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THE HYDRODYNAMICS OF THE NEWARK BAY – KILLS SYSTEM

PREPARED AS A COMPONENT OF THE
NEW JERSEY TOXICS REDUCTION WORK PLAN FOR NY-NJ HARBOR
STUDY I-E (SIT COMPONENT)

by

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Prepared for

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EXECUTIVE SUMMARY

NJ Toxics Reduction Workplan for NY-NJ Harbor
Study I-E Hydrodynamic Studies

SIT and Rutgers University Components

The Newark Bay Complex, which is part of New York-New Jersey Harbor, consists of Newark Bay, the Arthur Kill and Kill van Kull tidal straits, and the Passaic and Hackensack Rivers. The presence of toxic chemicals in water and sediments throughout the harbor estuary has resulted in reduced water quality, fisheries restrictions/advisories, reproductive impairments in some species, and general adverse impacts to the estuarine and coastal ecosystems. In addition, problems associated with the management of contaminated dredged material have resulted in uncertainty regarding planned construction and future maintenance of the maritime infrastructure that supports shipping in the Harbor.

The New Jersey Toxics Reduction Workplan for NY-NJ Harbor (NJTRWP) includes a series of studies designed to provide the NJ Department of Environmental Protection with the information it needs to identify sources of the toxic chemicals of concern, and to prioritize these sources for appropriate action. As part of the NJTRWP, a comprehensive hydrodynamic study was completed between the years 2000 and 2002 to begin to understand the effects of tidal, meteorological, and freshwater forces on circulation patterns in the system. This was by far the most comprehensive deployment of hydrodynamic monitoring equipment of this type ever to occur in this economically important and complex estuarine system.

Study I-E of the NJTRWP, undertaken by Stevens Institute of Technology (SIT) and Rutgers University, focuses on the analysis of the hydrodynamics data collected from long-term instrument moorings deployed in the harbor during 2000-2002. In addition, because the data collected was not continuous enough in time or space to gain a complete understanding of the system, a three-dimensional hydrodynamic model of the area has been developed by SIT. The model of the Newark Bay Complex developed for this study replicates the available water elevation, salinity, and current velocity data. Thus, the model may be utilized with confidence, along with the NJTRWP data, to investigate the hydrodynamics of the system.

Circulation Patterns

Although it is difficult to define a "normal" pattern of circulation in the Newark Bay Complex, this study and several prior studies have indicated that the circulation responds in a **complex event-driven fashion** to a combination of influences, both short-lived (winds and freshwater inflow) and longer term (classic estuarine gravitational circulation). The end result is that the identification of a long-term average circulation pattern is difficult. In light of this finding, it is best to examine the responses of the Newark Bay Complex to each of the possible primary influences.

Gravitational Circulation

Within the navigation channel of Newark Bay, classic estuarine gravitational circulation occurs, with daily averaged currents (the current averaged over several tidal cycles) directed seaward near the surface and landward near the bottom. The same estuarine circulation pattern occurs in the Kill van Kull and the southern portion of the Arthur Kill. However, in these tidal straights this pattern is not as pronounced during periods with a large range in tidal height (e.g., Spring tides). Figure 1 illustrates this classic estuarine circulation pattern in NY-NJ Harbor.

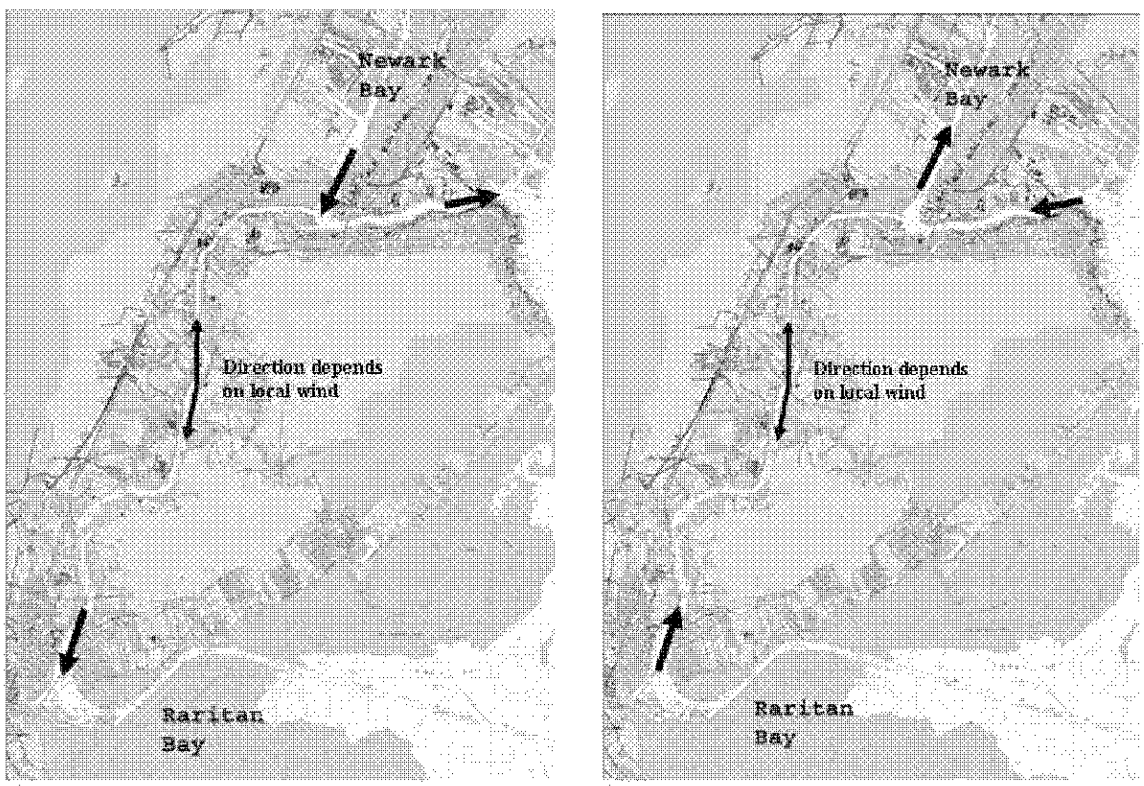

Figure 1: Daily Averaged Currents Associated with Estuary Gravitational Circulation, Near-Surface (left panel) and Near-Bottom (right panel).

The NJTRWP Study I-E data also suggests that while the mean depth-averaged flow in the main navigation channel of Newark Bay is landward, the net flow along the channel flanks is seaward.

This classic estuarine gravitational circulation pattern can be broken down – that is, the daily averaged currents become uniform throughout depth – during periods of very low freshwater discharge from the Passaic River. During these periods, the daily averaged currents in Newark Bay are directed largely landward (north) at all depths except near the surface.

An illustration of the effects of the competing influences of the tidal motion and gravitational circulation associated with the Passaic River freshwater inflow is shown in Figure 2, which presents the measured daily averaged currents at Newark Bay, the Kill van Kull and Perth Amboy during March, 2001. Days 66 to 68 were characterized as Spring Tide (large tidal range) and very low freshwater inflow. Days 77 to 79 were characterized as Neap Tide (small tidal range) and high freshwater inflow. Days 87 to 89 were characterized as Spring Tide and moderately high freshwater inflow. During days 66 to 68, the daily averaged currents are nearly uniform throughout depth at all three locations, and are directed landward (north) in Newark Bay at all depths except very close to the water surface. By contrast, the periods during days 77 to 79 and 87 to 89, when the freshwater inflow was considerably higher, are characterized by daily averaged currents with considerable vertical variability: seaward directed currents in the upper layers and landward directed currents in the lower layers. The exception to this pattern is the Kill van Kull during days 87 to 89, which exhibited nearly uniform, seaward directed daily averaged currents. This is likely the result of very strong vertical mixing produced by the combination of the Spring Tide and the storm conditions that existed during this period. Thus, there is significant spring/neap tide variability in the vertical structure of the currents (and salinity), even during times of low Passaic River discharge.

Meteorological Events

Strong and persistent winds can have a major effect on water circulation in the Newark Bay Complex, and in the estuary as a whole. During periods of strong west winds acting synoptically over the New York Bight region (that is, including the coastal ocean area offshore of the harbor estuary), the water level in Raritan Bay is lowered, producing a strong pressure gradient from the Kills to the open ocean. Under this condition, the daily averaged currents are directed seaward (south) out of Newark Bay and through the Kill van Kull. During periods of strong east winds acting synoptically over the New York Bight region, the water level in Raritan Bay is raised, producing a strong pressure gradient from the open ocean toward the Kills. Under this condition, the daily averaged currents are directed landward in through the Kill van Kull and into Newark Bay. The daily averaged currents in the Arthur Kill are strongly influenced by local (north/south) winds. The effects of these meteorological events are shown in Figure 3.

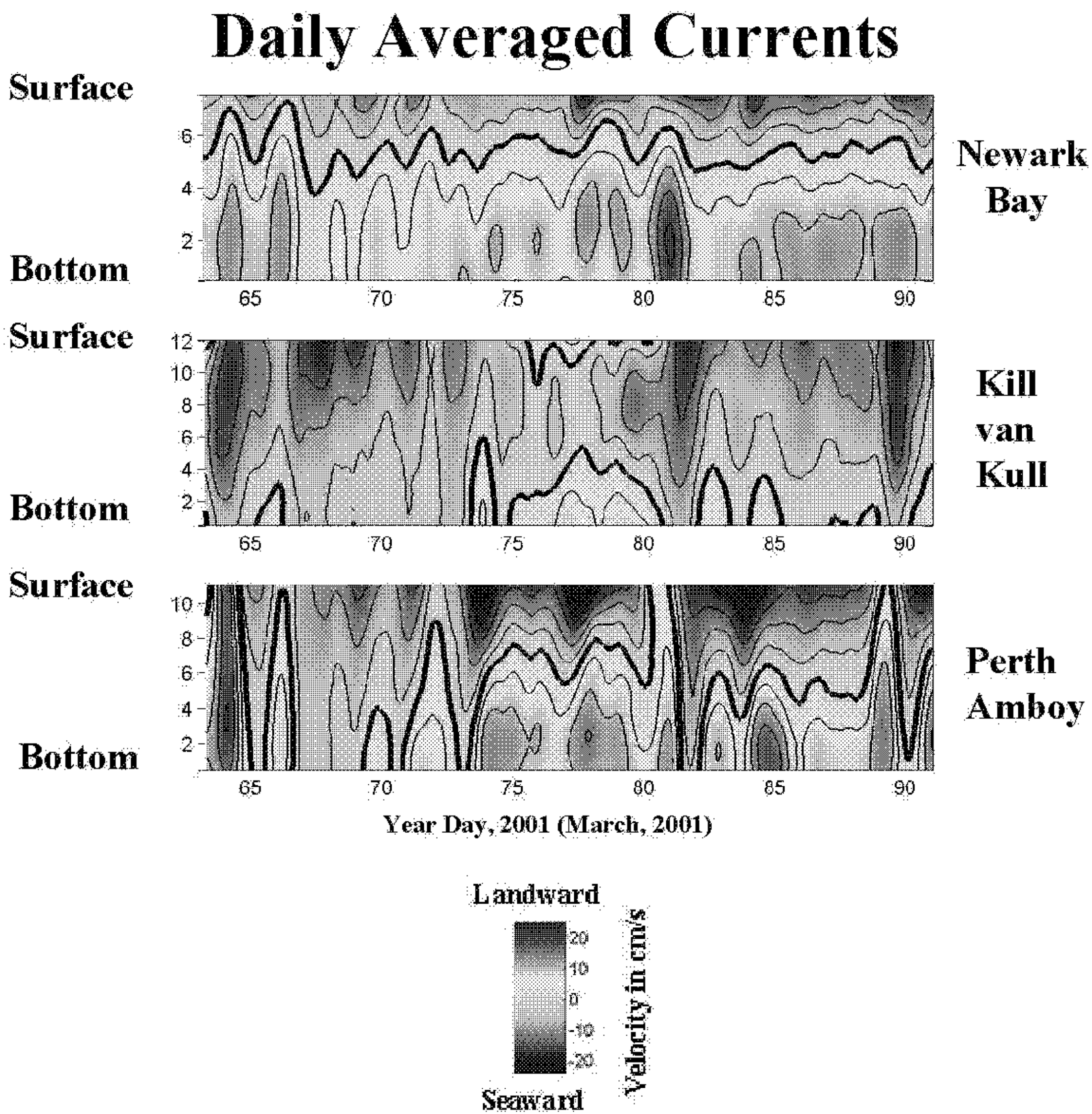

Figure 2: Daily Averaged Currents during March, 2001.

