity boundary condition

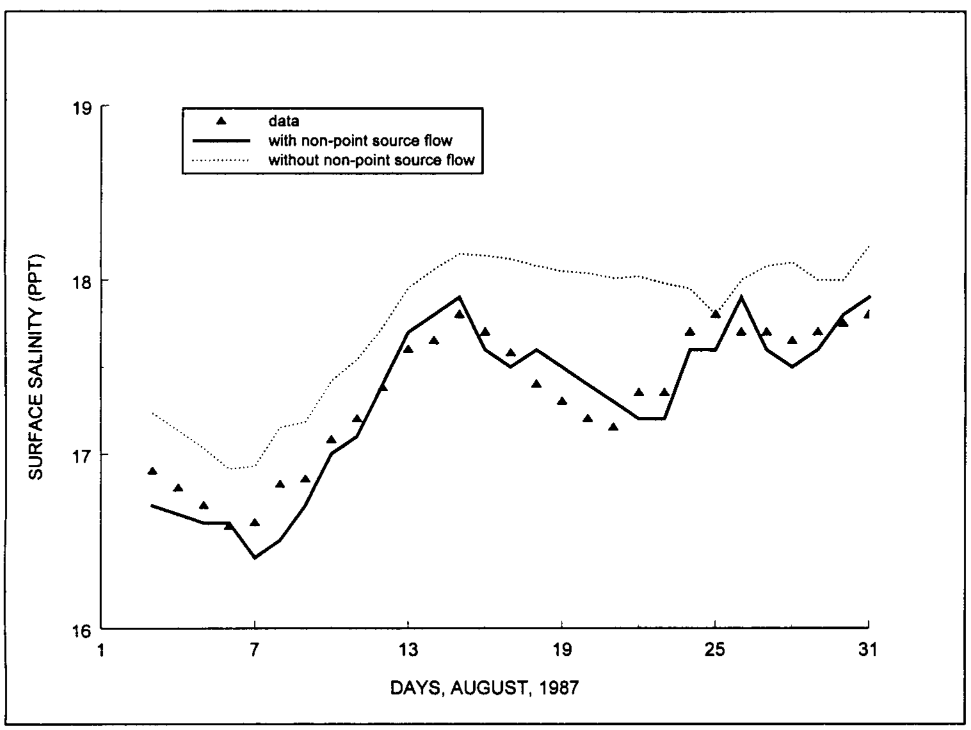
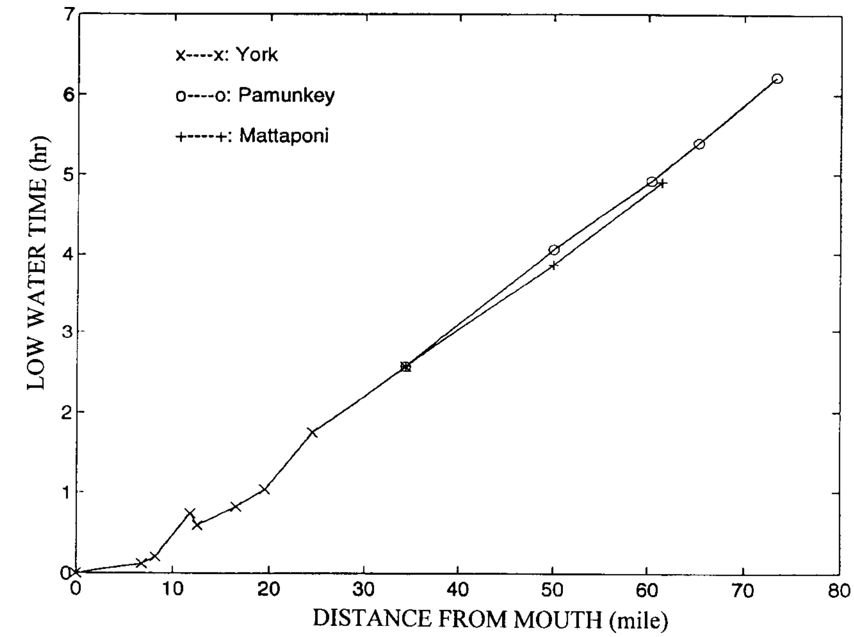
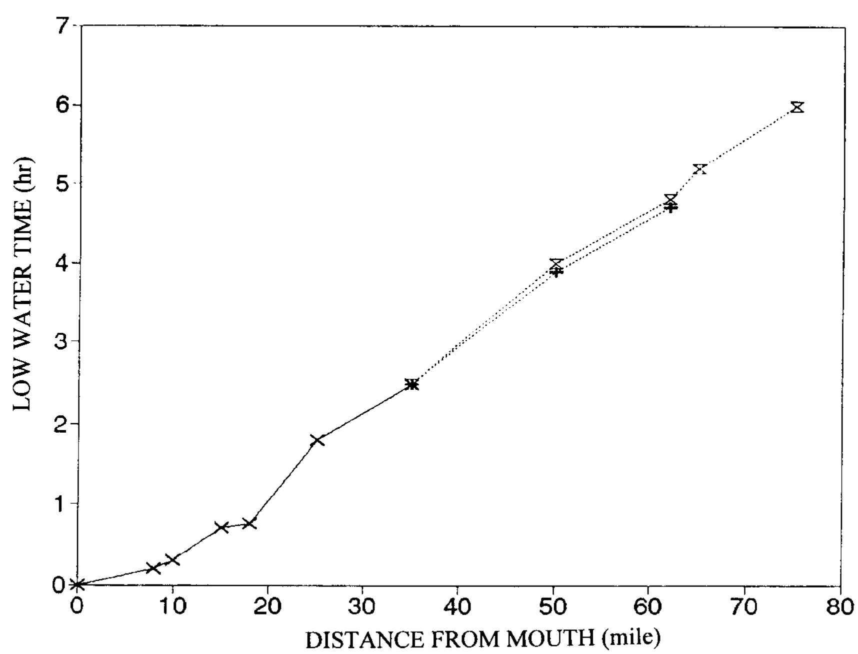


Figure 7. Impact of using watershed model flows on salinity on Rappahannock River

