5.0 Hydrodynamic and Salinity Modeling

5.1 Introduction

The spatial and temporal distribution of salinity within the Delaware Estuary has been an important water quality issue for over 60 years. Although salt occurs naturally in Atlantic Ocean water at the bay mouth and in very low concentrations in upland discharges, the estuary system is susceptible to adverse impacts from man-made changes in the factors which affect salt distribution. There are two basic categories of human impacts which can affect salt distribution in the estuary. The first category includes impacts on the supply of freshwater to the system, such as: reservoir construction and management; out of basin transfers of water; and in basin consumptive uses of water. The second category includes factors which may affect the interaction of freshwater inflows with ocean derived saltwater within the estuary, such as changes to the three dimensional geometry of the estuary. The proposed deepening of the Delaware River navigation channel falls within the second category.

In the region from Trenton (RM 134) downstream to Wilmington (RM 70), Delaware River water is utilized for a number of industrial and municipal water supply purposes. The City of Philadelphia obtains its municipal water supply by withdrawal of river water at Torresdale (RM 110). Many industrial users directly obtain both process and cooling water from the river in the Trenton to Wilmington reach. Above RM 98, the river provides a portion of the recharge to aquifers which supply groundwater in the Camden Metropolitan area in New Jersey. This heavily urbanized area of the river is thus sensitive to increases in salinity which might adversely affect industrial and municipal water uses, particularly under drought conditions. Salinity is also a key factor regulating the distribution of both fauna and flora in an estuarine environment. While salinities fluctuate seasonally and from year to year, a permanent shift in salinity patterns could adversely impact a variety of ecosystem components, depending on the magnitude of the change. In order to estimate the potential for the proposed channel deepening to affect salinity distribution, a model-based approach was adopted.

5.2 Objectives

The principal goal of the modeling effort was to identify and quantify any impacts of the proposed 5 foot channel deepening on spatial and temporal salinity distribution. It was considered necessary that a number of modeling scenarios be developed to represent a range of boundary and forcing conditions of potential importance to both human and non-human resources of the Delaware

Estuary.

5.3 Previous Investigations

A number of research efforts have been performed during the past five decades, and particularly within the last ten years, which have contributed to the understanding of the principal physical processes relevant to circulation and salinity distribution in the Delaware Estuary. Prior to any decision to develop a new model specifically to address the impacts of the proposed channel deepening, a careful review of recent and historic research was performed to determine if any previous research or existing modeling methodology suited the specific needs of this study. The following section presents an overview of significant research efforts reviewed for potential applicability to this study.

Mason and Peitch (1940) presented a report titled "Salinity Movement and its Causes in the Delaware River Estuary" on work performed for the Sun Oil Company, Marcus Hook, Pennsylvania. Their research was motivated in part by proposals in 1930 to divert water from the upper basin of the Delaware River to New York City, which coincided with drought conditions occurring in the Delaware Basin between 1929 and 1932. They conducted an empirical investigation of salt movement in the estuary in response to a range of freshwater inflows during the period 1930 to 1936. This work resulted in calculated mean discharges required to "stabilize" the location of the 50 ppm isochlor at a range of locations from Torresdale downstream to Artificial Island. The data utilized in this study predated the channel modifications accomplished between 1939 and 1942. This work deepened the navigation channel to 40 feet from the bay mouth to the Philadelphia Navy Yard (RM 92).

Durfor and Keighton (1954), and Keighton (1966), present results of empirical studies performed by the US Geological Survey (USGS). These studies documented the chemical characteristics of the Delaware River between Trenton, NJ, and Marcus Hook, PA, based on analysis of hundreds of water samples collected between 1949 and 1952. This work was used to develop relationships between the electrical conductivity of the water and its total dissolved solids and chlorinity concentrations, and is still considered valid. The conductivity-salinity and conductivity-chlorinity relationships are important because the existing US Geological Survey (USGS) and DRBC salt front monitoring program in the estuary is based on measurement of conductivity. Conductivity values are then converted to chlorinity using Keighton's relationships. The later work by Keighton documented the continuing evolution of knowledge of the interaction of freshwater discharges and salinity distribution, based on flow and salinity data obtained between 1949 and 1963, for then-existing conditions of channel and estuary geometry.

The Philadelphia District of the US Army Corps of Engineers initiated a "Long Range Spoil Disposal Study" in 1967 to investigate short- and long-term solutions to the problem of Delaware River dredged material disposal. A comprehensive set of prototype observations was collected over three periods in 1968 and 1969 to document currents, salinity, and suspended sediment concentrations. These measurements were obtained primarily to assess the impact of these parameters on the high shoaling rate experienced in the Marcus Hook range of the navigation channel. The data obtained in this study provide quantitative data on water, salt, and suspended sediment fluxes during the range of hydrologic conditions occurring in the observation periods.

Although each of the previously discussed research efforts contributed to the improvement of knowledge regarding salinity distribution and the importance of freshwater inflow for the Delaware Estuary, none of these studies was capable of providing insight into how salinity distribution might respond to changes in estuary geometry. The investigations summarized in the following paragraphs differ from the preceding studies in that they utilize prototype data to develop models with the ability to predict changes in circulation and salinity resulting from changes in estuary geometry and boundary conditions.

The Delaware River Basin Commission (DRBC) has supported the development and evolution of a 1-dimensional salinity model for the Delaware Estuary for the past 20 years. The model, referred to as the Transient Salinity Intrusion Model (TSIM), represents the geometry of the estuary with a series of 100 cross sections between the bay mouth and Trenton. In this model, flow and salt transport are treated as laterally and vertically averaged at each section. The model has been used by DRBC as a planning tool for simulation of various scenarios of drought management and reservoir operation. The model has also been used in a number of studies to assess the impacts of potential changes in forcing functions, including sea level rise, depletive uses, and out of basin transfers.

During the Feasibility Study phase for the proposed deepening project, the Philadelphia District contracted with DRBC in 1988 to apply the TSIM in assessing the impacts of the proposed channel deepening under hydrologic conditions of the drought of record, 1961 through 1965, but with 1986 depletive uses assumed and the present reservoir regulation scheme in place. The model predicted that the maximum intrusion of the "salt front", defined as the seven-day average location of the 250 ppm isochlor, during a repeat of year 1965 hydrologic conditions would extend 1.3

miles further upstream (to RM 97.8) with the 45 foot deep channel as compared to the location with the existing 40 foot channel. Other less severe hydrologic conditions represented by years 1961-1964 would cause lesser changes. The model also predicted that the maximum 30-day average chlorinity at RM 98 would increase from 130 to 143 ppm during October 1965, the period with the highest observed salinity encroachment during the 1961 to 1965 drought. It should be noted here that present water quality standards supported by DRBC call for 30-day average chlorinity at RM 98 to be below 180 ppm. This standard was adopted to provide protection against salinity intrusion into aquifers exposed on the river bottom above RM 98. Above RM 98, there are significant exposures of the Potomac-Raritan-Magothy (PRM) aquifer which supply groundwater for the Camden, New Jersey, Metropolitan area. It is also noted that DRBC has discussed a more restrictive 30-day chlorinity standard, 150 ppm chlorinity, for RM 98.

Wong and Garvine (1984) and Wong (1991) present analyses of tide and current observations in Delaware Bay, the Chesapeake and Delaware (C&D) Canal, and upper Chesapeake Bay. Their studies document the influence of the C&D Canal on currents and water levels in the Delaware estuary at sub-tidal frequencies (i.e. for periods longer than the 12.4 hour tidal cycle.) The work of Wong and Garvine, and other investigators from the University of Delaware, has shown that atmospheric forcing (wind) on the continental shelf and over Chesapeake Bay exerts a significant effect on transport processes in the upper portion of Delaware Bay. Wong developed a linearized, frequency-dependent analytical model to simulate the impacts of the C&D Canal on Delaware Bay at sub-tidal frequencies. Wong's work also showed that at tidal frequencies the circulation in Delaware Bay is largely controlled by the ocean tides occurring at the mouth of the bay.

Galperin and Mellor (1990) used the extensive set of prototype circulation (currents, tide, salinity, etc.) data collected by the National Ocean Service (NOS) in 1984 and 1985 to develop a 3-dimensional circulation model of the Delaware estuary and adjacent Atlantic Ocean shelf. Their model utilized a 1 km square grid in the Delaware Estuary and a 5 x 4 km grid on the shelf. The model was calibrated to the NOS 1984-85 observations, and used to investigate sub-tidal residual circulation and three-dimensional flow fields.

Walters (1992) investigated salt transport processes of Delaware Bay in response to potential climate-driven sea level changes. Walters developed a 3-dimensional finite-element model with forcing provided by harmonic (synthetic mean tidal) water levels at the bay mouth, under low flow (5,000 cfs) conditions. The model was used to predict the tidal hydraulic and salinity changes associated with a potential 1 meter rise in sea level.

DiLorenzo et al (1992) developed a model for USEPA's Delaware Estuary program to investigate the effects of historic dredging on the tidal hydraulics and salinity distribution of the Delaware estuary. The investigators also evaluated the salinity impacts associated with the deepening of the Delaware River navigation channel to 45 feet. The model used in this investigation was the 3-dimensional finite element RMA-10, which was operated in vertically-averaged (2-D) mode. The model was calibrated to December 1985 and March-April 1987 prototype data sets. The model was then used to hindcast tidal hydraulic and salinity conditions associated with the geometry of the estuary in 1890, which predated significant estuary geometry changes resulting from channel dredging and associated shoreline modifications (disposal area construction).

Model results showed that there were significant impacts resulting from the channel deepening and shoreline changes accomplished between 1890 and the present. For example, the model successfully reproduced the observed historic increase in tidal range at Trenton, New Jersey from 4 feet in 1890 to 8 feet presently. The model also showed increases in salinity on the order of 5 to 25 percent at a number of locations in the middle portion of the estuary between 1890 and the present under modeled boundary conditions. In contrast, the model comparisons of the existing estuary geometry (40 foot channel) with the 45 foot channel in place showed insignificant changes in tidal hydraulic parameters and salinity under the range of boundary conditions simulated.

The research described in the preceding paragraphs was carefully reviewed for potential applicability to the present study. It is reiterated here that principal objective of modeling in the PED phase was to <u>define impacts on salinity and circulation caused by the proposed channel modifications</u>. These modifications consist of deepening the navigation channel from 40 to 45 feet across its full width, which is 1,000 feet between RM 7 and RM 41, 800 feet from RM 41 to RM 95, and 400 to 500 feet from RM 95 to the upstream limit of proposed deepening, RM 99. This review showed that although there have been significant improvements in our understanding of and predictive capabilities for salt transport and distribution processes in the Delaware Estuary, there was no modeling tool available in 1992 (the start of Pre-Construction Engineering and Design (PED) study scoping) which uniquely met the specific requirements of this study, i.e., the ability to evaluate the salinity and circulation impacts of 5 feet of channel deepening under a wide range of inflow and tidal boundary conditions. As a result, it was determined that a new, project-specific model was required.

5.4 Modeling Methodology Adopted

The Philadelphia District coordinated with the Hydraulics Laboratory (HL) of the US Army Corps of Engineers Waterways Experiment Station (WES) to discuss options for model development and application to meet the specific needs of the PED study. Based on previous work at WES for the Philadelphia District and others, the decision was made to apply the 3-dimensional numerical hydrodynamic/salinity model, CH3D-WES (Curvilinear Hydrodynamics in Three Dimensions), in this study.

CH3D-WES simulates the most important physical factors affecting circulation and salinity within the modeled domain. As its name implies, CH3D-WES makes computations on a curvilinear, or boundary fitted, planform grid. Physical processes affecting baywide hydrodynamics that are modeled include tides, wind, density effects (salinity and temperature), freshwater inflows, turbulence, and the effect of the earth's rotation. The representation of vertical turbulence is crucial to a successful simulation of stratification in the bay. The boundary fitted coordinates feature of the model provides enhancement to fit the scale of the navigation channel and irregular shoreline of the bay and permits adoption of an accurate and economical grid schematization. The vertical dimension is Cartesian which allows for modeling stratification on relatively coarse horizontal grids.

The following sections of this report present an overview and summary of the 3D hydrodynamic/salinity modeling studies performed to assess the impacts of channel deepening.

5.5 Prototype Data Collection Program

In order to assure the validity of the model to assess potential effects of channel deepening on salinity and circulation, it was first necessary to test the ability of the model to reproduce flow and salt distribution under existing channel geometry (40 foot channel). The prototype data necessary for model validation include: freshwater inflows; tides at the Delaware Bay entrance, at Annapolis, Maryland (MD), and at various interior stations; wind data at one or more stations; and currents and salinity at locations throughout the system. With such a large area to be modeled, there is a lack of historic synoptic data sets covering Delaware Bay, the Chesapeake and Delaware Canal, and upper Chesapeake Bay suitable for model validation. Therefore, a one-year prototype data collection program was proposed and implemented by the WES Hydraulics Laboratory, Prototype Measurements Branch. A separate WES technical report ("Delaware Bay Field Data Report", March 1995) was prepared to document this effort.

The field data collection program consisted of short term and long term continuous recording of tide, velocity, temperature, and salinity data. Two short term (two-week) field data sets covered the periods 12-25 October 1992 and 19-30 April 1993. These data sets were collected from boats. The two-week periods were utilized to obtain data representing the range of tidal conditions during neap-spring tidal cycles. The data collection stations were positioned at various locations from Wilmington, Delaware to the entrance of Delaware Bay, as well as within the C&D Canal and in Upper Chesapeake Bay. A total of seven data collection ranges with 2 to 4 stations per range were monitored for current and salinity at 3 to 5 depths.

The long-term data collection program was performed over the October 1992 to October 1993 period. A total of ten moored stations was maintained at various times throughout Delaware Bay, the C&D Canal, and the Upper Chesapeake Bay to provide data on water surface elevations, velocity, and salinity at an interval of 15 minutes. Due to equipment problems and the loss of several instruments, all stations did not record data for the complete year. A more complete discussion of model verification and the application of the prototype data sets is presented in a later section on "Model Verification".

5.6 Interagency Coordination

A series of open workshops was held periodically at the District office in order to bring together members of the research and regulatory communities and interested members of the public with the District and WES investigators to discuss the proposed modeling plan, and to identify areas and conditions which are considered to be of particular importance. These workshops provided a mechanism for discussion and comment on the progress and focus of the modeling effort. This process offered District and WES staff a continuing insight into the concerns of other agencies in order to assure that the modeling effort addresses the most important issues associated with channel deepening. This process also assured that interested parties, in particular the agencies with review and comment authority on the project and final report, had the opportunity to participate actively in addressing the most significant circulation, salinity, and water quality issues related to the proposed deepening. Workshops were held in July 1992, April 1993, August 1993, December 1993, June 1994, and June 1995. At the June 1994 coordination workshop, channel deepening production scenarios were determined and ranked in importance. These scenarios address the most important combinations of assumed boundary conditions, including inflow, season, reservoir regulation schemes, and sea level, deemed to be the most critical to the potential for changed/increased salinity intrusion.

5.7 Model Sensitivity Tests

Before model verification to prototype events was initiated, several sensitivity studies were conducted in order to optimize the application of the model to relevant salinity and circulation issues. These studies included tests of grid and computational time step convergence, and a sensitivity test to assess the impact of channel deepening on conditions at the mouth of Delaware Bay.

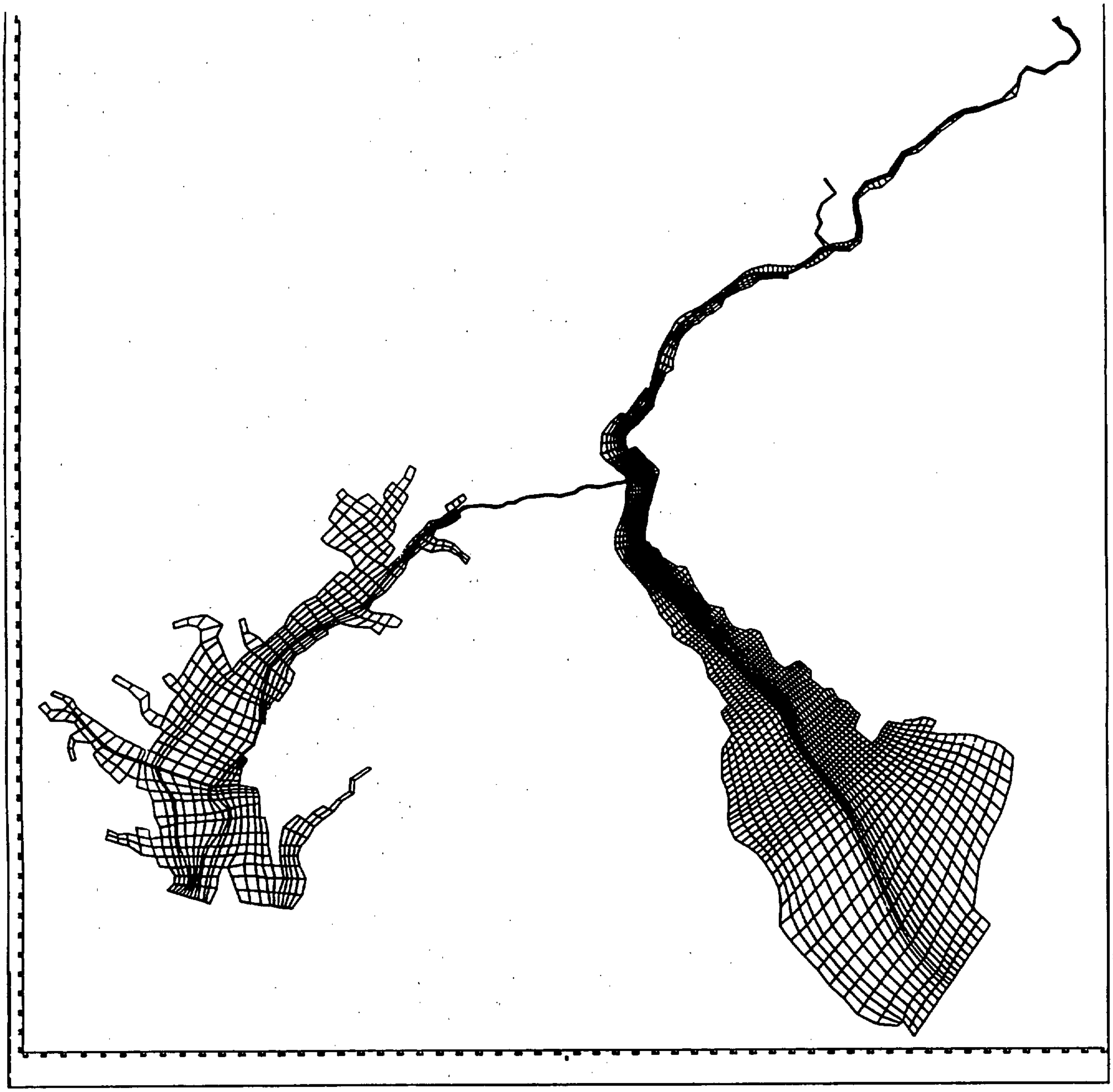
5.7.1 Grid Convergence Results

The initial planform boundary-fitted grid for the modeled system was generated with model grid lines which followed the navigation channels in the Delaware and Upper Chesapeake Bays and represented the geometry reasonably while keeping the total number of grid cells to a minimum. Although the grid was considered suitable for this study based upon experience, an integral part of grid generation for any numerical model study is to assess the impact of the grid on the computed solution.

To address this question, the initial grid resolution was doubled in lower Delaware Bay, with the results from this grid compared with results obtained from the initial grid. Computed results from both grids at selected locations were virtually identical. Thus, based upon the grid convergence runs, the initial grid was considered suitable for this study. However, coordination with resource agencies revealed that additional spatial resolution was desired in the lower bay where oyster beds exist, and in the vicinity of Philadelphia where water supply intakes and groundwater recharge areas exist. Thus, the grid presented in Figure 5-1 was selected as the final grid to be utilized in this study. This grid contains 3,500 planform cells. With a maximum of 18 layers in the vertical, the total number of computational cells is 13,000. Each of the vertical layers is 5 feet thick, except the top layer which varies in thickness with the tide. Typical horizontal dimensions of the grid in the Delaware River are 400 feet by 1,000 feet, whereas those in the lower bay are 1,000 feet by 3,000 feet.

5.7.2 Time Step Convergence Results

As is the case with any numerical model, the solution scheme employed in CH3D-WES contains truncation errors associated with not only the spatial discretization (described above) but also



DELAWARE RIVER
MAIN CHANNEL DEEPENING PROJECT

FINAL MODEL GRID

U.S. Army Corps of Engineers,
Philadelphia District

Figure 5-1

the computational time step. Thus, there is a need to assess the impact of the time step on the solution being computed. This was accomplished by making model runs with decreasing time steps and comparing computed results at several locations throughout the computational grid. Results showed that there was a noticeable difference between the solution generated using a 4 minute time step and that generated using a time step of 2 minutes. However, the solutions generated using a 2 minute step and a 1 minute time step were virtually identical. Results were similar at several locations where comparisons were made. Therefore, all computations were subsequently made using a 2 minute time step.

5.8 Selection of the Tidal Boundary for Delaware Bay

An issue with regard to numerical hydrodynamic/salinity models of estuaries is the appropriate location for the tidal/salinity boundary used to drive the model. The concern is whether the model can be verified with the tidal/salinity boundary at the bay mouth, or if the boundary must be located out on the shelf, away from the localized geometric, hydraulic, and salinity gradients often present at the bay mouth. The field data collection program for this study obtained data for model verification with the seawardmost data collected at the mouth. However, before the observed data at the bay mouth could be used to drive model runs under existing and deepened conditions, the impact of the deepening on conditions at the mouth had to be determined.

To provide insight, computations were made on a numerical grid that extended approximately 50 miles offshore of the bay mouth. Model runs were made with the existing (40 foot) and deepened (45 foot) channels. September 1984 data obtained from Hsieh, Johnson, and Richards (1993) provided a portion of the boundary condition data for the model runs. However, the water surface elevation time-series used to drive the model's open water boundaries were derived from harmonic analysis using Schwiderski's Global Ocean Random-Point Tide (RPTIDE) program (Schwiderski and Szeto, 1981). Tidal elevations along the cross-shore boundaries were linearly interpolated between tidal elevations at the coast and the offshore boundary. Constant salinity was specified along the open ocean boundaries.