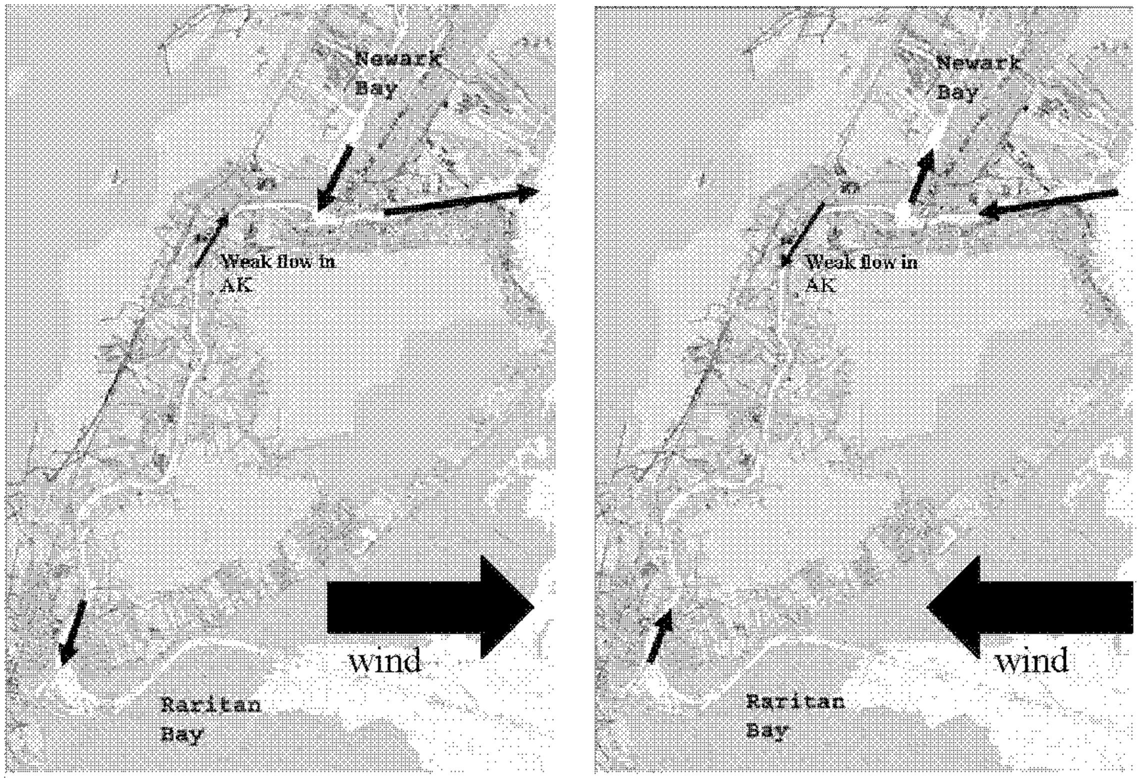

Figure 3: Tidal Residual Currents during Strong, Large-Scale Winds from the West (left panel) and the East (right panel).

Fate of Passaic River Suspended Sediment

Based on the NJTRWP Study I-E observations and the results from a simple sediment transport model developed by SIT, estuarine gravitational circulation plays a primary role in determining the fate of suspended sediment from the Passaic River. Large flow events from the Passaic River produce higher suspended sediment concentrations in Newark Bay. The fate of this suspended sediment load will depend on the settling rate of the suspended material. High discharge events increase both vertical stratification and the flow rate in the landward-flowing bottom layer in Newark Bay, and thus effectively trap material that rapidly settles to the lower layer. However, high flow events also increase the surface outflow and can transport slowly settling material towards the Kill van Kull, where stronger tidal currents can easily carry this material into upper New York Harbor.

An initial estimate of the suspended sediment flux through the Kill van Kull completed by Rutgers University indicates that approximately 100,000 metric tons of suspended sediment (net) are transported from Upper New York Bay into Newark Bay each year. Finally, the partitioning of contaminants across sediment size and the settling velocity of the suspended sediment particles will significantly modify the fate and transport of contaminants in NY-NJ Harbor.

Effects of Navigation Channel Deepening

Computer model runs were performed by SIT to simulate future conditions in the Newark Bay Complex when navigation channels in the harbor are deepened to 50 feet. Deepening all of the navigation channels was shown to increase the tidal flux in the Arthur Kill and Kill van Kull by 17% and 2%, respectively. This may increase transport of sediment into (or out of) the system from Upper New York Bay and Raritan Bay. Tidal velocities would be reduced, which might result in increased sediment deposition in Newark Bay, and also limit the resuspension of sediment. Greater salt intrusion into the system could also result in the trapping of more sediment.

Summary and Main Findings

- **Circulation in the Newark Bay Complex responds to a combination of influences in a complex event-driven fashion, making the identification of a long-term average circulation pattern difficult.**

- **Within the navigation channel of Newark Bay, classic estuarine gravitational circulation occurs, with daily-averaged currents directed seaward near the surface and landward near the bottom. The same pattern also generally occurs in the Kill van Kull and lower Arthur Kill.**

  - **Larger Passaic River flows are associated with greater water column stratification and enhanced gravitational circulation. This produces higher daily averaged currents in the Newark Bay channel.**

  - **This circulation pattern in Newark Bay can be broken down during periods of very low discharge from the Passaic River, such that daily averaged currents are largely directed landward throughout most of the water column.**

- **Persistent wind events can produce large "flow-through" flushing events in the Newark Bay Complex. During periods of strong, large-scale west winds over the region, the daily averaged currents are directed seaward out of Newark Bay and through the Kill van Kull. During periods of strong, large-scale east winds, the daily averaged currents are directed landward in through the Kill van Kull and into Newark Bay.**

  - **The daily averaged currents in the Arthur Kill are strongly influenced by local (north/south) winds.**

- **Large Passaic River flow events produce higher suspended sediment concentrations in Newark Bay. Such events also increase both vertical stratification and the current velocity in the landward-flowing bottom layer of the bay, and thus can trap material that rapidly settles to this layer. However, these events also increase the surface outflow and can transport slowly settling material towards the Kill van Kull, where stronger tidal currents can carry this material into Upper New York Bay. The fate of the suspended sediment will depend on the settling rate of the particles.**

  - **The partitioning of contaminants across sediment size and the settling velocity of the suspended sediment particles will significantly modify the fate and transport of contaminants in NY-NJ Harbor.**

- **An initial estimate of the suspended sediment flux through the Kill van Kull indicates that approximately 100,000 metric tons of suspended sediment (net) are transported from Upper New York Bay into Newark Bay each year.**

Contents

1 Introduction and Objectives **2**

1.1 NJTRWP Project Reports – Introduction 2

1.2 Description and Objectives 4

2 Previous Studies **8**

3 Data Collection **12**

4 Numerical Modeling **23**

4.1 Model Description 23

4.2 Model Grid and Bathymetry 25

4.3 Forcing Functions 26

4.3.1 Water Elevation 26

4.3.2 Temperature and Salinity 29

4.3.3 Surface Wind Stress 31

4.3.4 Freshwater Inputs 31

4.4 Model Calibration and Validation 32

4.4.1 Elevation 32

4.4.2 Salinity 36

4.4.3 Velocity 41

5 Characterization of the Data **49**

5.1 Tidal Propagation 49

5.2 Salinity 51

5.3 Winds 51

5.4 River flow from the Passaic 52

6 Model/Data Synthesis **54**

6.1 Estuarine Circulation Dynamics 54

6.2 Meteorological Events 61

6.3 Fate of Suspended Sediment in the Passaic River 77

6.4 Effects of Channel Deepening 84

7 Conclusions **90**

8 Bibliography **92**

Appendices **98**

A Water Level Data **98**

B Bottom Mount Data **102**

C Moored Vessel Salinity Profiles **131**

D Vessel Transect Salinity Profiles **154**

E Model Data Comparison **249**

F Meteorological Events **270**

List of Figures

1.1 Bathymetry of Newark Bay (depth is in meters) 5

3.1 NJTRWP Hydrodynamic Data Inventory for 2000-2002 13

3.2 Typical Bottom Mount Setup 16

3.3 Bottom Mount Data at NB1 for December 2000 17

3.4 Moored Salinity (psu) Profile on 15 December 2000. 19

3.5 Location and Profile for March 13, 2001 20

3.6 Salinity Profile March 13, 2001 21

4.1 Velocity Coordinate System 24

4.2 Bathymetry and Model Grid for Newark Bay (depth is in meters) 27

4.3 Enlarged View of Bathymetry and Model Grid for Newark Bay (depth is in meters) . . 28

4.4 Real and Synthetic Water Levels (m) at Perth Amboy Yacht Club for 2001 30

4.5 Model-Data Comparison for NB1 March-May 2001 33

4.6 Model-Data Comparison for NB1 September-October 2001 34

4.7 Model-Data Water Level Comparison for August-November 2001. 35

4.8 Model-Data Salinity Comparison at NB1 Over All Time Periods 38

4.9 Profile Comparison of CTD and Model at NB1 40

4.10 Model-Data Depth-Averaged Velocity Comparison at NB1 42

4.11 Model-Data Depth-Averaged Band-passed Velocity Comparison at NB1 for periods of greater than 34 hours and less than 5 days. 43

4.12 Monthly Power Spectral Density of Depth Averaged Currents at NB1 45

5.1 Histograms for Wind Data December 2000 to April 2002 52

5.2 River Flow from the Passaic December 2000 to April 2002. 53

6.1 Surface and Bottom Salinity in the Newark Bay Complex 55

6.2 Surface and Bottom Velocity During Flood Tide 57

6.3 Surface and Bottom Velocity During Ebb Tide 58

6.4 Longitudinal salinity sections in Newark Bay for period of low freshwater flow 59

6.5 Longitudinal salinity sections in Newark Bay for period of high freshwater flow 60

6.6 Monthly average cross-section of salinity and velocity in Newark Bay for period of low freshwater flow 62

6.7 Monthly average cross-section of salinity and velocity in Newark Bay for period of high freshwater flow 63

6.8 Diagram of Ekman transport in Newark Bay due to wind from west. 65

6.9 Low-passed data from December 2000 66

6.10 Low-passed data from March 2001 67

6.11 Surface Salinity (psu) and Currents for December 2000 68

6.12 Flow Directions in the Kills During Modes 1 and 2 72

6.13 Sediment Distribution in Bottom Layer at End of Month (mg/L) 79

6.14 Monthly Average of Bottom Currents for May 2001 (m/s) 81

6.15 Sediment Distribution at the End of Month for Synthetic Cases 83

6.16 Tidal Flux Comparison for Flood Tide 86

6.17 Low-pass Flux Comparison of Regular and Deepened Channel Runs May 2001 88

6.18 Bottom Salinity May 2001 (psu) 89

List of Tables

3.1 Water Elevation Data Available 15

3.2 Bottom Mount Data Available 16

3.3 Moored Vessel Data Inventory 18

3.4 Transecting Vessel Data Inventory 22

4.1 Model-Data Elevation Comparison 37

4.2 Comparison of M_2 Tidal Constituents 38

4.3 Model-Data Salinity Comparison 39

4.4 Comparison of Model and Data Averages for Salinity at NB1 39

4.5 Comparison of Hourly Model and Data Velocity: Depth-averaged, near surface, and near bottom 46

4.6 Comparison of Long-term Model and Data Velocity: Periods between 34 hours and 5 days, and periods longer than 5 days 47

4.7 Volume Flux in Kills for 0 slope between boundaries 48

4.8 Volume Flux in Kills for Arthur Kill boundary 1cm higher than Kill van Kull boundary 48

4.9 Volume Flux in Kills for Kill van Kull boundary 1cm higher than Arthur Kill boundary 48

5.1 M_2 Constituents for Elevation and Velocity from Bottom Mounted ADPs and Tide Gages 50

6.1 Correlation table for meteorological events for January 2001 to April 2002 68

6.2 EOF Analysis Results January 2001 to April 2002 70

6.3 Correlation table for meteorological events December 2000 74

6.4 EOF Analysis Results December 2000 75

6.5 Sediment Distribution at the End of Month 80

6.6 Change in M_2 Tide Constituents As a Result of Channel Deepening 85

Chapter 1

Introduction and Objectives

1.1 NJTRWP Project Reports – Introduction

The New York-New Jersey Harbor estuary system is of enormous and interdependent ecological and economic importance. However, the presence of toxic chemicals in the water and sediments results in reduced water quality, fisheries restrictions/advisories, reproductive impairments in some species, and general adverse impacts to the estuarine and coastal ecosystems. The Port of New York and New Jersey is the largest port on the East Coast of the United States and central to the economy of the region. However, problems associated with the management of contaminated dredged material have resulted in uncertainty regarding planned construction and future maintenance of the maritime infrastructure that supports shipping in the harbor.

The New Jersey Toxics Reduction Workplan for NY-NJ Harbor (NJTRWP) includes a series of studies designed to provide the NJ Department of Environmental Protection (NJDEP) with the data and information it needs to meet the following primary objectives:

- to identify sources of the toxic chemicals of concern, and to prioritize these sources for appropriate action (management, regulatory, trackdown, clean-up).

- to identify selected contaminated sediments for future remediation and restoration activities

NJTRWP Phase One Studies I-C, I-D and I-E are monitoring studies of selected ambient water quality and suspended sediment parameters throughout various tributaries to the Newark Bay Complex and the NY-NJ Harbor estuary system. Study I-G consists of the monitoring of discharges from selected municipal wastewater treatment facilities, combined sewer outfalls (CSOs), and storm water outfalls (SWOs). These four studies have been coordinated with each other, and with various monitoring studies included in the analogous New York State toxics reduction workplan, under the umbrella of the NY-NJ Harbor Estuary Program Contaminant Assessment and Reduction Program. The combined objective of the NJTRWP studies is to determine the relative significance of loadings of toxic chemicals and sediment throughout the harbor from sources (1) above the head of tide of major tributaries, and (2) within the watersheds of the major tributaries, including the Newark Bay Complex.

This Project Report documents the methods, results, analyses, and conclusions of Study I-E (SIT hydrodynamics component) of the NJTRWP. The primary objective of the hydrodynamics component of NJTRWP Study 1-E is to characterize the transport patterns of suspended sediments and the chemicals of concern within these estuarine areas. Specifically, the Study I-E hydrodynamics work will provide hydrodynamics data which can be used to characterize and understand the transport and fate of suspended sediments and the chemicals of concern within the Newark Bay Complex, Arthur Kill, and Kill Van Kull.