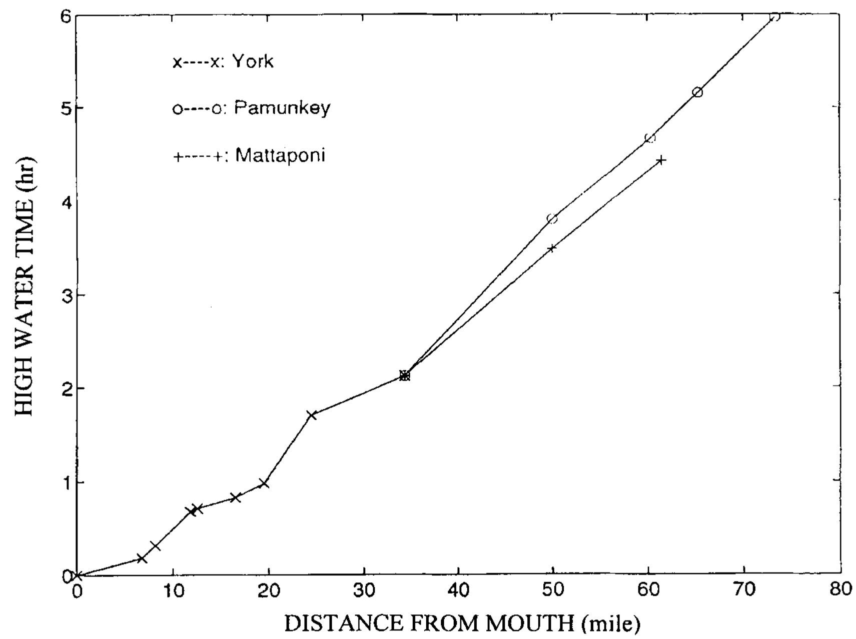


a. Tide Tables

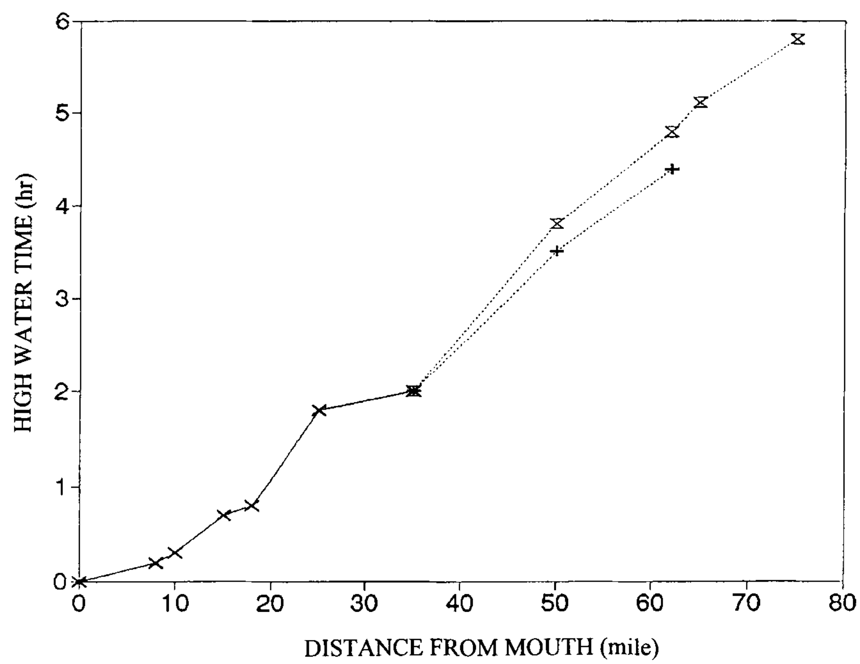


b. Computed

Figure 8. Comparison of computed and tabulated time to low water on York River

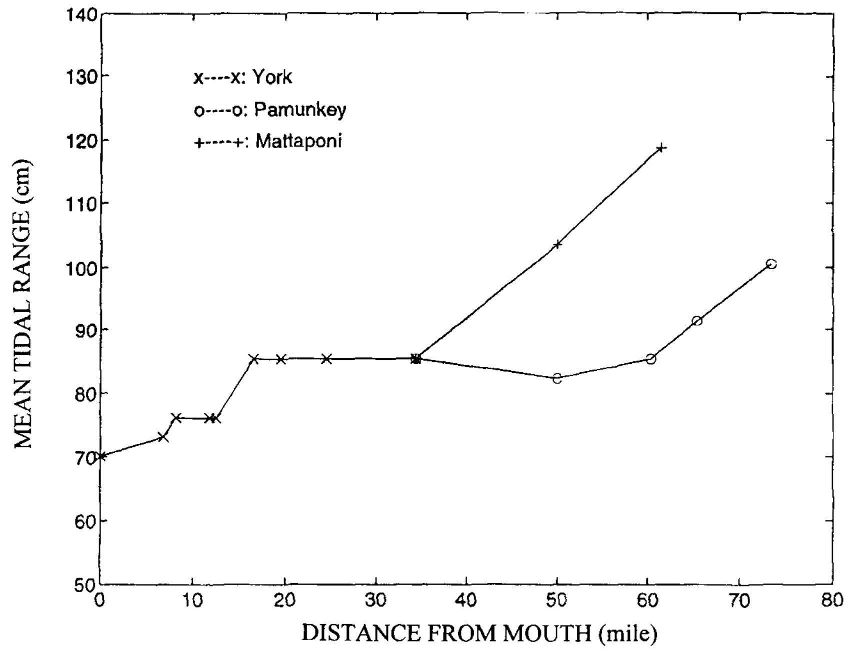


a. Tide Tables

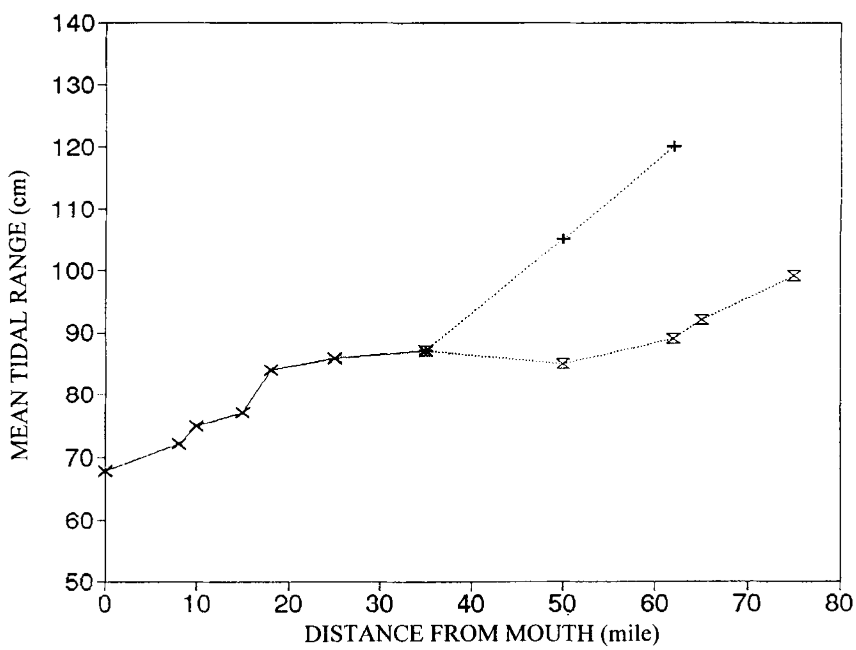


b. Computed

Figure 9. Comparison of computed and tabulated time to high water on York River

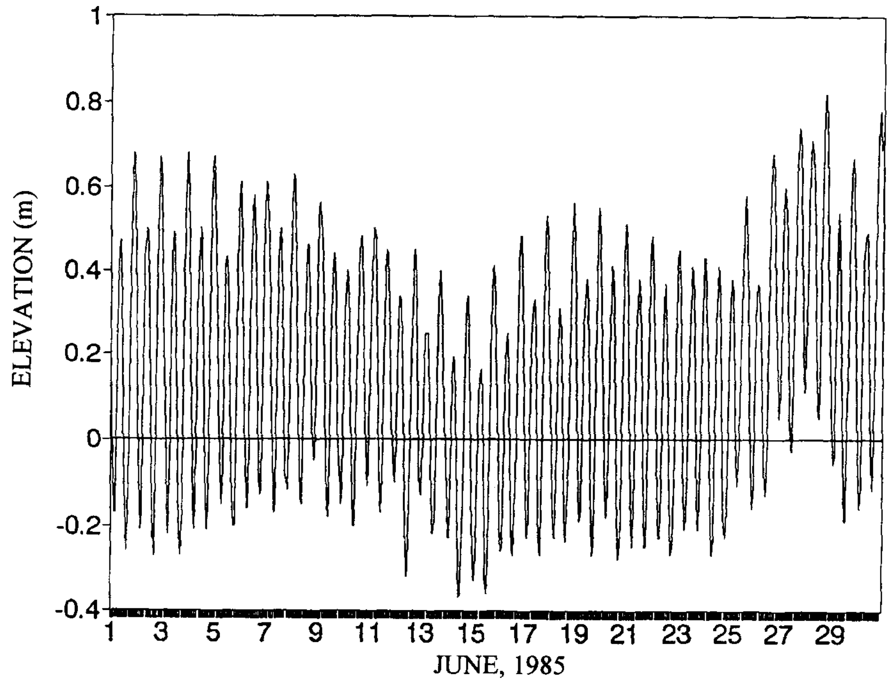


a. Tide Tables

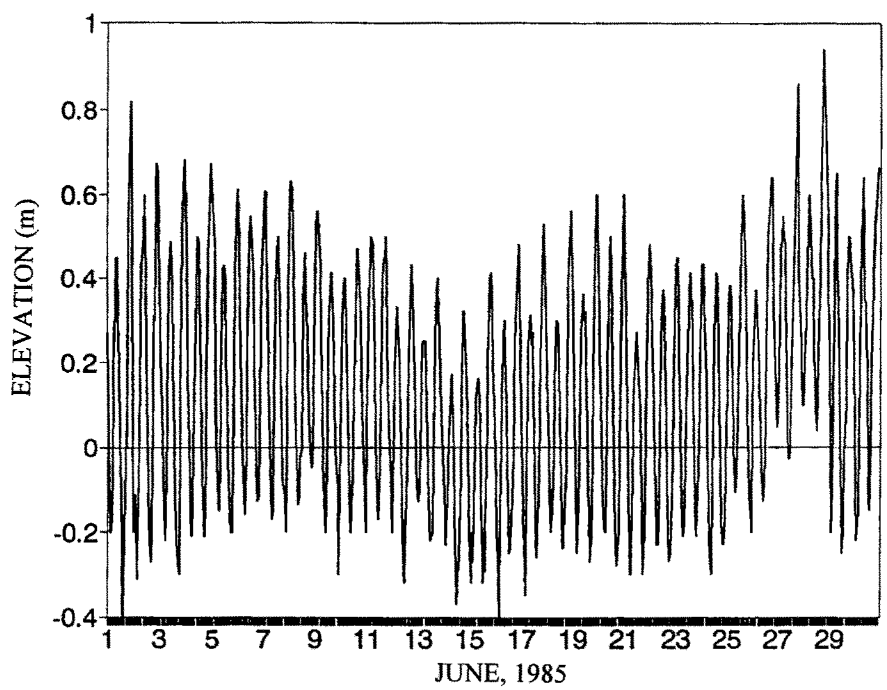


b. Computed

Figure 10. Comparison of computed and tabulated mean tide range on York River