Comparison of the water surface elevations at the bay mouth with and without the deepened channel showed difference of less than 0.1 cm. This demonstrated that the deepened channel has negligible impact on the water surface elevations at the bay mouth. Similarly, comparisons of computed near-surface and near-bottom velocities and salinity at the same locations showed a maximum difference in velocity of 0.41 cm/sec, with the maximum difference in salinity of 0.06 ppt. The impact of the deepened channel on velocity and salinity at the bay mouth is thus considered negligible. These results show that since the channel deepening begins approximately 6 miles inside the bay mouth, the impacts on existing flow conditions at the mouth are negligible. Therefore, the numerical grid selected as a result of the grid convergence tests was considered appropriate for use without the ocean segment. The tidal and salinity boundary conditions for all subsequent model runs were specified with observed data at the bay mouth.

5.9 Model Verification

Field data collected during October 1992 and April 1993, along with data from the drought period of June-November 1965, were used to verify the 3-dimensional hydrodynamic/salinity model. Results from the simulations with each of these data sets are presented in the following sections.

5.9.1 October 1992 Simulation

During October 1992 inflow conditions were slightly below long-term averages for this month, with mean discharge on the Delaware River at Trenton, New Jersey approximately 5,000 cfs. Surface and bottom salinity field data indicate that salinity was typically higher by about 2 ppt at the northern (NJ) side of the bay mouth compared to the southern (Lewes, DE) side. Thus, the Lewes salinities were applied at the southern end of the bay mouth and then linearly increased across the bay mouth by 2 ppt at the northern end to approximate the observed lateral salinity gradient. There was no lateral salinity variation prescribed at the Annapolis boundary. There was little vertical salinity stratification at the Delaware Bay mouth during this period, whereas salinity differences between the surface and bottom of the water column at Annapolis, MD were about 5 ppt.

Wind data were available at four locations, namely, Baltimore-Washington International Airport (BWI), Dover (Delaware) Air Force Base, Wilmington International Airport, and Millville (NJ) Municipal Airport. It is important to note that these data are for winds over land. Factors to convert the BWI data to winds over water were obtained from Johnson, et. al. (1991). Factors for the other stations were not available. Thus, after experimentation with various combinations of wind fields it was decided to apply one wind field over the entire grid that was an average of all of the records. The factors for conversion of over land winds to over water winds were selected to be 2.0 for the north-south component and 1.0 for the east-west component.

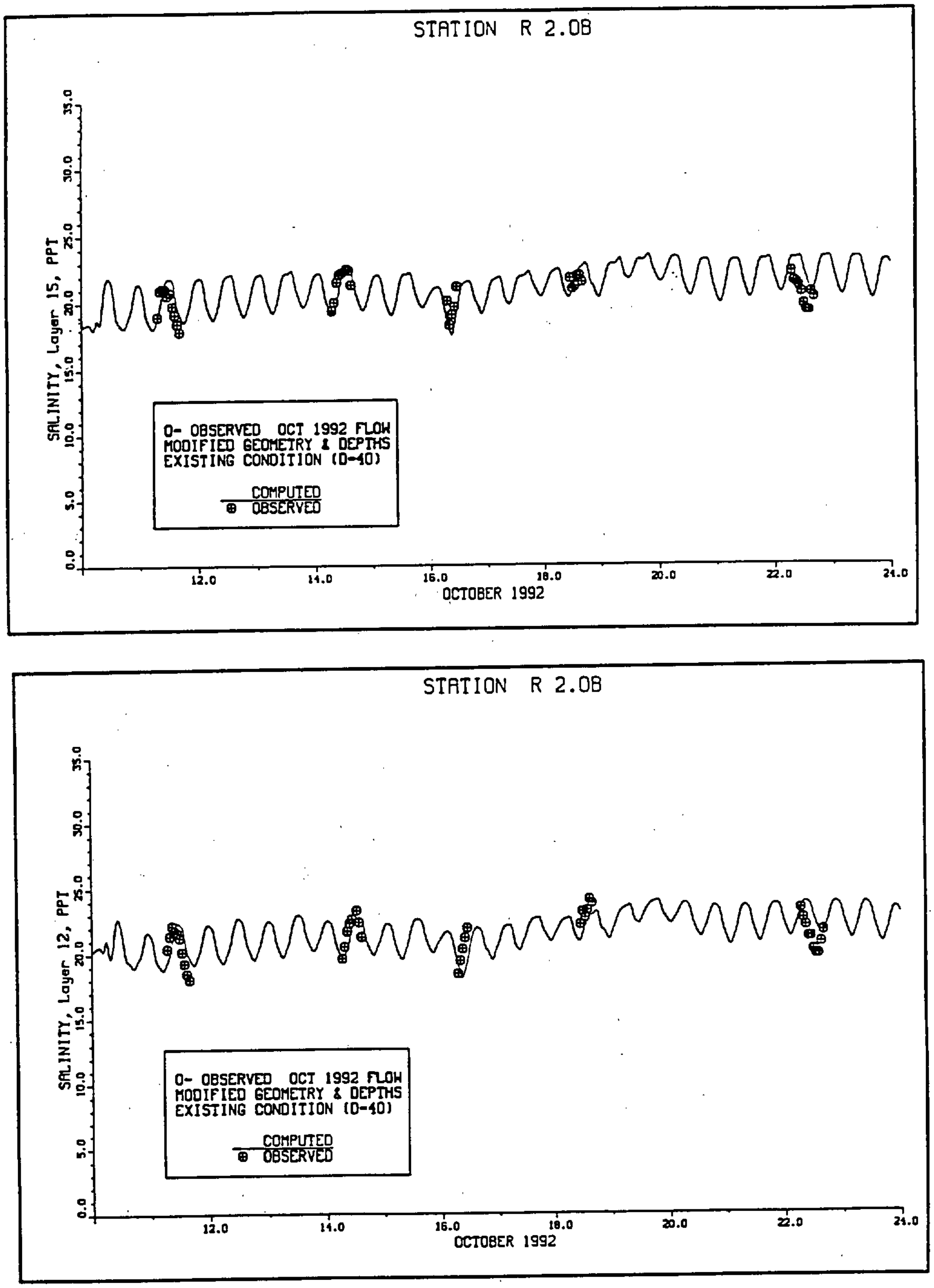
To begin a numerical simulation, the initial states of the model variables must be specified. Generally the starting water surface is treated as flat, and there is no fluid motion. The initial conditions are "flushed" from the system at the speed of a free-surface gravity wave, i.e., the square root of the water depth times the acceleration of gravity. However, since the 3D model is a variable density model, salinity is modeled and directly coupled with the solution for the fluid motion through the water density. Thus, the initial salinity field must be specified. Greater accuracy is required for specifying the starting salinity distribution, since the effects of initial salinity conditions are removed from the system at the speed of the residual flow velocity which is typically on the order of 5-10 cm/sec. Therefore, to reduce the model "spin up" time, the initial salinity field was constructed using available field data, and held constant for the first five days of the simulation. The 3D numerical model was then run for the month of October 1992.

Comparisons of model to prototype water surface elevations and tidal velocities showed that the model successfully reproduced the hydrodynamics of the Delaware Bay-C&D Canal-Upper Chesapeake Bay system, including the flow exchange between the two bays. Comparisons of computed and observed salinities during October 1992 at selected sites are presented in Figure 5-2 (Delaware Bay, RM 30), and Figure 5-3 (Delaware River, RM 69). The absolute value of salinity is reproduced well, as is the longitudinal salinity distribution within the estuary. For these inflow conditions, maximum salt concentrations of about 3-4 ppt occur at Range 7, which is at RM 69. This corresponds well with the data collected for this period and with observations noted by other researchers, e.g., Cohen and McCarthy (1962).

5.9.2 April 1993 Simulation

Inflow conditions during April 1993 were high compared to long-term averages for this period. The freshwater inflow at Trenton peaked at over 100,000 cfs, and averaged nearly 50,000 cfs during the month of April. Unlike the October 1992 conditions, Delaware Bay was partially stratified during April 1993, and Upper Chesapeake Bay was highly stratified. Lateral variations in boundary conditions and initial flow and salinity fields, as discussed for the October 1992 simulations, were also applied for this simulation.

Modeled water surface elevations and velocities were in good agreement with prototype data. Surface and bottom salinity comparisons are presented in Figure 5-4 (RM 45). The effect of the high flow conditions is obvious, as salinity levels are pushed further down the estuary as compared to conditions in October 1992, with a resulting steeper longitudinal salinity



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October 1992 Model and Prototype Salinity, RM 30

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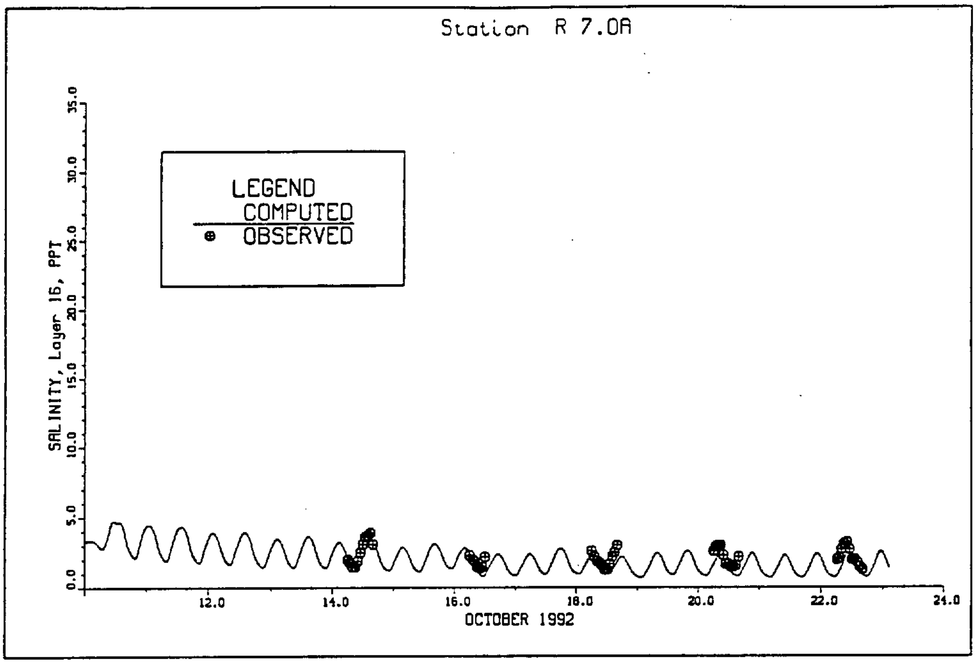
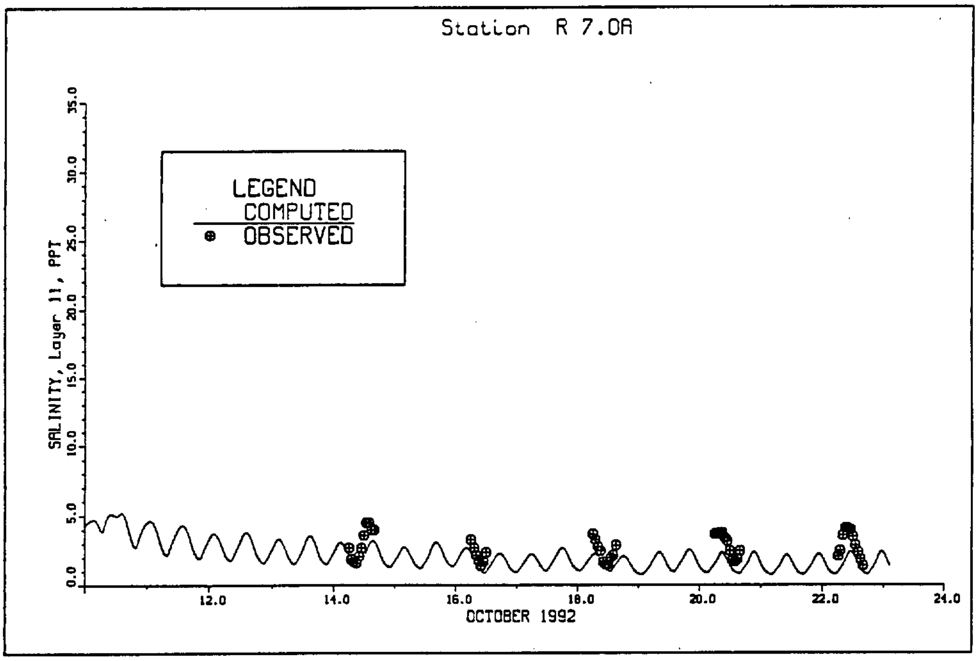
Philadelphia District

Figure 5-2





DELAWARE RIVER
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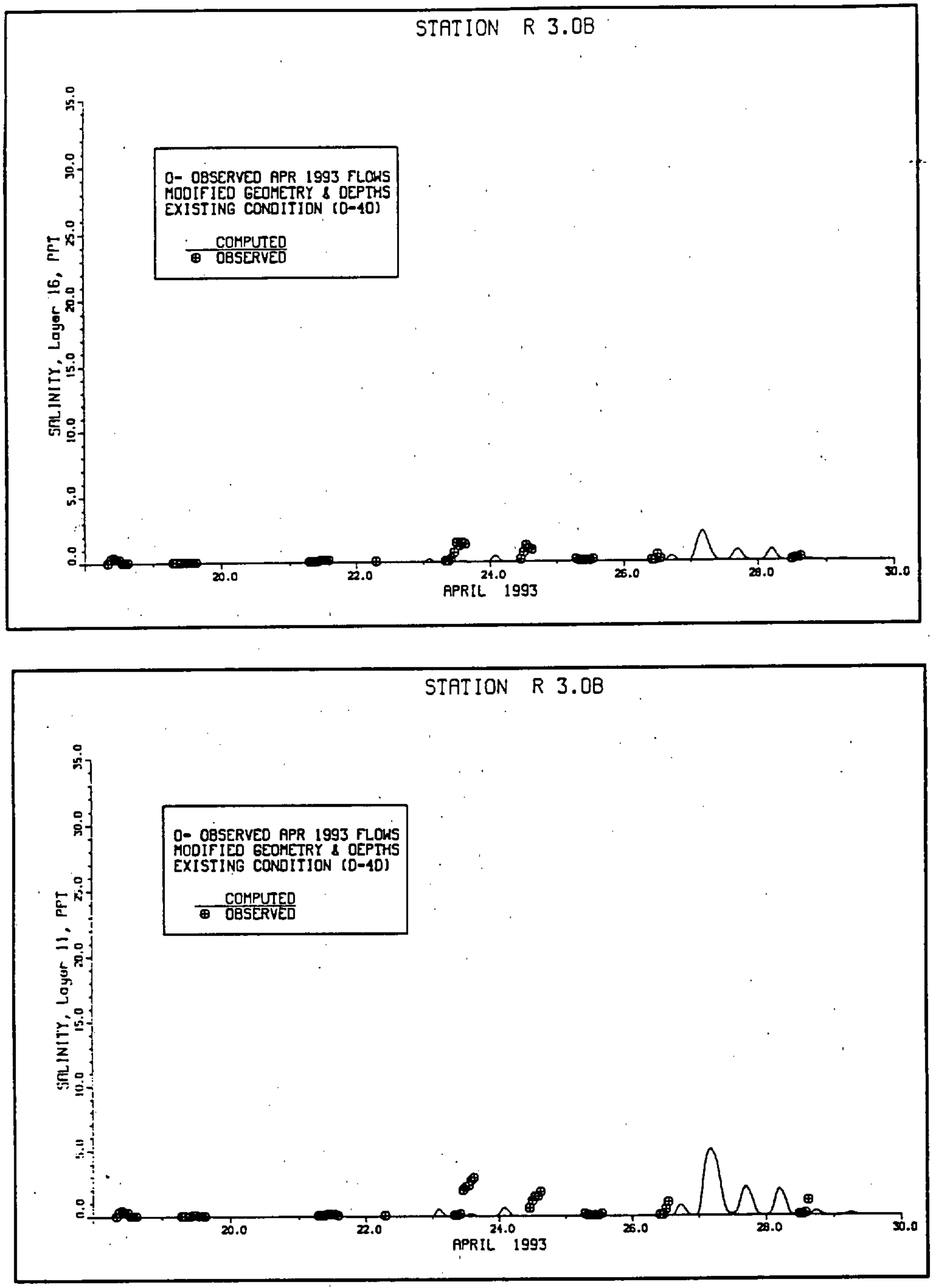
October 1992 Model and Prototype Salinity,
RM 69

U.S. Army Corps of Engineers,
Philadelphia District

Figure 5-3



DELAWARE RIVER
MAIN CHANNEL DEEPENING PROJECT

April 1993 Model and Prototype Salinity, RM 45

U.S. Army Corps of Engineers, Philadelphia District

Figure 5-4

gradient. Vertical salinity stratification predicted by the model under this high-flow condition agreed well with prototype data. For example, at Range 3.0 B (RM 45), differences between near surface and near bottom salinities are computed to be about 5 ppt for some periods, whereas for the lower-flow event in October 1992, salinities over the water column were relatively well-mixed. These results demonstrate that the numerical model responds properly to changing freshwater inflows.

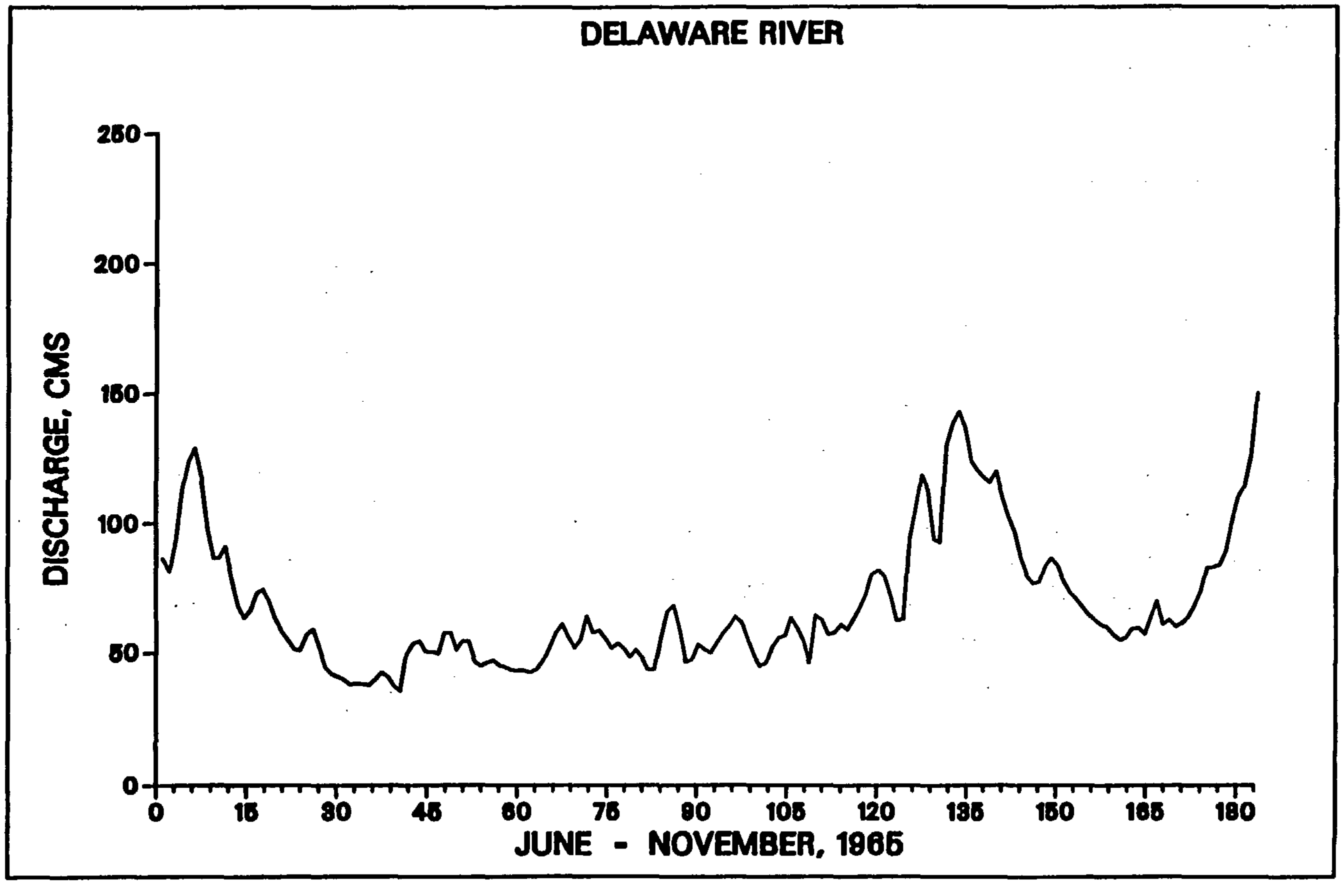
5.9.3 June-November 1965 Simulation

The final flow event reproduced for model verification was the drought period of June-November 1965. The discharge hydrographs for the Delaware and Schuylkill Rivers are presented in Figures 5-5 and 5-6, and show that the extremely low flows were about 20% of the average annual flows. These conditions resulted in the movement of salinity upriver to the vicinity of Philadelphia. Accurately reproducing the conditions which occurred in this period was considered critical because the drought of 1961 to 1966 now represents the DRBC drought planning scenario for the management of basin freshwater resources.

Tide, wind, and salinity boundary condition data for this period were constructed from data obtained by USGS, NOS, DRBC, and NWS. Salinity data at Annapolis, MD were not available for this period. Therefore, salinities were specified to be 19 ppt near the bottom and 15 ppt near the surface by using computed results from the Chesapeake Bay numerical model of Johnson, et al (1991) for flow conditions approximating those occurring during this period. No lateral salinity variation was prescribed at either boundary. For the results presented herein, 21 inflow points were prescribed, with 15 ppm background chlorinity attached to the fresh water inflow at Trenton, NJ and at the Schuylkill River at Philadelphia, PA.

Observed data for comparison with model results were limited for this simulation. No current velocity data were available. Comparison of observed and modeled near-surface salinity was possible for two locations in the upper river, at RM 82 near Chester, Pa, and at the Ben Franklin Bridge in Philadelphia (RM 100). Continuous conductivity data were collected at these locations.