1.2 Description and Objectives

The Newark Bay Complex, shown in Figure 1.1, is part of the Port of New York and New Jersey. As the third largest container port in the United States, this area plays an essential role in both the local and national economies. In 2003, the port brought in more than $100 billion worth of cargo, and provided numerous jobs for residents in the region (Port Authority of New York and New Jersey, 2004).

This complex estuarine system consists of two freshwater inputs from the north, the Passaic and Hackensack Rivers, and two tidal straits. These straits are the Kill van Kull, which connects Newark Bay to Upper New York Bay, and the Arthur Kill, which joins Newark Bay to Raritan Bay. The depth of this complex is naturally shallow, and shipping channels must be dredged through the system to maintain a depth sufficient for the safe navigation of ships calling the port. The Army Corps of Engineers has recently completed a project which deepened the shipping channels in Newark Bay and the Kill van Kull to 13.7 meters (45 feet), and has plans to complete a current project to deepen the Arthur Kill to 12.5 meters (41 feet) by the end of 2005. An agreement which was finalized on May 28, 2004, authorizes the Army Corps of Engineers to award contracts to deepen the Kill van Kull, Newark Bay, and the Arthur Kill shipping channels to 15.2 meters (50 feet) to accommodate the newest class of container ships with deeper draft.

The maintenance of the shipping channels in this area will continue to be an ongoing project, since the system tends to revert back to its naturally shallow state. To further complicate this, the sediments in the area are contaminated with a variety of toxic chemicals (Suszkowski, 1978; Crawford, et. al., 1995; Huntley, et. al., 1997; Ianuzzi, et. al. 1997, Wolfskill, et. al., 1998; Abood, et. al., 1999), which leads to a high cost for the disposal of these sediments. In order to viably maintain these channels, the maintenance dredging costs for the area need to be clearly understood. To do this, the hydrodynamics of the region must first be investigated; it is the currents and flows that will determine the sediment and chemical transport in the area.

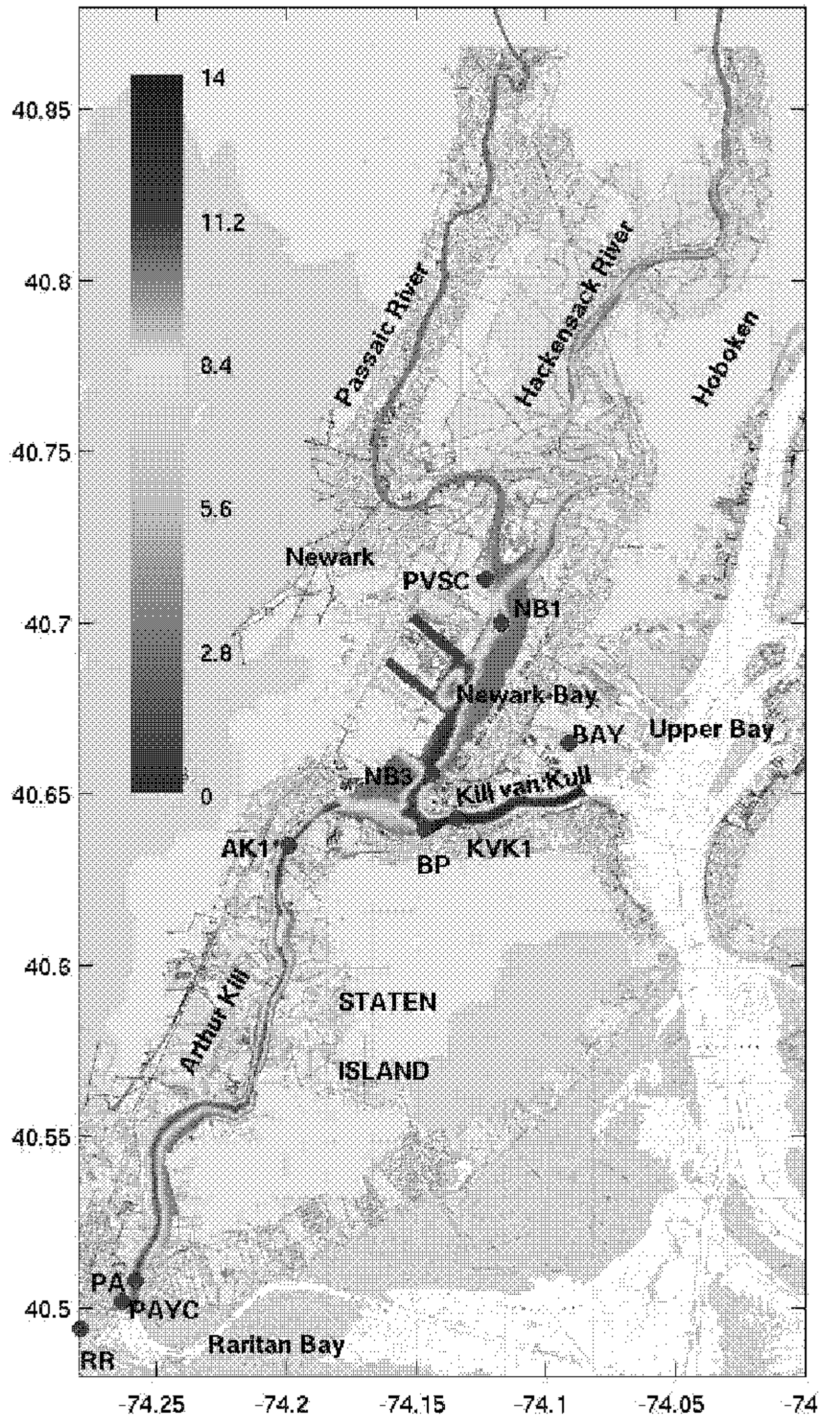

Figure 1.1: Bathymetry of Newark Bay (depth is in meters)

Investigations in this report seek to determine the circulation patterns in this area, and the factors which control them by analyzing a complex data set collected in hydrodynamic and water quality studies completed in the Newark Bay Complex as part of Study 1-E (Stevens Institute of Technology Component) the New Jersey Toxics Reduction Workplan (NJTRWP) for the New York-New Jersey Harbor. The NJTRWP is the New Jersey component of the New York-New Jersey Harbor Estuary Program Contaminant Assessment and Reduction Project. Data were collected at various stations within this region between 2000 and 2002, with hydrodynamic measurements that included current profiles, conductivity, temperature and depth measurements, suspended sediment concentration measurements, and water level measurements. Since this data is not continuous enough in time or space, a high-resolution three-dimensional hydrodynamic model of the area was also developed as a tool to further interpret the system as a whole. This report attempts to combine the data set from NJTRWP with the model in order to accurately describe the general circulation patterns in the area, and how these patterns are affected by meteorological, tidal and freshwater forcing. Specifically, this report will address the following questions:

- How does the tide propagate through the system, and what are the phasing differences in velocity and elevation between the different areas of the estuary?
- What are the estuarine circulation dynamics in a complex, multi-connected, multi-tributary system, and how do they vary seasonally and tidally?
- What types of meteorological events in the system cause significant filling or emptying of Newark Bay, and what are the flow patterns of these events in the Kills?
- What is the fate of the water in the Passaic River (a major source of contamination in the system)?
- What would the effects on flow patterns in Newark Bay be as a result of deepening of the shipping channels?

The answers to these questions will play an important role in determining the pathways of the contaminants that exist in the area, as well as the possible alteration of these pathways with the proposed deepening of the shipping channels. It is hoped that these findings will aid in the future maintenance of the port, as well as a comprehensive cleanup of Newark Bay.

Chapter 2

Previous Studies

Estuaries can be influenced by a number of external forcing mechanisms, including tides, freshwater inflows, and meteorological effects. The combination of these forces cause estuaries to be both complicated and dynamic environments. Estuaries have been actively studied and investigated over the past five decades, and a great deal of literature has been published on various topics involving them. From the early studies of Pritchard (1954) on the salt balance in the James River Estuary, Hansen and Rattray (1966) on the classification of different estuary types, and Fischer (1972) on mass transport mechanisms to the more recent work of Lerczak and Geyer (2004) on lateral circulation, estuaries continue to be evaluated. The study of estuaries continues to evolve as technology and sophistication of analysis continues.

There have been many studies completed in the New York/New Jersey Harbor estuary region, comprised of both data collection studies and hydrodynamic modeling. This region contains the Newark Bay Complex, but also includes the Hudson River, Harlem and East Rivers, New York Harbor, Long Island Sound, Raritan Bay, and the New York Bight. Oey, Mellor and Hires (1985b, 1985c) developed a three-dimensional simulation of the New York/ New Jersey Harbor region, validated using water elevation, current, and salinity data throughout the region. They performed salt flux analysis on the Sandy Hook-Rockaway Point Transect, the Raritan Bay, and the Narrows section (Oey, Mellor, and Hires, 1985d). Oey, Mellor, and Hires (1985a) also used a two-dimensional, depth-averaged model to determine the tidal flow characteristics in the New York/New Jersey Harbor.

Blumberg, et al, (1999) also constructed a three-dimensional hydrodynamic model of the New York/New Jersey Harbor that was validated using considerable elevation, current, temperature, and salinity data. Results from this model showed that the residual flow from the Kill van Kull combined with the flow from Newark Bay to flow out through the Arthur Kill in a counter-clockwise pattern around Staten Island. It also demonstrated that both Newark Bay and the Arthur Kill were well-mixed, and the Kill van Kull showed weak vertical stratification. Most of these studies include all of New York-New Jersey Harbor Complex, but none have focused specifically on the Newark Bay Complex.

Some other hydrodynamic studies have focused on specific areas within the Newark Bay Complex. Chant (2002) analyzed data collected during a 301-day deployment of an acoustic Doppler current profiler in the Kill van Kull. He finds a low-frequency variability in residual vertical shear associated with spring/neap variability, with an expected increase of shear during neap tides. The higher shears define periods of strong two-layer estuarine circulation, while weaker shears identify times of weak estuarine circulation. Variations in shear are also used as a proxy for changes in salinity stratification. Additionally, Chant finds residual shear to be approximately twice as high during high-flow (from the Passaic River) neap tide conditions than during low-flow neap tide conditions. Chant also presents observations on the effects of tidal range and river discharge on the secondary circulation (circulation in a cross-channel direction as opposed to an along-channel direction) in the Kill van Kull.

Caplow, et. al. (2003), performed an SF_6 tracer study in Newark Bay, by injecting the tracer into the north end. The findings of this research were a net seaward flushing of SF_6 through Kill van Kull into Upper New York Bay, contrary to the residual flow into Newark Bay as determined by Blumberg, et. al., (1999) and Chant (2002). Additionally, they found that the seaward transport was approximately one order of magnitude lower in the Arthur Kill than the Kill van Kull. The residence time for the tracer in Newark Bay was calculated at approximately at 8 days.

Two dissertations completed at the Stevens Institute of Technology have focused on portions of Newark Bay, specifically the Arthur Kill and the Kill van Kull. A PhD dissertation, by Thomas (1993), investigates the wind, tide and buoyancy induced residual circulation in the Arthur Kill. Thomas used the model results from the two-dimensional, depth-averaged model of Oey, Mellor and Hires (1985a) to drive the boundaries of a higher resolution model of the Arthur Kill. Thomas found that east-west component of wind stress is well correlated with sea surface elevation in the Arthur Kill, but that the transport was correlated to the north-south component of the wind. He also found greater stratification at the southern end of the Arthur Kill due to the turns through the northern end which cause the water there to be well-mixed.

A second work, a master's thesis written by Kaluarachchi (2003), estimated the volume and salt fluxes through the Arthur Kill and the Kill van Kull. Kaluarachchi, using the model described above of Blumberg, et. al., (1999) found that the salt flux through the Arthur Kill seemed to be dominated by the elevation gradient between the entrance to the Kill van Kull and Perth Amboy. The salt flux through the Kill van Kull is affected by the same elevation gradient, though not dominated by it. The density gradient did not appear to have an effect on the flux through either of these straits.

Another dissertation, written by Suszkowski (1978), investigated the sedimentology of Newark Bay through a simple advective transport model to quantify fluxes at the Kill van Kull, the Arthur Kill, the Hackensack and Passaic Rivers. Suszkowski found that largest sources of sediment to Newark Bay were downstream sources (the Kill van Kull and the Arthur Kill), which contributed 64% of the increasing quantities of inorganic suspended sediments, while the Passaic River contributed only 9%.

Though significant work has been performed in analyzing the hydrodynamics in and around the Newark Bay Complex, this report is the first attempt to combine a spatially and temporally large data set from the area with a high-resolution, three-dimensional hydrodynamic model. The NJTRWP data set is one of the largest hydrodynamic data sets that has been collected in the area, spanning an 18-month period for the entire Newark Bay Complex. Thomas's (1993) work uses only one month of data, and only from the Arthur Kill region. Chant's (2002) work spans a much longer time period, 301 days, but focuses only in the Kill van Kull. Blumberg, et. al., (1999) have longer data sets to verify their model, but the resolution in the Newark Bay Complex is much lower than the model used for this report, because the focus of that study was the entire New York/New Jersey Harbor. (As an example, Blumberg's model grid has one cell across the width of the Arthur Kill and the Kill van Kull, while the grid for this report has up to six in the same areas.) The abundance of data coupled with the high-resolution model will enable a more complete analysis, leading to a deeper understanding of the hydrodynamic processes in this Newark Bay Complex.