a. Observed



b. Computed

Figure 11. Comparison of observed and computed water surface at Ft Eustis

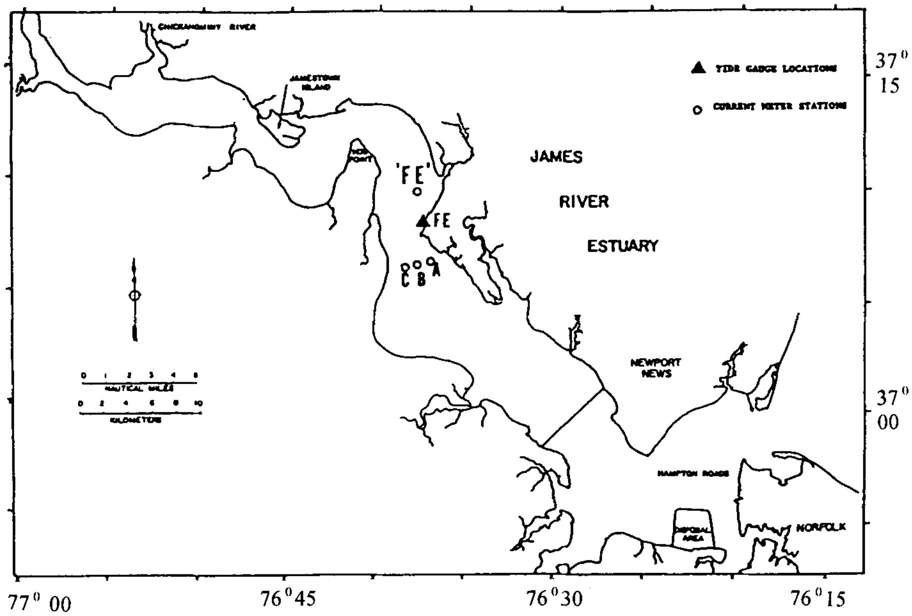


Figure 12. Location of Ft Eustis

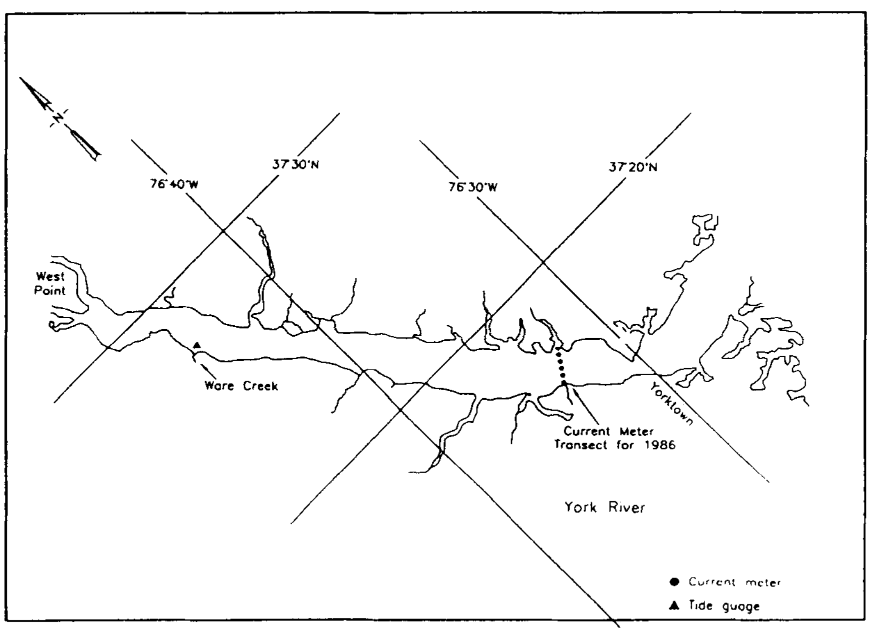
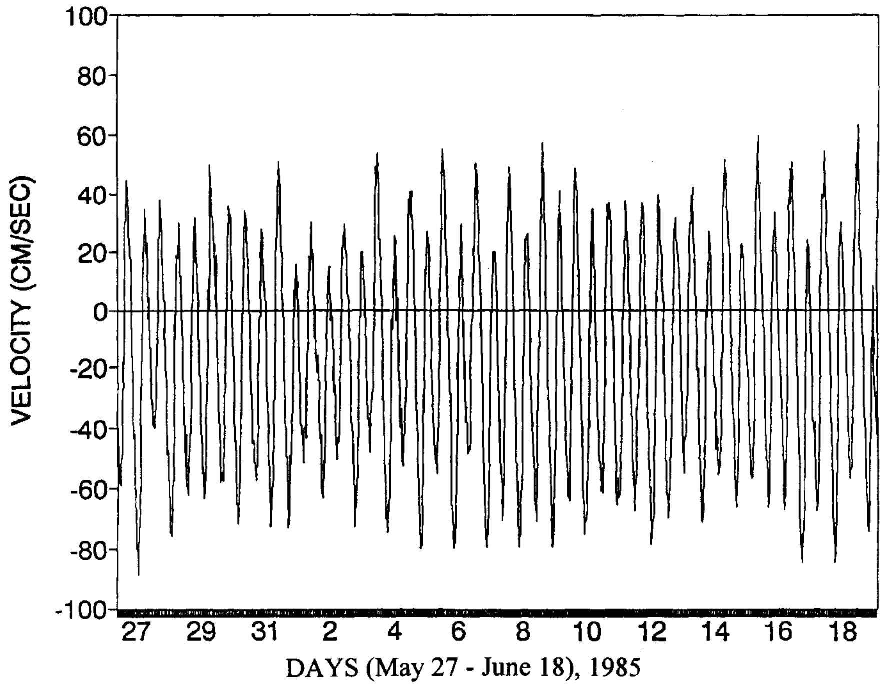
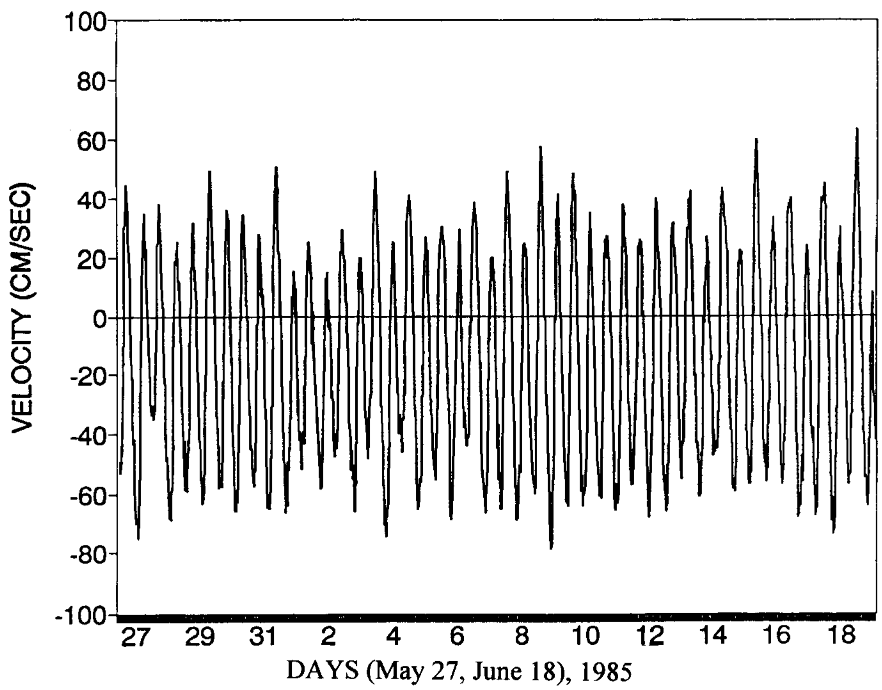


Figure 13. Location of observed data on York River

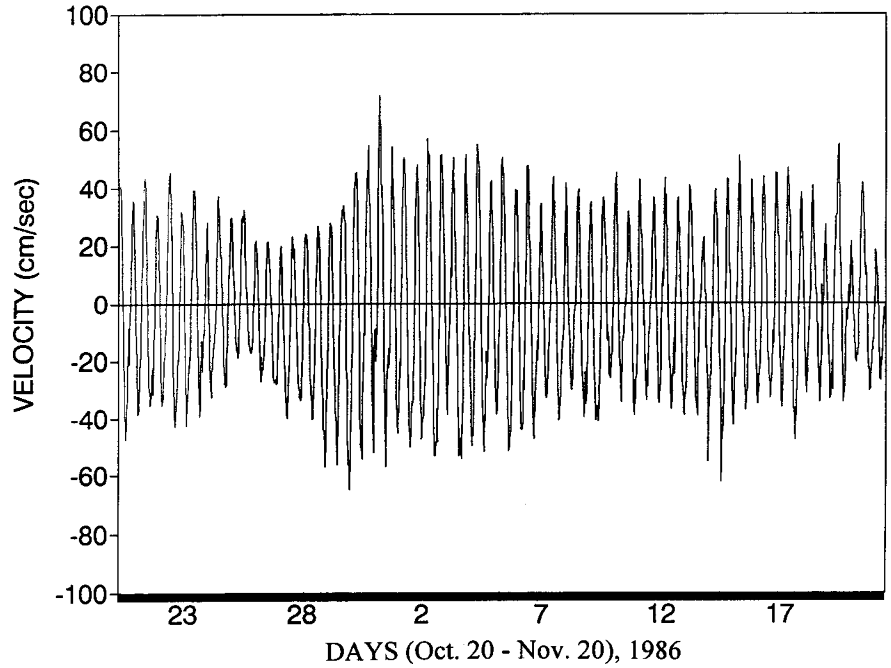


a. Observed

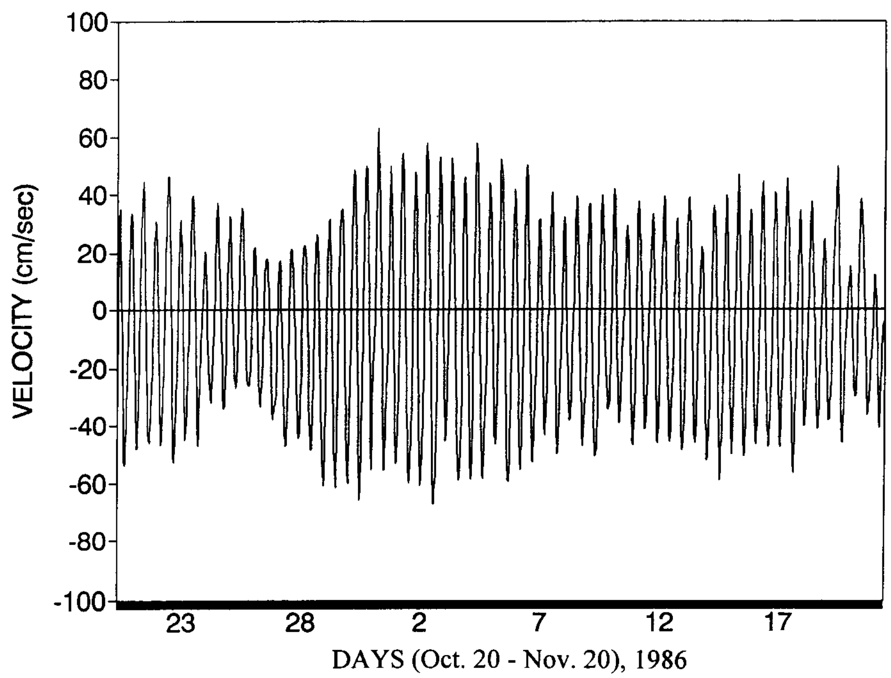


b. Computed

Figure 14. Comparison of observed and computed tidal velocity along the James River at Fort Eustis