In order to reasonably compare model-predicted salinity values to measured conductivity data in the estuary, it is useful to first review the methods by which chlorinity and salinity are measured or calculated. In sea water, chloride ions constitute a relatively constant fraction of the total dissolved solids (TDS), typically about 55% by weight. Thus "average sea water" with a TDS concentration of about 34 ppt has a chlorinity of about 19

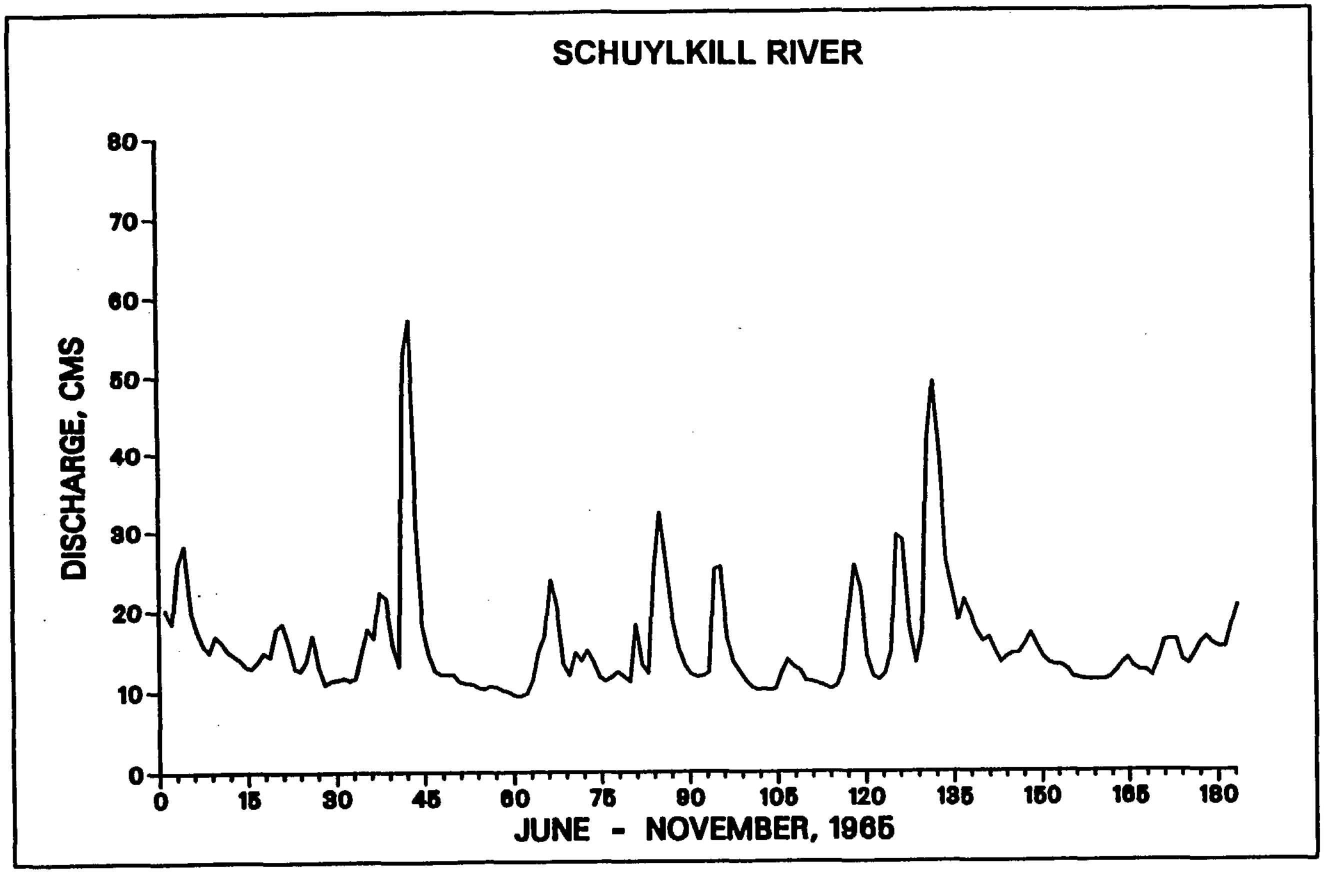


DELAWARE RIVER
MAIN CHANNEL DEEPENING PROJECT

Delaware River Inflow Hydrograph,
June - November 1965

U.S. Army Corps of Engineers,
Philadelphia District

Figure 5-5

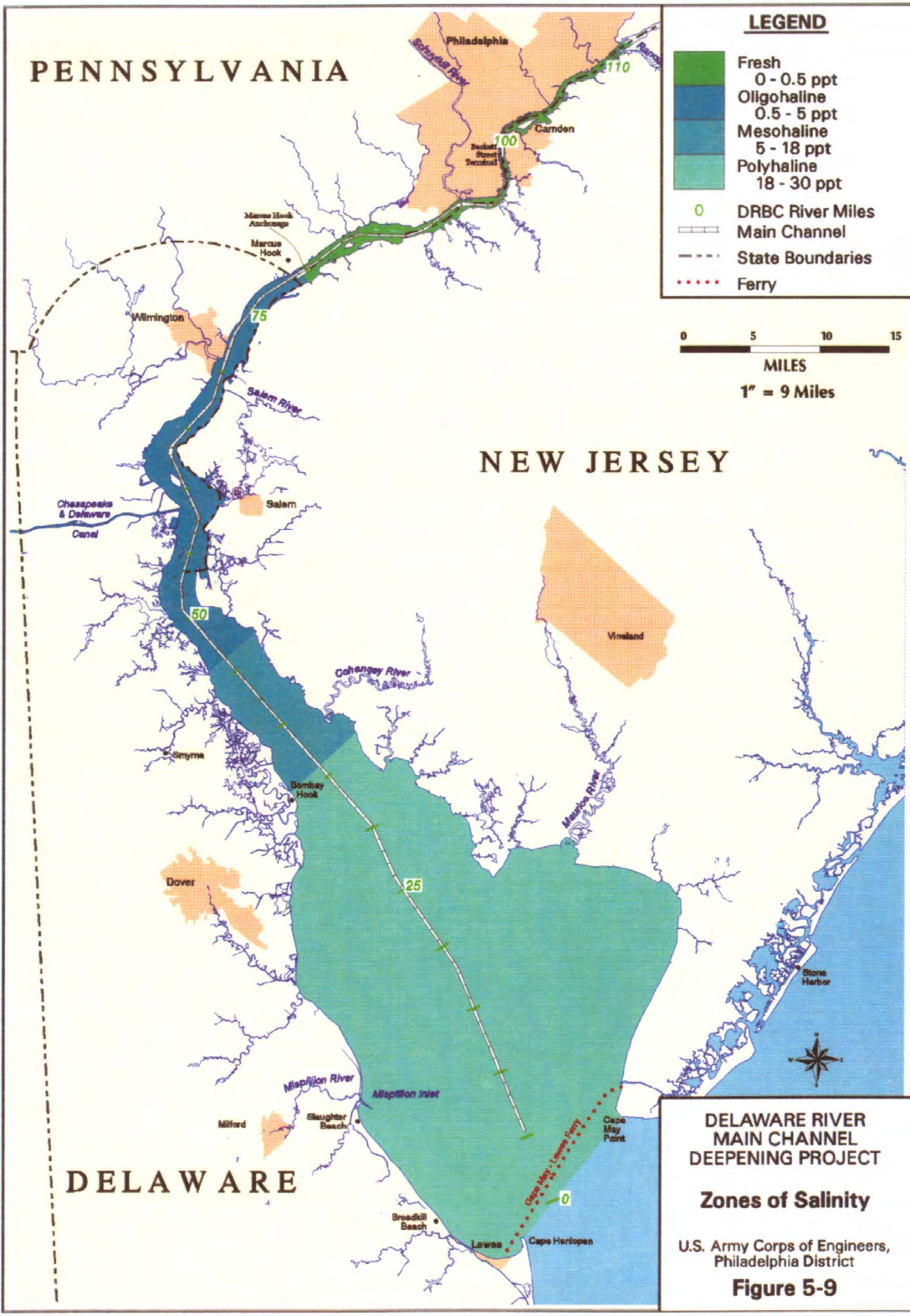


DELAWARE RIVER
MAIN CHANNEL DEEPENING PROJECT

Schuylkill River Inflow Hydrograph,
June - November 1965

U.S. Army Corps of Engineers,
Philadelphia District

Figure 5-6



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DEEPENING PROJECT

Zones of Salinity

U.S. Army Corps of Engineers,
Philadelphia District

Figure 5-9

ppt. Even as sea water is diluted in the estuary to very low salinity values, the ratio of chlorides to TDS remains effectively constant. In the numerical model simulations, the ocean boundary condition includes a specified time history of salinity in terms of TDS (ppt). As the model simulates the transport, dispersion, and dilution of this ocean-derived salinity within the estuary, it assumed that chlorinity at any point is 55% of the model value of (ocean-source) salinity.

However, due to the predominance of other ionic species, chlorides typically constitute a smaller fraction of TDS in tributary inflows of fresh water to the Delaware Estuary, as compared to sea water. For example, USGS regularly collects water samples above the head of tide on the Delaware River at Trenton and on the Schuylkill River at Philadelphia. Analysis of these samples shows that chlorides in tributary inflows averaged about 9% of TDS in 1964-65, and about 13% in the period 1988-92.

USGS maintains permanent, continuous water quality monitoring stations on the Delaware River in the vicinity of Philadelphia. Measurements at these stations include conductivity and temperature, but not direct measurement of chlorinity. In lieu of direct chlorinity measurement, DRBC has developed and adopted empirical relationships between conductivity and chlorinity. Chlorinity at water quality monitoring stations is computed from the observed conductivity data using the following relationships developed by DRBC:

Conductivity Range K = Specific Conductance (microsiemens/cm at 25°C)	**Equation:** Cl (ppm) = $f(K)$
$K < 249.6$	$8.092 \times 10^{-4} (K)^{1.7687}$
$249.6 \leq K \leq 525.7$	$3.236 \times 10^{-5} (K)^{2.3518}$
$K \geq 525.7$	$2.686 \times 10^{-2} (K)^{1.2789}$

For example, based on these equations, the range of conductivities from 0 to 525.7 corresponds to computed chlorinities from 0 to 81 ppm, respectively. It is noted here that the DRBC equations are based on an empirical best-fit to a finite number of analyzed water samples. Therefore, the predicted value of chlorinity is an approximation, not an absolute measure of the chloride ion concentration. Confidence limits for these conductivity-chlorinity relationships have not been established. Therefore, exact correlation is not expected when comparing model-predicted chlorinity to conductivity-predicted chlorinity. Instead, acceptable verification of model results is demonstrated if the model produces reasonable agreement in spatial and temporal salinity distribution and trends with respect to the spatially-limited prototype conductivity-chlorinity data available.

Figures 5-7 and 5-8 present comparisons of model versus prototype salinity at RM 82 and RM 100, for November 1965. It can be seen that the model reproduces the up-estuary movement of salinity during extremely low flow periods quite well, especially trends in the salt movement, and transient events such as occurred around 18 November.

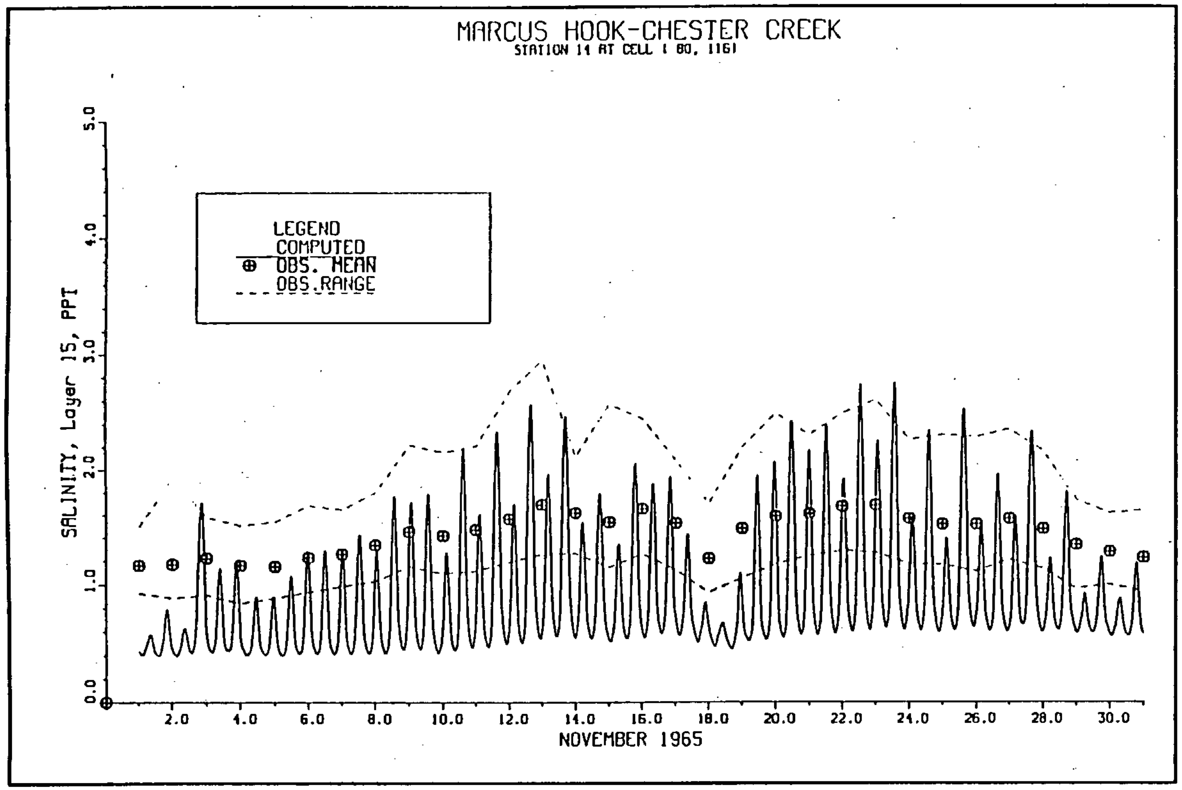
In summary, model verification has covered a wide range of inflow conditions ranging from the high inflows during April 1993 to extreme low flows during 1965. The model has been shown to reproduce water levels, flow velocities, and salinities well over this range of events. Bottom friction and horizontal diffusivity are the two principal parameters which are varied to attain verification of the model. These parameters were established for the October 1992 simulation, and were held constant for the other two verification simulations (April 1993 and June-November 1965), and for the production runs discussed in the following section.

5.10 Resources That Were Evaluated

5.10.1 Water Supply

The U.S. Environmental Protection Agency criterion for chlorides in domestic water supplies is 250 mg/l (USEPA, 1986). This criterion is based more on palatability than on health protection. For health purposes it is more important to consider sodium intake. It has been determined that for very restricted sodium diets, 20 mg/l in water would be the maximum, while for moderately restricted diets 270 mg/l would be maximum (USEPA, 1986). To date, the USEPA has not recommended maximum sodium concentrations for domestic water supplies. The State of New Jersey has adopted a sodium standard of 50 mg/l for drinking water.

In 1967, the DRBC adopted water quality standards to maintain acceptable salinity distribution throughout the tidal portion of the Delaware River (USACE, 1982). Seasonal streamflow objectives at Montague and Trenton, NJ, were established by DRBC for drought conditions in the Delaware River Basin. The flow objectives are defined as a function of season and the location of the "salt front," the seven-day average location of the 250 ppm isochlor.

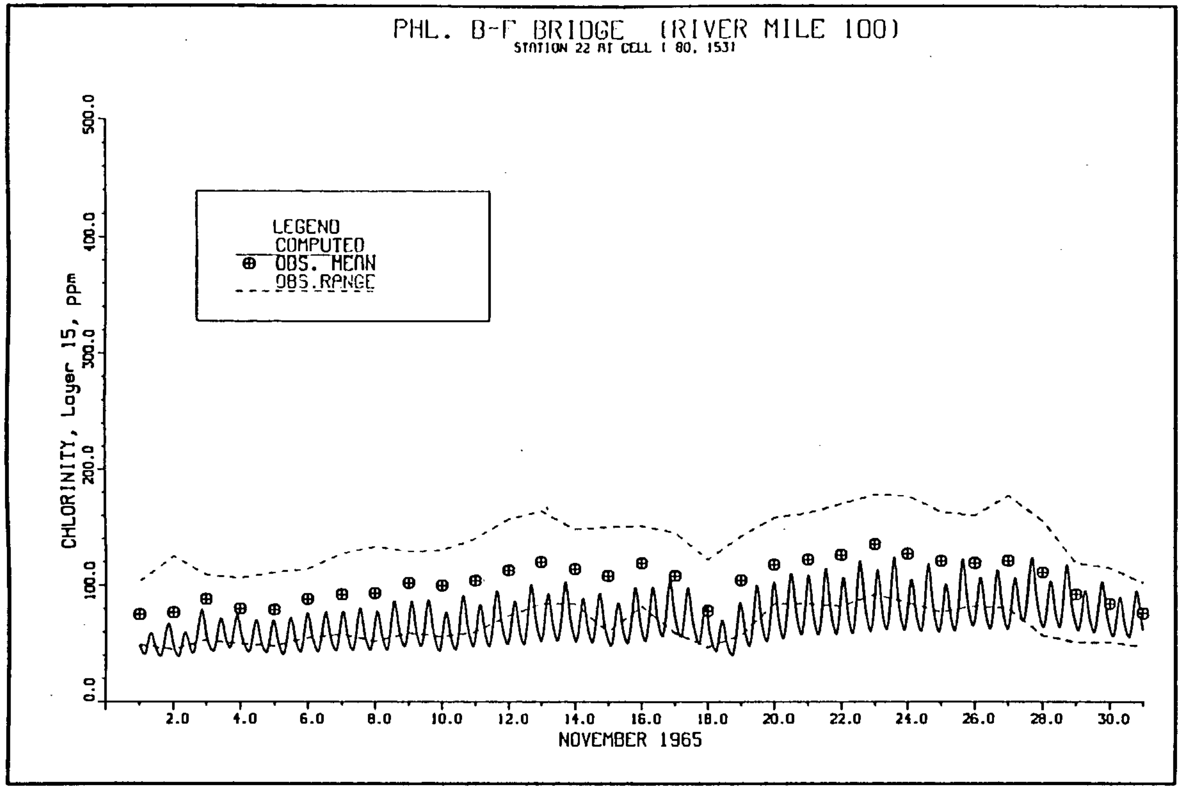


DELAWARE RIVER
MAIN CHANNEL DEEPENING PROJECT

November 1965 Model and
Prototype Salinity, RM 82

U.S. Army Corps of Engineers,
Philadelphia District

Figure 5-7



DELAWARE RIVER
MAIN CHANNEL DEEPENING PROJECT

November 1965 Model and
Prototype Salinity, RM 100

U.S. Army Corps of Engineers,
Philadelphia District

Figure 5-8

The location of the salt front is considered, along with Delaware River Basin reservoir storage, to manipulate reservoir releases to meet the flow objectives.

To evaluate potential impacts to water supplies, model output provided the maximum intrusion of the 250 mg/l isochlor and the 30-day average of the chloride concentration at River Mile 98. A 30-day average chloride concentration of less than 180 mg/l at RM 98 is the current DRBC chloride standard for the estuary. The RM 98 standard was established with the intent of protecting groundwater supplies in the Camden-metropolitan area of New Jersey from salt contamination. Based on the ratio of chloride ion to sodium ion concentration in sea water, a chlorinity of 180 mg/l is approximately equal to a sodium ion concentration of 100 mg/l. Considering the maximum rate of aquifer recharge from the Delaware River, and the State of New Jersey drinking water standard of 50 mg/l for sodium, the existing chloride standard was set at River Mile 98 as a reasonable interim objective for protecting the aquifer system.

The Potomac-Raritan-Magothy aquifer system is a significant water supply source for the Camden, New Jersey metropolitan area. River Mile 98 is the estimated seaward limit of the major connection between the estuary and the aquifer system (DRBC, 1981). Within the area of hydraulic connection between the river bed and the PRM aquifer, a portion of aquifer recharge, estimated by USGS (Navoy and Carleton, 1995) to be on the order of 23% of the total aquifer recharge, is from the Delaware River. Maintenance of appropriate salinity concentrations at River Mile 98 is intended to protect the aquifer system from salt water intrusion.

Additional USGS information provided by Navoy (USGS letter, January 1996) indicates that transient high-chlorinity events in the vicinity of RM 98 may not be as detrimental to PRM aquifer water quality as previously assumed. This is due to the combined effects of the travel time of river water recharging the aquifer, and the dilution of the recharging water within the aquifer. USGS has identified the vicinity of RM 105 (Pennsauken, NJ) as the zone of river-proximal wells with significant drawdown and hence a larger potential impact from transient high chlorinity water in the Delaware River. USGS ground water modeling of transient high-chlorinity events comparable to the drought of record indicate that ground water quality in river-proximal wells will not violate potability standards. These recent findings by USGS are not reflected in the DRBC standard for chlorinity at RM 98; the 30-day average chlorinity standard for RM 98 remains as "less than 180 ppm." The DRBC Flow Management Technical Advisory Committee (1996) has undertaken a comprehensive review and reconsideration of the basin drought operations plan and modeling assumptions with respect to the appropriateness of the present RM 98 chlorinity standard. The DRBC (1989) indicated that the Parties to the Good Faith Agreement for the Delaware River Basin recommended a more stringent salinity objective at River Mile 98 for aquifer protection. This objective would have a 30-day average of less than 150 mg/l of chlorides. In order to meet this more stringent objective, it has been determined that additional reservoir storage would be required to maintain the necessary streamflow within the Delaware River at Trenton, New Jersey (USACE, 1982). As such, this contemplated salinity objective would not be put in place until additional reservoir storage is available.

5.10.2 Aquatic Resources

Salinity distribution in the Delaware Estuary is primarily the result of saltwater inflow from the adjacent Atlantic Ocean and freshwater flow from the Delaware Basin drainage area (Smullen et al., 1983). The mixing of fresh and salt water forms a gradient from less than 0.5 parts per thousand (ppt) in the tidal river to about 32 ppt at the mouth of the bay (Ichthyological Associates, 1980). The U.S. Fish and Wildlife Service (1981a) characterized four salinity zones within the Delaware Estuary. These are polyhaline (18 - 30 ppt) from the mouth of the bay to the vicinity of the Leipsic River (River mile 34), mesohaline (5 - 18 ppt) from the Leipsic River to the vicinity of the Smyrna River (River Mile 44), oligohaline (0.5 - 5 ppt) from the Smyrna River to the vicinity of Marcus Hook (River Mile 79), and fresh 0.0 - 0.5 ppt) from Marcus Hook to Trenton (Figure 5-9).