Chapter 3

Data Collection

As part of the NJTRWP, hydrodynamic and water and suspended sediment quality studies have been completed in Newark Bay, the Arthur Kill, and the Kill van Kull (New Jersey Department of Environmental Protection, February 2, 2001; New Jersey Department of Environmental Protection, February 23, 2001). Hydrodynamic data was collected at various locations within this region from 2000 to 2002, using four different methods: permanent tide gages, bottom mounts, stationary vessel profiling, and vessel transect sampling. Sampling was performed under various tide, freshwater and meteorological conditions.

Figure 3.1 shows an inventory of the hydrodynamic data that was collected during the 2000-2002 time frame, with four panels that show the different types of data that were collected. The top panel shows the water level data available from the tide gages located at Bergen Point (BP), Passaic Valley Sewerage Commission (PVSC), Constable Hook in Bayonne (BAY), and Perth Amboy Yacht Club (PAYC). These locations can be viewed on the bathymetric map in Figure 1.1. The panel below this displays the bottom mount data that is available from the Hackensack River (HACK), Perth Amboy (PA), the north end of the Arthur Kill (AK1), the western end of the Kill van Kull (KVK1), the north end of Newark Bay (NB1), and at the south end of Newark Bay (NB3). The third panel down shows the current and salinity profiles made from the moored vessels. These locations are

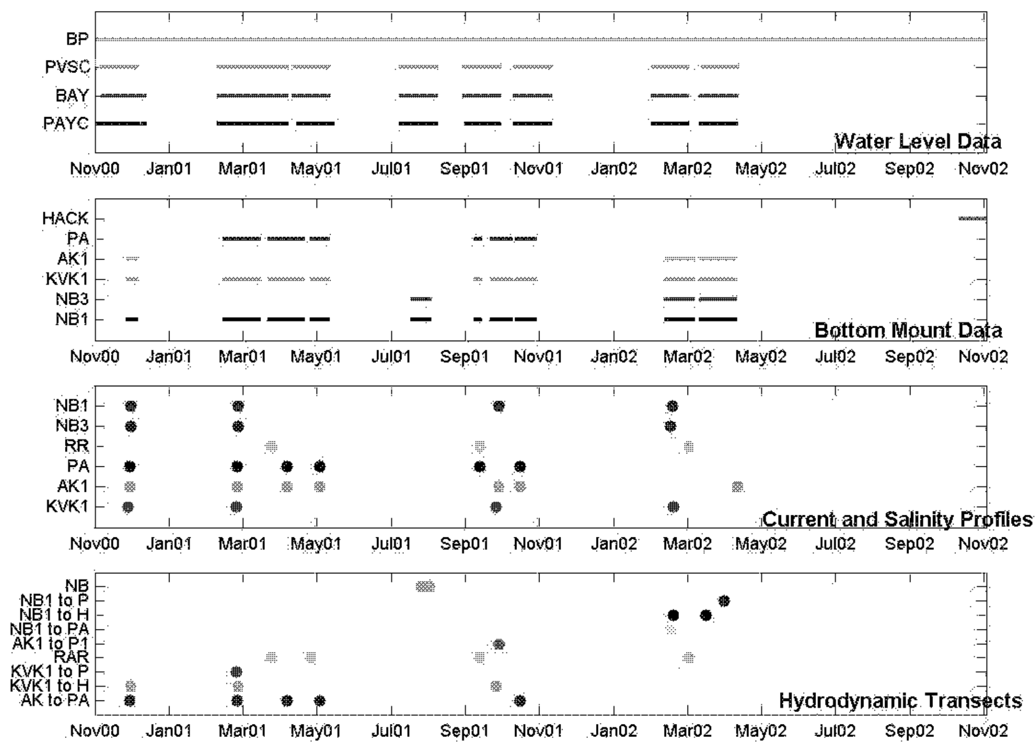

Figure 3.1: NJTRWP Hydrodynamic Data Inventory for 2000-2002 for tide gage data (panel 1), bottom mount data (panel 2), moored vessel profile data (panel 3) and hydrodynamic transect data (panel 4).

the same as was described for the bottom mounts, with an additional location in the Raritan River (RR), which feeds into Raritan Bay south of Perth Amboy. The bottom panel shows data collected during vessel transects. The abbreviation definitions are as follows:

NB = transect in Newark Bay

NB1 to P = transect from NB1 into the Passaic River

NB1 to H = transect from NB1 into the Hackensack River

NB1 to PA = transect from NB1 to Perth Amboy

AK1 to P1 = transect from AK1 into the Passaic River

RAR = transect through the Raritan River

KVK1 to P = transect from KVK1 into the Passaic River

KVK1 to H = transect from KVK1 into the Hackensack River

AK to PA = transect from the north end of the Arthur Kill to Perth Amboy

Though there is a significant amount of data, there are gaps in both time and space which make it difficult to gain a complete understanding of the estuarine circulation in this area.

Three acoustic tide gages provided the water level data for this experiments. These were permanently installed at the Passaic Valley Sewage Commission (PVSC, Figure 1.1), located at the north end of Newark Bay, Constable Hook in Bayonne (BAY), located slightly north of the east end of the Kill van Kull, and Perth Amboy (PA), located at the south end of the Arthur Kill. (A permanent station which measures water level operated by the National Oceanic and Atmospheric Administration (NOAA) is located towards the west end of the Kill van Kull, at Bergen Point, and was also used as part of the data set for this experiment.) Water level data was collected via the NOAA's National Ocean Service (NOS) sampling method, which is data acquired at one Hz with three minute ensemble averages (181 samples) every six minutes (50% duty cycle) (NOAA/NOS 2004). Table 3.1 below shows the approximate dates during which valid water elevation data is available from each station (some stations may have a few days more or less of data on either side of this time period). Plots of all the data available from 2000-2002 for each station are included in Appendix A. There was some loss of data when the water level dropped below the measuring distance of the acoustic tide gage.

Water Level Stations	Time Period for Data Collection
BAY, PAYC, PVSC	12/01/2000-12/21/2000
BAY, PAYC, PVSC	02/25/2001-04/26/2001
BAY, PAYC, PVSC	05/03/2001-6/03/2001
BAY, PAYC, PVSC	07/28/2001-08/29/2001
BAY, PAYC, PVSC	09/20/2001-10/21/2001
BAY, PAYC, PVSC	10/31/2001-12/02/2001
BAY, PAYC, PVSC	02/24/2002-03/31/2002
BAY, PAYC, PVSC	04/05/2002-05/07/2002

Table 3.1: Water Elevation Data Available

Bottom mounts (Figure 3.2) were typically deployed concurrently at three different locations for month-long periods. Each bottom mount contained a SonTek Acoustic Doppler Current Profiler (ADP) with pressure sensor, which obtained measurements of water currents through the water column, as well as water elevation via pressure. The ADP was set to sample for twenty minutes every half-hour with a ten-second averaging interval. The bin size was 0.5 m, and usable data was collected between 0.4 m above the head of the ADP and about 1 m (2 bins) below the surface. The bottom mounts also contained Conductivity-Temperature-Depth (CTDs) sensors, which recorded a point measurement of temperature and salinity, optical backscatter sensors (OBSs) which measured relative turbidity, and Laser In-Situ Scatterer and Transmissometers (LISSTs), which measured both suspended sediment concentration and size distribution. The CTD and OBS sampled once every ten seconds (at the ten second averaging interval for the ADP). The LISST collected a single ensemble average of 64 samples every ten minutes on the hour. Table 3.2 below shows the approximate dates and locations where bottom mount data is available (some stations may have a few days more or less of data on either side of this time period).

Figure 3.3 below shows, as an example, a plot of one-hour averages of the elevation, temperature, salinity, and along-channel bottom and surface current data for the NB1 mooring from December 2000 (time is GMT). Currents are considered positive entering Newark Bay (i.e. north is positive in the Arthur Kill and Newark Bay; west is positive in the Kill van Kull). Similar plots of data for each mooring deployment and location are included in Appendix B. During the April 9, 2001, to May 9, 2001, deployment of the PA bottom mount, the ADP recorded erroneous current data from about April 9 to April 24 due to the instrument rolling along the bottom (viewable through the roll and pitch information collected). The instrument righted itself on approximately April 25, after which time the data is valid again.

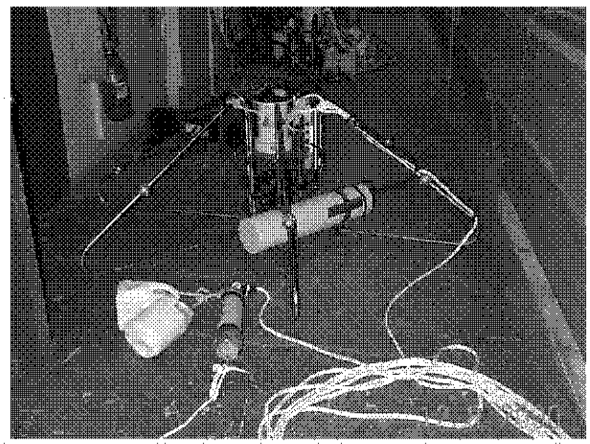

Figure 3.2: Typical Bottom Mount Setup

Bottom Mount Stations	Time Period for Data Collection
NB1, AK1, KVK1	12/11/2000-12/21/2000
NB1, PA, KVK1	03/02/2001-04/02/2001
NB1, PA, KVK1	04/09/2001-05/09/2001
NB1, PA, KVK1	05/14/2001-05/30/2001
NB1, NB3	08/06/2001-08/23/2001
NB1, PA, KVK1	09/28/2001-10/05/2001
NB1, PA, KVK1	10/12/2001-10/30/2001
NB1, PA, KVK1	11/02/2001-11/19/2001
NB1, NB3, AK1, KVK1	03/07/2002-04/01/2002
NB1, NB3, AK1, KVK1	04/05/2002-05/06/2002

Table 3.2: Bottom Mount Data Available

During each month-long deployment, 2 to 3 research vessels would sample during various wet and dry events. One or two vessels would anchor to single stations, and the other would perform

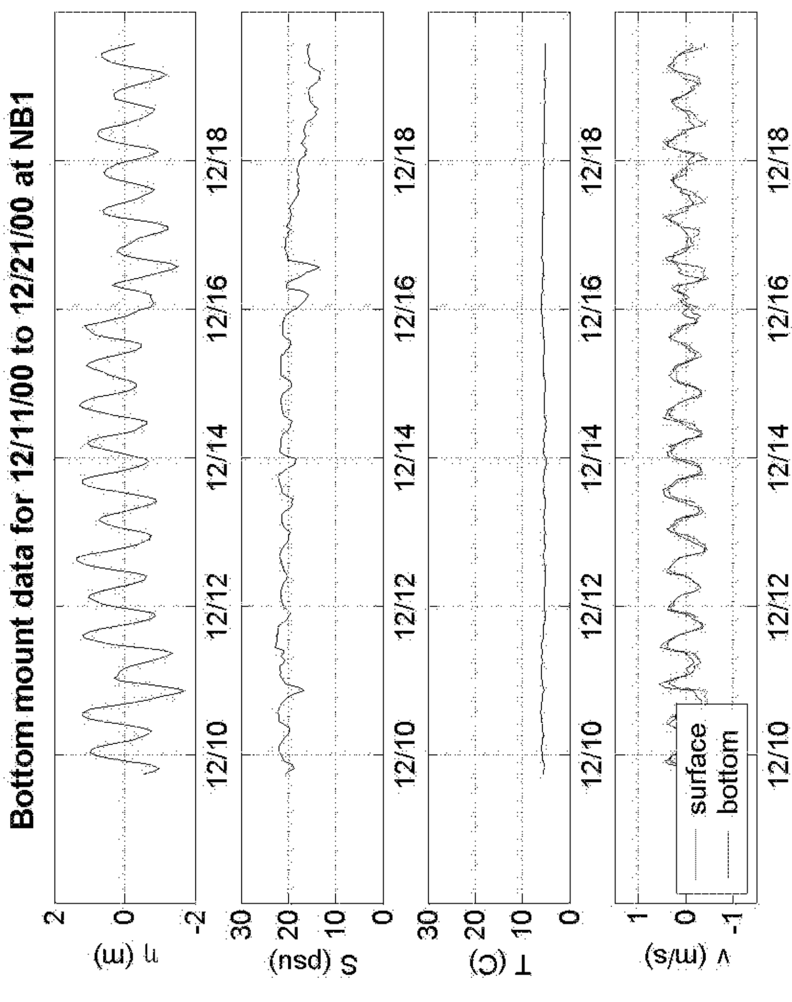

Figure 3.3: Bottom Mount Data at NB1 for December 2000, showing water elevation (panel 1), bottom salinity (panel 2), bottom temperature (panel 3) and surface and bottom velocity (panel 4).

transects of a certain section of the Newark Bay Complex. Each vessel would perform casts over the side using a CTD (with an OBS attached) and a LISST to gather salinity, temperature, and suspended sediment data through the water column. The CTD and OBS sampled continuously at 5 Hz, while the LISST sampled continuously at 4 Hz. Table 3.3 below shows the dates and locations for anchored vessel data collection. A sample of this data is included in Figure 3.4 below, which shows the CTD salinity profile data collected from an anchored vessel on December 15, 2000, at NB1 (time is GMT). Similar plots are included in Appendix C for all other anchored vessels. Both the moored and vessel transect activities were coordinated with the NJTRWP Study 1-D water quality sampling activities (New Jersey Department of Environmental Protection, February 2, 2001).