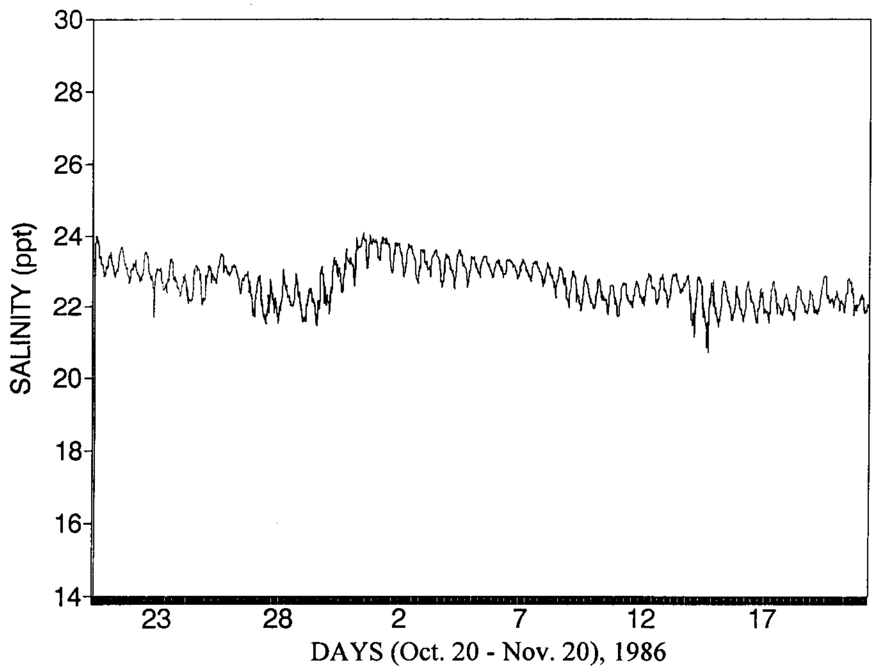


a. Observed

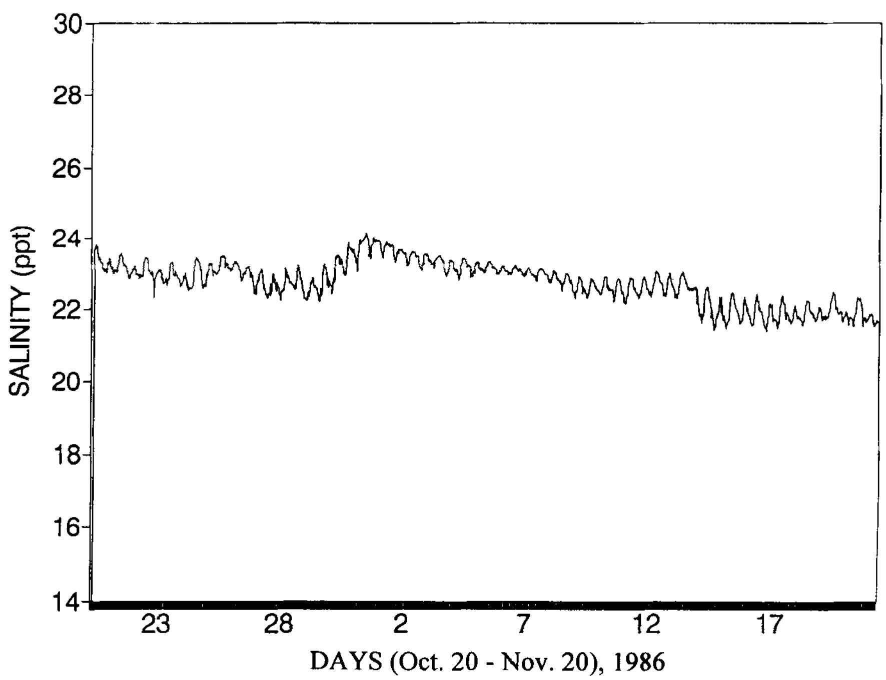


b. Computed

Figure 15. Comparison of observed and computed component of tidal velocity along the York River



a. Observed



b. Computed

Figure 16. Comparison of observed and computed salinity on York River

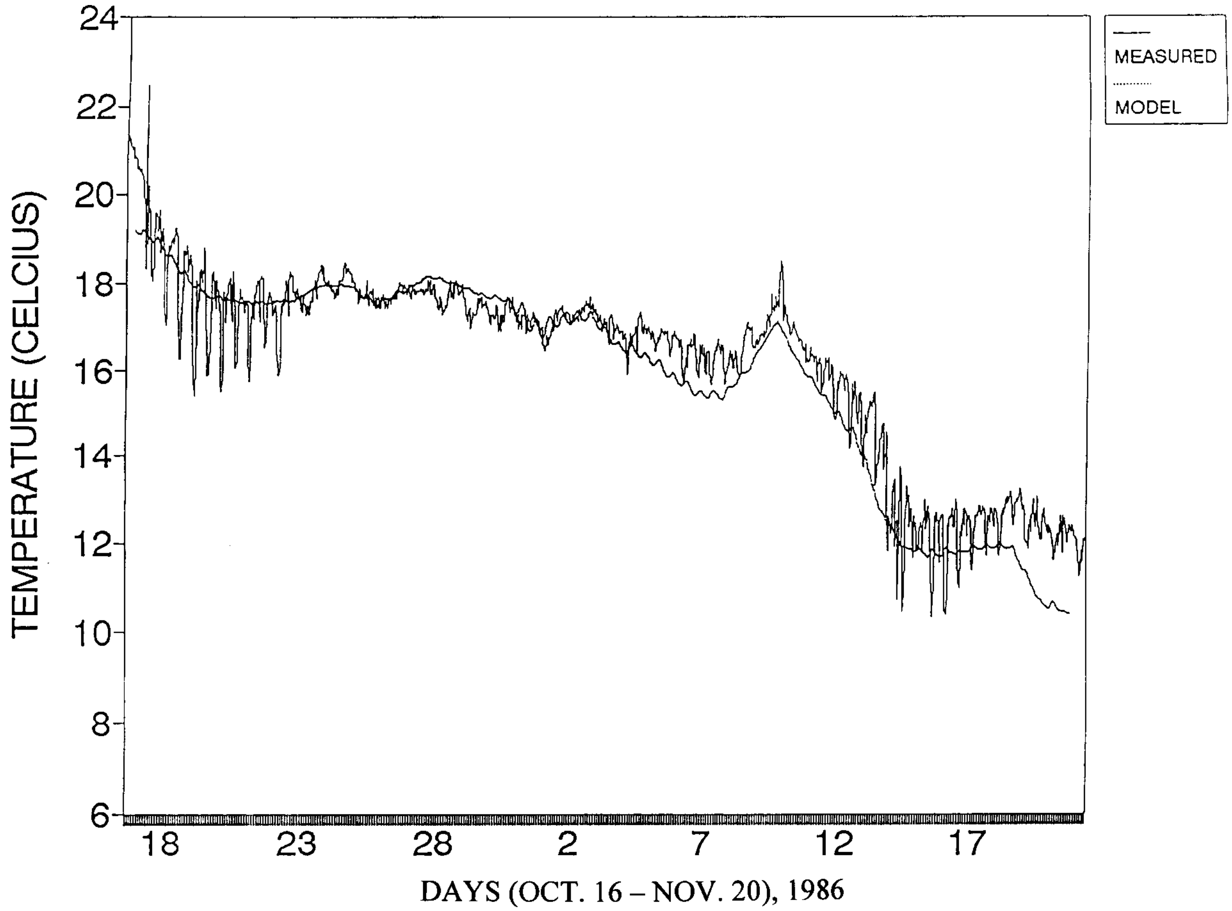


Figure 17. Comparison of observed and computed temperature on York River

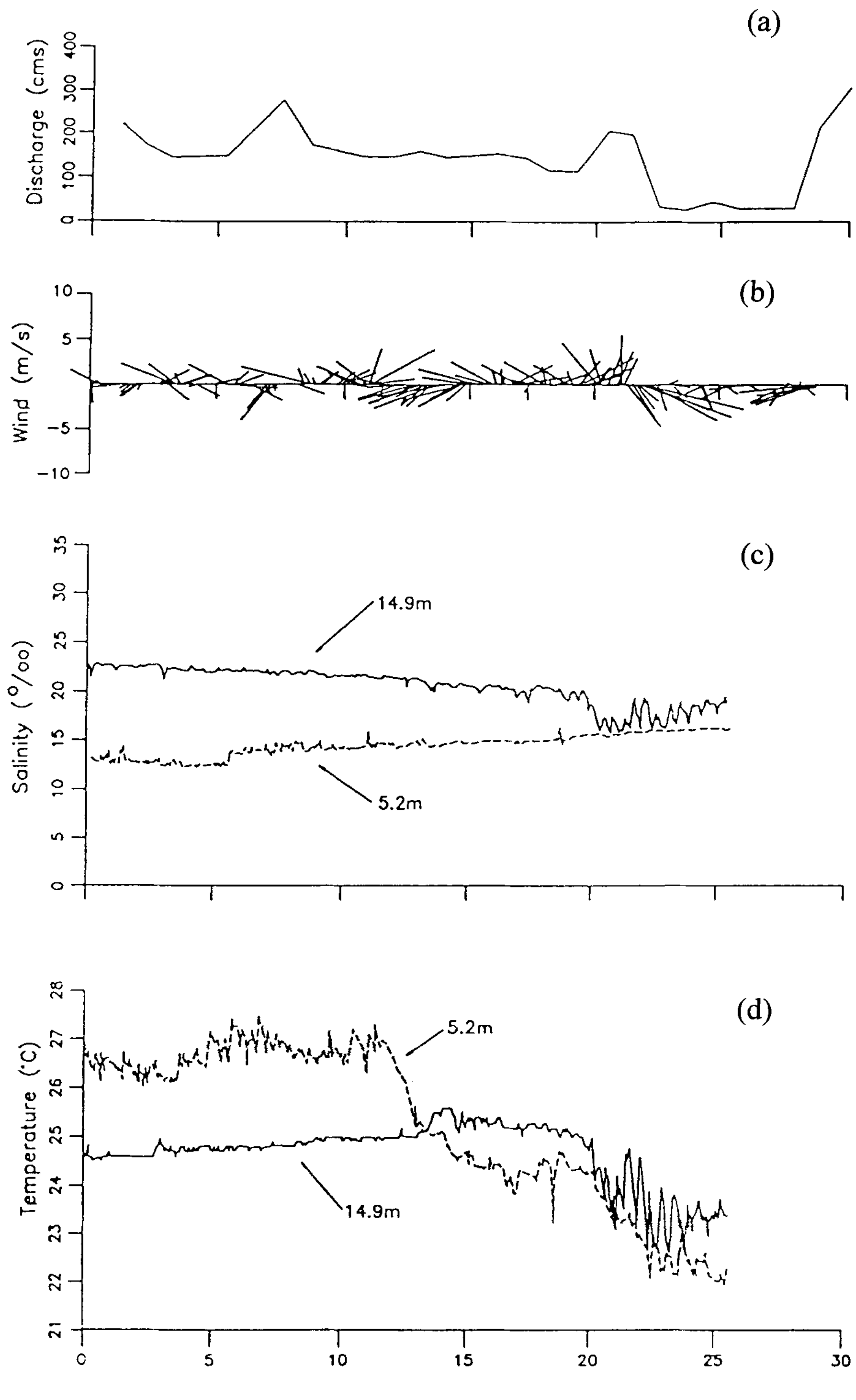
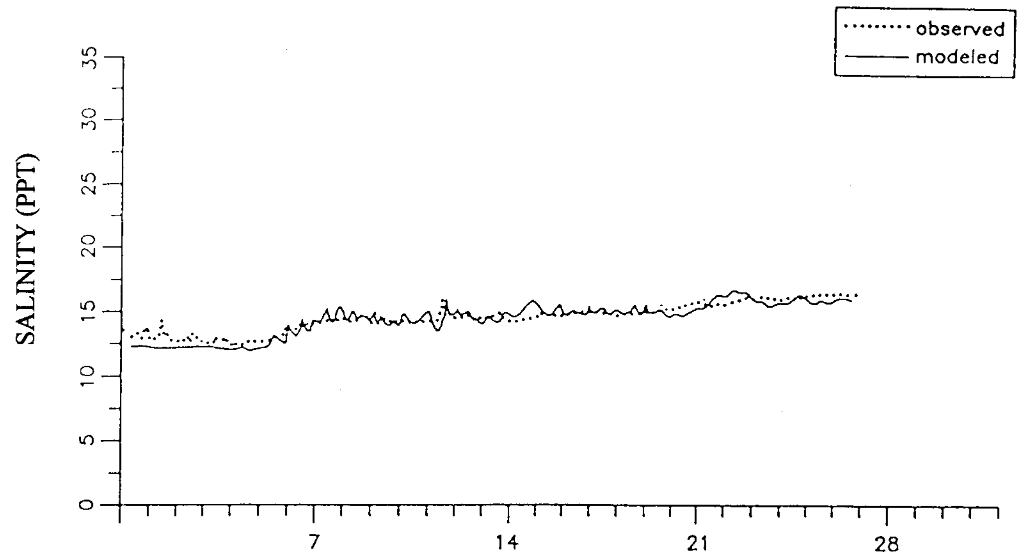
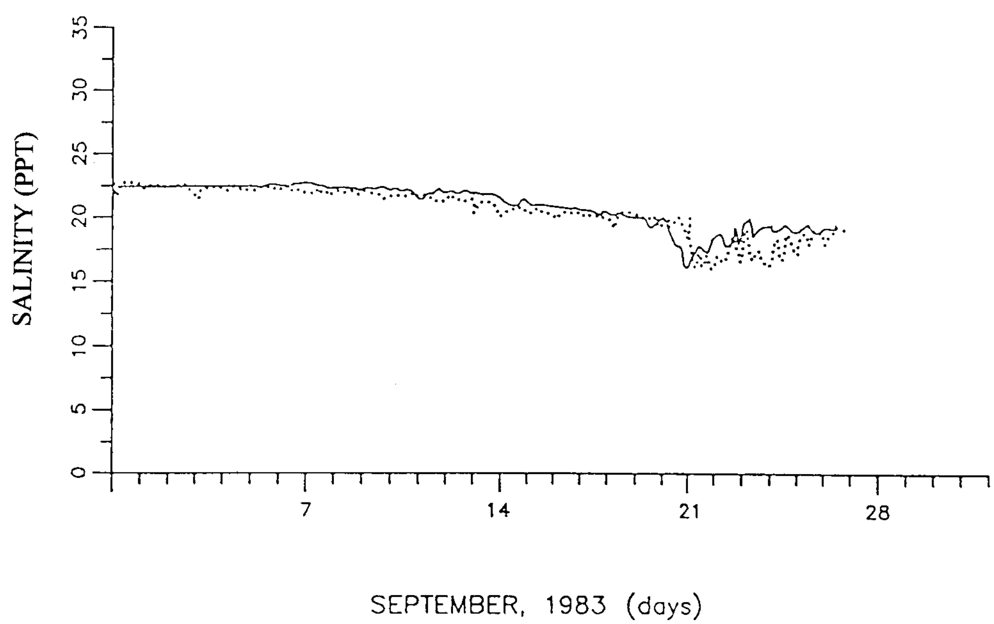