The Delaware Estuary salinity gradient is not a static environmental condition, but one subject to short and long-term change. Due to variations in factors such as freshwater flow, tidal height and stage, and weather conditions, specific salinities move within the estuary from 10 to greater than 20 miles. The upper and lower zones of the estuary are dominated by fresh water and salt water flows, respectively. The extreme dominance of one type of water in each of these zones maintains relatively stable salinity levels over time. The mid-estuary serves as a mixing zone for fresh and salt water. As such, this zone is more heavily influenced by fluctuations in tidal and river flow, and subject to greater variations in salinity.

Vegetation, aquatic organisms, and to a lesser degree, wildlife distribute themselves within the estuary, based on their salinity tolerances. Freshwater organisms, those that can not tolerate high salinity, restrict their distribution to the freshwater portion of the estuary generally located above Wilmington, Delaware. Marine organisms, those that require high salinities, restrict their distribution to the lower bay. Organisms that can function over a broad range of salinity will inhabit the portion of the estuary that is within their tolerance range. It should be kept in mind that salinity is only one environmental factor affecting the distribution of organisms within the estuary. It would be necessary to consider a variety of other factors to precisely define the limits of a particular species within the estuary.

In 1981, the U.S. Fish and Wildlife Service prepared a planning aid report in support of the Philadelphia District's Delaware Estuary Salinity Intrusion Study (USFWS, 1981a). That report provides a discussion of how various components of the Delaware Estuarine ecosystem relate to salinity, and require specific salinity patterns to carry out portions of their life cycle. The following excerpt from the report characterizes the influence of salinity on the oligo-mesohaline portion of the estuary:

> "The information we have reviewed shows that salinity exerts strong influence on the Delaware estuarine ecosystem. Briefly, it influences the distribution of marsh plants, benthic invertebrates, fishes and certain wildlife. Relatively few aquatic species are tolerant of the entire salinity gradient from fresh water to salt water. Most species occupy portions of the gradient beyond which survival is threatened. Salinity affects seed germination and growth of marsh plants; oyster drill predation and probably MSX disease in the oyster seed beds; movement of blue crab larvae; location of blue crab spawning, nursery and mating grounds; movement of fish eggs and larvae; location of spawning, nursery and feeding grounds of fishes; muskrat production; and, waterfowl feeding and resting grounds. The overall effect of the salinity gradient is to create numerous niches, fostering wide ecologic diversity and high productivity. Literally hundreds of plant and animal species, some with populations numbering in the many thousands, utilize the Delaware estuary."

The report concludes that a shift in salinity patterns could result in a variety of impacts, which would cumulatively lower the overall productivity of the estuarine system. While more stable, relative to salinity, the freshwater and polyhaline zones of the estuary could also be affected by extreme events of drought or flood.

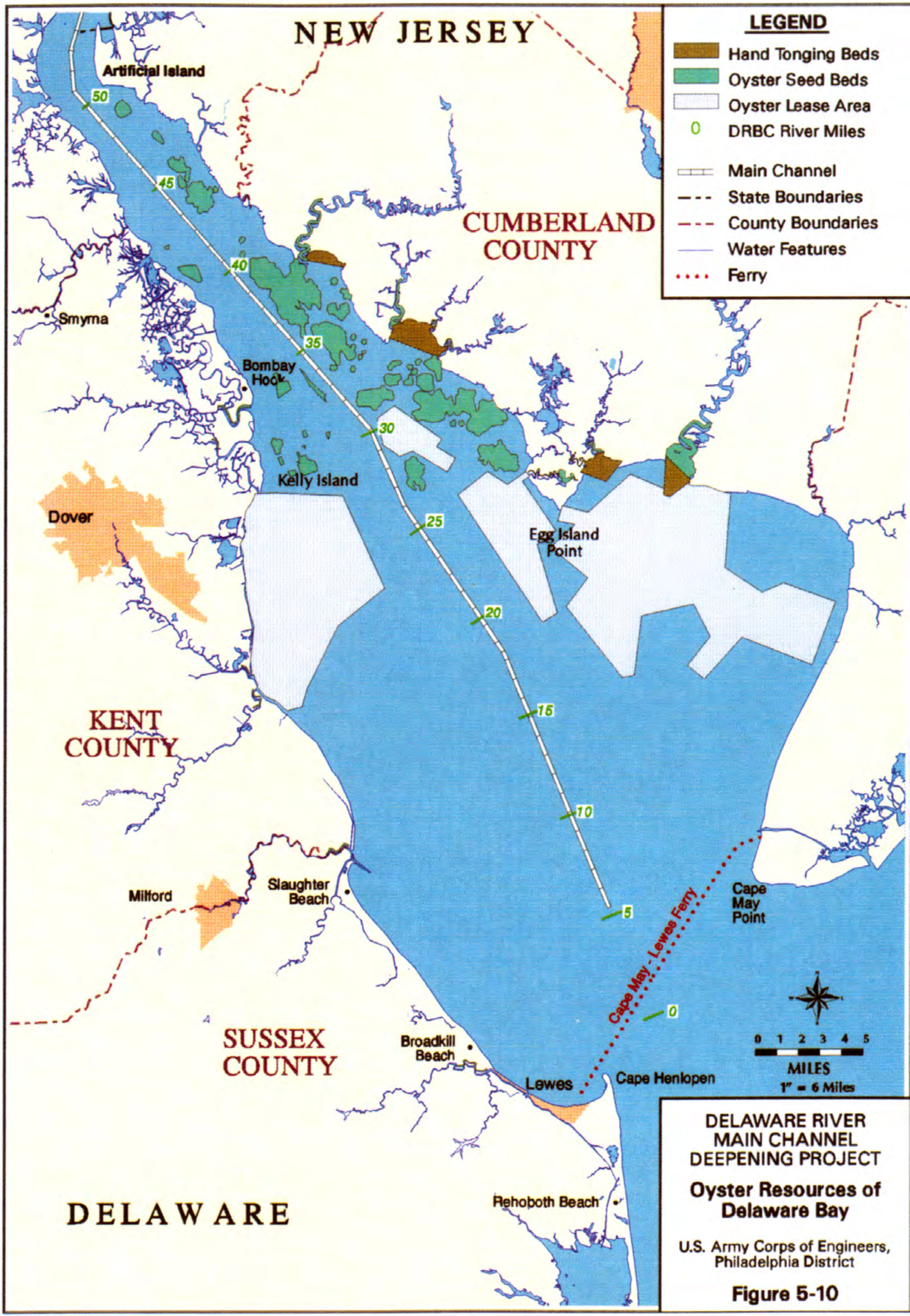
Based on the 1989 DRBC 1-D salinity modeling of the drought of record and the computed movement of the 250 mg/l isochlor with a deepened channel, concerns were raised relative to a potential increase in salinities throughout the estuary, and the ecological impacts associated with such an increase. In order to address these concerns, the WES 3-D model was used to provide data pertaining to the movement of three other isohalines for the existing and deepened channel geometries. Isohalines were selected to cover various locations in the estuary and/or to correspond to salinities of significance relative to various components of the estuarine ecosystem. The isohalines were 15 ppt (equivalent to approximately 8303 mg/l chlorinity), 10 ppt salinity (5535 mg/l chlorinity), and 5 ppt salinity (2768 mg/l chlorinity).

The isohaline corresponding to 15 ppt salinity was selected because it is considered significant relative to the protection of the American oyster (Crassostrea virginica) in Delaware Bay. Traditionally, the Delaware Bay oyster industry has been dependent on two locations within the bay. In waters within the State of Delaware, oysters occur in naturally reproducing seed beds offshore and north of Kelly Island and in leased bed areas south of Kelly Island down to the Mispillion River area. In New Jersey waters, oyster seed beds occur from south of Artificial Island to Fortescue; lease beds occur from southwest of Egg Island Point throughout much of the lower Bay (See Figure 5-10). These low salinity seed bed areas provide a refuge for young oysters to grow, free from predation and competition that limits survival success in higher salinity, downbay water. It has been common practice to remove young oysters from these beds in May and June, and transplant them to privately leased beds. The higher salinity in this area promotes faster growth of the oysters, bringing them to market size in less time.

A major predator of the oyster in Delaware Bay is the oyster drill (Urosalpinx sp.). The oyster drill can cause substantial damage to oyster beds when present in abundance. Reproductive success and distribution of the oyster drill is correlated with salinity levels (USFWS, 1979). Salinities below 15 ppt will control reproduction and limit drill infestation, thus minimizing damage to oyster beds.

Delaware Bay oysters are also subject to high mortalities during outbreaks of a sporozoan parasite classified as Perkinsus marinus. This parasite is commonly referred to as MSX. The initial MSX kill in Delaware Bay occurred in 1957 when nearly half the oysters on the New Jersey leased grounds died within six weeks. A second kill in 1958 spread over all of the lower bay and onto the seed beds as far upbay as the Cohansey River.

Patterns of MSX occurrence suggest that salinities of about 15 ppt or greater favor the spread of the organism. While salinity does not account for all phases of MSX activity, 15 ppt salinity or less appears to be sufficient to protect the oyster. Based on the above, the 15 ppt isohaline was tracked in the model to



DELAWARE RIVER
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Oyster Resources of Delaware Bay

U.S. Army Corps of Engineers,
Philadelphia District

Figure 5-10

assess potential impacts to oysters from the oyster drill and MSX. Powell (1995) states that there would be no problems for oysters with an average salinity increase of up to 1 ppt; a increase in the range of 1 ppt to 5 ppt may cause problems; and an increase greater than 5 ppt would cause problems for oysters.

The isohaline corresponding to a salinity of five ppt was selected because it relates to a shift in tidal wetland vegetation from freshwater to brackish. Walton and Patrick (1973) stated that salinity appears to be the principal factor influencing the composition of emergent vegetation along the Delaware Estuary. A variety of freshwater species such as wild rice (Zizania aquatica), arrowhead (Sagittaria spp.), dotted smartweed (Polygonum punctatum), and spatterdock (Nuphar luteum) cannot tolerate salinities above five ppt for extended periods of time (USFWS, 1981b). Prolonged exposure to high salinities result in plant stress and ultimately death of vegetation. High salinities also inhibit seed germination processes. The combined result of these impacts would be lower productivity. Freshwater tidal wetland habitats occur in the Delaware Estuary from Trenton, New Jersey to Wilmington, Delaware (Schuyler, 1988). Shoreline plant species that usually grow in brackish conditions now extend farther upstream in the Delaware River than they did earlier in the 20th century. Conversely, common shoreline species usually associated with freshwater conditions have not been found as far downstream as they have in the past. These upstream and downstream distributional changes indicate that an increase in dissolved solids and chlorides has occurred in the Delaware River (Schuyler, Andersen, and Kolaga. 1993).

The third isohaline tracked with the 3-D Model corresponded to a salinity of 10 ppt. This isohaline can fluctuate over a 30-mile stretch of the estuary, generally between Egg Island Point and Artificial Island. This portion of the estuary provides valuable spawning and nursery habitat for a variety of estuarine fishes. A shift in salinity patterns could reduce the amount of habitat available for spawning and early growth. This isohaline was also selected because it is midway between isohalines corresponding to five and 15 ppt, which were selected for the reasons stated above. Results of the isohaline tracking are presented and discussed in the following paragraphs.

5.11 Simulations to Assess the Impacts of a 45 Foot Channel

Several scenarios were identified and selected for application in the 3-D model to address the impact of channel deepening on salinity distribution and subtidal circulation in the Delaware Estuary. The selection of these sets of conditions was based on coordination accomplished through the interagency workshops described earlier in this section of the report. The selected scenarios include:

1. The June-November 1965 drought of record, with Delaware River discharges adjusted to reflect the existing reservoir regulation plan and corresponding flows ("Regulated 1965");

2. Long-term monthly-averaged inflows with June-November 1965 wind and tide forcings; and

3. A high flow transition period, represented by the April-May 1993 prototype data set.

Each of these periods was simulated first with the existing 40 foot navigation channel, and then with the proposed 45 foot channel in place.

Several types of model output were developed to aid in the analysis and presentation of impacts of channel deepening. These include time series plots of salinity at several locations throughout the modeled system; time history of 30-day average chlorinity at RM 98; the location of the 30-day average 180 ppm and 7-day average 250 ppm isochlors as a function of time; the location of monthly averaged salinity contours of 0.25 ppt, 5.0 ppt, 10.0 ppt, and 15.0 ppt; and subtidal circulation plots.

Since the model computes the transport and distribution of salinity (total dissolved solids), rather than chlorinity as is used by DRBC for water quality standards in the Philadelphia area, model values of salinity were converted where necessary to equivalent values in chlorinity units using the relationship described previously in the section on the June-November 1965 verification. The principal chlorinity-based water quality standards adopted by DRBC for the Philadelphia region include: the seven-day average location of the 250 ppm isochlor (adopted as the "salt front"); and the 30-day average chlorinity at RM 98 (180 ppm chlorinity is the standard for maximum allowable chlorinity intended to protect groundwater recharge from the river into the PRM aquifers which supply groundwater to the Camden Metropolitan area in New Jersey).

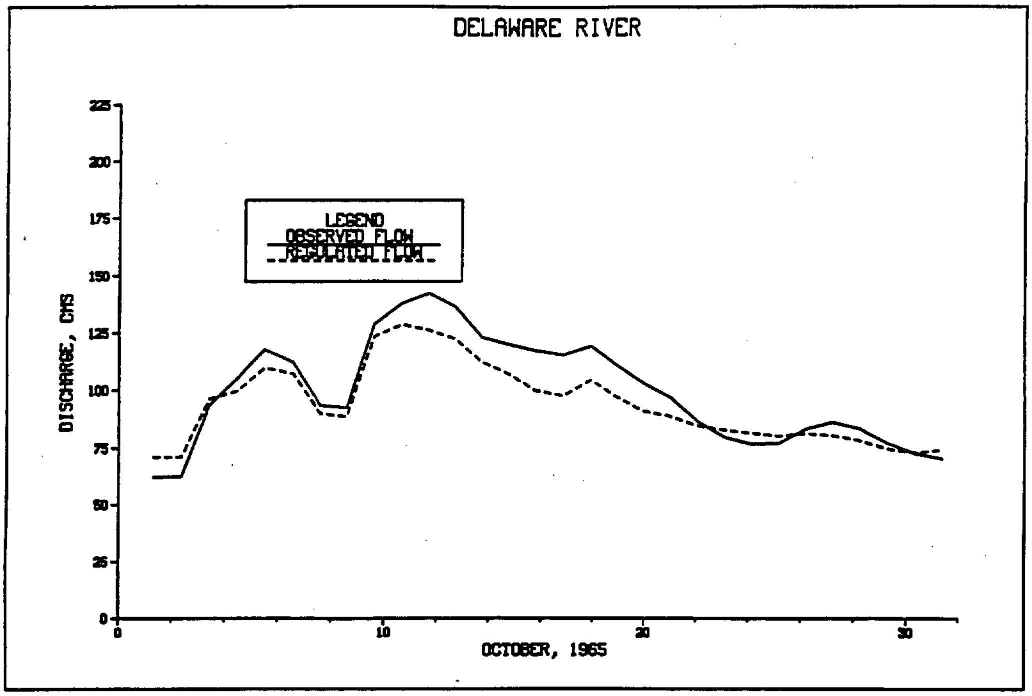
5.11.1 Regulated June-November 1965 Simulation

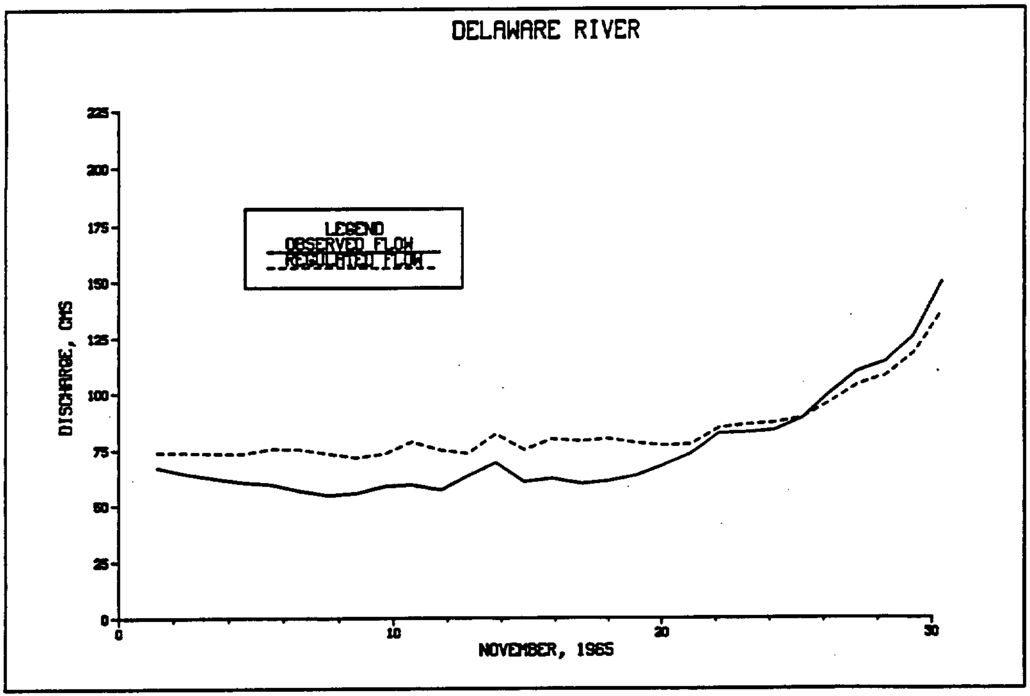
This simulation is considered the most critical of the scenarios modeled. It represents the salinity impacts of channel deepening accompanying a recurrence of the drought of record, modified to reflect the existing drought management plan which allows for augmented flows at Trenton, New Jersey in the interest of salinity repulsion. A comparison of the hypothetical regulated flow at Trenton and the actual flows that occurred during this period October-November 1965 is presented in Figure 5-11. The historic and regulated flow data were provided by DRBC. All other model boundary conditions were the same as in the historic June-November 1965 data set. The figure shows that when the actual flow is greater than about 3500 cfs (99 cms) the regulated flow is lower, whereas when the actual flow dropped below about 2625 cfs (74 cms) the regulated flow is higher. As will be demonstrated in the results presented below, the regulated flow scenario produces salinity conditions in the Philadelphia vicinity which are not as severe as those which occurred under the actual 1965 flow conditions.

Time series plots for the regulated November 1965 period showing the impact of channel deepening on the salinity regime at selected sites throughout the bay and river sections of the Delaware Estuary are presented in Figures 5-12, 5-13, and 5-14. The top panel of each figure show model-predicted near-bottom salinity for the 40 and 45 foot channels. The bottom panel shows the salinity difference between the 40 and 45 foot channels. The data show that deepening the channel has practically no impact on salinities in the lower bay, i.e., at RM 27. At RM 69, the salinity increase attributable to channel deepening is approximately 0.5 ppt, with absolute salinities on the order of 4 to 6 ppt. At RM 98, the maximum instantaneous near-bottom chlorinity for the deepened channel attains a value of about 270 ppm in the November 1965 simulation. The chlorinity increase due to deepening at RM 98 averages about 50 ppm for the November 1965 simulation.

Figure 5-15 displays data on the 30-day average chlorinity at RM 98, near-surface and near-bottom, for the month of November 1965. It can be seen that although the deepened channel increases the 30-day average near-bottom chlorinity from about 120 ppm to 160 ppm at RM 98 in November, the DRBC standard of 180 ppm is never attained. Near-surface 30-day average chlorinity for the same period remains below 150 ppm with the deepened channel. It should be noted that the USGS conductivity-temperature measurements at RM 100 are obtained from a near-surface sensor in the river.