Location	**Dates**
NB1, NB3	12/15/00, 03/15/01, 10/19/01, 03/13/02
PA, AK1	12/14/00, 03/14/01, 04/25/01, 05/22/01, 11/06/01
KVK1	12/13/00, 03/13/01, 10/17/01, 03/14/02

Table 3.3: Moored Vessel Data Inventory

In addition, the transecting vessel would tow a bottom-tracking ADCP to measure water currents through the time of sampling. The ADCP would sample continuously and record every ping. The bin size was 0.5 meters with a blanking distance of 0.4 meters. Table 3.4 below shows the dates and locations for transects. A sample of this data is shown in Figure 3.5, which displays the locations and profiles for each cast performed during the transect on March 13, 2001. Figure 3.6 shows the variation in salinity profiles with distance along the estuary. Similar plots are included in Appendix D for all other transecting vessels with useable data (Data from 5/22/2001 was not useable due to instrument error).

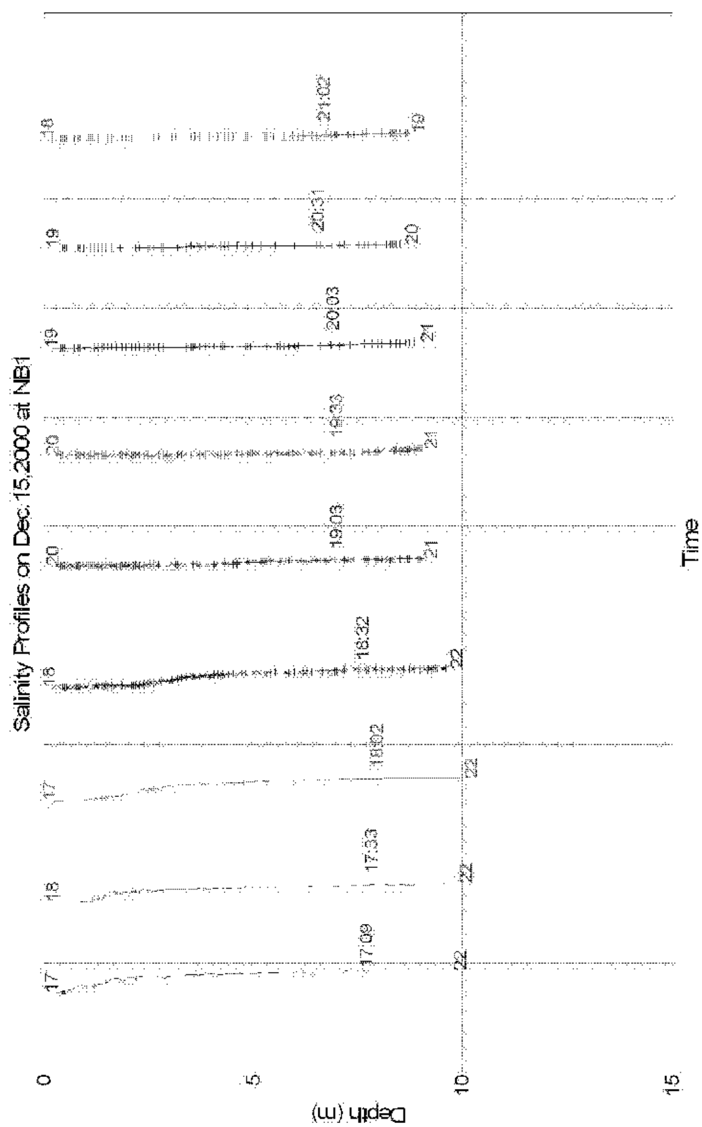

Figure 3.4: Moored Salinity (psu) Profile on 15 December 2000.

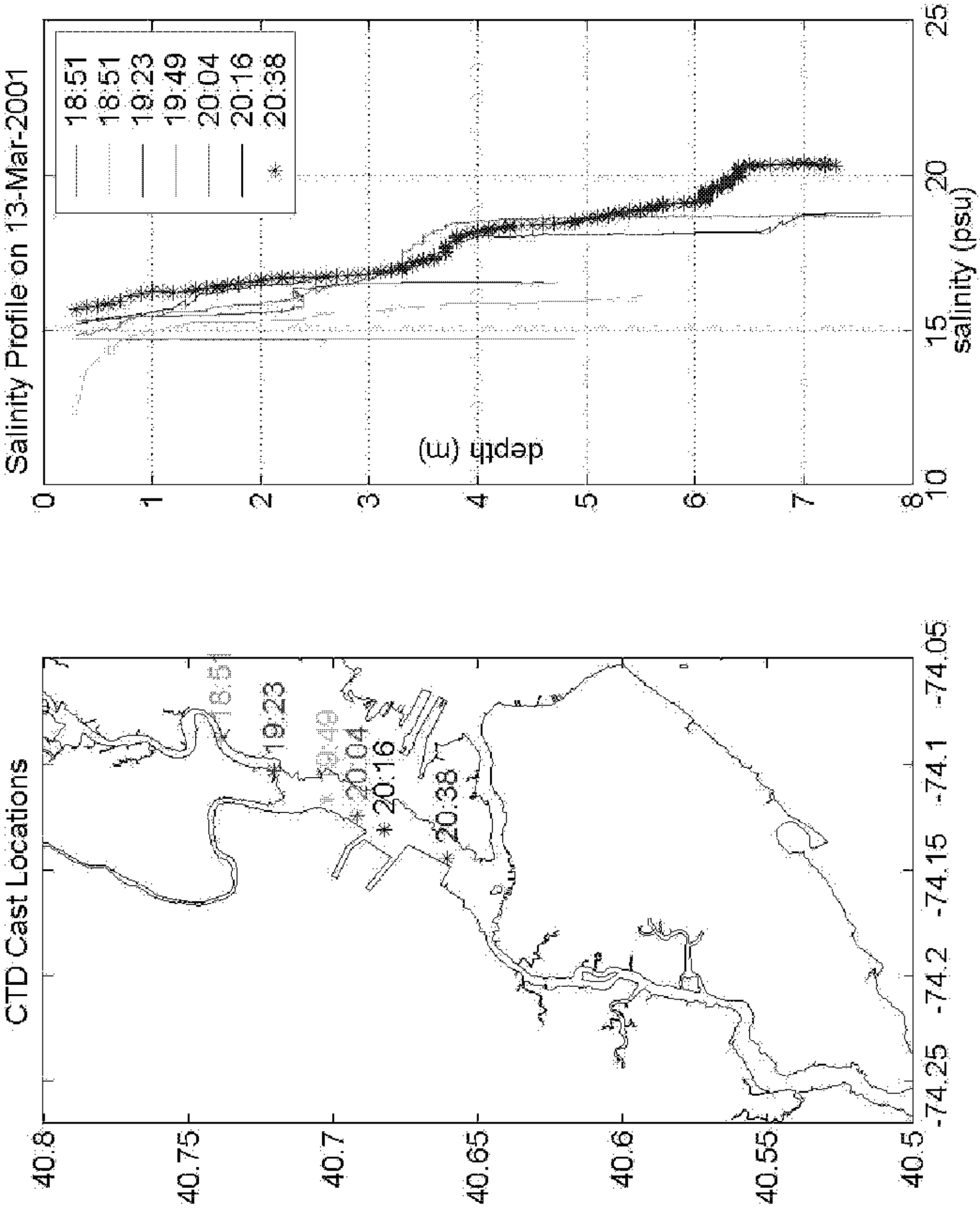

Figure 3.5: Location and Profile for March 13, 2001

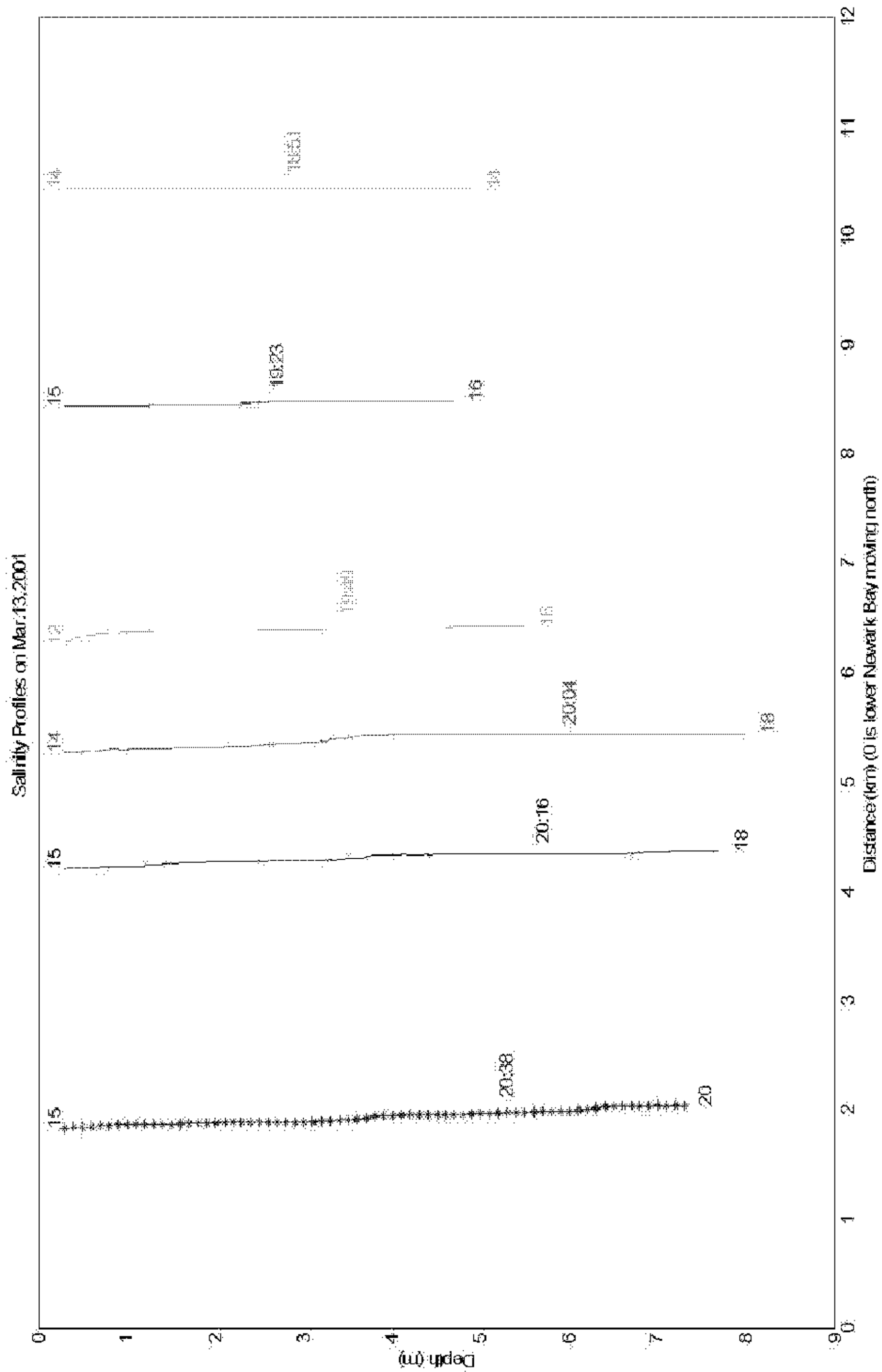

Figure 3.6: Salinity Profile March 13, 2001

Location	**Dates**
KVK-P1	3/13/2001, 3/12/2002
NB-P1	10/19/2001, 4/25/2002
KVK-H1	12/15/2000, 3/15/2001, 10/17/2001, 3/14/2002
NB-H1	4/10/2002
NB	8/15/2001, 8/22/2001
AK-PA	12/14/2000, 3/14/2001, 4/12/2001, 4/25/2001, 11/6/2001

Table 3.4: Transecting Vessel Data Inventory

Chapter 4

Numerical Modeling

4.1 Model Description

The hydrodynamic model that was used in this study is the three dimensional, time dependent model developed by Blumberg and Mellor, called the Estuarine, Coastal and Ocean Model (ECOM). This model has been used successfully in a number of applications to ocean, coastal and estuarine regions, including the model of the New York Harbor region by Blumberg, et. al., (1999). A detailed description of the development and underlying equations for this model can be found in Blumberg and Mellor (1987).

ECOM solves a coupled system of differential, three-dimensional equations that describe velocity and surface elevation fields, as well as temperature and salinity fields. Two assumptions are made to simplify the equations. These are the hydrostatic assumption, which states that the vertical pressure is balanced by weight of fluid, and the Boussinesq assumption, stating that the density is nearly constant unless being multiplied by gravity for calculations of pressure. The following are the governing equations in terms of velocity $U_i = (U, V, W)$ (see Figure 4.1), temperature, T, salinity, S, the Coriolis parameter, f, and the reference density, ρ_0:

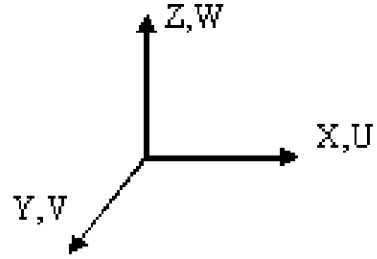

Figure 4.1: Velocity Coordinate System

$$\frac{\partial U_i}{\partial x_i} = 0 \tag{4.1}$$

$$\frac{\partial}{\partial t} + \frac{\partial}{\partial x_i}[U_i(U,V)] + f(-V,U) = -\frac{1}{\rho_0}(\frac{\partial P}{\partial x}, \frac{\partial P}{\partial y}) + \frac{\partial}{\partial z}[K_m \frac{\partial}{\partial z}(U,V)] + (F_u, F_v) \tag{4.2}$$

$$\frac{\partial T}{\partial t} + \frac{\partial}{\partial x_i}(U_i T) = \frac{\partial}{\partial z}(K_H \frac{\partial T}{\partial z}) + F_T \tag{4.3}$$

$$\frac{\partial S}{\partial t} + \frac{\partial}{\partial x_i}(U_i S) = \frac{\partial}{\partial z}(K_H \frac{\partial S}{\partial z}) + F_S \tag{4.4}$$

These equations are based in a system of orthogonal Cartesian coordinates with x increasing to the east, y increasing northward, and z increasing vertically upward. The following is the hydrostatic assumption:

$$\frac{P}{\rho} = g(\eta - z) + \int_z^\eta g \, \frac{\rho' - \rho_0}{\rho_0} \, dz' \tag{4.5}$$

where P is pressure, g is the gravitational acceleration, and ρ is density, a function of S and T, as defined by Fofonoff (1962). The F_u, F_v, F_T, and F_S terms describe small-scale mixing processes that are not resolved by the model grid. These processes are parameterized as horizontal diffusion using horizontal mixing coefficients as suggested by Smagorinsky (1963). The vertical mixing coefficients, K_m and K_h, are calculated using the second order turbulence closure scheme of Mellor and Yamada (1982).