Figure 18. Observed data illustrating wind mixing (a) Susquehanna River flow (b) wind at Patuxent Naval air station ; (c) salinity (d) temperature at station CCA

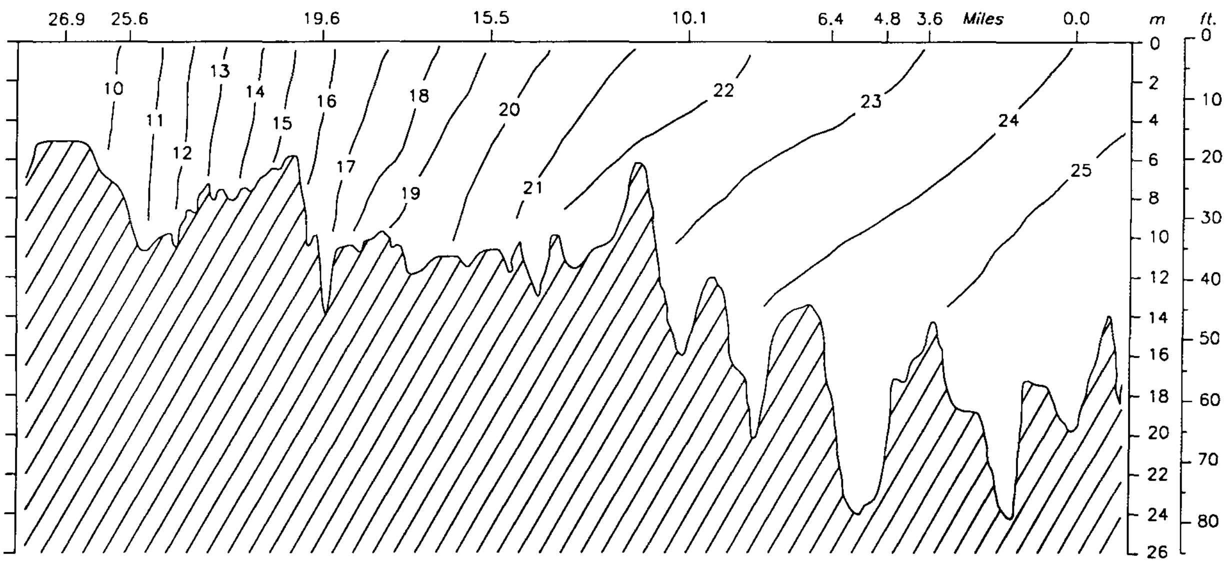


a. Near-Surface

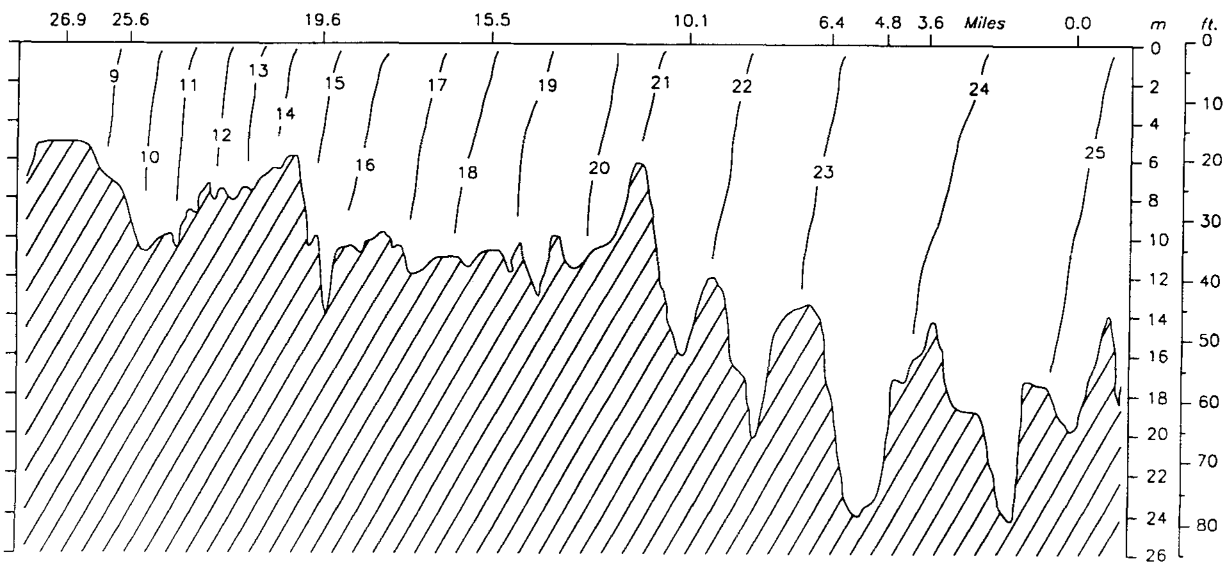


b. Near-Bottom

Figure 19. Computed salinity illustrating wind mixing

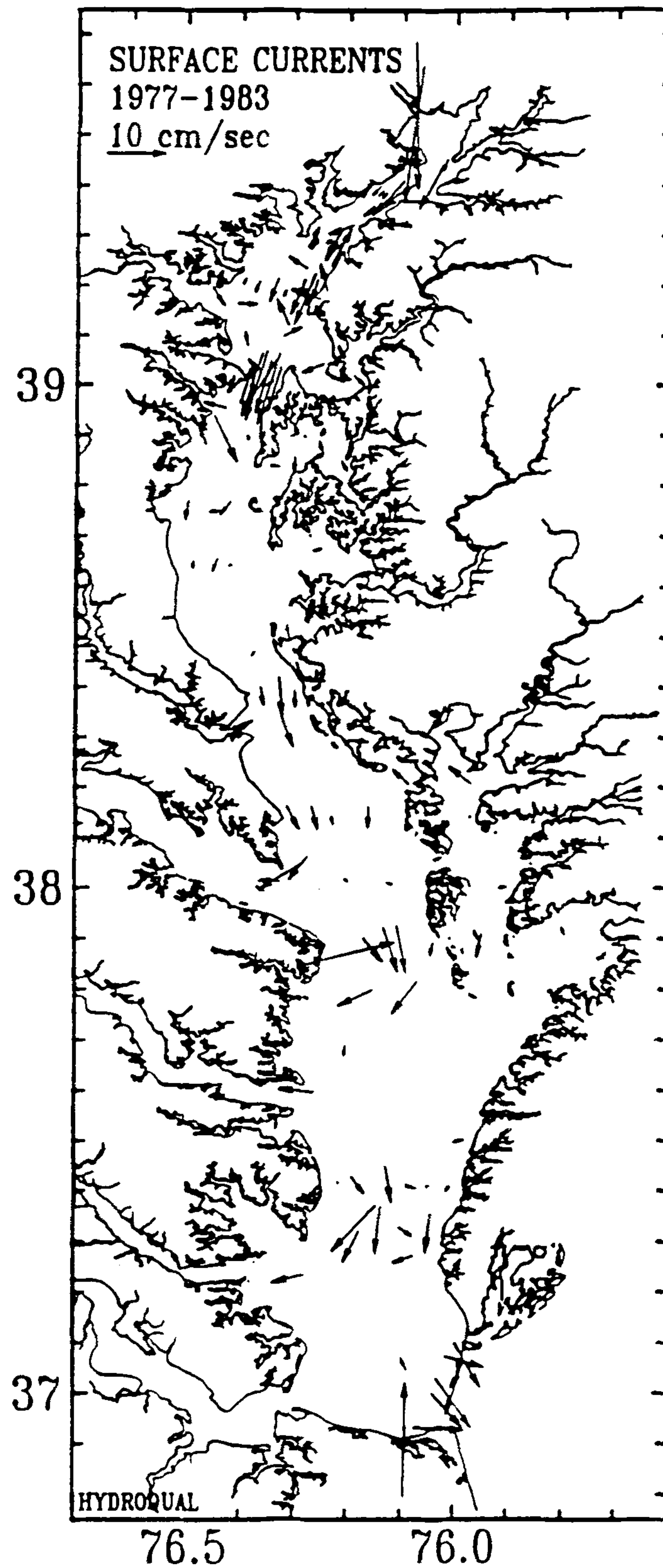


a. Neap



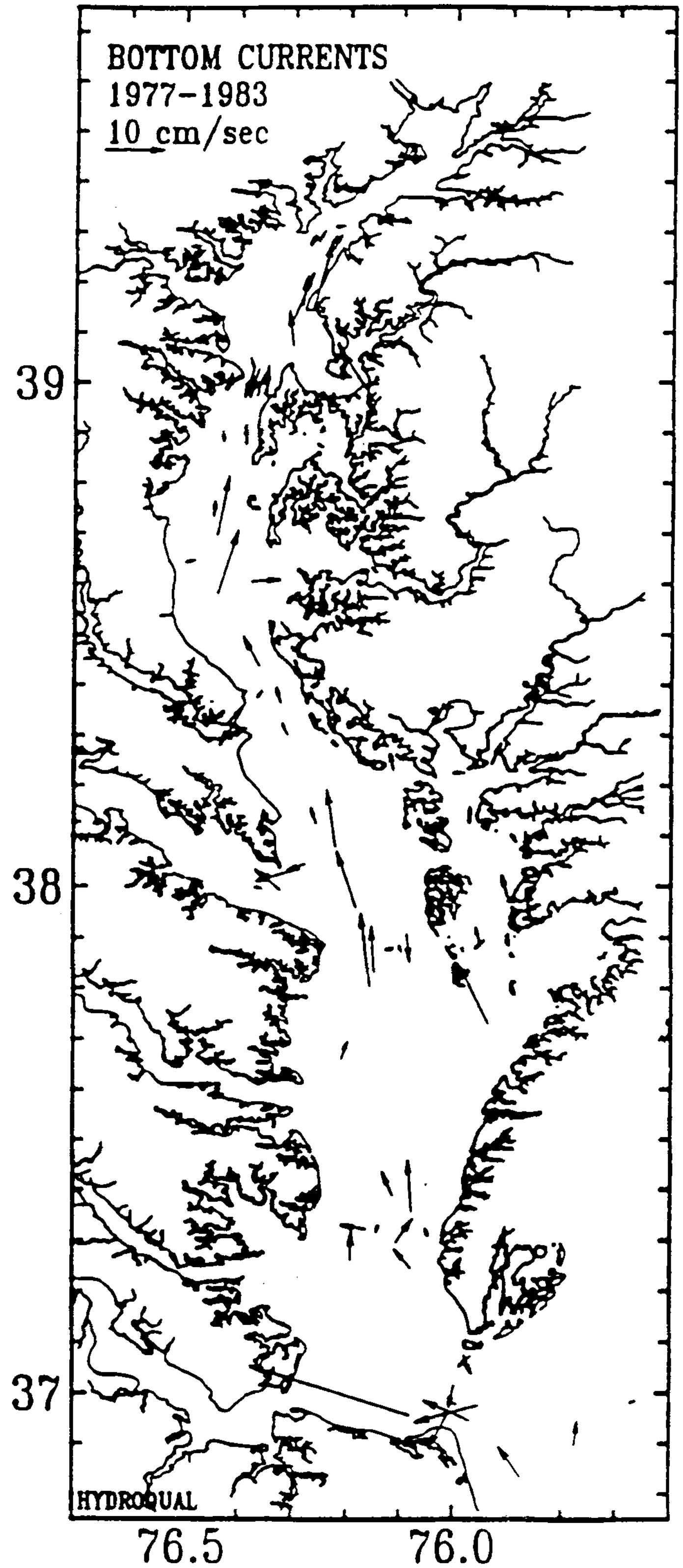
b. Spring

Figure 20. Illustration of computed neap-spring stratification in the York River



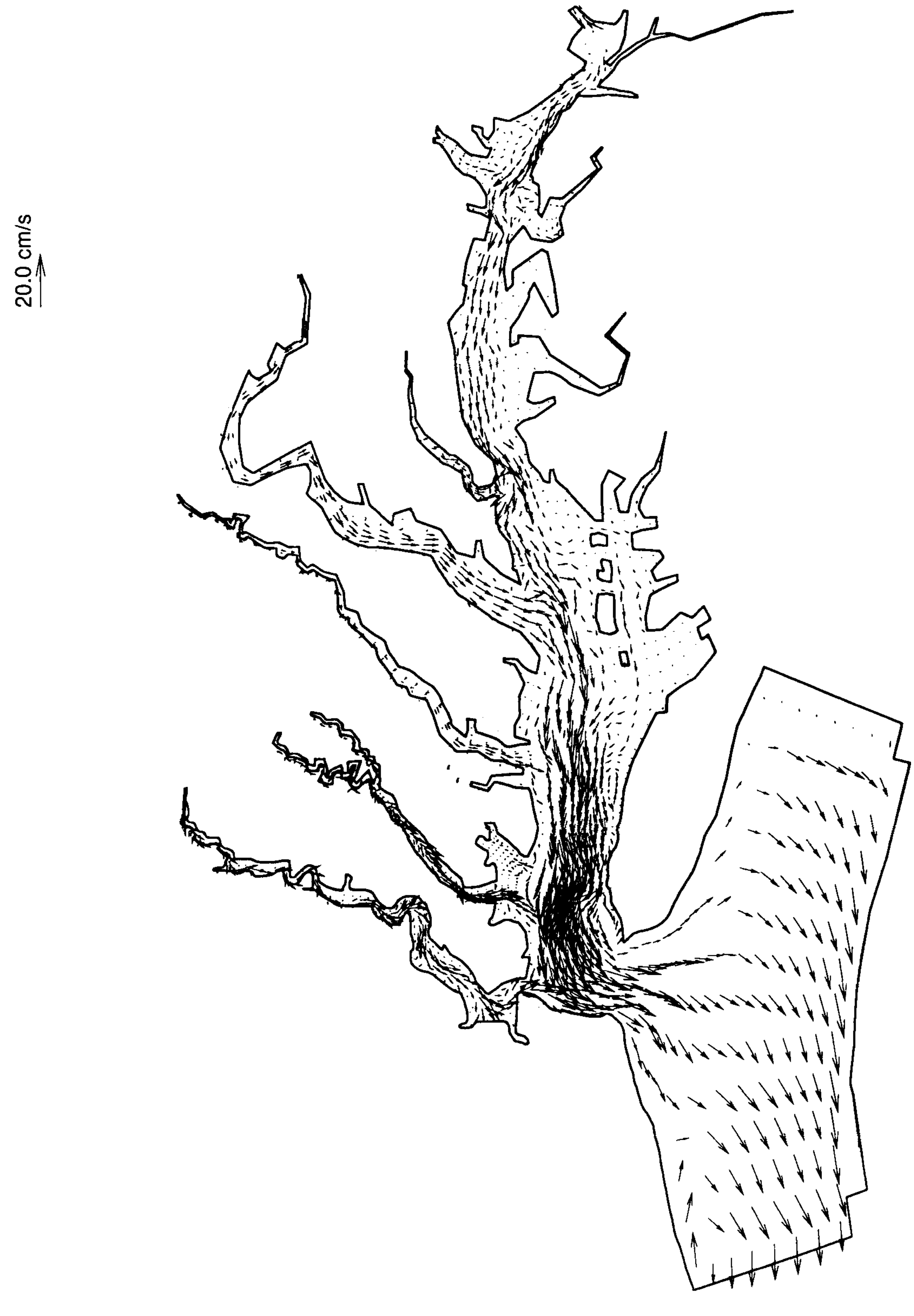
a. Near-Surface

Figure 21. Residual currents computed from observed data (Sheet 1 of 2)



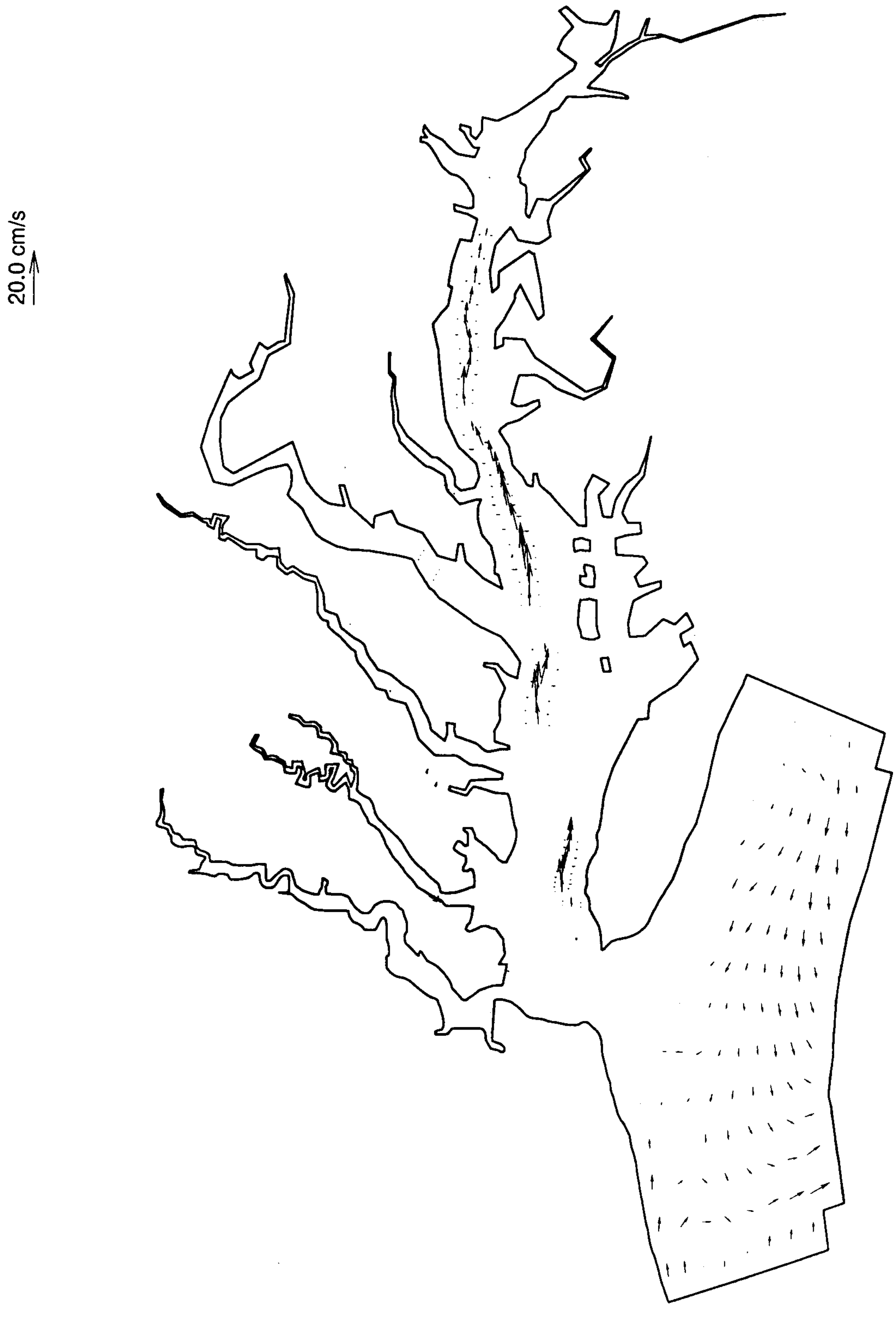
b. Near-Bottom

Figure 21. Sheet 2 of 2



a. Near-Surface

Figure 22. Residual currents computed by model (Sheet 1 of 2)