A number of summary tables have been created from the large amount of data generated by the model to characterize the distribution of salinity throughout the estuary for the regulated July-November 1965 simulation, and to characterize the range of salinity impacts associated with the channel deepening. Table 5-1 presents the monthly maximum values of the 30-day average chlorinity at RM 98. For the months of July through November 1965, values are presented for the 40 foot channel, the 45 foot channel, and the difference between them. Table 5-2 shows the typical monthly range in salinity at the 16 sites at which data



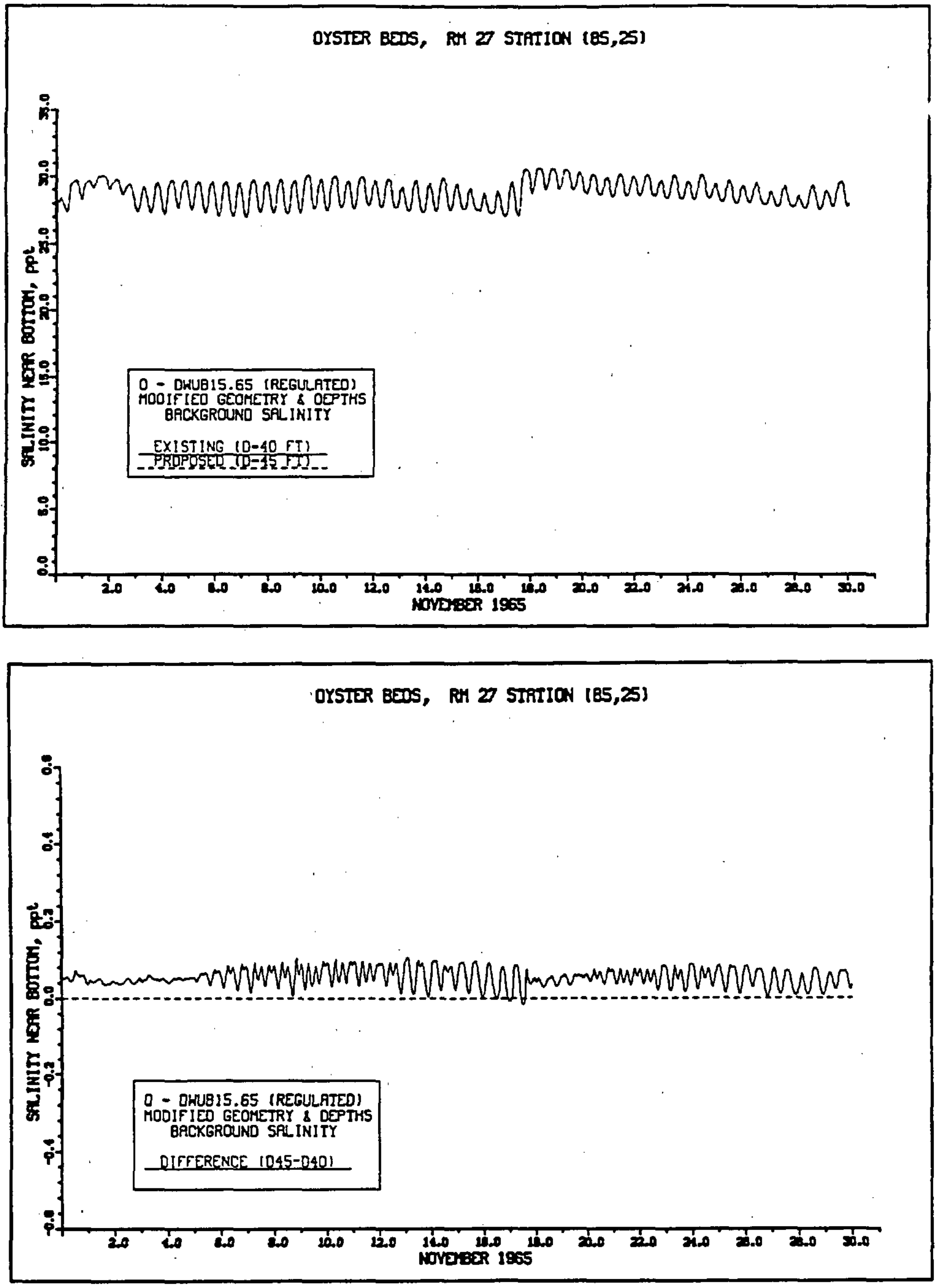


DELAWARE RIVER
MAIN CHANNEL DEEPENING PROJECT

October - November 1965 Historic and Regulated Flows,
Delaware River at Trenton

U.S. Army Corps of Engineers,
Philadelphia District

Figure 5-11

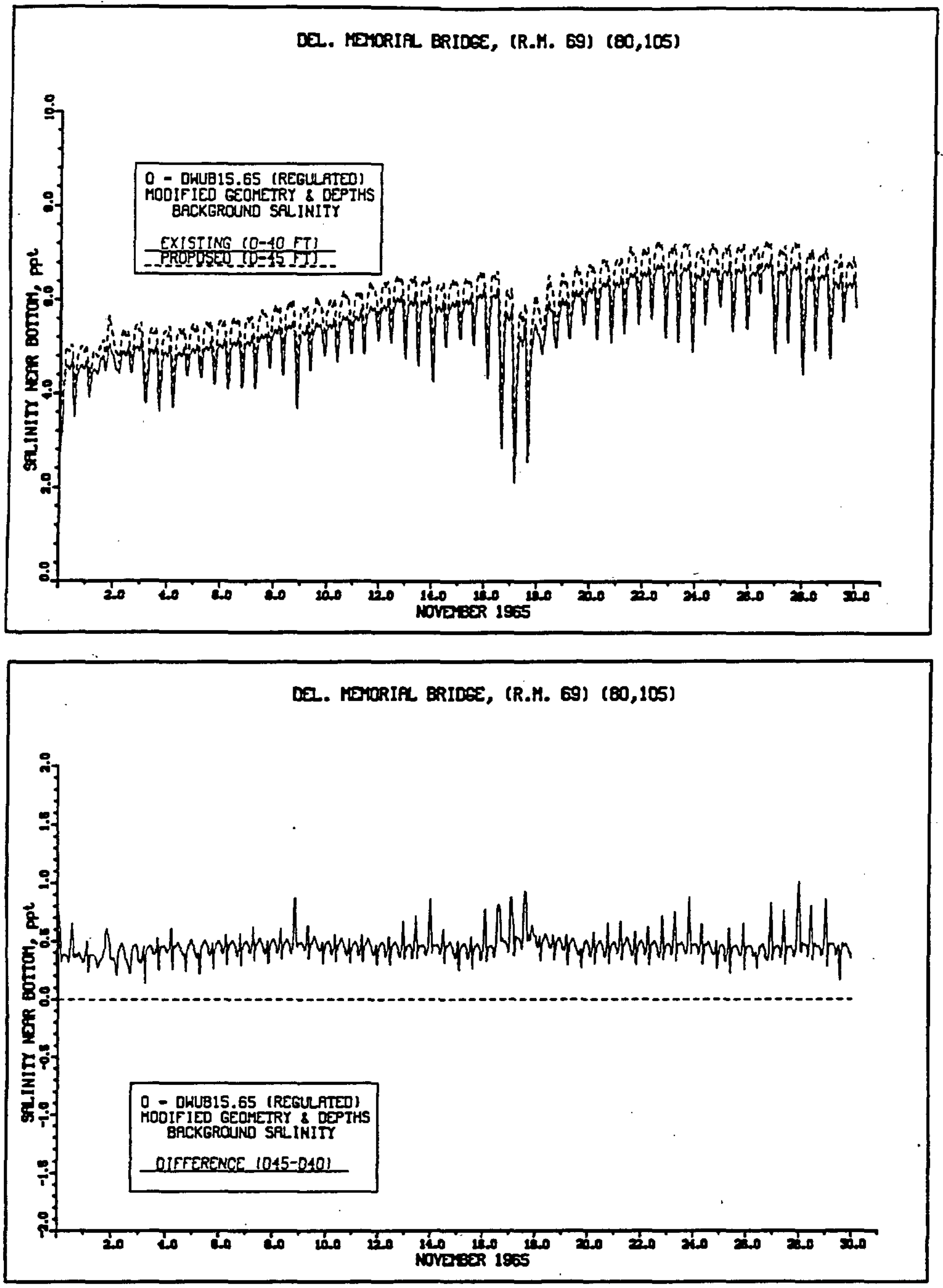


DELAWARE RIVER
MAIN CHANNEL DEEPENING PROJECT

Regulated Nov 1965 Scenario
RM 27 Bottom Salinity,
40 ft vs 45 ft Channel Comparison

U.S. Army Corps of Engineers,
Philadelphia District

Figure 5-12

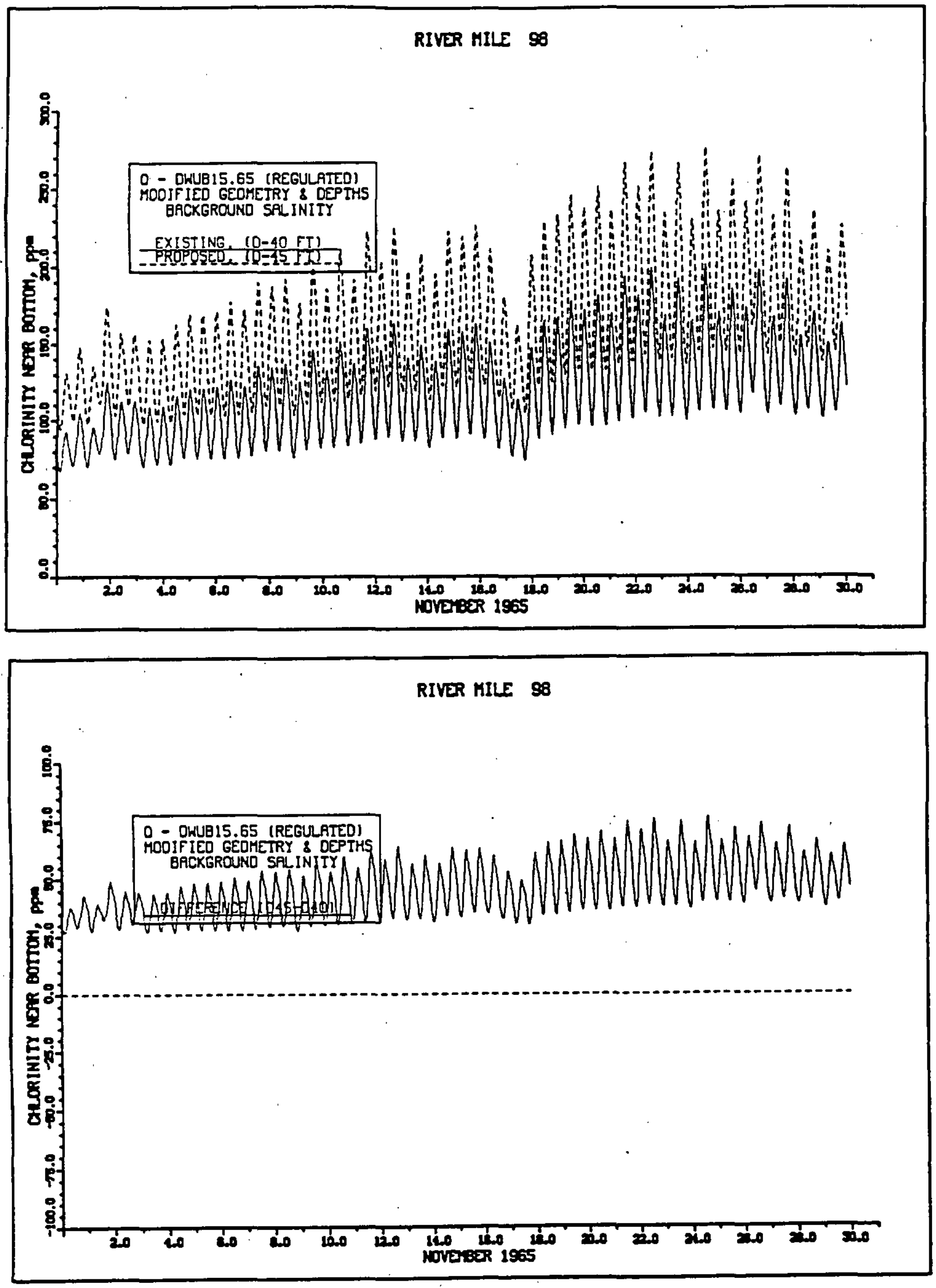


DELAWARE RIVER
MAIN CHANNEL DEEPENING PROJECT

Regulated Nov 1965 Scenario
RM 69 Bottom Salinity,
40 ft vs 45 ft Channel Comparison

U.S. Army Corps of Engineers,
Philadelphia District

Figure 5-13

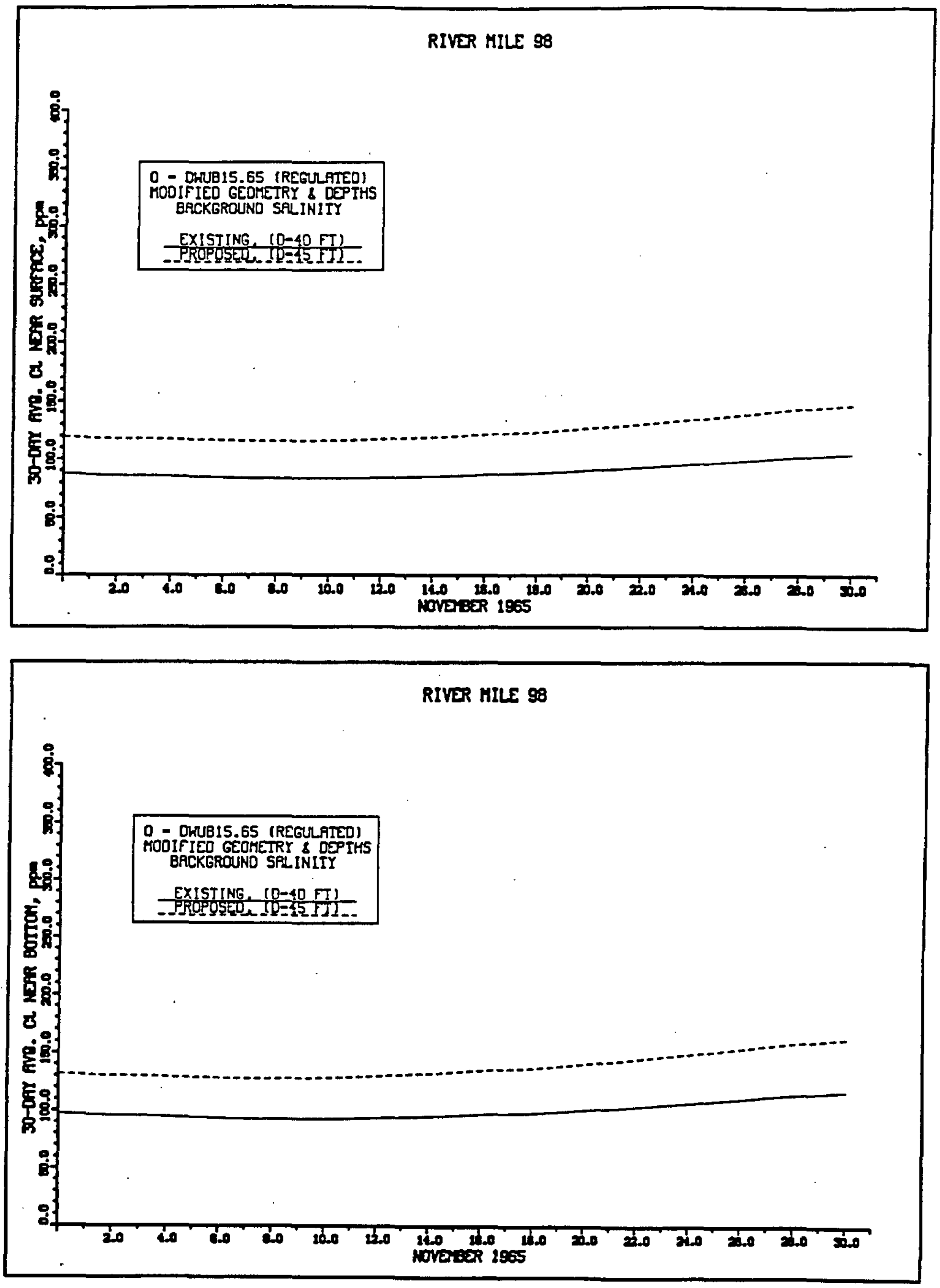


DELAWARE RIVER
MAIN CHANNEL DEEPENING PROJECT

Regulated Nov 1965 Scenario
RM 98 Bottom Salinity,
40 ft vs 45 ft Channel Comparison

U.S. Army Corps of Engineers,
Philadelphia District

Figure 5-14



DELAWARE RIVER
MAIN CHANNEL DEEPENING PROJECT

Regulated Nov 1965 Scenario
RM 98 30-day Average Chlorinity
40 ft vs 45 ft Channel Comparison

U.S. Army Corps of Engineers,
Philadelphia District

Figure 5-15

Table 5-1. Thirty-day Average Chlorinity (ppm) at RM 98.
Scenario: Regulated Drought, July - November 1965.
Monthly Maximum Values, Near-Surface and Near-Bottom.
3-D Model Results.

	JULY 1965		AUGUST 1965		SEPT 1965		OCTOBER 1965		NOVEMBER 1965	
	SURF	BOT	SURF	BOT	SURF	BOT	SURF	BOT	SURF	BOT
40 FT CHANNEL	44	49	73	81	98	105	101	109	109	118
45 FT CHANNEL	59	62	96	108	128	137	132	144	150	163
DIFFERENCE	15	13	23	27	30	32	31	35	41	45

Table 5-2. Salinity at Selected Locations within Delaware Estuary.
Scenario: Regulated Drought, July - November 1965.
Salinity Range with 40 ft Channel, and Difference with 45 ft Channel.
3-D Model Results.

SALINITY DIFFERENCES DUE TO DEEPENING FROM 40 TO 45 FT

	JULY 1965		AUGUST 1965		SEPTEMBER 1965		OCTOBER 1965		NOVEMBER 1965	
	SALINITY (ppt)		SALINITY (ppt)		SALINITY (ppt)		SALINITY (ppt)		SALINITY (ppt)	
LOCATIONS	Month Range 40 ft Channel	Month Avg Diff @ 45	Month Range 40 ft Channel	Month Avg Diff @ 45	Month Range 40 ft Channel	Month Avg Diff @ 45	Month Range 40 ft Channel	Month Avg Diff @ 45	Month Range 40 ft Channel	Month Avg Diff @ 45
RM 100 (ppm Cl)	10 - 55	15	40 - 80	25	60 - 100	25/30	50 - 120	25/30	60 - 135	35/40
RM 98 (ppm Cl)	15 - 65	15	50 - 90	25	70 - 125	30/35	60 - 130	30/35	70 - 165	45/50
RM 79	0.3 - 2.0	0.2	0.4 - 2.0	0.2	0.5 - 2.0	.2/.3	0.5 - 2.0	.2/.3	0.5 - 3.0	.3/.4
RM 69	2 - 5	0.1/0.2	2 - 5	.2/.3	3 - 5	.2/.3	3 - 5	.3/.4	3 - 7	.4/.5
RM 54	6 - 11	0.2/0.4	6 - 11	.2/.3	6 - 12	.2/.4	7 - 13	.4/.6	8 - 17	.4/.6
RM 43 (OYST. A)	15 - 21	0.1	14 - 21	0.1	15 - 22	0.1	16 - 23	0.1	18 - 26	.05
(OYST. B)	15 - 20	0	13 - 20	.05	16 - 20	.05	15 - 22	.05	17 - 24	0
(OYST. C)	15 - 20	0	13 - 20	.05	16 - 20	0	14 - 21	.05	16 - 24	0
RM 38 (OYST. D)	21 - 25	0	19 - 24	.05	21 - 25	.05	21 - 27	0	24 - 28	0
(OYST. E)	19 - 23	0	18 - 22	.05	20 - 23	0	19 - 24	0	22 - 26	0
(OYST. F)	19 - 22	0	18 - 21	0	19 - 21	0	18 - 22	0	20 - 25	0
RM 36	21 - 26	0/0.1	20 - 26	0/0.1	22 - 26	0/0.1	23 - 28	0/0.1	25 - 29	0/0.1
RM 27 (OYST. G)	25 - 28	.05	24 - 28	.05/0.1	25 - 29	.05	25 - 30	.05	27 - 30	.05
(OYST. H)	22 - 25	.05	22 - 25	.05	22 - 26	.05	23 - 27	.05	24 - 28	.05
(OYST. I)	20 - 24	0	20 - 23	.05	20 - 23	.05	21 - 24	0	22 - 26	0
RM 24	26 - 30	.05/0.1	25 - 29	.05/0.1	27 - 30	.05/0.1	27 - 31	.05/0.1	29 - 31	.05

NOTE: Column "MONTH AVG DIFF @ 45" - if single value shown, diff. at surface and bottom are approx. equal.
If two values shown, first is diff. at surface, second is diff. at bottom.

were saved during the 40- and 45-foot channel simulations. For each month of the simulation, the first column of data presents the range of salinity with the 40 foot channel, and the second column presents the change attributable to the deepening to 45 feet. Note that data at RM 98 and RM 100 are presented in units of "ppm Cl" rather than in units of "ppt salinity" applied to other data save points. This change of units was adopted to facilitate comparison of model data from RM 98 and 100 to the DRBC standards, which are defined in units of ppm chlorinity.

Table 5-2 shows the monthly salinity range and differences due to deepening at selected locations for the July to November 1965 period. In the polyhaline portion of the estuary, represented by River Miles 24 and 27, the model predicts monthly average salinity increases on the order of 0.0 to 0.1 ppt. In the mesohaline portion of the estuary, represented by data at RMs 36, 38, and 43, the model predicts monthly average salinity increases on the order of 0.0 to 0.1 ppt. In the oligohaline portion of the estuary, represented by RMs 54, 69, and 79, the model predicts monthly average salinity increases on the order of 0.2 to 0.6 ppt. In the fresh water portion of the estuary, represented by RMs 98 and 100, the model predicts chlorinity increases in the range of 15 to 50 ppm.

Table 5-3 presents a summary of the seven-day average location of the 250 ppm isochlor (the "salt front" per DRBC definition) for the regulated July through November 1965 simulation. Results are tabulated as "minimum RM", "maximum RM", and "average RM", reflecting the upstream/downstream movement of this indicator as a result of dynamic boundary conditions of inflow, tide, source salinity, and wind. These results indicate that in the Regulated 1965 Drought simulation there would have been a 4.0-mile increase in maximum penetration of the salt front in November (from RM 92.2 to RM 96.2, Table 5-3), and a 45 ppm increase in 30-day average chlorinity at River Mile 98 in November (Table 5-1), attributable to the deepened channel.

Table 5-3 shows that with the 40 ft channel, the maximum intrusion of the 7-day average 250 ppm isochlor ranged between RM 83.4 in July and RM 92.2 in November. For the 45 ft channel, the maximum intrusion ranged between RM 84.8 and RM 96.2. Thus the 7-day average 250 mg/l isochlor (salt line) is predicted to penetrate further upstream during a recurrence of the drought of record with a deepened channel. This increase in penetration is predicted to range from 1.4 to 4.0 miles.

Table 5-4 provides summary data on the monthly-average location of selected isohalines for the 40 foot and 45 foot channels. The data are presented in two categories, "maximum intrusion" and

Table 5-3. Seven-day Average Location of 250 ppm Isochlor, by River Mile (RM).
Scenario: Regulated Drought, July - November 1965.
Values with 40 ft and 45 ft Channels, and Differences.
3-D Model Results.

LOCATION OF 7-DAY AVG 250 ppm ISOCHLOR

MONTH	MIN RM			MAX RM			AVG RM		
	40 FT	45 FT	DIFF	40 FT	45 FT	DIFF	40 FT	45 FT	DIFF
JULY	81.0	80.2	-0.8	83.4	84.8	1.4	82.2	82.5	0.3
AUGUST	80.0	83.2	3.2	84.0	87.2	3.2	82.0	85.2	3.2
SEPT	81.4	85.6	4.2	87.8	90.8	3.0	84.6	88.2	3.6
OCT	81.0	85.0	4.0	88.8	92.0	3.2	84.9	88.5	3.6
NOV	81.4	86.6	5.2	92.2	96.2	4.0	86.8	91.4	4.6

Table 5-4. Monthly-averaged Location of Selected Isohalines,
by River Mile (RM).
Scenario: Regulated Drought, August - November 1965.
Values with 40 ft and 45 ft Channels, and Differences.
3-D Model Results.