The governing equations shown in (4.1)- (4.4) are transformed into orthogonal curvilinear coordinate system horizontal plane. They are also transformed from the z-plane into sigma coordinates which are bottom following to allow the same number of vertical layers everywhere even in the presence of large bathymetric irregularities. A mode splitting technique in the model solves barotropic and baroclinic equations using different time steps to limit computational time. A more detailed description of this model can be found in Blumberg and Mellor (1980, 1987).

4.2 Model Grid and Bathymetry

The curvilinear, orthogonal grid used by this model was generated using the Delft-RGFGRID grid generator (Kernkamp, 1999) and is shown in Figure 4.2. The grid covers the entire Newark Bay Complex, which includes the tidal portions of the Hackensack and Passaic Rivers (to the Oradell and Dundee Dams, respectively), Newark Bay, the Kill van Kull and the Arthur Kill. Enlarged views are shown for the intersection of the Passaic River, the Hackensack River and upper Newark Bay, and the intersection of lower Newark Bay, the Arthur Kill and the Kill van Kull. The average resolution of the grid in the Newark Bay region is about 140m by 280m, with an average resolution in the Arthur Kill of about 110m by 420m and 300m by 100m in the Kill van Kull. The Passaic River averages about 70m by 300m, while the Hackensack River is about 120m by 220m. There are ten vertical sigma layers. An enlarged view of the grid is shown in Figure 4.3.

The bathymetry of the Newark Bay Complex (Figure 4.2) is characterized by a deep shipping channel along the center of both the Arthur Kill and the Kill van Kull, as well as the west side of Newark Bay, with shallower side banks. The average depth of the shipping channel in the Arthur Kill is about 11 meters MSL (38 feet), while the average shipping channel depth in the Kill van Kull and Newark Bay are 13 meters MSL (43 feet). During the period of 2000-2002, the shipping channels in the area were in a constant state of change due to the Army Corps dredging projects, which made it impossible to define the correct bathymetry for the full 2 years. The water depths in each grid cell for the model were determined using depths from NOAA nautical charts of the area, as well as information from the Army Corps of Engineers website about the dredging schedule (US Army Corps of Engineers, 2004).

4.3 Forcing Functions

The model is driven along two open boundaries; one is along the south end of the Arthur Kill where it joins Raritan Bay, and the other is along the eastern end of the Kill van Kull, where it joins Upper New York Bay. Water elevation, temperature, and salinity are specified along these boundaries for the duration of the model simulation.

4.3.1 Water Elevation

Although the permanent tide gages located at Perth Amboy Yacht Club and at Constable Hook provided the necessary water level data for the Arthur Kill and Kill van Kull boundaries, respectively, their operation was not continuous, as shown above in Figure 3.1. Additionally, there were times when the water level dropped below the measuring range of the tide sensor, particularly at Constable Hook. Water level data from Bergen Point was available for the entire time period, and could be used to help interpolate the missing data from the boundaries.

First, the water levels at the boundaries were corrected for the times when the water level dropped below the measuring range of the instrument. To do this, the difference between the data at each tide gage and the data from the Bergen Point NOAA station was determined. This difference would have a typical range (from about -0.1 to 0.1 meters) over most of the time period, but would become quite large when the water level had dropped beneath the measuring range of the tide sensor. A relationship was determined between the tide gages and the NOAA station for the time period when the water level was within the measuring range to fill in the values for the few times when the water level was out of range.

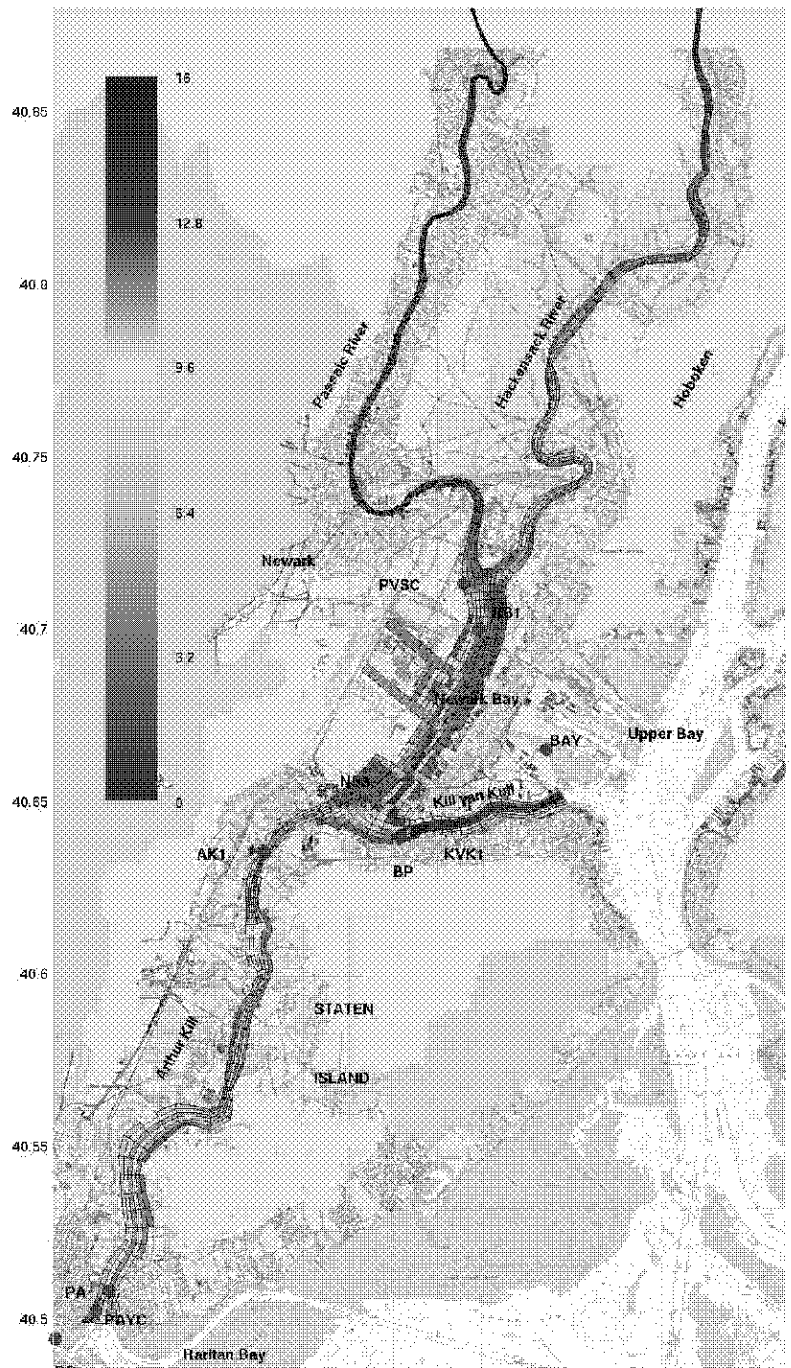

Figure 4.2: Bathymetry and Model Grid for Newark Bay (depth is in meters)

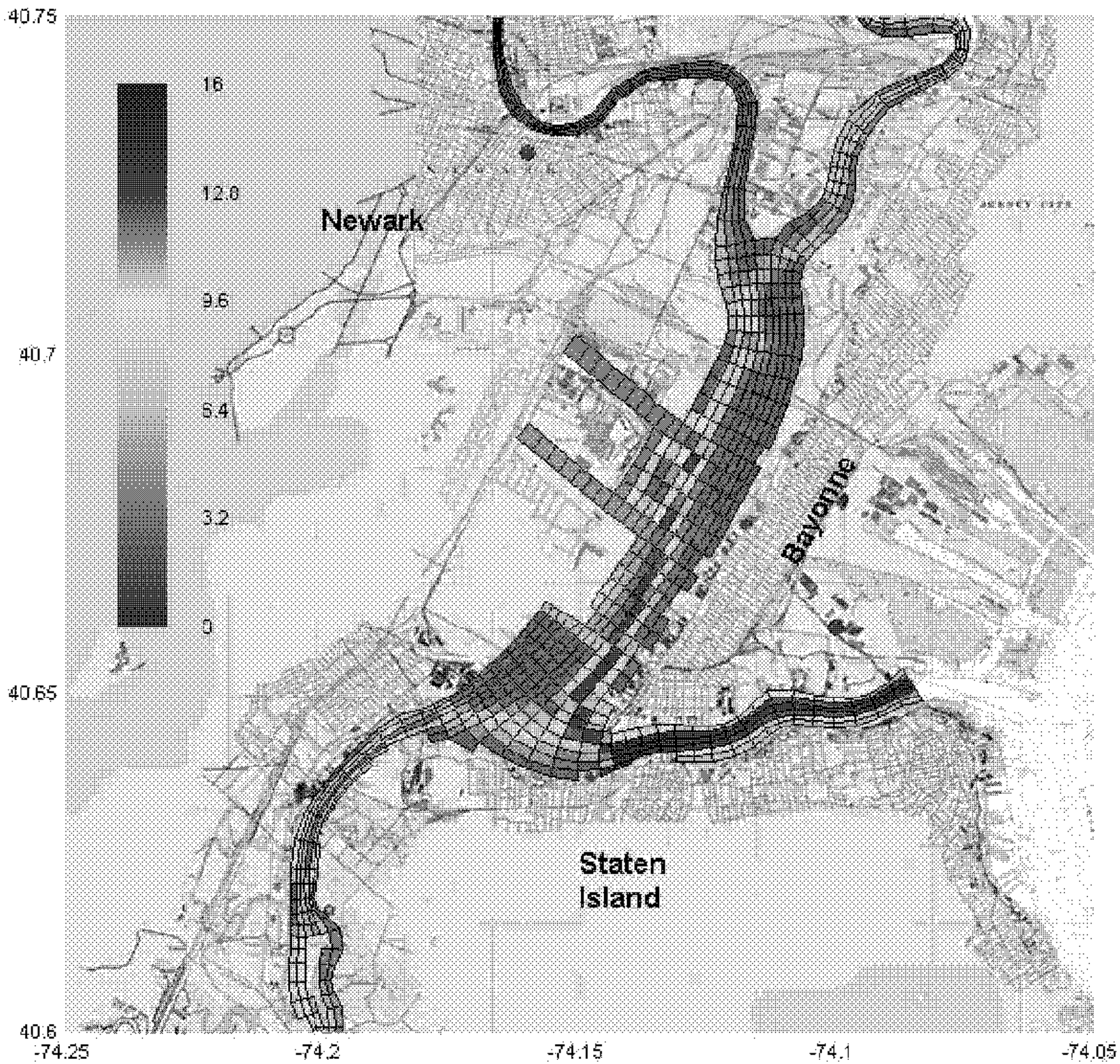

Figure 4.3: Enlarged View of Bathymetry and Model Grid for Newark Bay (depth is in meters)

After the existing water levels were corrected, they could then be used to simulate water level data for the times when the tide gages were not available. This was done in two separate steps: first by predicting the tide heights alone, and then superimposing the low-passed water level which would account for the offshore meteorological effects. The amplitude and phase of the principal tidal constituents (S_2 (principal solar semidiurnal), M_2 (principal lunar semidiurnal), N_2 (lunar elliptic semidiurnal), K_1 (lunisolar diurnal), P_1 (solar diurnal), O_1 (principal lunar diurnal)) was calculated for each available data set from the tide gages using the IOS tidal package for FORTRAN (Foreman, 1977). The mean values over the entire time range were then determined, and used in the same program to generate the boundary tidal signal for the times when tide gage data was unavailable. To determine the low-passed water level, a relationship was determined between the low-frequency Bergen Point water level and the low-frequency Perth Amboy Yacht Club water level, as well as between the low-frequency Bergen Point water level and the low-frequency Constable Hook water level for the time periods when data existed. This relationship was then used to determine the low-frequency water level for both boundaries for the entire time period, since the Bergen Point station continuously recorded data. The low-frequency water level was then superimposed on the tidal signal for each boundary. For time periods when water level data existed, the actual data was used (after being corrected for out-of-range values). The synthetic water levels were used when this data was unavailable. Figure 4.4 shows the synthetic (blue) and real (red) water level in meters at Perth Amboy Yacht Club for 2001.