b. Near-Bottom

Figure 22. Sheet of 2

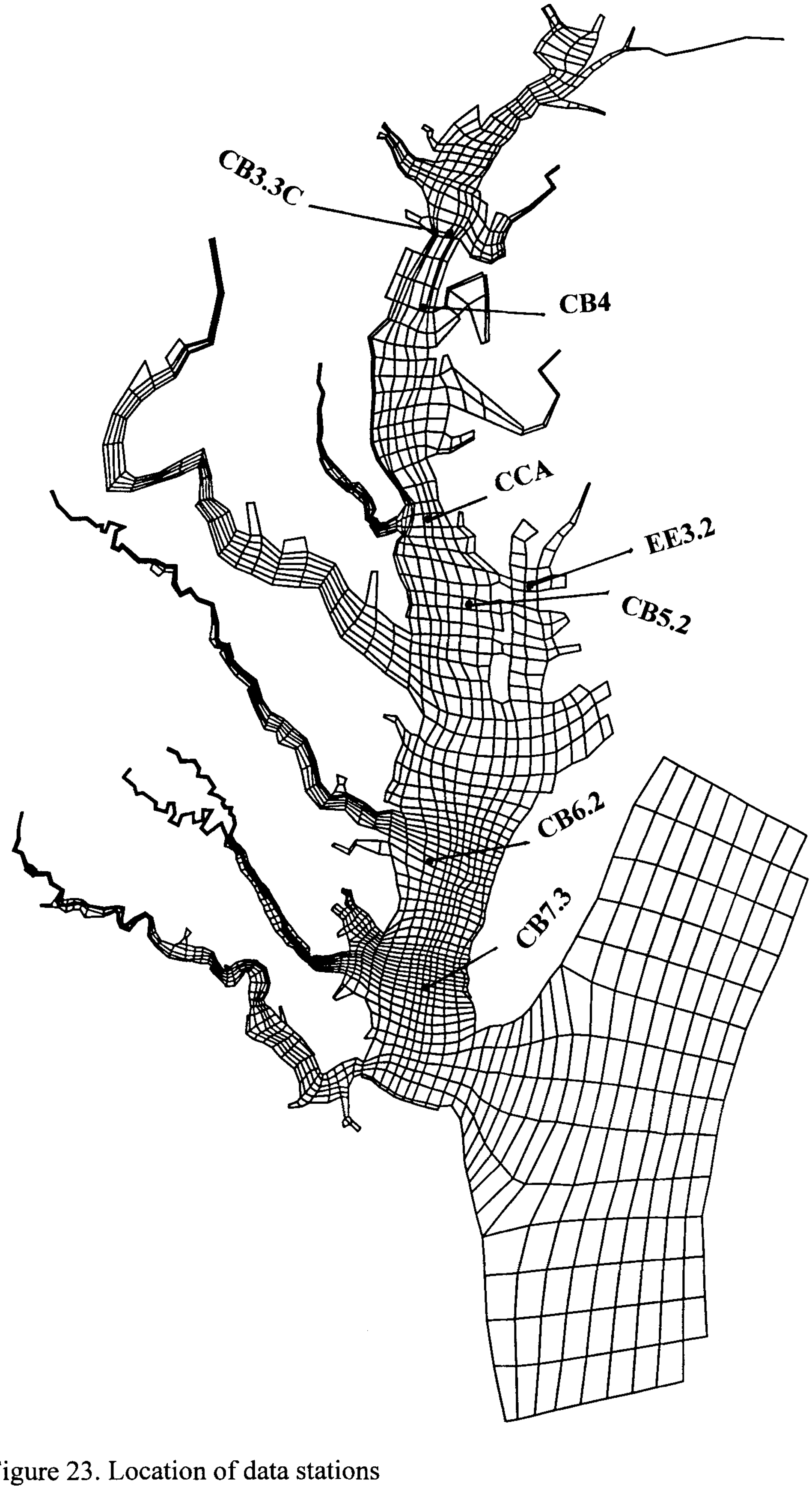


Figure 23. Location of data stations

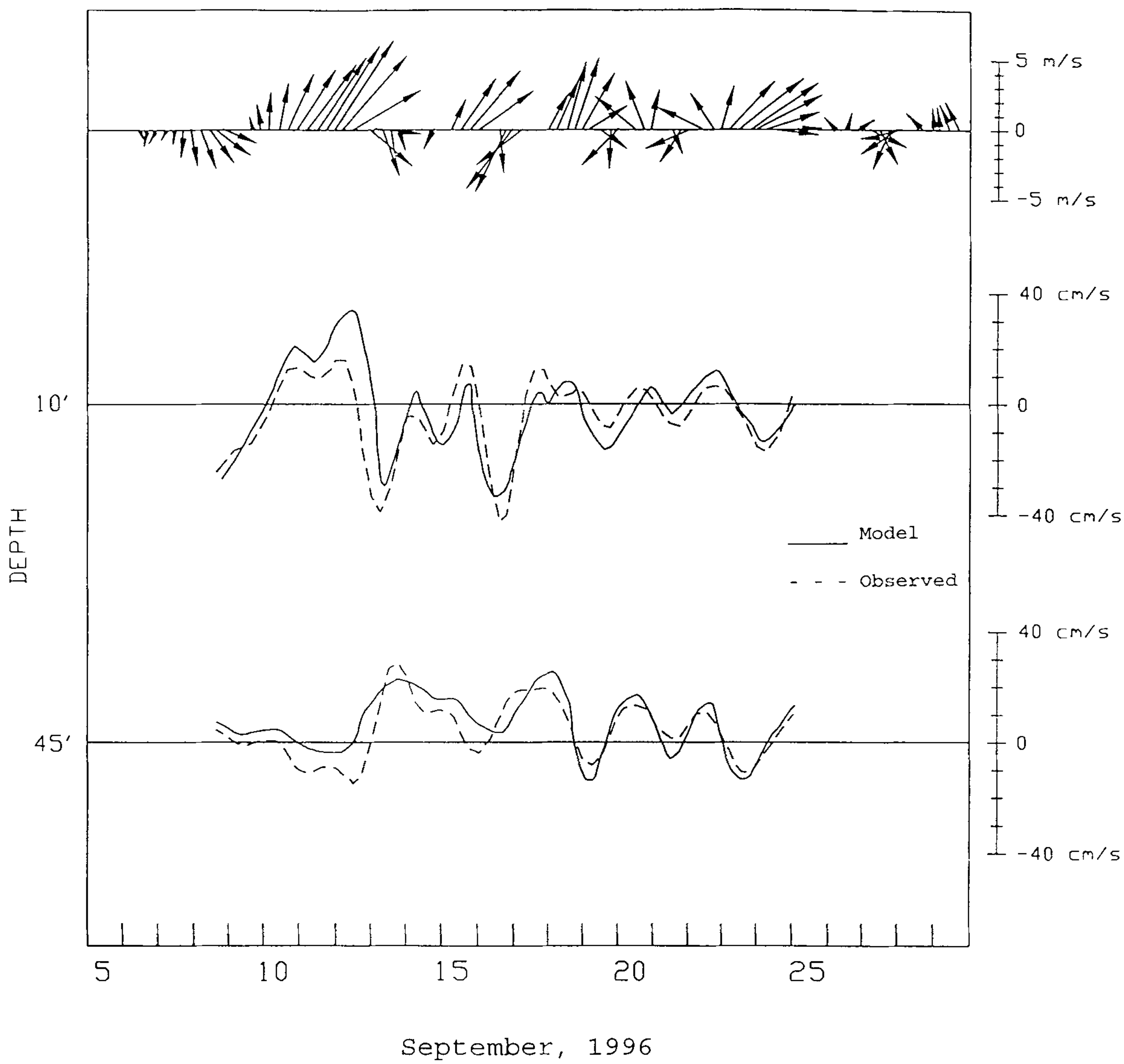


Figure 24. Comparison of low pass observed and computed velocity at Station CCA

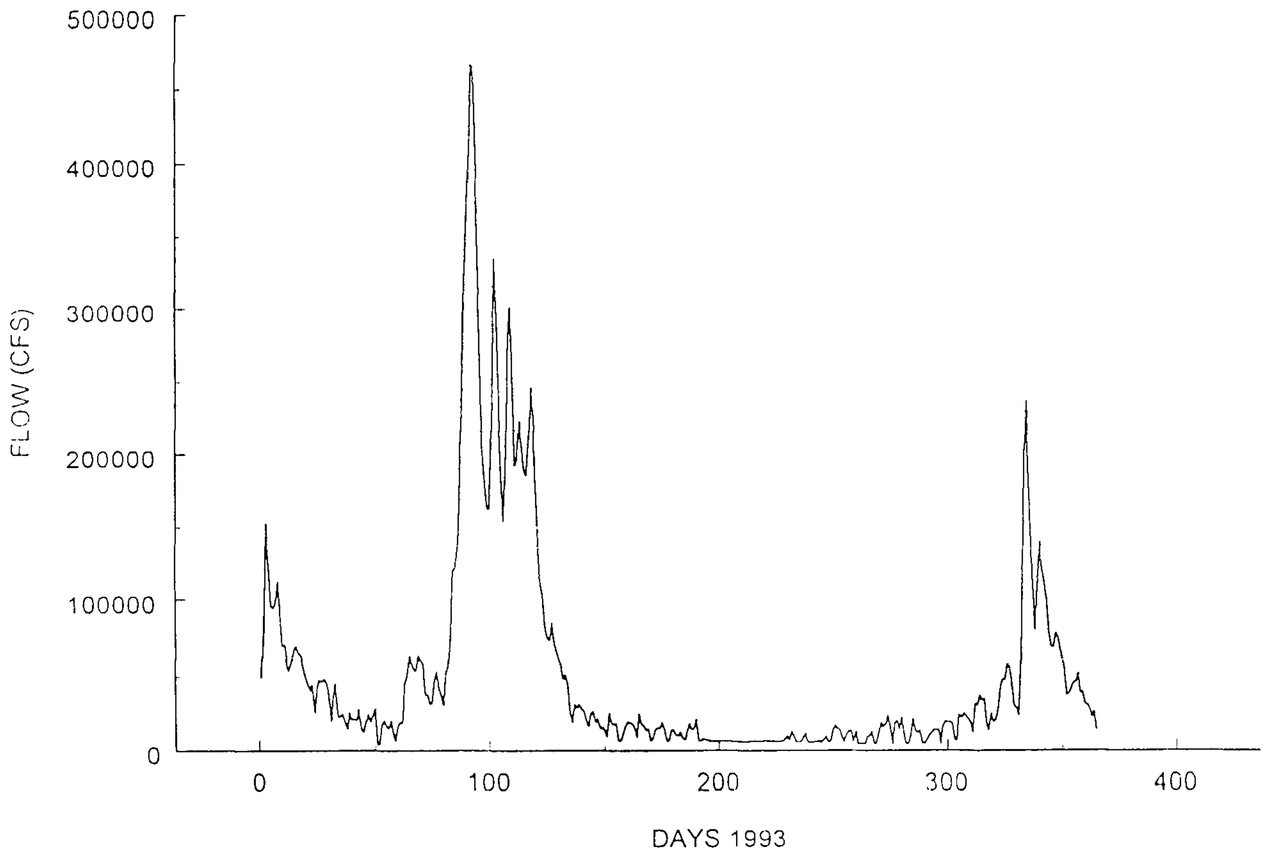
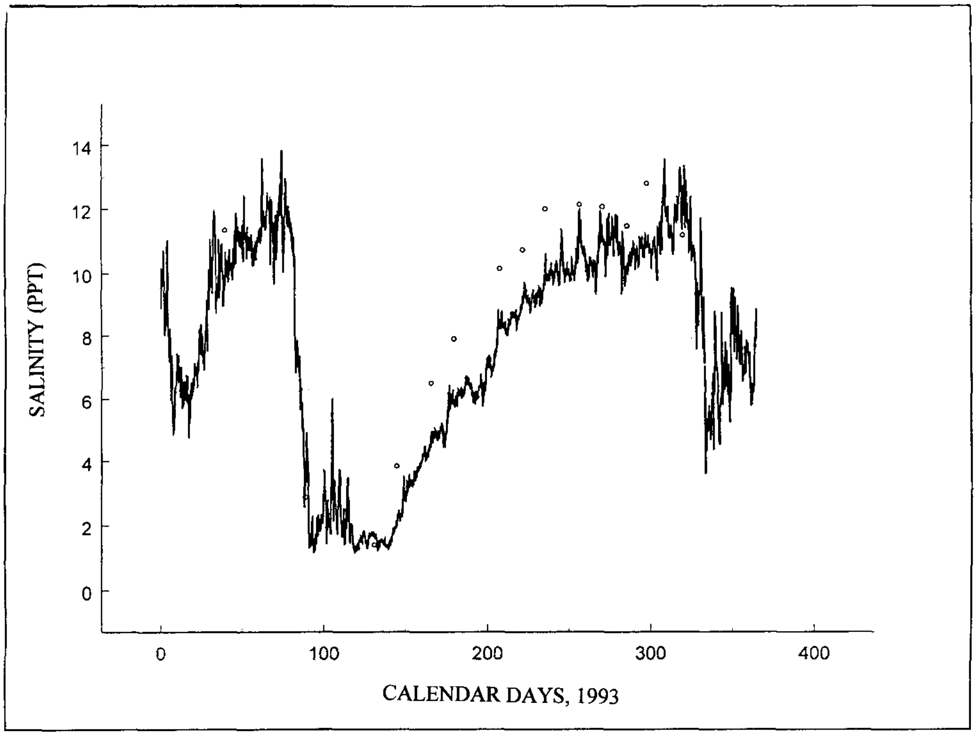
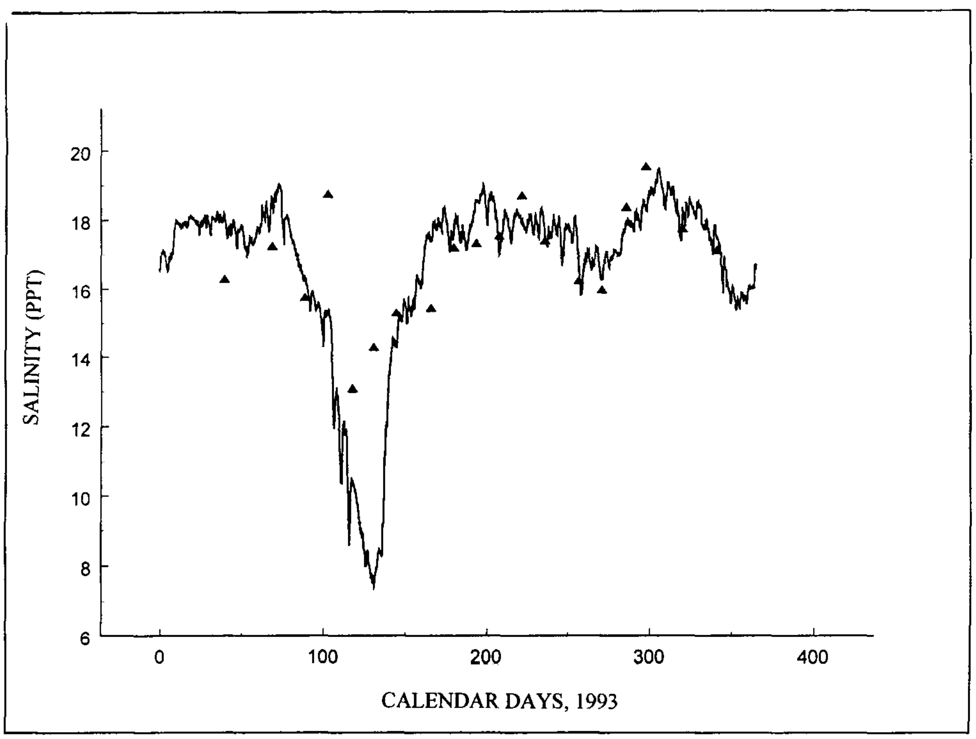