MONTHLY AVG LOCATION OF 0.5 ppt ISOHALINE (RM)

	MAX INTRUSION			AVG ACROSS FRONT		
MONTH	40 FT	45 FT	DIFF	40 FT	45 FT	DIFF
AUGUST	85.8	88.9	3.1	83.3	86.2	2.9
SEPT	88.4	88.9	0.5	85.3	88.4	3.1
OCTOBER	86.6	88.9	2.3	85.3	88.4	3.1
NOVEMBER	88.9	92.8	3.9	88.4	91.7	3.3

MONTHLY AVG LOCATION OF 5 ppt ISOHALINE (RM)

	MAX INTRUSION			AVG ACROSS FRONT		
MONTH	40 FT	45 FT	DIFF	40 FT	45 FT	DIFF
AUGUST	66.9	68.0	1.1	64.0	64.7	0.7
SEPT	69.1	69.9	0.8	65.7	66.9	1.2
OCTOBER	69.9	69.9	0.0	66.9	68.0	1.1
NOVEMBER	73.9	75.0	1.1	70.6	71.5	0.9

MONTHLY AVG LOCATION OF 10 ppt ISOHALINE (RM)

	MAX INTRUSION			AVG ACROSS FRONT		
MONTH	40 FT	45 FT	DIFF	40 FT	45 FT	DIFF
AUGUST	54.3	54.8	0.5	53.3	53.3	0.0
SEPT	55.3	55.8	0.5	54.3	54.8	0.5
OCTOBER	57.3	57.8	0.5	55.3	56.3	1.0
NOVEMBER	60.6	61.1	0.5	60.1	60.3	0.2

MONTHLY AVG LOCATION OF 15 ppt ISOHALINE (RM)

	MAX INTRUSION			AVG ACROSS FRONT		
MONTH	40 FT	45 FT	DIFF	40 FT	45 FT	DIFF
AUGUST	47.1	47.7	0.6	45.8	46.5	0.7
SEPT	48.4	49.1	0.7	47.7	47.7	0.0
OCTOBER	49.9	51.7	1.8	47.7	49.1	1.4
NOVEMBER	54.8	54.8	0.0	53.3	53.8	0.5

"average across front." This distinction is made to reflect the fact that the model shows the month-average locations of the selected isohalines to penetrate further upstream in mid-channel than at the shorelines. Thus "maximum intrusion" represents the location of a given isohaline attained at or near mid-channel, whereas "average across front" effectively represents the mean location of a given isohaline for each month. For the simulation of the drought of record, the incremental intrusion attributable to channel deepening ranged from 0.5 to 3.9 miles for the 0.5 ppt isohaline. For the 5.0 ppt isohaline, the incremental intrusion ranged from 0.0 to 1.2 miles; for the 10.0 ppt isohaline, 0.0 to 1.0 miles; and for the 15.0 ppt isohaline, 0.0 to 1.8 miles.

The 15 ppt isohaline, which is considered important to the survivability of the American oyster, would shift a maximum of 1.8 miles with the channel deepening. A change of salinity of less than 1 ppt will have no impact on oysters (Powell. 1995. Personal Communication). As seen from Table 5-2, the change in salinity in the oyster seed beds and lease areas, due to the 45 foot channel, was a maximum of 0.1 ppt. Data in Table 5-2 also indicate that the oyster seed bed areas will be exposed to salinity in excess of 15 ppt during a recurrence of conditions existing in the drought of record with or without the channel deepening. These data indicate that the deepened channel will not add significantly to the salinity levels at the oyster seed bed areas during severe drought conditions.

In its 1981 Planning Aid Report, the U.S. Fish and Wildlife Service indicated that a shift in salinity zones would also shift spawning and nursery areas for estuarine fishes. Such a shift could move eggs and larvae closer to the Salem Nuclear Generating Station (RM 53), which could possibly result in greater impingement and entrainment losses. Eggs and larvae of some species could also be moved closer to the Philadelphia pollution zone, which could result in lower survivability. The 10 ppt isohaline, which can fluctuate naturally over a 30 mile zone of the estuary and represents a reach that provides valuable spawning and nursery habitat for a variety of fishes, moved upstream an average of from 0.0 to 1.0 miles with the deepened channel (Table 5-4). Table 5-2 shows that the maximum monthly average increase in salinity within the mesohaline zone was 0.1 ppt. This does not represent a significant increase, and will not significantly impact the fish resources in this area.

The U.S. Fish and Wildlife Service (1981) also indicated that higher salinities could result in lower plant productivity, which could reduce food supplies for waterfowl and other wildlife. The 5 ppt isohaline represents a transition from fresh water to brackish vegetation. This isohaline would experience incremental intrusion due to channel deepening between 0.0 miles and 1.2 miles during a recurrence of the drought of record (Table 5-4).

Freshwater aquatic vegetation extends as far down stream as Wilmington, Delaware (Schuyler. 1988) at approximately RM 69. Table 5-2 shows that model-predicted salinity at RM 69 attained or exceeded 5 ppt from July thru November with the existing 40 ft channel. At RM 69, the largest increment in salinity attributable to channel deepening is 0.5 ppt. At RM 79, salinity does not exceed 3.0 ppt between July and November 1965 with the 40 foot channel. The largest increment in salinity in this period attributable to channel deepening is 0.4 ppt. It is possible that there would be a temporary, minor decrease in the distribution and productivity of freshwater aquatic plants, especially in the lower reaches of their range, during a severe drought with the deepened channel. After the drought period ends, the freshwater aquatic vegetation would be expected to recover.

In the freshwater portion of the estuary (0.0 - 0.5 ppt), the model predicts that during a recurrence of the drought of record, monthly average chlorinity would increase on the order of 15 to 50 ppm (Table 5-2) with the deepened channel. This chlorinity increment corresponds to a salinity increment between 0.03 and 0.09 ppt TDS. This portion of the estuary normally extends from Marcus Hook, Pennsylvania to Trenton, New Jersey. Salinities less than 0.5 ppt would not stress wetland vegetation in this portion of the estuary. Likewise, freshwater fishes can also tolerate low salinities. Many freshwater species that occur in the Delaware River are found in salinities as high as 10 ppt. Salinities less than 0.5 ppt would not influence the distribution of freshwater fishes in this portion of the estuary.

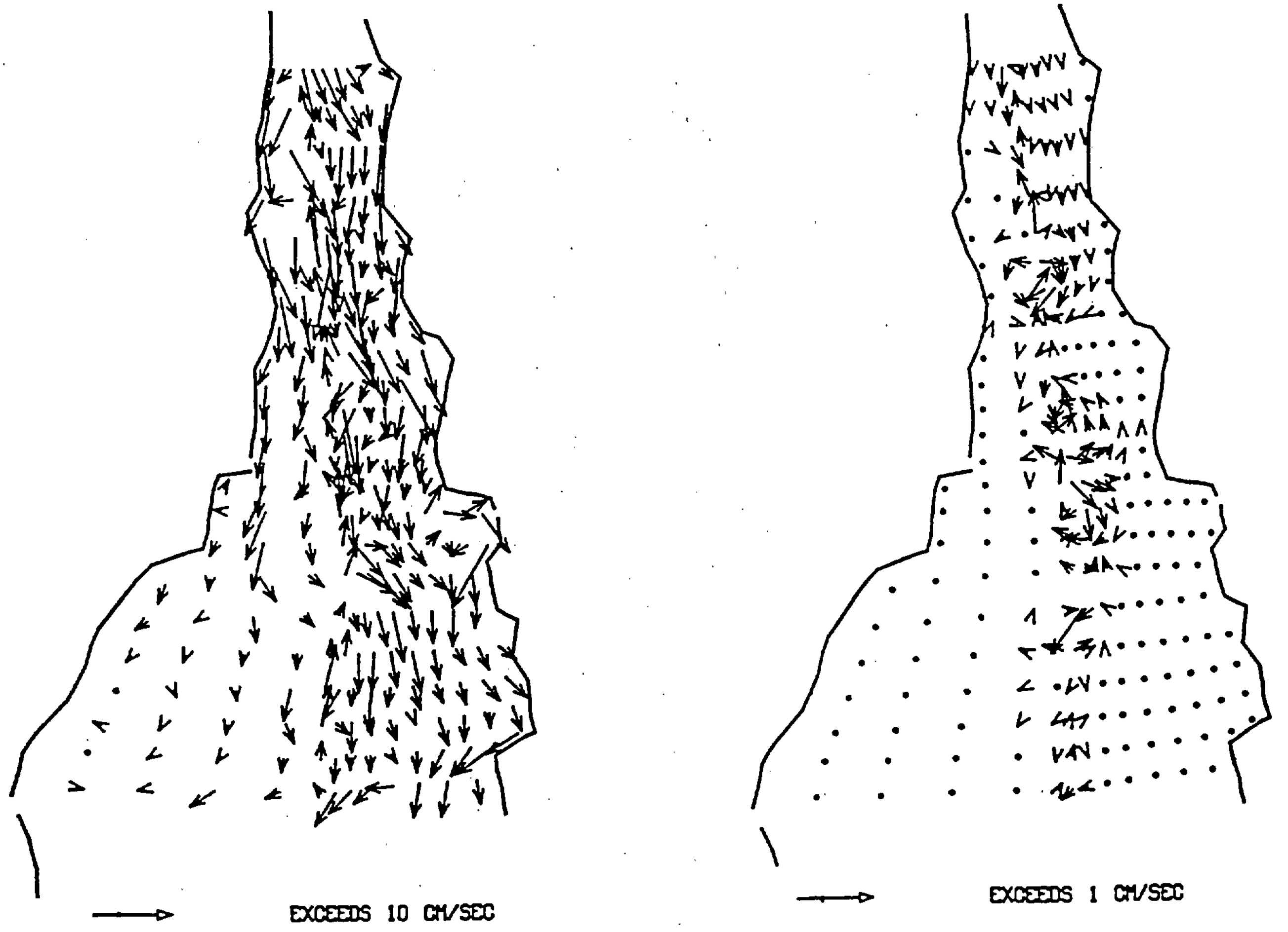
To this point, the discussion has focused on the predicted spatial (upstream) shift in salinity distribution attributable to the proposed deepening during a recurrence of the drought of record. There is a natural seasonal salinity cycle within the estuary that reflects typical seasonal changes in fresh water inflow. Salinity typically increases in the estuary from a minimum in April to a maximum in October or November, and then decreases to the following April. A salinity shift with a deepened channel means that a given salinity would reach a particular point in the estuary somewhat earlier than it would with the existing channel condition. On average, channel deepening with a recurrence of the drought of record would result in a given isohaline being from 0.0 to 3.3 miles further upstream compared to the 40 ft channel condition (Table 5-4). This shift is not considered large enough to diminish overall estuarine productivity, and is significantly less than salinity fluctuations resulting from semi-diurnal tidal exchange. As noted in Table 5-2, the greatest salinities occur in October and November. This time of the year is not considered significant relative to biological activity such as plant growth, fish spawning or nursery activities, blue crab spawning or nursery activities, or benthic productivity.

The impact of channel deepening on circulation in the estuary is illustrated in Figure 5-16. The plot shows near-surface residual current velocity for the month of November 1965. Residual current is defined as the average velocity over a period of time sufficiently long to remove the effects of the periodic, short-term tidal circulation. This type of plot was generated to address environmental concerns for potential circulation changes in the vicinity of oyster beds. The results show that changes in the residual circulation caused by channel deepening will be significantly less than 1.0 cm/sec, compared to total residual currents of less than 10.0 cm/sec.

Based on the simulation of a recurrence of the drought of record with the present DRBC regulated inflow scheme in place, it is concluded that the predicted changes in Delaware Estuary salinity patterns resulting from a five-foot deepening of the existing navigation channel would not result in a perceptible decline in estuarine productivity or adversely impact water supplies in the vicinity of Philadelphia. The predicted upstream movement in salinity due to deepening would be significantly less than the seasonal changes in salinity distribution resulting from normal variations in river flow. The highest salinities would occur in October and November when significant biological functions such as spawning and nursery activities and plant growth do not occur.

5.11.2 Simulation of Monthly Average Flows

The simulations described in the preceding section, with regulated inflows during a recurrence of the drought of record, are particularly important with regard to impacts of channel deepening on Philadelphia area salinities. However, to provide insight on potential impacts during more normal conditions, model runs were made using the June-November 1965 winds, tides, and salinity boundary conditions combined with long-term average monthly inflows specified for the Delaware, Schuylkill, and Susquehanna Rivers. Figures 5-17 and 5-18 present time series of salinity at RM 27 and at RM 69, locations for which results were presented in the preceding discussion of the regulated June-November 1965 simulation. There is no ocean-derived salinity present at RM 98 for the monthly-averaged inflow condition, thus no plot of RM 98 salinity is presented. Under monthly-averaged inflow conditions, the maximum salinity at RM 69 is less than 1.0 ppt compared to 5-7 ppt for the regulated June-November 1965



a. Existing channel

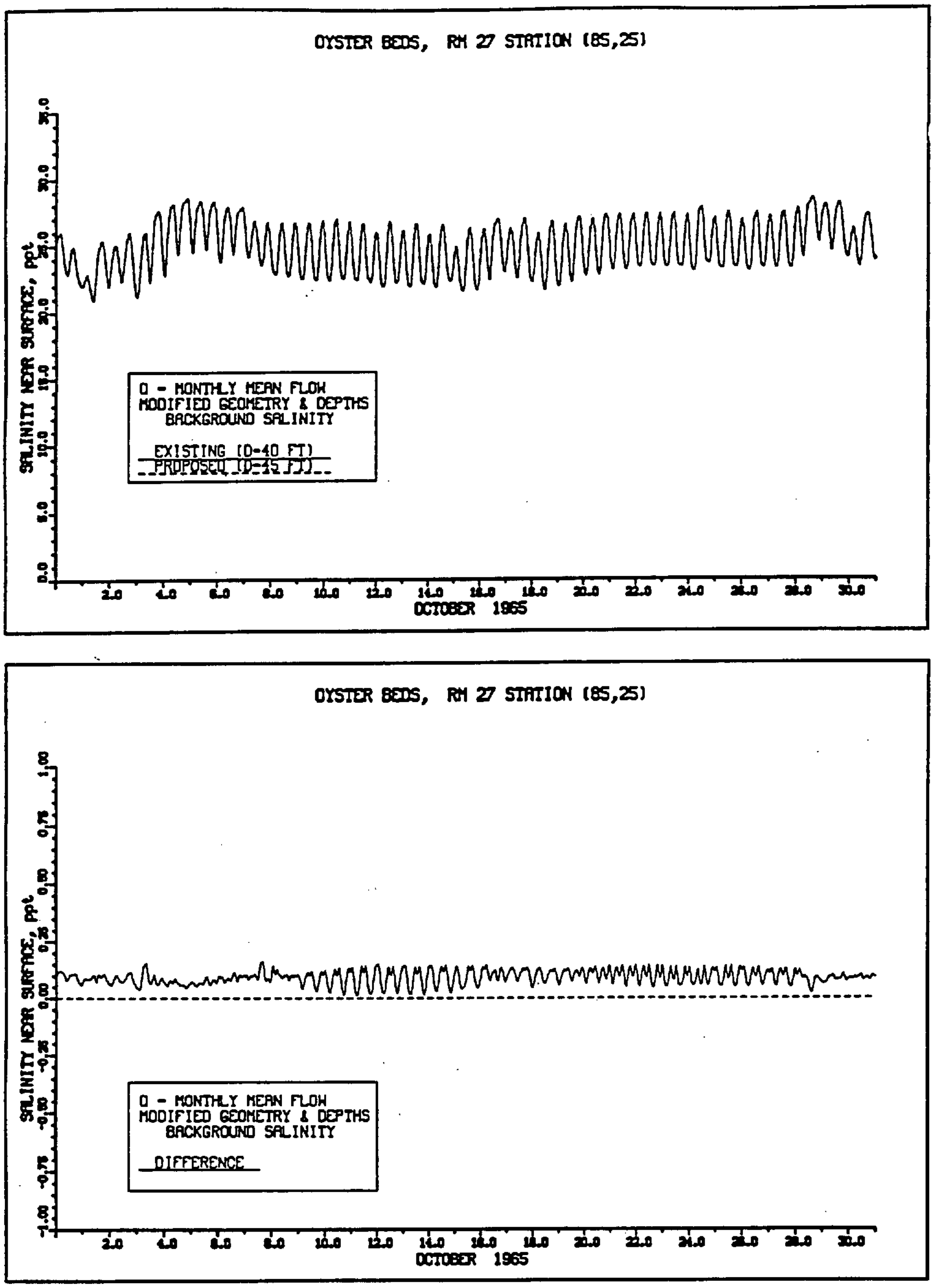
b. Impact of deepened channel

DELAWARE RIVER
MAIN CHANNEL DEEPENING PROJECT

Regulated Nov 1965 Scenario
Residual Near-surface Currents
40 ft vs 45 ft Channel Comparison

U.S. Army Corps of Engineers,
Philadelphia District

Figure 5-16

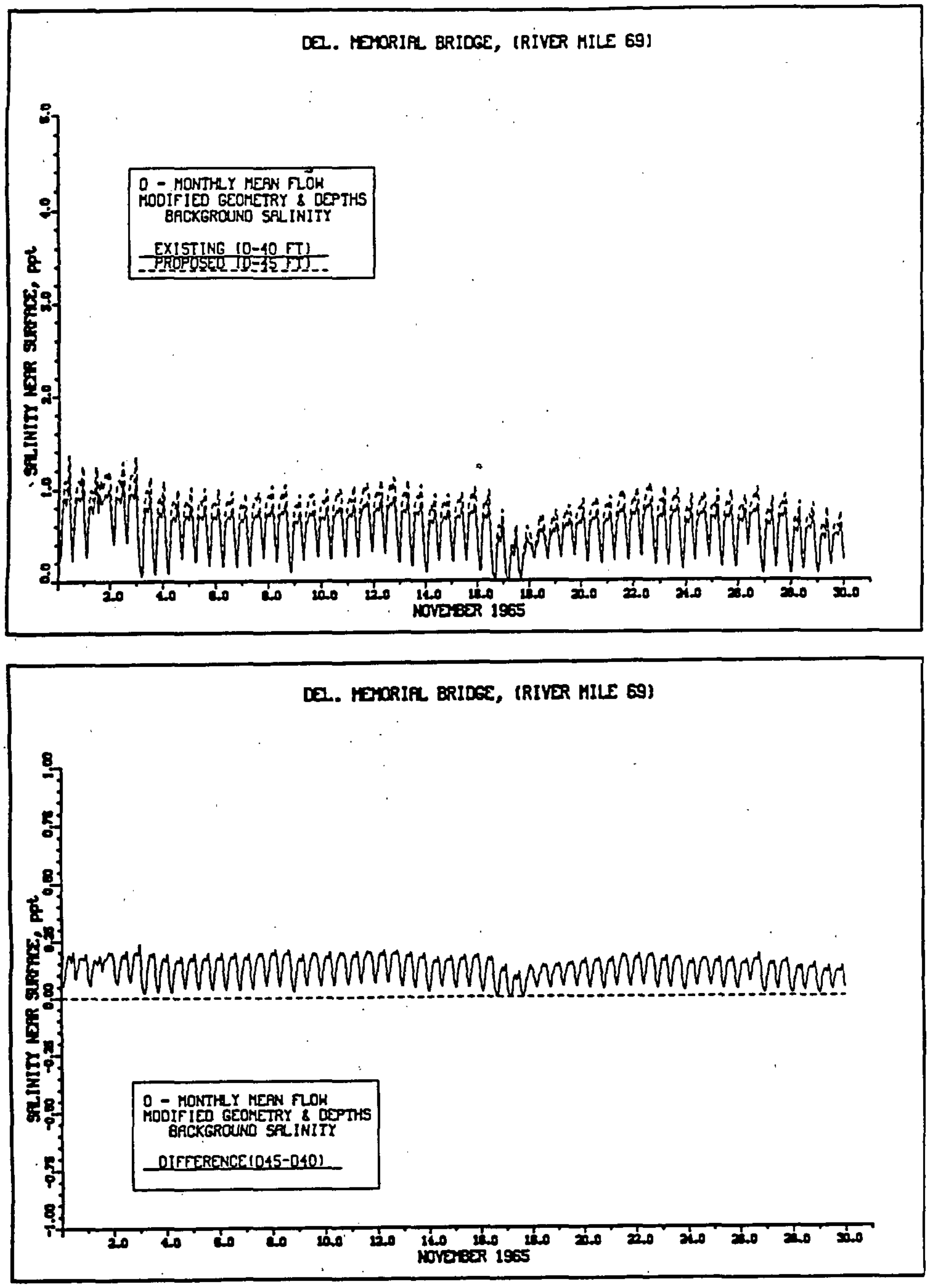


DELAWARE RIVER
MAIN CHANNEL DEEPENING PROJECT

Monthly Averaged Inflow Scenario, November
RM 27 Surface Salinity
40 ft vs 45 ft Channel Comparison

U.S. Army Corps of Engineers,
Philadelphia District

Figure 5-17



DELAWARE RIVER
MAIN CHANNEL DEEPENING PROJECT

Monthly Averaged Inflow Scenario, November
RM 69 Surface Salinity
40 ft vs 45 ft Channel Comparison

U.S. Army Corps of Engineers,
Philadelphia District

Figure 5-18

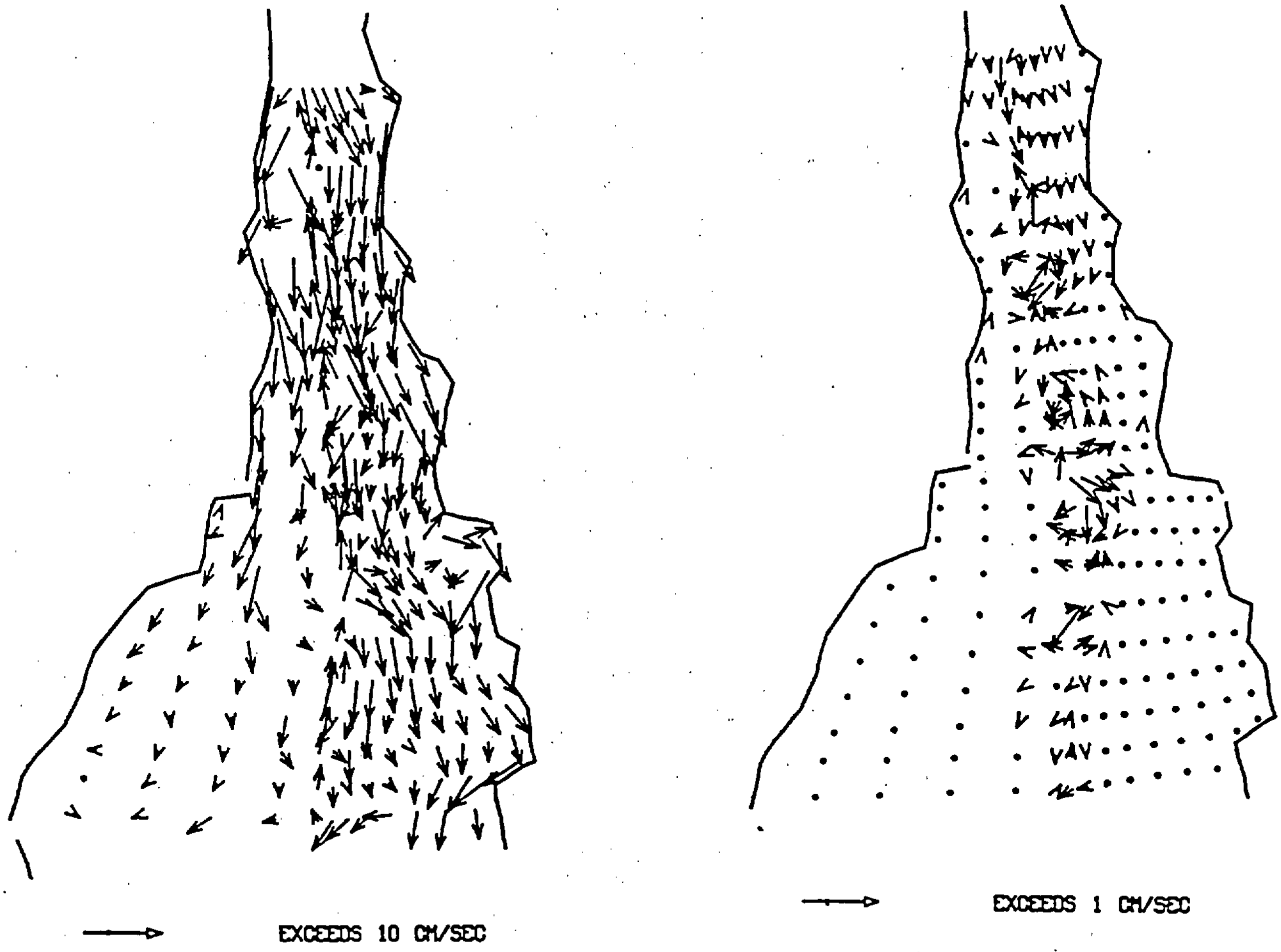
condition.