4.3.2 Temperature and Salinity

The temperature and salinity boundary conditions were taken from measurements made by the bottom mounts located at PA and AK1 for the boundary at Perth Amboy, and by the bottom mount located at KVK1 for the Kill van Kull entrance boundary. The data were assumed the same at the boundary as at the mooring, though the data collection locations were not right on the model boundaries. (A sensitivity analysis did not show significant improvement in model-data comparisons at interior points if a lag was applied to the bottom mount data before it was shifted

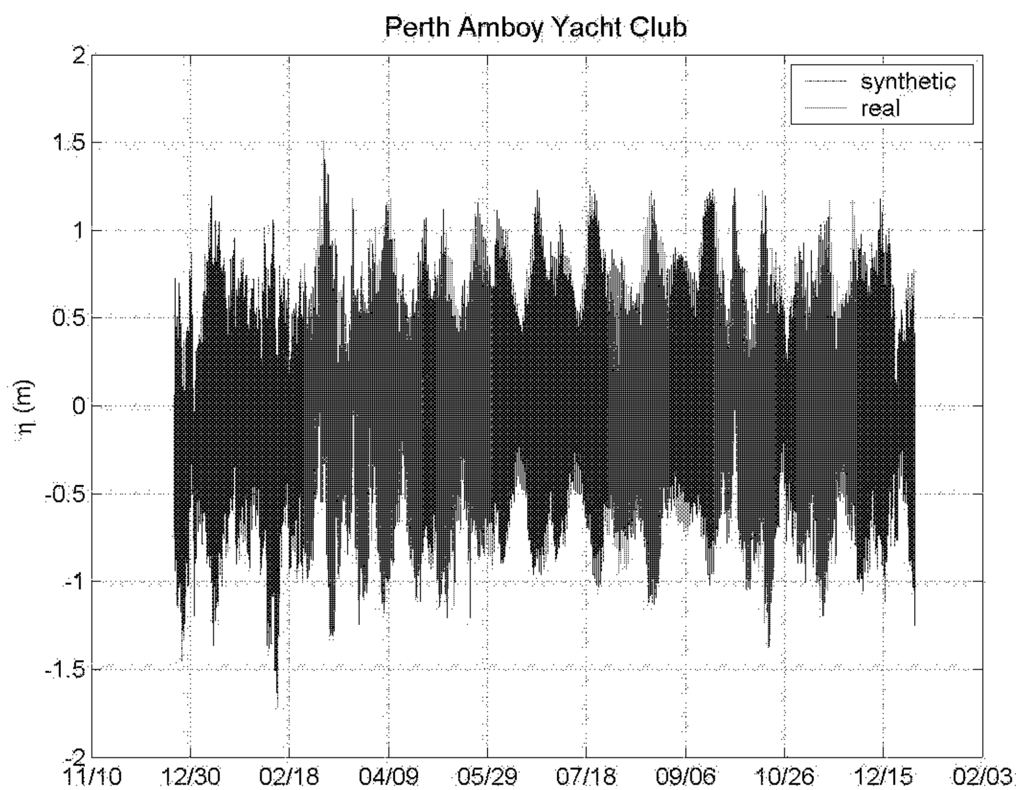

Figure 4.4: Real and Synthetic Water Levels (m) at Perth Amboy Yacht Club for 2001

to the boundary at Perth Amboy or the Kill van Kull.) Temperature and salinity were recorded at only one point approximately 0.5m off of the bottom, and the values were also assumed the same from top to bottom. (A sensitivity analysis showed little variation between model-data comparisons at interior points whether salinity boundary condition values were the same top to bottom or if a gradient was applied.) Temperature and salinity values were specified hourly only while the bottom mounts were in operation; linear interpolation was used during the times where data did not exist.

During March and April 2002, the salinity gradient between NB1 and KVK1 increased significantly due to the completion of dredging operations in the Kill van Kull which allowed greater salinity intrusion from Upper New York Bay. The measured boundary conditions from KVK1 could not be used, so conditions were generated using a relationship between the interior mooring at NB1 and the mooring at KVK1 from another time period with similar freshwater conditions.

4.3.3 Surface Wind Stress

Directional wind speed was specified hourly using data from NOAA's Bergen Point meteorological station and was assumed the same for every grid cell.

4.3.4 Freshwater Inputs

Hourly freshwater inflows were specified at thirteen locations within the model area. These include: the Passaic River, the Saddle River (located on the Passaic River), the Hackensack River, an industrial discharge along the Kill van Kull, discharge from the Bergen County Utilities Authority, discharge from the joint meeting of Essex and Union counties, discharge from the Rahway Sewerage Authority, and combined sewer overflows (CSOs) from along the Passaic, the Hackensack and the Arthur Kill. All of the values for these freshwater inflows were contributed by HydroQual, who estimated the CSO flows of coastal areas using the Rainfall Runoff Model (personal communication; Kim, 2004). Though the Elizabeth and Rahway Rivers (which feed into the Arthur Kill) are not explicitly included in the model, most of their drainage areas are included in the Rainfall Runoff Model. During the NJTRWP sampling, some river flows and discharges were measured by a team from the United States Geological Survey (USGS). The flows from HydroQual compared well with these measurements.

4.4 Model Calibration and Validation

The model was set to run for 17 months from December 2000 to April 2002, the time period for which boundary data was available. Comparisons were made between time series of model output and data that was collected for the NJTRWP project from December 2000 to April 2002, at interior points on the model, including KVK1, NB1, AK1, BP and PVSC for the hourly values of water surface elevation, bottom salinity, and along-channel velocity. Figure 4.5 and Figure 4.6 shows a comparison of bottom-mount data at NB1 for March-April 2001 and September-November 2001. In this figure, the top panel shows water level in meters, the second panel shows salinity in psu, the third panel shows along-channel near-surface velocity, and the last panel shows near-bottom along channel velocity. Similar plots for all other time periods and locations can be found in Appendix E.

4.4.1 Elevation

Figure 4.7 shows the agreement between model output and tide gage data at Bergen Point (BP) and Passaic Valley Sewerage Authority (PVSC) for hourly and 34-hour low-passed elevation, where events with a period of occurrence of less than 34 hours have been removed. (Plots for all time periods can be found in Appendix E). Table 4.1 shows the summary of statistics between water elevation model output and all data. There is good agreement between the water level measured by NOAA at BP and the model over the entire time period, with an r^2 of 0.96 and an RMS error of about 4% of the range. The model also compares well to the tide gage located at PVSC (which is located at the upper end of Newark Bay) over all time periods, with an average r^2 of 0.97 and about 5% RMS error. The rest of the data is from bottom-mounted pressure sensors, which have an average RMS error of about 5% and r^2 of 0.96. The average r^2 for all comparisons is 0.96, with a mean error of 5.%. This is reasonable when compared with Blumberg, et. al., (1999), where the average r^2 for water level was 0.94, with a mean error of about 11% for stations within the New York Harbor Region.

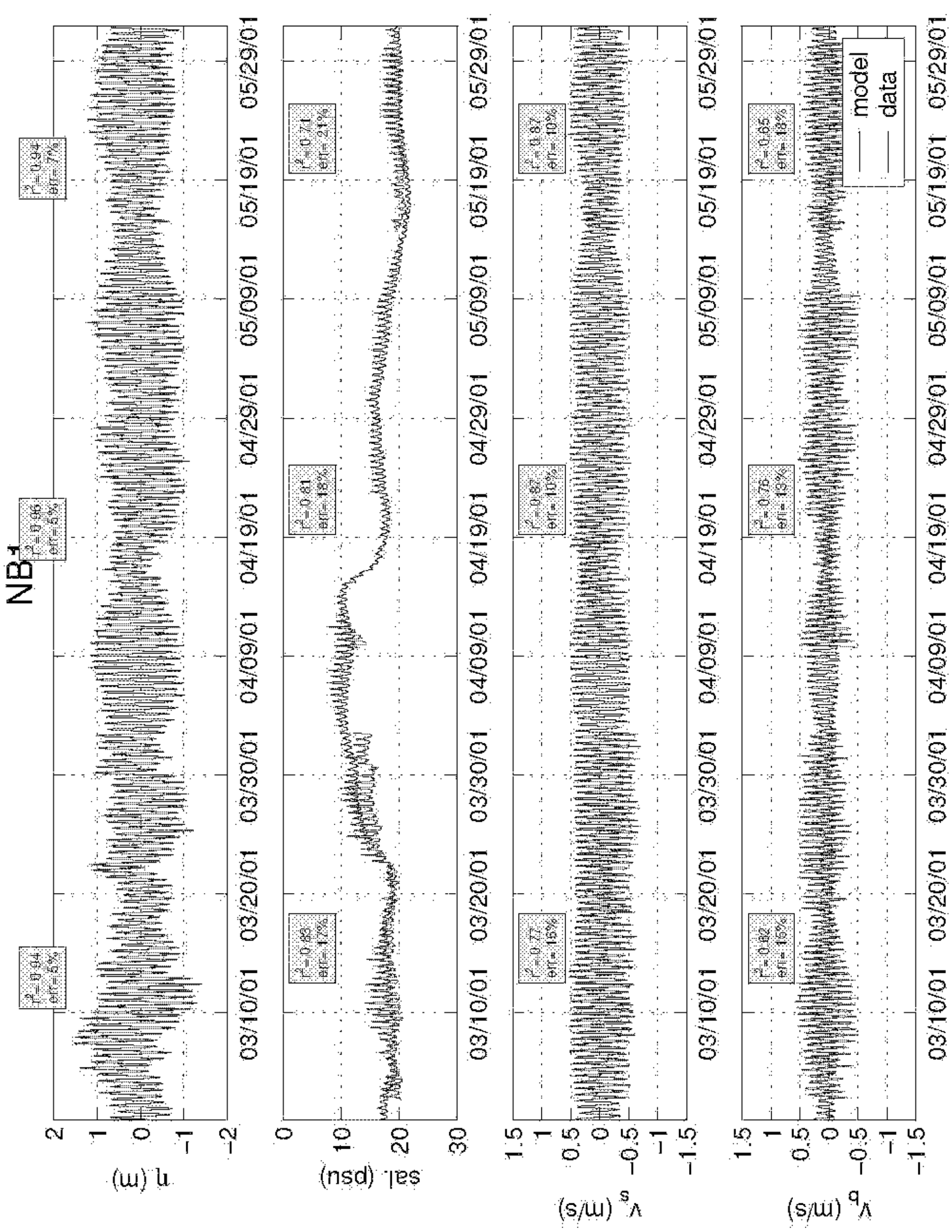

Figure 4.5: Model-Data Comparison for NB1 March-May 2001. Top panel shows water level (meters), second panel shows bottom salinity (psu), third panel shows along-channel near-surface velocity (m/s), and last panel shows near-bottom along channel velocity (m/s).

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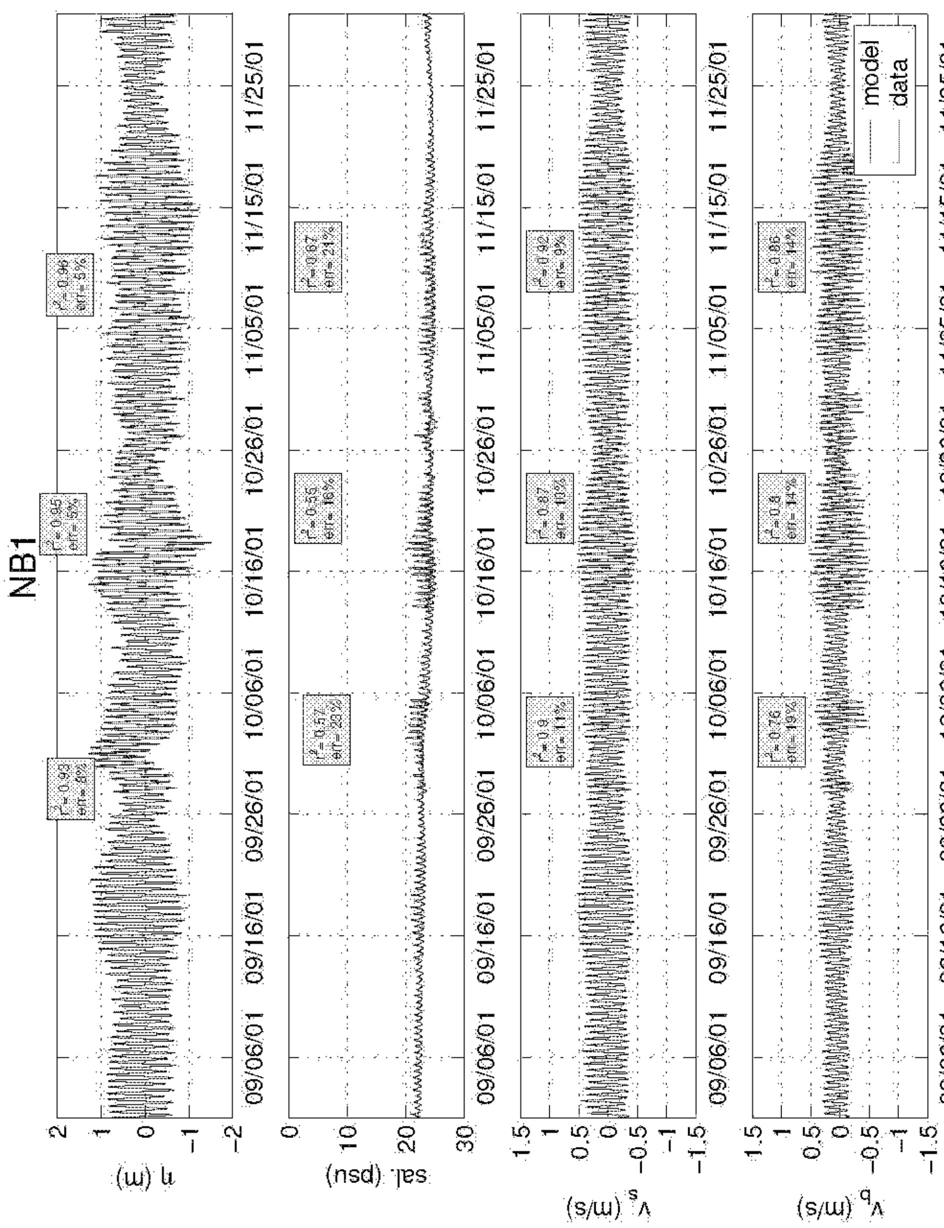


Figure 4.6: Model-Data Comparison for NB1 September-October 2001. Top panel shows water level (meters), second panel shows bottom salinity (psu), third panel shows along-channel near-surface velocity (m/s), and last panel shows near-bottom along channel velocity (m/s).