Figure 25. Susquehanna River discharge during spring of 1993

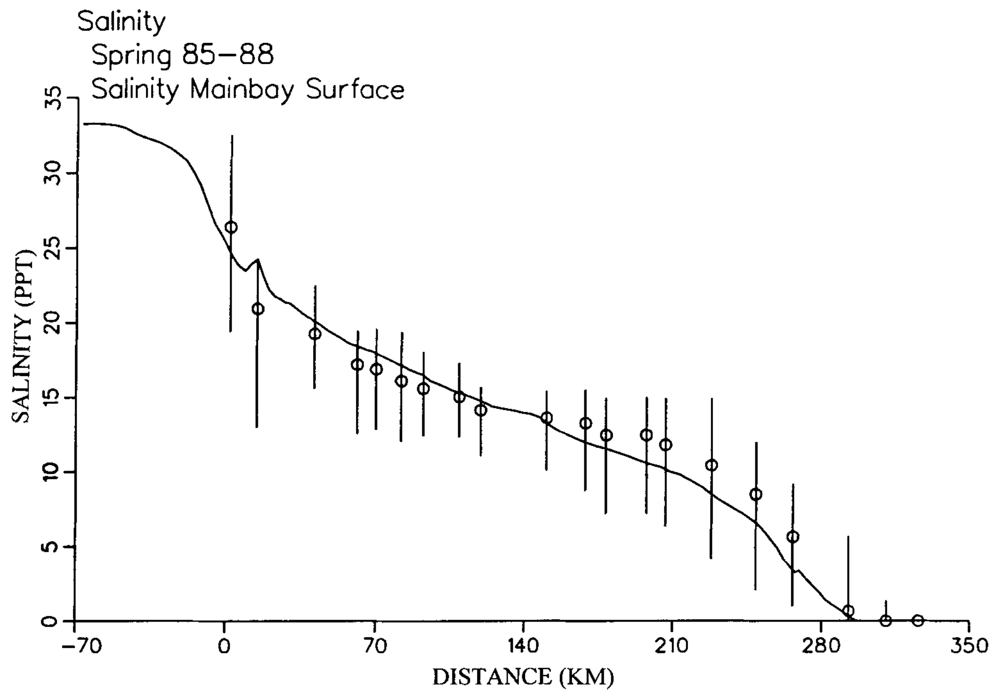


a. Near-surface

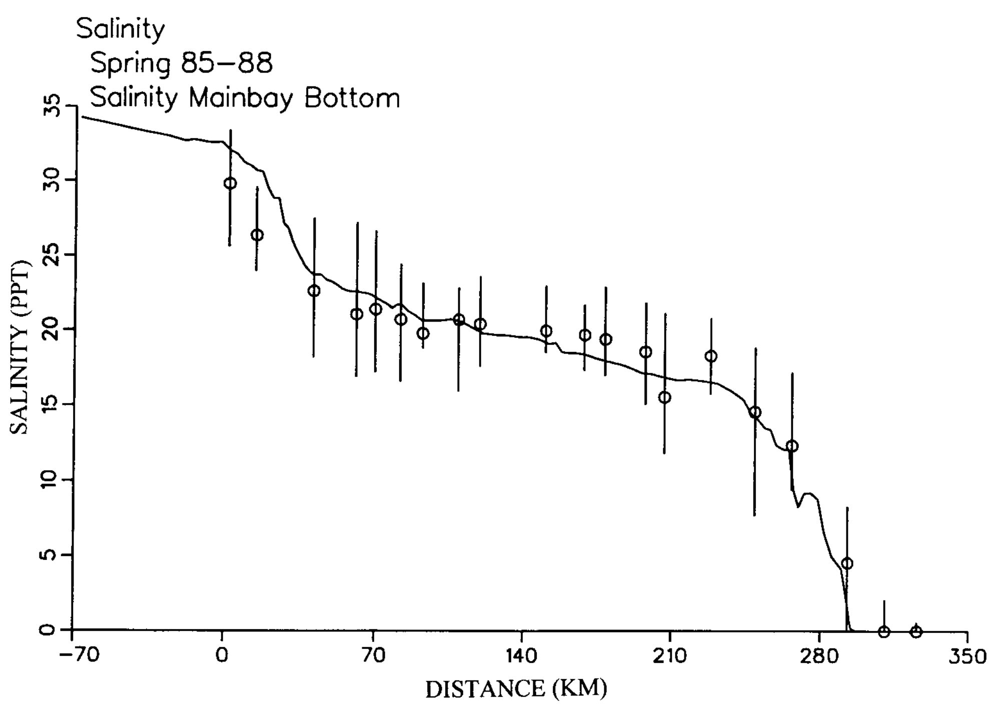


b. Near-bottom

Figure 26. Comparison of observed and computed salinity at CB3.3C during 1993 spring runoff

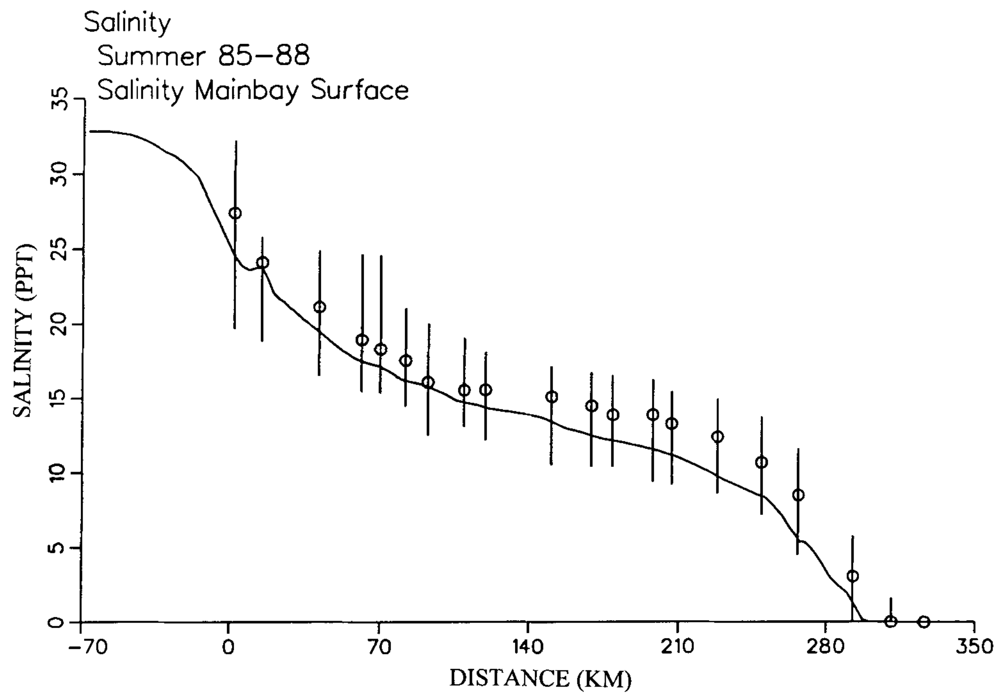


a. Near-Surface

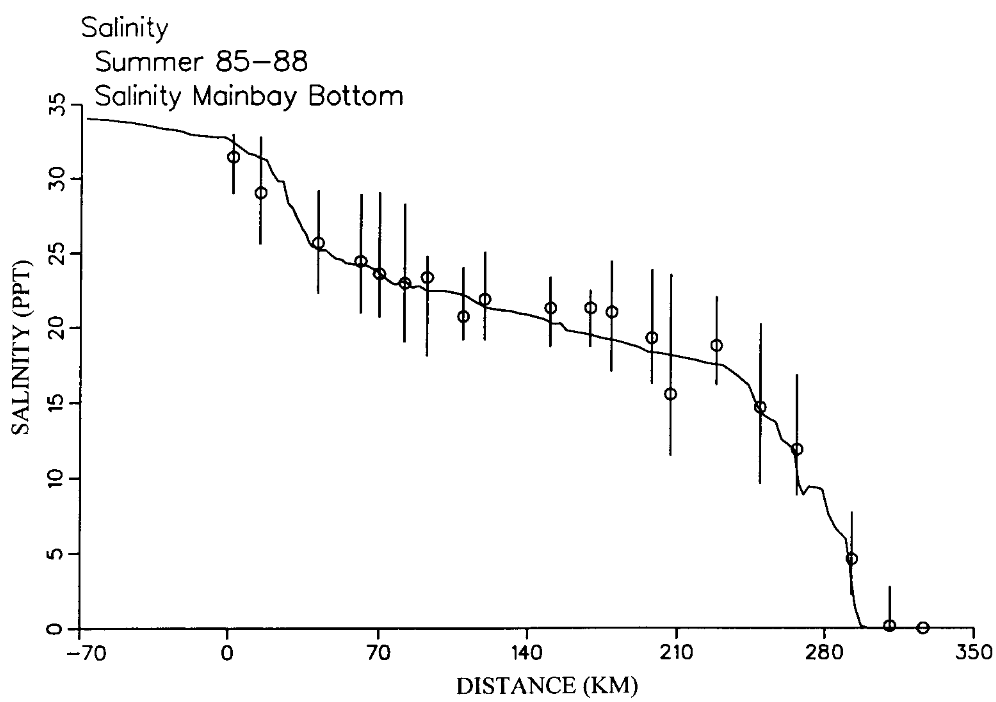


b. Near-Bottom

Figure 27. Seasonal-average salinity transect along main bay for springs of 1985-88



a. Near-Surface



b. Near-Bottom

Figure 28. Seasonal-average salinity transect along main bay for summers of 1985-88