Figure 5-19 displays the impact of channel deepening on residual circulation for the November monthly-average flow condition. The impact is similar to that for the regulated drought condition, i.e., changes in the residual circulation due to channel deepening are less than 1.0 cm/sec.

Table 5-5 shows the typical monthly range in salinity at the 16 sites at which data were saved during the 40 foot channel and 45 foot channel simulations. For each month of the simulation, the first column of data presents the range of salinity with the 40 foot channel, and the second column presents the change attributable to the deepening to 45 feet. In the polyhaline portion (18 - 30 ppt) of the estuary, represented by River Miles 24 and 27, salinity will increase from 0.05 ppt to 0.15 ppt; in the mesohaline portion (5 - 18 ppt) of the estuary, represented by RMs 36, 38 and 43, salinity will increase from 0.05 ppt to 0.3 ppt; in the oligohaline portion (0.5 - 5 ppt) of the estuary, represented by RMs 54, 69, and 79, salinity will increase from 0 ppt to 0.8 ppt; and in the fresh water portion (0 - 0.5) of the estuary, represented by RMs 98 and 104, no salinity was present in either the existing or deepened channel scenario.

Table 5-6 presents the monthly averaged location of the 0.5, 5, 10, and 15 ppt isohalines for the 40 foot and 45 foot channel simulations, and the difference between them. Results of this comparison show that channel deepening leads to a maximum of 1.7 miles additional intrusion of the 15 ppt isohaline in October, with the other tracked isohalines intruding smaller distances with the channel deepening. Salinities typically increase within the estuary from July and August to a maximum in November. The range of incremental intrusion due to deepening for the tracked isohalines was: 0.5 ppt (0 - 1.1 miles); 5.0 ppt (0.5 - 1.5 miles); 10.0 ppt (0 -0.9 miles); and 15.0 ppt (0 - 1.7 miles).

Larger changes in the salinity due to channel deepening are predicted at locations over the oyster beds in the lower bay for the long-term monthly mean flow conditions compared to the changes computed for the regulated drought of record scenario. This is because the longitudinal salinity gradient is steeper due to the effects of the increased freshwater inflows. A general conclusion from modeling this scenario is that deepening the channel will have no impact on salinity conditions in the upper river since ocean salinity does not intrude that far. However, minor salinity changes are predicted over the oyster beds in the lower bay. The 15 ppt isohaline, which is considered important to the survivability of the American oyster, would shift up to 1.7 miles with the channel deepening. A change of salinity of up to 1 ppt will have no impact on oysters (Powell. 1995. Personal



Existing channel

Impact of deepened channel

DELAWARE RIVER
MAIN CHANNEL DEEPENING PROJECT

Monthly Averaged Inflow Scenario, November
Residual Near-surface Currents
40 ft vs 45 ft Channel Comparison

U.S. Army Corps of Engineers,
Philadelphia District

Figure 5-19

Table 5-5. Salinity at Selected Locations within Delaware Estuary.
Scenario: Monthly-averaged Inflows, July - November.
Salinity Range with 40 ft Channel, and Difference with 45 ft Channel.
3-D Model Results.

SALINITY DIFFERENCES DUE TO DEEPENING FROM 40 TO 45 FT

LOCATIONS	JULY		AUGUST		SEPTEMBER		OCTOBER		NOVEMBER	
	SALINITY (ppt)		SALINITY (ppt)		SALINITY (ppt)		SALINITY (ppt)		SALINITY (ppt)	
	Month Range 40 ft Channel	Month Avg Diff @ 45	Month Range 40 ft Channel	Month Avg Diff @ 45	Month Range 40 ft Channel	Month Avg Diff @ 45	Month Rang 40 ft Channe	Month Avg Diff @ 45	Month Range 40 ft Channel	Month Avg Diff @ 45
RM 100	0	0	0	0	0	0	0	0	0	0
RM 98	0	0	0	0	0	0	0	0	0	0
RM 79	< 0.04	0	< 0.04	0	< 0.05	0	< 0.06	0	< 0.06	0
RM 69	0.2 - 1.0	.05	0.2 - 0.8	0.1	0.3 -1.0	0.1	0.7 - 1.6	0.2/.25	0.2 - 1.2	0.15/0.2
RM 54	1 - 6	.05/0.1	1 - 6	0.3/0.4	2 - 7	0.3/0.5	3 - 8	0.15	2 - 9	0.5/0.8
RM 43 (OYST. A)	8 - 17	0.2/0.3	7 - 17	0.25	10 - 17	0.2	10 - 20	0.2	13 - 21	.15/0.2
(OYST. B)	8 - 15	0.2	7 - 15	0.2	10 - 16	0.2	10 - 18	0.15	11 - 19	0.1
(OYST. C)	8 - 14	0.2	7 - 14	0.2	10 - 15	0.15	9 - 16	0.1	9 - 17	0.1
RM 38 (OYST. D)	16 - 22	0.5	14 - 21	.05/0.1	17 - 22	.05/0.1	17- 24	.05/0.1	20 - 26	.05
(OYST. E)	14 - 19	0.1	12 - 18	0.1	15 - 19	.05/0.1	15 - 20	.05	16 - 22	.05
(OYST. F)	13 - 17	0.1	11 - 16	0.1	14 - 17	.05/0.1	13 - 18	.05	14 - 20	0.1
RM 36	17 - 24	0/0.2	16 - 24	.05/0.2	17 - 24	.05/.20	19 - 25	.05/0.2	21 - 27	.05/0.2
RM 27 (OYST. G)	22 - 27	.05/0.1	19 - 26	0.1	21 - 27	0.1	22 - 28	0.1	24 - 28	0.1
(OYST. H)	17 - 23	0.05	17 - 22	0.1	18 - 22	0.1	19 - 24	0.1	20 - 25	0.1
(OYST. I)	15 - 21	.05/0.1	15 - 19	0.1	16 - 20	0.1	16 - 20	0.1	18 - 21	0.1
RM 24	24 - 29	.05/0.1	22 - 28	.05/0.1	24 - 29	0.1/.15	25 - 30	0.1	27 - 30	0.1

NOTE: Column "MONTH AVG DIFF @ 45" - if single value shown, diff. at surface and bottom are approx. equal.
If two values shown, first is diff.at surf[illegible] second is diff. at bottom.

Table 5-6. Monthly-averaged Location of Selected Isohalines, by River Mile (RM).
Scenario: Monthly-averaged Inflows, August - November.
Values with 40 ft and 45 ft Channels, and Differences.
3-D Model Results.

MONTHLY AVG LOCATION OF 0. 5 ppt ISOHALINE (RM)

	MAX INTRUSION			AVG ACROSS FRONT		
MONTH	40 FT	45 FT	DIFF	40 FT	45 FT	DIFF
AUGUST	73.0	73.9	0.9	70.6	70.6	0.0
SEPT	75.0	76.1	1.1	72.2	73.0	0.8
OCTOBER	76.1	76.1	0.0	73.9	73.9	0.0
NOVEMBER	73.9	75.0	1.1	71.5	72.2	0.7

MONTHLY AVG LOCATION OF 5 ppt ISOHALINE (RM)

	MAX INTRUSION			AVG ACROSS FRONT		
MONTH	40 FT	45 FT	DIFF	40 FT	45 FT	DIFF
AUGUST	53.3	53.8	0.5	51.7	52.6	0.9
SEPT	54.8	56.3	1.5	53.3	54.8	1.5
OCTOBER	57.8	58.3	0.5	55.8	56.3	0.5
NOVEMBER	57.8	58.8	1.0	55.8	56.8	1.0

MONTHLY AVG LOCATION OF 10 ppt ISOHALINE (RM)

	MAX INTRUSION			AVG ACROSS FRONT		
MONTH	40 FT	45 FT	DIFF	40 FT	45 FT	DIFF
AUGUST	46.5	47.1	0.6	44.1	44.9	0.8
SEPT	49.1	49.1	0.0	47.1	47.1	0.0
OCTOBER	50.8	51.7	0.9	48.4	49.1	0.7
NOVEMBER	52.6	52.6	0.0	49.9	49.9	0.0

MONTHLY AVG LOCATION OF 15 ppt ISOHALINE (RM)

	MAX INTRUSION			AVG ACROSS FRONT		
MONTH	40 FT	45 FT	DIFF	40 FT	45 FT	DIFF
AUGUST	41.9	42.4	0.5	38.9	38.9	0.0
SEPT	42.9	44.1	1.2	40.4	41.4	1.0
OCTOBER	45.8	46.5	0.7	42.4	44.1	1.7
NOVEMBER	47.1	47.1	0.0	43.4	44.9	1.5

Communication). As seen in Table 5-5, the maximum change in salinity due to the 45 foot channel was 0.3 ppt in the oyster areas. These data indicate that the deepened channel will not add significantly to the salinity levels at the oyster seed bed areas under these conditions.

A shift in salinity zones would also shift spawning and nursery areas for estuarine fishes. Such a shift could move eggs and larvae closer to the Salem Nuclear Generating Station which is located at RM 53, which could possibly result in greater impingement and entrainment losses. Eggs and larvae of some species could also be moved closer to the Philadelphia pollution zone, which could result in lower survivability. The 10 ppt isohaline, which can fluctuate over a 30 mile stretch of the estuary and represents a reach that provides valuable spawning and nursery habitat for a variety of fishes, moved upstream from 0 to 0.9 miles with the deepened channel (Table 5-6). Table 5-5 shows that the maximum increase in salinity within this reach (the mesohaline) was 0.3 ppt. This does not represent a significant increase, and is not likely to impact the fish resources in this area.

Higher salinities could result in lower plant productivity, which could reduce food supplies for waterfowl and other wildlife. The 5 ppt isohaline represents a shift from fresh water to brackish vegetation. This isohaline would have a maximum additional intrusion of from 0.5 miles in August to 1.5 miles in September. Freshwater aquatic vegetation extends as far down stream as Wilmington, Delaware (Schuyler. 1988) which is at approximately River Mile (RM) 69. Table 5-5 shows that salinity at RM 69, both with and without the deepened channel, will not exceed 1.6 ppt in long-term monthly mean inflow scenario. The highest increment of increase in salinity that is attributed to the channel deepening at RM 69 is 0.25 ppt. At RM 79 there is no change in salinity with channel deepening. These predicted changes should not cause any significant impacts to aquatic vegetation. In the freshwater portion of the estuary (0.0 - 0.5 ppt) no salinity would occur under the long-term monthly mean inflow scenario.

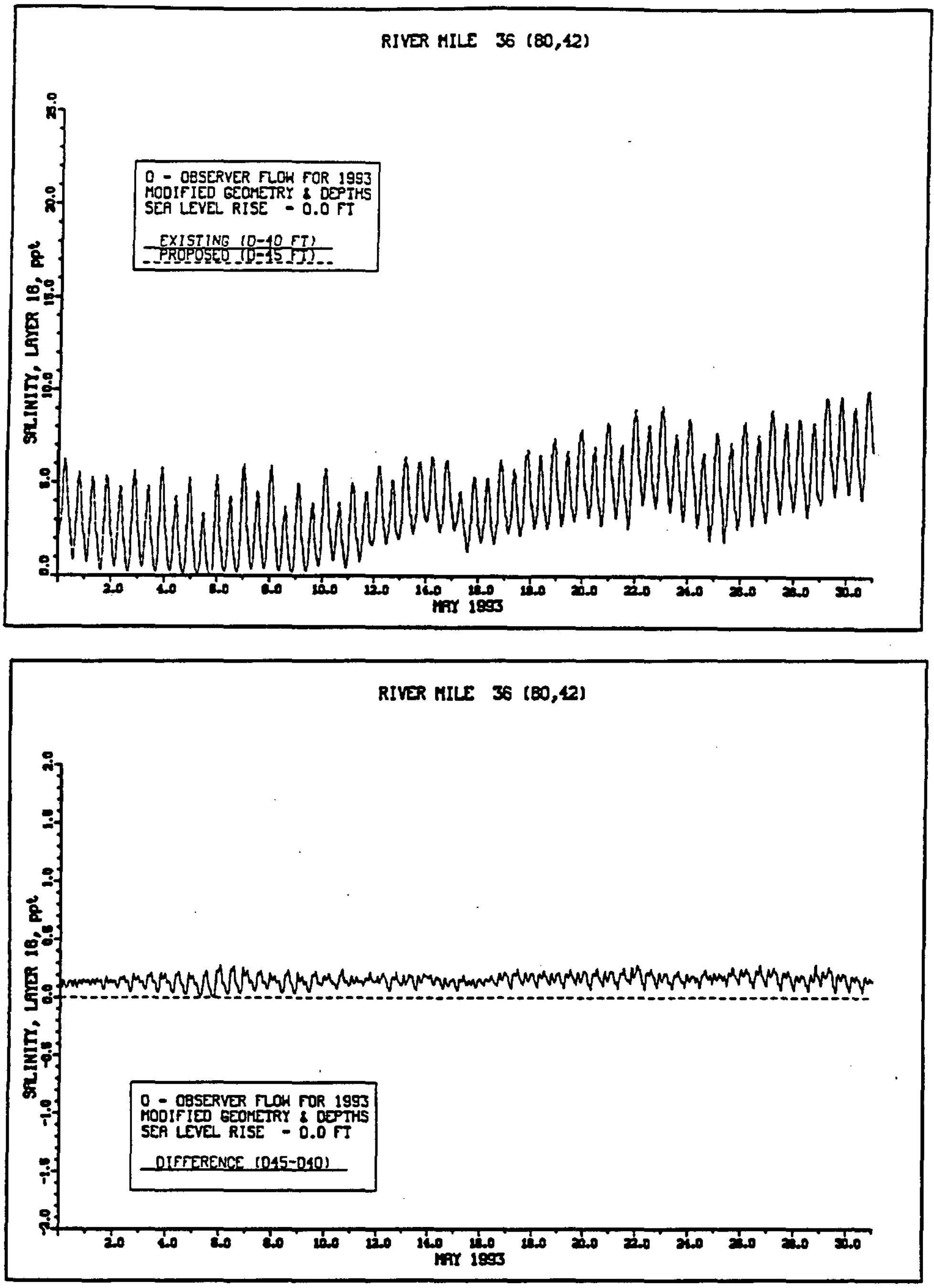
As previously mentioned, there is a natural, seasonal salinity cycle within the estuary that reflects seasonal changes in freshwater flow. Salinities increase in the estuary from a minimum in April to a maximum in October or November, and then decrease to the following April. For most of the year, a salinity shift with a deepened channel means that a particular salinity would reach a particular point in the estuary a little earlier than it would with the existing channel condition. On average, deepened channel salinities would be in the range of 0.0 to 1.7 miles ahead of existing channel salinities, at any particular time of the year. This time shift is not considered large enough to diminish estuarine productivity, and is likely to be less than salinity fluctuations resulting from daily tidal changes. As noted in Table 5-5, the greatest salinities occur in October and November. This time of the year is not considered significant relative to biological activity such as plant growth, fish spawning or nursery activities, blue crab spawning or nursery activities, or benthic productivity.

Based on the results of the 3-D model data sets for long-term mean monthly flows, it is concluded that the predicted changes in Delaware Estuary salinity distribution resulting from a five-foot deepening of the existing navigation channel, would not result in a perceptible decline in estuarine productivity or adversely impact water supplies in the vicinity of Philadelphia. The predicted upstream movement in salinity would be much less in comparison to yearly fluctuations in salinities resulting from variations in river flow. The highest salinities would occur in October and November when significant biological functions such as spawning and nursery activities, and plant growth do not occur.

5.11.3 April-May 1993 Simulations.

During coordination workshops for the 3D modeling, there was an interest expressed in analyzing the impact of channel deepening during transitional flow periods toward the end of typical spring freshet inflows. High freshwater inflow occurred during April 1993, with a monthly mean discharge at Trenton of 49,000 cfs. A substantial drop in this flow occurred, with a May mean discharge of 11,000 cfs at Trenton, New Jersey. The average wind field, tides, and salinity boundary conditions were all derived from prototype measurements at locations previously discussed for the October 1993 verification. No lateral variations were prescribed in the water surface elevations at the bay mouth, but lateral variations in the bay mouth salinities were specified.

The impact of the large freshwater inflow during most of April 1993 and the subsequent transition to lower flows during May is evident in Figures 5-20 and 5-21, which show the May 1993 time series of near-surface and near-bottom salinities, respectively, at RM 36. The top panel of each figure shows the salinity comparisons for the 40 foot and 45 foot channel simulations, and the bottom panel shows the model predicted salinity difference between the 40 and 45 foot channel conditions. Maximum salinities near the surface during the first half of May are about 5 ppt with maximum bottom salinities about 10 ppt. Minimum salinities occurring during each tidal cycle are essentially zero throughout the water column during the first half of May. This is indicative of a condition in which the near-bottom salinity at RM 36 varies by as much as 10 ppt over a single tidal cycle.