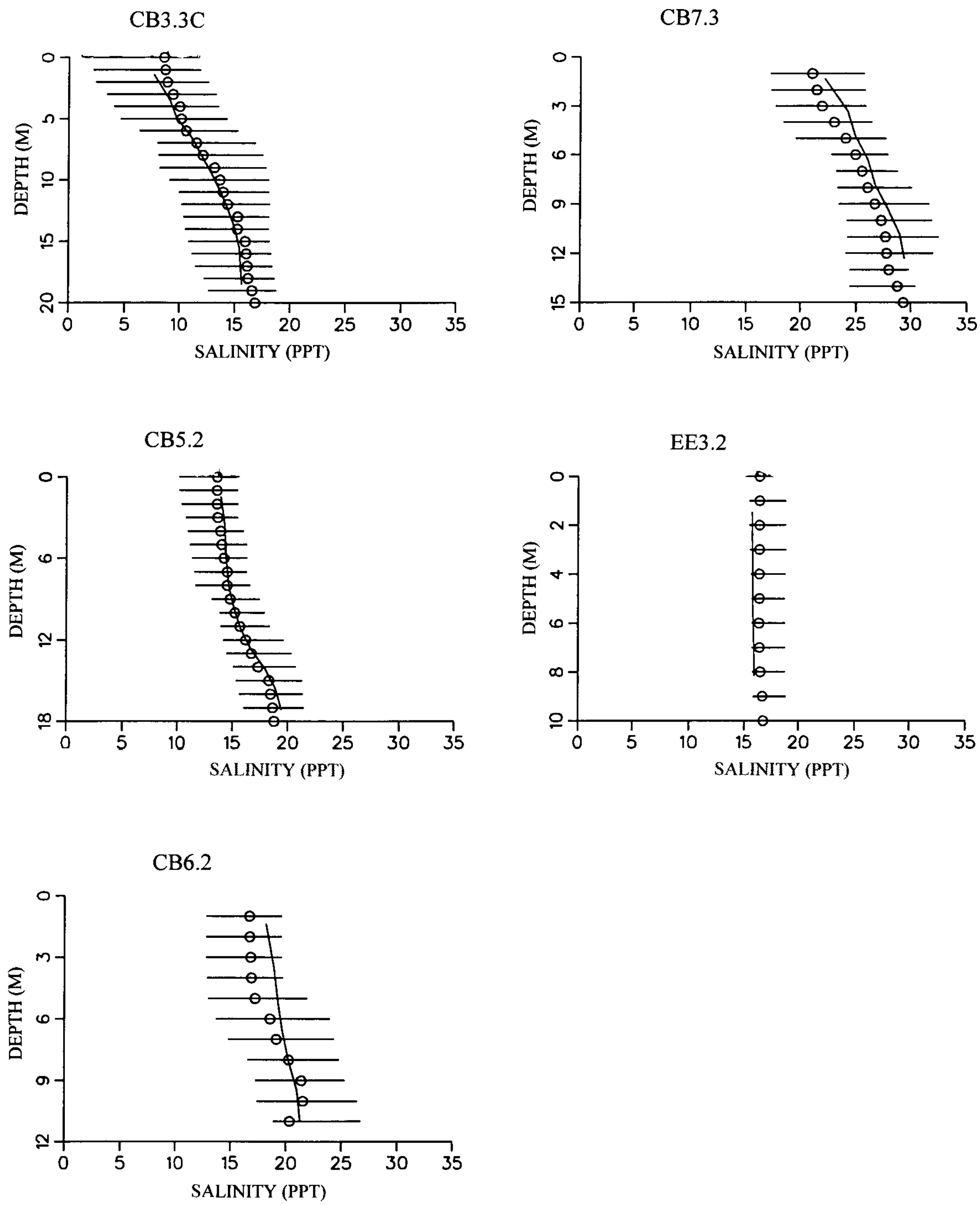


Figure 29. Seasonal-average vertical profiles of salinity for springs of 1985-88

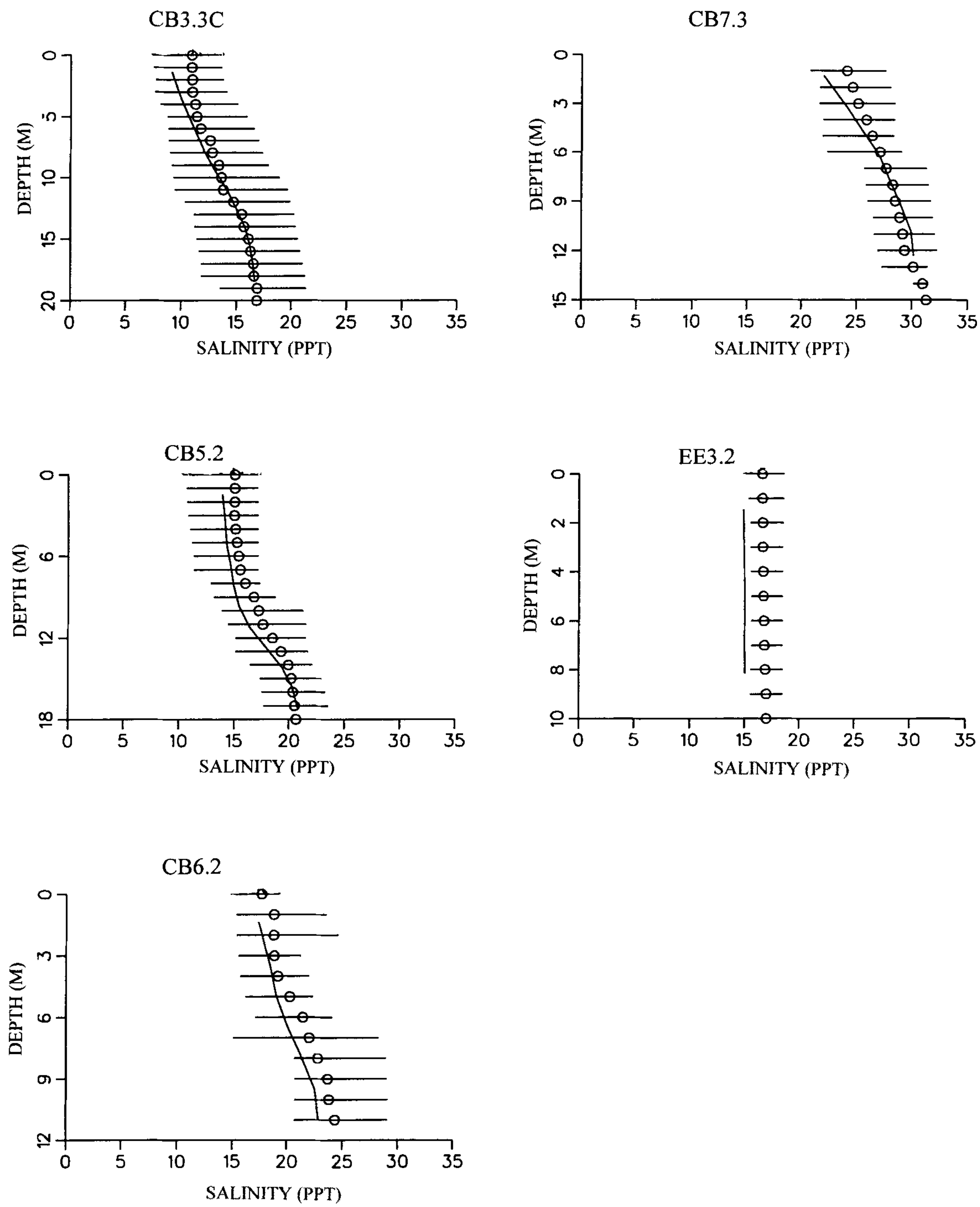
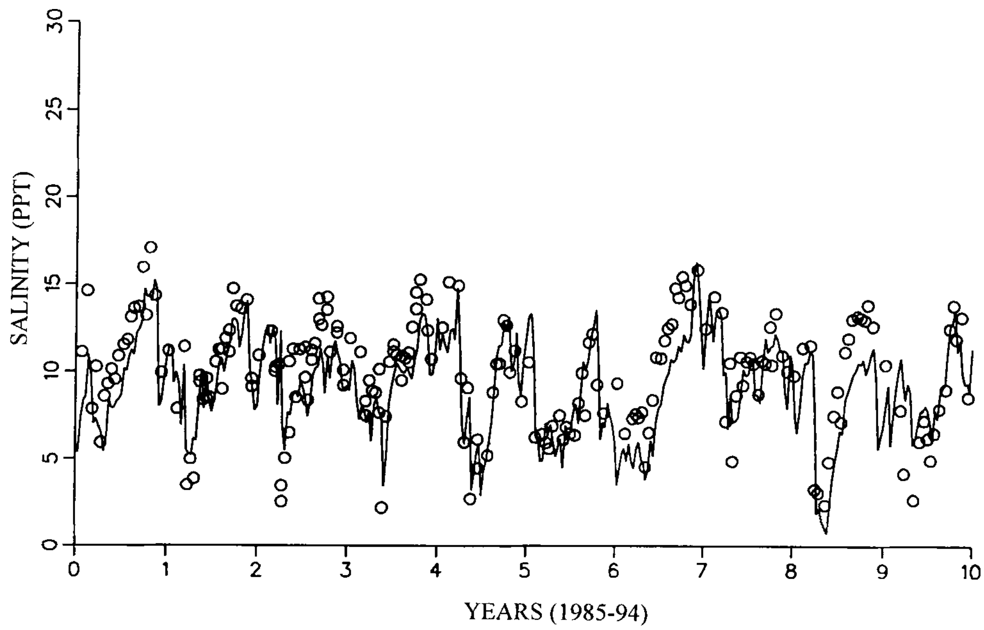
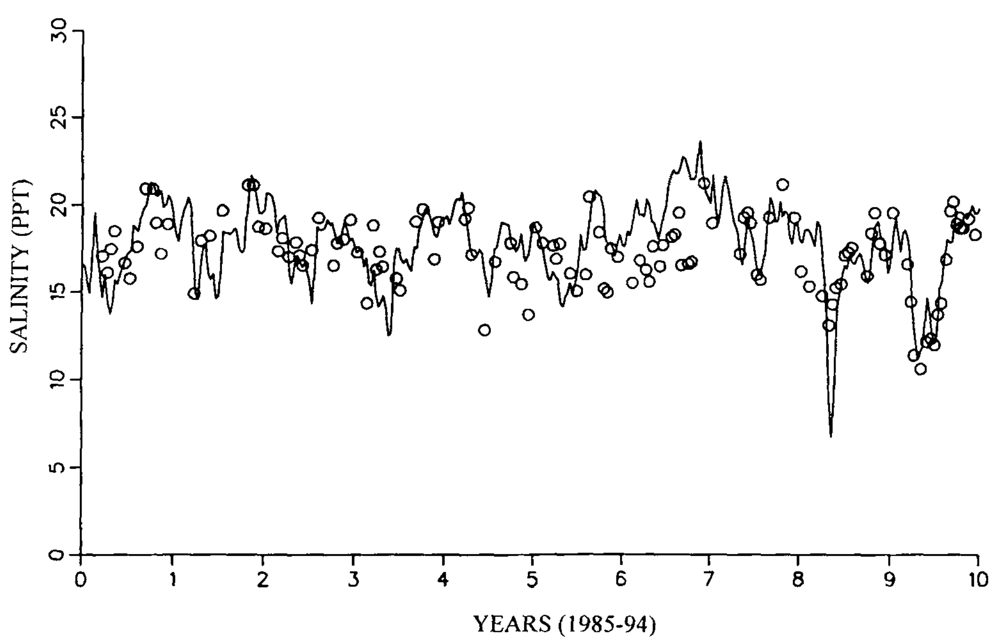


Figure 30. Seasonal-average vertical profiles of salinity for summers of 1985-88

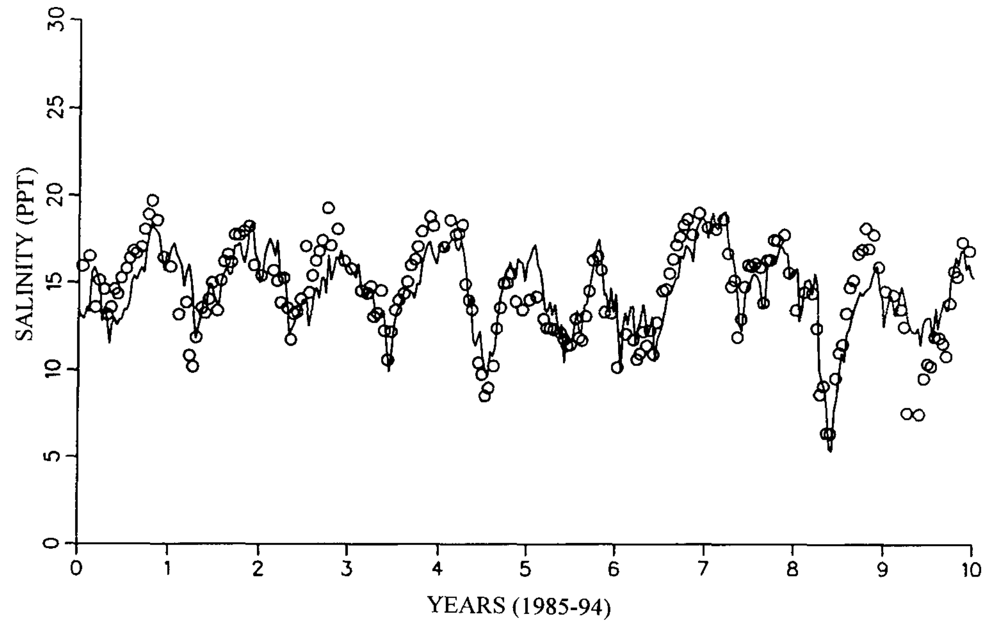


a. Near-Surface

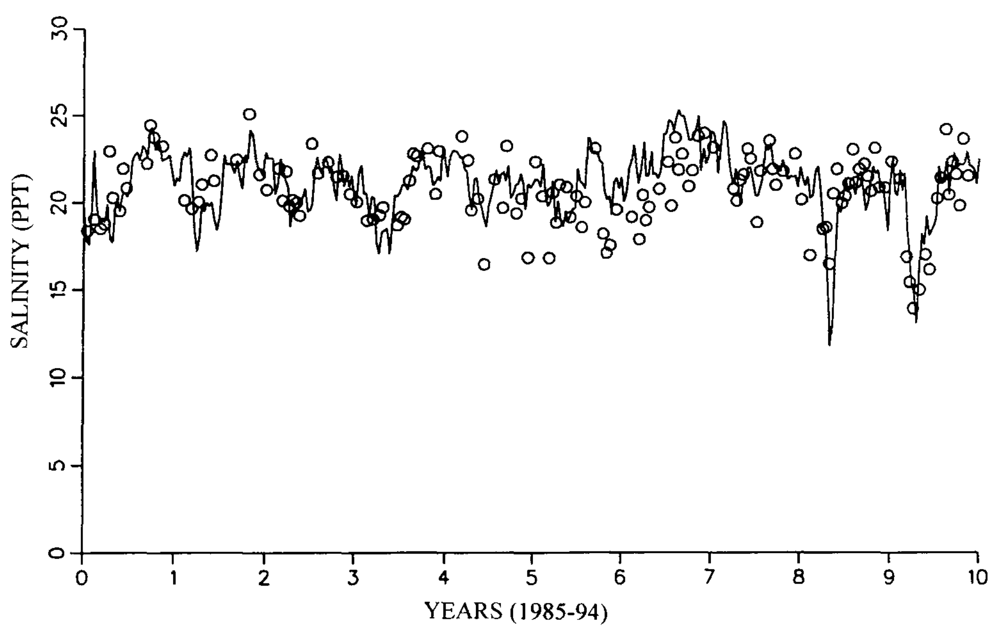


b. Near-Bottom

Figure 31. Ten years of observed and computed salinity at CB3.3C

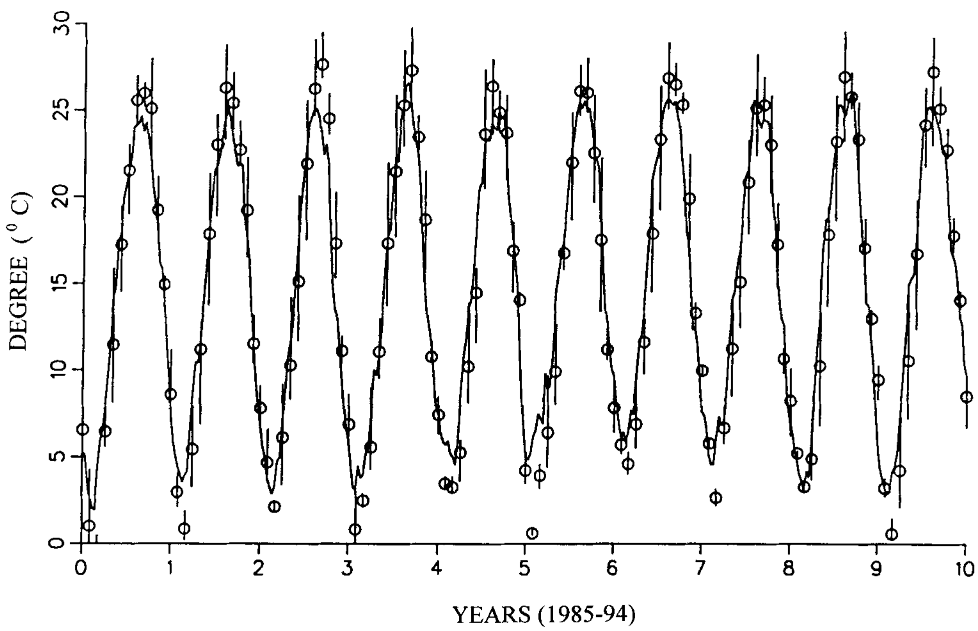


a. Near-Surface

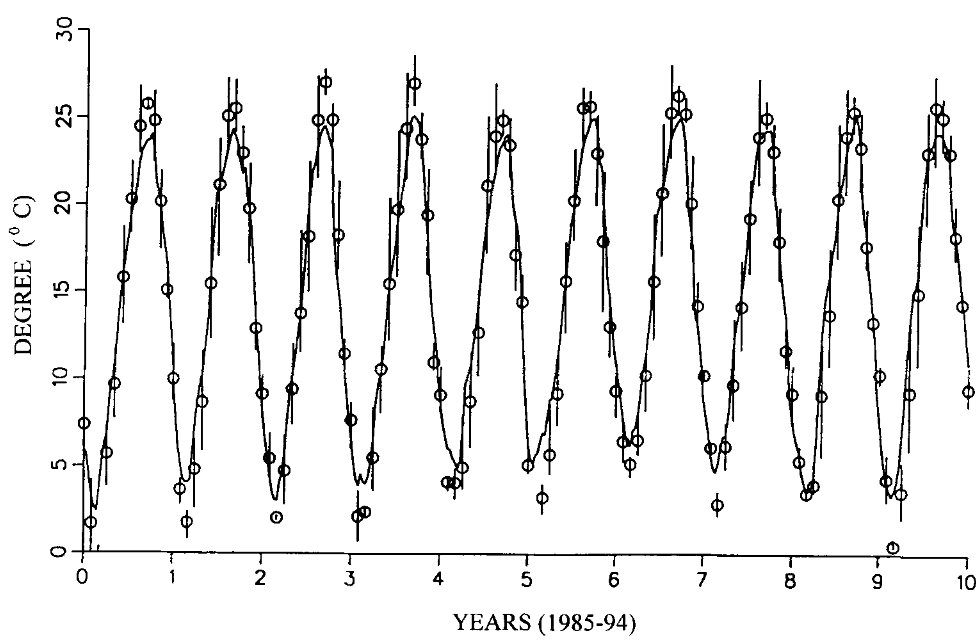


b. Near-Bottom

Figure 32. Ten years of observed and computed salinity at CB5.2



a. Near-Surface



b. Near-Bottom

Figure 33. Ten years of observed and computed temperature at CB4

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