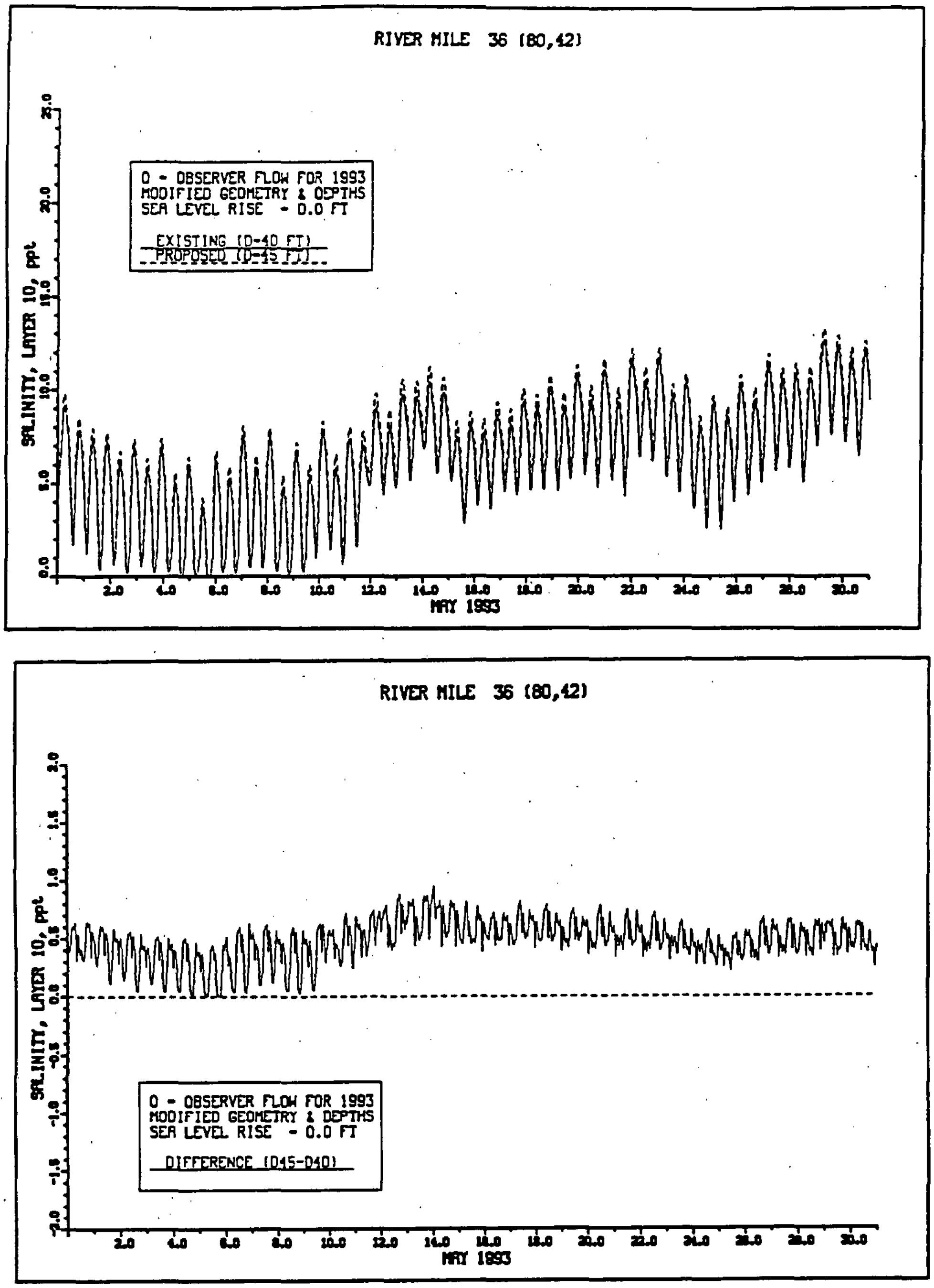


DELAWARE RIVER
MAIN CHANNEL DEEPENING PROJECT

May 1993 Simulation
RM 36 Surface Salinity
40 ft vs 45 ft Channel Comparison

U.S. Army Corps of Engineers,
Philadelphia District

Figure 5-20



DELAWARE RIVER
MAIN CHANNEL DEEPENING PROJECT

May 1993 Simulation
RM 36 Bottom Salinity
40 ft vs 45 ft Channel Comparison

U.S. Army Corps of Engineers,
Philadelphia District

Figure 5-21

In the April-May 1993 period, freshwater inflow began to decrease around the first of May, and salinities at RM 36 begin to rise near the middle of May. The channel deepening results in salinity increases at RM 36 on the order of 0.1 to 0.2 ppt near the surface and about 0.5 ppt near the bottom toward the end of May. Model results showed no salinity at any time during the simulation at RM 54 and all locations above RM 54. These results also indicate that relatively strong stratification can develop in Delaware Bay during high flow periods. Detailed graphical and tabular results, as presented for the previous two simulation scenarios, have not been prepared for the April-May 1993 simulation because of the dominance of the fresh water (i.e., zero salinity) inflow over much of the length of the estuary. There should be no significant impacts to the environmental resources in the Delaware Estuary due to deepening for the spring high-flow transitional period. Because there is no salinity recorded above RM 54, there will be no impacts to water supply at Philadelphia, including the freshwater aquifers. In addition, there will be no impacts to freshwater aquatic vegetation, since this occurs above RM 69. Nor should there be any adverse impacts to oysters, since the increase in salinity at the oyster seed bed areas will stay below 15 ppt and will increase by less than 1 ppt.

5.11.4 Simulations to Assess the Impact of Sea Level Rise

One of the issues identified during interagency coordination on the model involved the potential salinity impact of channel deepening combined with sea level rise. In order to address this concern, the regulated June-November 1965 boundary conditions were adopted, with the addition of an assumed sea level rise of one foot. The tidal boundary conditions at the mouth of Delaware Bay were increased by 1.0 foot (0.30 m). To determine the proper amount to raise the tide signal at Annapolis, MD, the Chesapeake Bay model of Johnson, et al (1991) was run for September 1983 conditions. The data set used in that study was adjusted with the tidal signal at the Chesapeake Bay mouth increased by 1.0 ft (0.30 m). The 1.0 ft tidal increase at the Chesapeake Bay mouth raised the mean water level at Annapolis by 0.90 ft (0.27 m). This value was then added to the June-November 1965 tide at Annapolis. It should be noted that the C&D Canal was not included in the Johnson, et. al. (1991) study. Thus, the 0.9 feet increase in the mean tide at Annapolis, MD may not be completely realistic. The most accurate way to address this issue would be to model the entire Chesapeake Bay and Delaware Bay system. One other limitation of the manner in which the sea level rise impact has been determined is that surface area of the bays will increase with sea level rise. However, the surface area of the estuary was not modified in this simulation.

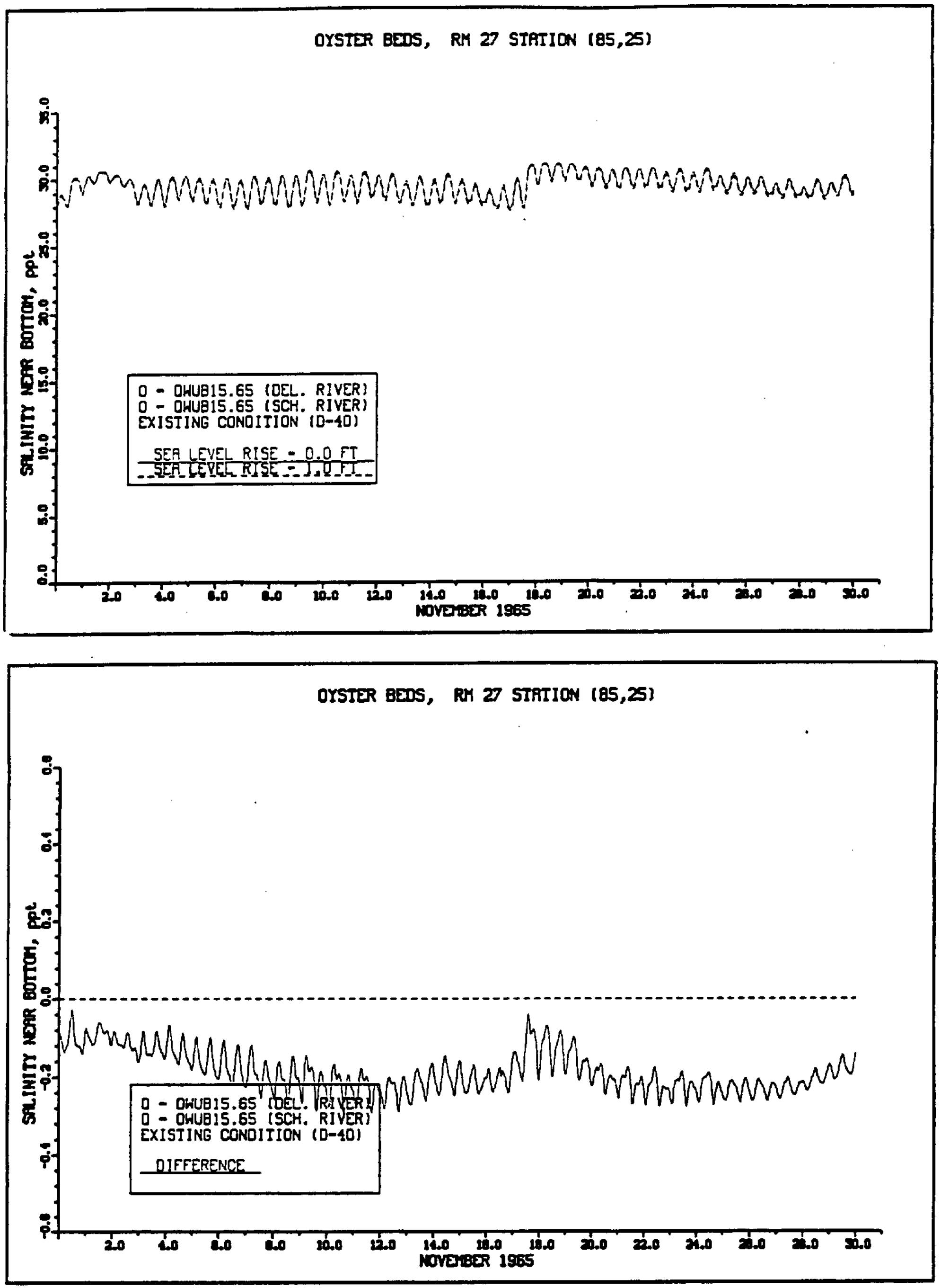
Time series plots of salinity at two locations showing the impact of the selected 1.0 foot sea level rise scenario are presented for November 1965 in Figures 5-22 (RM27), 5-23 (RM 69), and 5-24 (RM 98). These plots show increases in salinity due to the rise in sea level in some locations but decreases at other locations. The greatest decrease occurs over the oyster beds in the lower bay near RM 27, with the greatest increase occurring at RM 69. The modeled salinity response of the system between RM 27 and RM 69 raises interesting questions. Generally, it would be expected that the overall salinity in the bay would increase with a rise in sea level, because the increased flow area at the mouth results in an increase of salt transported through the mouth on flood tide. In addition, the increase in conveyance area along the estuary decreases the retarding effect of the freshwater inflow, resulting in an increase in salt intrusion. However, if flow diversions are created as a result of the sea level rise, such as flow through the C&D Canal, the salinity could decrease in some locations. In addition, the impact of raising the mean tide level by 1.0 foot at the Delaware Bay mouth and by 0.90 feet at Annapolis, MD may impact the net transport through the canal. This could also have an impact on the salinity regime.

5.12 Summary

A 3D numerical model of the Delaware Bay-Chesapeake and Delaware Canal-Upper Chesapeake Bay system has been developed and applied to assess the impact of deepening the existing Federal Delaware River navigation channel from 40 to 45 feet. In addition, the model has been applied to determine the impact of a sea level rise of 1.0 foot. To provide data for model verification, as well as for comparison of salinity distribution with the 40 foot and 45 foot channels, a one-year field data collection program was conducted. These data, along with data from the June-November 1965 portion of the drought of record, constituted the study data bases.

Before verifying the model, several sensitivity experiments were conducted. These consisted of grid convergence runs, time step convergence runs, and model runs to investigate the impact of the deepening project on flow conditions at the mouth of Delaware Bay. After the sensitivity runs were completed, the final numerical grid and computational time step were selected for both model verification and model production runs.

Model verification involved reproducing the conditions

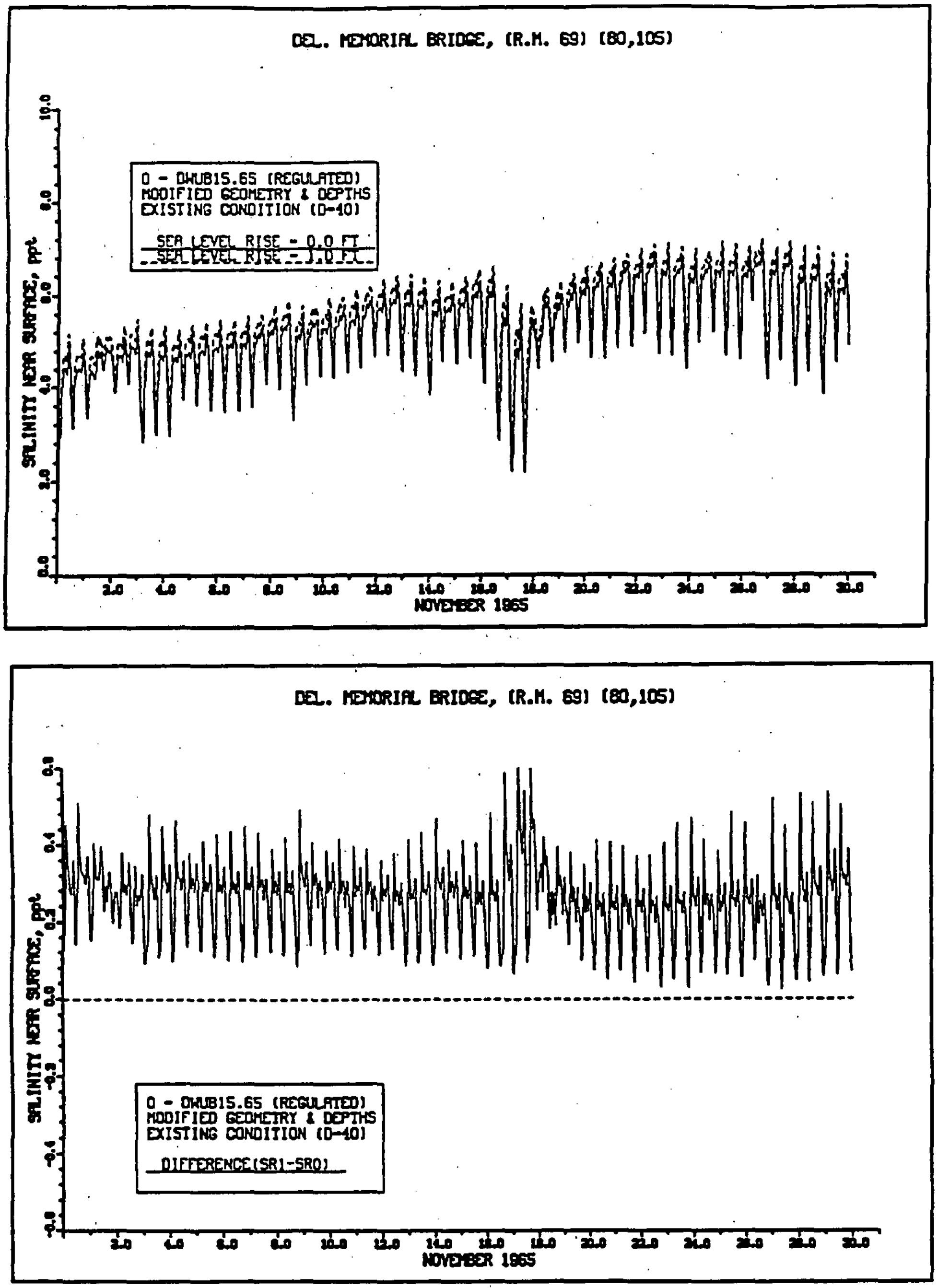


DELAWARE RIVER
MAIN CHANNEL DEEPENING PROJECT

Sea Level RiseScenario
RM 27 Salinity Comparison
Existing Sea Level vs 1 ft Rise

U.S. Army Corps of Engineers,
Philadelphia District

Figure 5-22

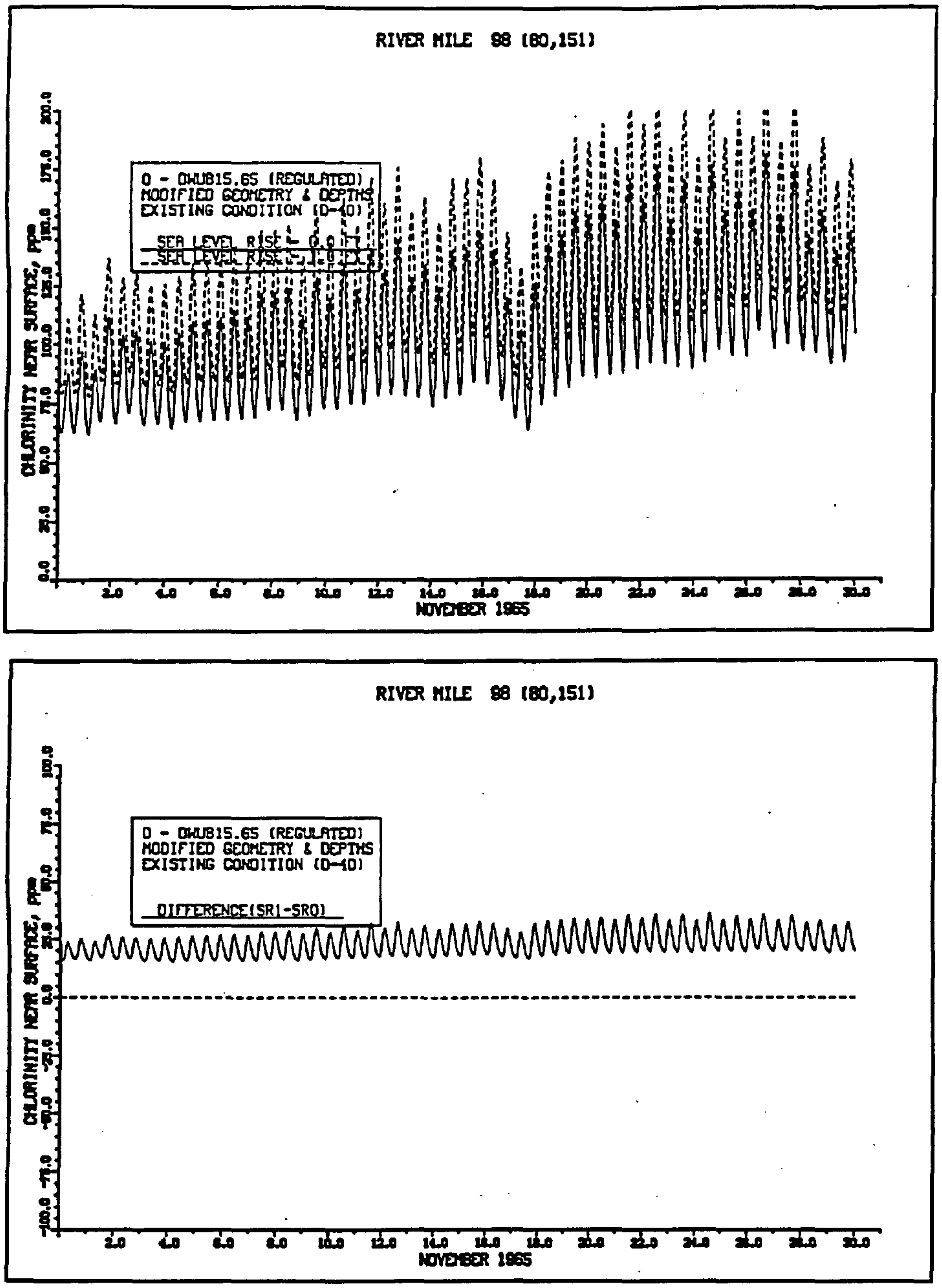


DELAWARE RIVER
MAIN CHANNEL DEEPENING PROJECT

Sea Level RiseScenario
RM 69 Salinity Comparison
Existing Sea Level vs 1 ft Rise

U.S. Army Corps of Engineers,
Philadelphia District

Figure 5-23



DELAWARE RIVER
MAIN CHANNEL DEEPENING PROJECT

Sea Level RiseScenario
RM 98 Salinity Comparison
Existing Sea Level vs 1 ft Rise

U.S. Army Corps of Engineers,
Philadelphia District

Figure 5-24

experienced during October 1992 (normal fall), April 1993 (high flow spring), and June-November 1965 (drought of record). The historical data for June-November 1965 represented an extreme low flow event during the 1961 to 1965 drought of record for the Delaware River Basin. Reproducing the drought event was considered crucial since municipal and industrial water supplies in the upper river may be adversely affected by encroaching salinity during such events.

Results from model runs with a 45 foot channel were compared with results from the existing 40 foot channel runs to assess the impact of channel deepening. Typical comparisons consisted of time series plots of salinity at several locations, locations of various time-averaged isohalines, and the impact on residual circulation patterns in the bay. In addition to the impact of channel deepening, the 3D model was applied to address questions concerning the impact of a sea level rise on the salinity regime of Delaware Bay.

5.13 Conclusions

A fundamental conclusion from the study is that deepening the existing navigation channel from 40 feet to 45 feet will result in salinity (chlorinity) increases in the Philadelphia area during a recurrence of the drought of record. However, the increases will not have an adverse impact on water supply. The present DRBC drought management plan, including reservoir storage added since the drought of record, prevents the intrusion of ocean salinity into the Philadelphia area in excess of existing standards. With the deepened channel and a recurrence of the drought of record, the maximum 30-day average chlorinity at RM 98 is about 150 ppm.

Historic groundwater withdrawals from the Potomac-Raritan-Magothy (PRM) aquifer in Camden County, New Jersey, have depressed the potentiometric surface of the aquifer system to a level as much as 100 feet below sea level in the central portion of the county. This has led to a condition in which a portion of the total recharge to the (PRM) aquifer system in Camden County is derived from Delaware River water. The present Delaware River Basin Commission drought management standard for RM 98 chlorinity is a maximum 30-day average of 180 ppm. This standard was adopted in order to limit the recharge by river water with elevated chlorinity into the PRM aquifers exposed at the bed of the Delaware River above RM 98 under low flow conditions.

Investigations of Camden County groundwater resources by the US Geological Survey (Navoy. 1996) have indicated that the rate of aquifer recharge from the river is principally controlled by groundwater withdrawals. Deepening of the Delaware River navigation channel will have a negligible effect on the recharge characteristics of the aquifer. Although the proposed channel deepening is predicted by the salinity model to increase RM 98 chlorinity with a recurrence of the drought of record, the resulting 30-day average chlorinity will still be below the present standard of 180 ppm. Transient increases in chlorinity of the river water recharging the aquifer under drought conditions will cause no loss of potability in the groundwater resource. Thus, it is concluded that the proposed channel deepening will not have a significant adverse impact on the hydrogeology or groundwater resources of Camden County, New Jersey. Increases in salinity attributable to channel deepening that could occur during a recurrence of the 1961-65 drought are unlikely to cause any additional adverse effect to environmental resources; freshwater aquatic vegetation will experience temporary decreases in distribution and productivity in the vicinity of RM 69, during a recurrence of the drought of record, but is expected to recover when the drought is over.

During normal to high flow periods with the deepened channel, oyster bed areas in the lower bay will experience increases in salinity due to steeper longitudinal salinity gradients which accompany high flow conditions. The impact of those increases on oyster production is viewed as negligible. Changes in the subtidal circulation over the oyster beds due to channel deepening will also be minimal, e.g., less than 1 cm/sec. Impacts that may occur to other environmental resources are also considered to be insignificant.

Results from the simulation of a 1.0 foot sea level rise combined with channel deepening are ambiguous due to a number of limitations. The principal limitation is the apparent need for a model domain encompassing the entire Chesapeake Bay, not just the portion of the bay above Annapolis, MD, as was the case with the present model. Model results clearly show the need to include the exchange between the Delaware Bay and the Upper Chesapeake Bay when addressing problems dependent upon subtidal processes. The impact of this exchange with the deepened channel depends upon the direction of the net flow through the Chesapeake and Delaware Canal. The direction of the net flow is highly variable in time and depends upon the particular winds, tides, and freshwater inflows.