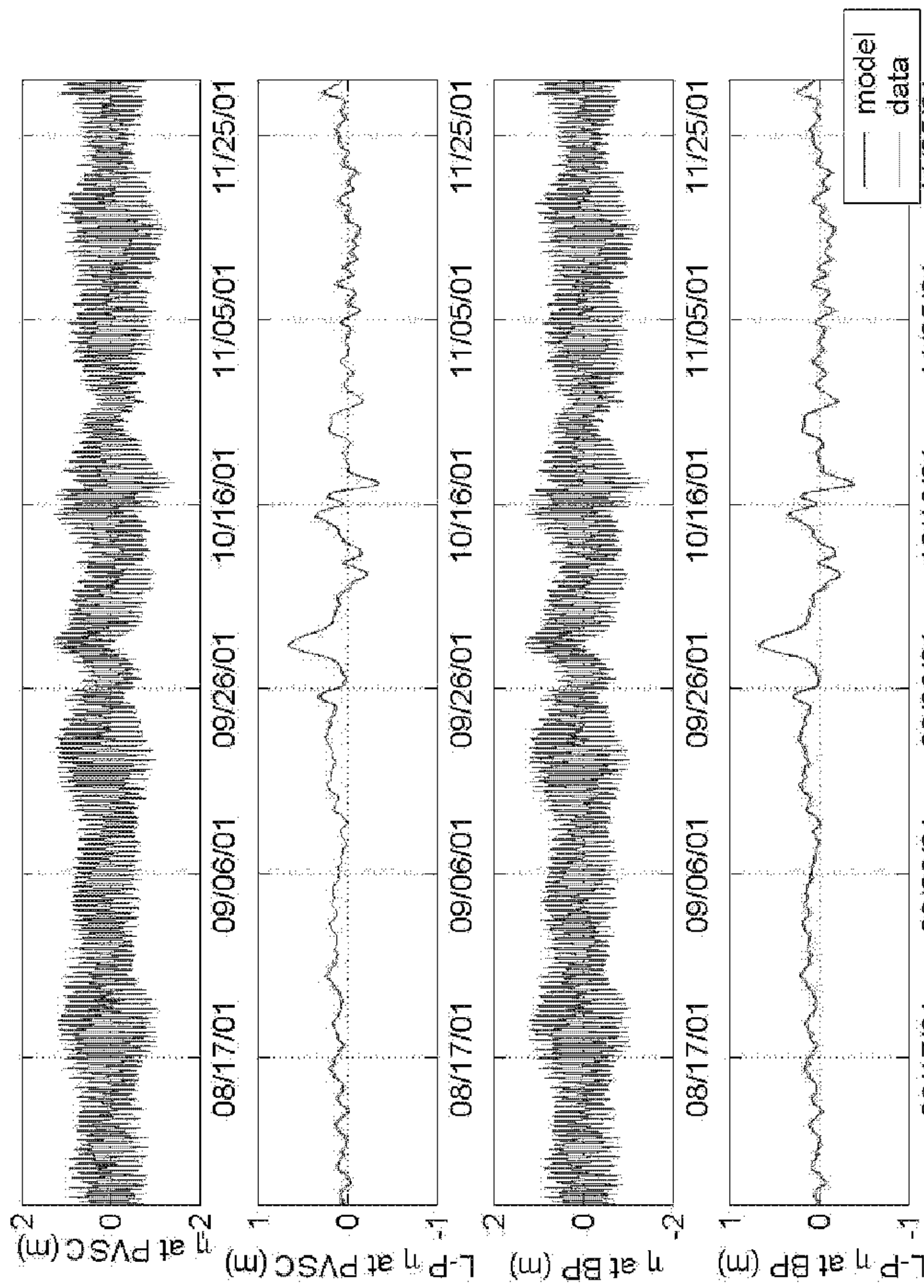


Figure 4.7: Model-Data Water Level Comparison for August-November 2001. Top panel shows hourly water level for PVSC (meters), second panel shows low-passed water level for PVSC, third panel shows hourly water level for Bergen Point, last panel shows low-passed water level for Bergen Point.

Table 4.1 also includes a summary of statistics between 34-hour low-passed water elevation model output and data. There is good agreement between the model and data at BP and PVSC, over all time periods with an average r^2 of 0.99 and an average RMS error of about 6%. The bottom-mounted pressure sensors have an average RMS error of about 4% and r^2 of 0.97. These statistics are reasonable when compared to the results of others; the mean r^2 value for low-passed data in New York Harbor from Blumberg, et. al., (1999) was 0.87, with an average error of 8%.

Table 4.2 includes the M_2 tidal constituents of the model and the M_2 components published by National Ocean Service's (NOS) accepted harmonic constants for nearby stations. The amplitudes and phases of the M_2 components from the model and NOS at similar locations are very close. These elevation comparisons suggest that the model is able to replicate water elevation throughout the area for various spring and neap tide conditions, as well as for both short and long-term events.

4.4.2 Salinity

Panel 2 of Figure 4.5 shows the agreement between hourly model output and salinity measurements at NB1 for March-May 2001. Similar plots for all other locations can be found in Appendix E, while Table 4.3 summarizes the statistical comparisons at all locations over all time periods. Statistics for the comparison of the model with data from KVK1 for March and April 2002 is not included because at that point the dredging of the channel in the Kill van Kull had been completed, and the data from this mooring was no longer reasonable for the original model set-up, as discussed in Section 4.3.2.

The r^2 values range between 0.03 and 0.93, with an average RMS error of about 19%. Lower correlations and greater errors for March and April 2002 are most likely because of the synthetic salinity boundary conditions imposed at KVK1, as discussed above. The salinity comparison at NB1 is the most important to examine since it is furthest from the boundaries; it has an r^2 range of 0.41 to 0.84, with an average RMS error of about 14%. Figure 4.8 shows the correlation between the model and data at NB1 over all time periods, with an r^2 of 0.82. Blumberg, et. al., (1999) showed r^2 values of 0.58 to 0.77 between model and data for 12-hour averages of salinity in the New York

Time Period	Location	Number of Points	Regular data Range (m)	RMS Error %	r^2	Low-passed data Range (m)	RMS Error %	r^2
All	BPt	18983	3.3	4	0.96	1.4	13	0.98
Dec-00	PVSC	455	2.9	3	0.99	1.0	9	1.00
Feb-Apr 2001	PVSC	1428	2.5	5	0.96	0.8	2	0.99
May-01	PVSC	699	2.2	6	0.97	0.3	5	0.99
Jul-Aug 2001	PVSC	733	2.1	7	0.96	0.3	8	0.96
Sep-Oct 2001	PVSC	734	2.6	5	0.96	1.0	2	1.00
Oct-Dec 2001	PVSC	733	2.4	6	0.97	0.4	6	0.99
Feb-Mar 2001	PVSC	733	2.7	5	0.96	1.0	2	0.99
Apr-May 2001	PVSC	542	2.4	5	0.97	0.4	6	0.99
Dec-00	NB1	231	3.1	3	0.99	1.0	2	1.00
Mar-01	NB1	734	2.8	5	0.94	0.8	2	1.00
Apr-01	NB1	712	2.5	5	0.96	0.5	7	0.93
May-01	NB1	374	2.0	7	0.94	0.2	10	0.89
Sep-01	NB1	181	2.1	8	0.93	0.6	3	0.99
Oct-01	NB1	426	2.7	5	0.95	0.7	4	0.97
Nov-01	NB1	400	2.5	5	0.96	0.4	4	0.97
Mar-02	NB1	589	2.6	5	0.95	1.0	2	0.99
Apr-02	NB1	600	2.4	4	0.97	0.4	3	0.99
Dec-00	KVK1	232	2.9	2	0.99	1.0	2	0.99
Mar-01	KVK1	762	2.7	4	0.96	0.8	2	0.99
Apr-01	KVK1	706	2.4	4	0.97	0.5	6	0.95
May-01	KVK1	374	1.9	6	0.95	0.2	13	0.78
Sep-01	KVK1	180	2.0	7	0.95	0.6	2	1.00
Oct-01	KVK1	428	2.6	4	0.96	0.7	2	0.99
Nov-01	KVK1	400	2.3	5	0.97	0.4	4	0.98
Mar-02	KVK1	380	2.3	5	0.95	1.0	1	1.00
Apr-02	KVK1	600	2.3	4	0.97	0.3	3	0.98
Dec-00	AK1	230	3.1	2	0.99	1.0	1	1.00
Mar-02	AK1	485	2.6	4	0.96	1.0	2	1.00
Apr-02	AK1	600	2.5	4	0.97	0.4	4	0.98
Maximum	-	-	3.3	8	0.99	1.4	13	1.00
Minimum	-	-	1.9	2	0.93	0.2	1	0.78
Mean	-	-	2.5	5	0.96	0.7	4	0.98

Table 4.1: Model-Data Elevation Comparison

	M_2 (model)			M_2 (NOS)			
	amp.	**phase**	**phase**	**amp.**	**phase**	**phase**	**station**
	(m)	(deg)	(hours)	(m)	(deg)	(hours)	
BP	0.69	15.2	0.53	0.75	21.20	0.73	Bergen Point
NB1	0.71	17.4	0.60	0.75	24.60	0.85	Port Elizabeth

Table 4.2: Comparison of M_2 Tidal Constituents

Harbor Region, so these comparisons seem reasonable.

The model also appears to be capable of replicating vertical variations. Figure 4.9 shows salinity depth profiles for three days where profiled CTD data was available, where the blue circles represent collected data and the red line shows the model output. The model does not show as much stratification as the data in March 2001, when freshwater events were significant.

Table 4.4 shows the average for the salinity data and the model output over each time period at NB1. Errors range from 0% to 6.4%, which are lower than the errors for hourly data. The model appears to be capable of replicating salinity over longer time periods.

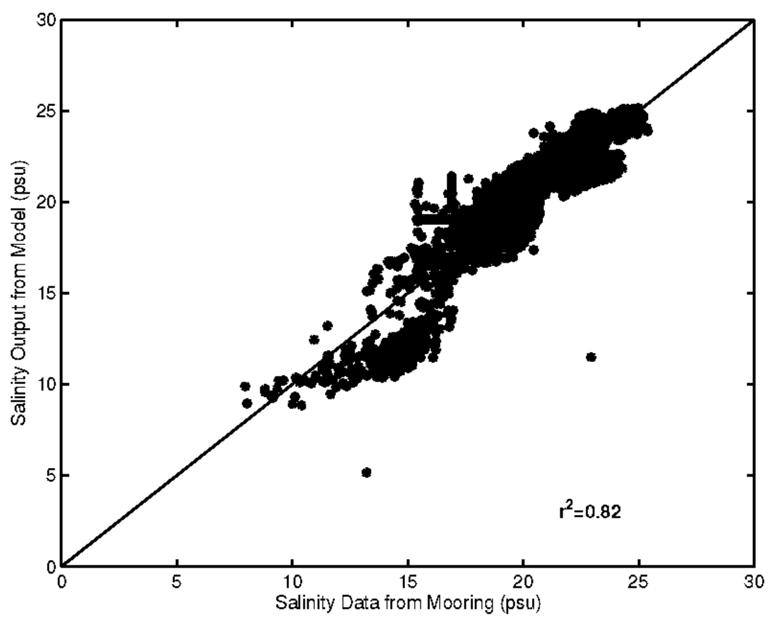


Figure 4.8: Model-Data Salinity Comparison at NB1 Over All Time Periods

Time Period	**Location**	**Number of Points**	**Range (psu)**	**RMS Error%**	r^2
Dec-00	NB1	231	9.5	14	0.84
Mar-01	NB1	734	9.8	17	0.83
Apr-01	NB1	712	6.4	18	0.81
May-01	NB1	374	4.5	21	0.71
Sep-01	NB1	181	3.3	23	0.57
Oct-01	NB1	426	5.2	16	0.55
Nov-01	NB1	193	2.8	21	0.67
Mar-02	NB1	589	3.0	26	0.41
Apr-02	NB1	600	7.2	22	0.49
Dec-00	KVK1	232	9.3	10	0.87
Mar-01	KVK1	762	7.9	8	0.93
Apr-01	KVK1	706	16.5	8	0.86
May-01	KVK1	374	6.6	11	0.78
Sep-01	KVK1	180	3.1	24	0.35
Oct-01	KVK1	428	3.1	16	0.39
Nov-01	KVK1	193	1.6	18	0.60
Dec-00	AK1	230	8.3	16	0.86
Mar-02	AK1	485	3.3	33	0.59
Apr-02	AK1	600	3.5	43	0.03
Maximum	-	-	16.5	43	0.93
Minimum	-	-	1.6	8	0.03
Mean	-	-	6.0	19	0.64

Table 4.3: Model-Data Salinity Comparison

Time Period	**Data Average**	**Model Average**	**% Error**
Dec-00	19.5	20.5	4.9
Mar-01	17.4	16.3	6.3
Apr-01	16.7	15.7	6.4
May-01	19.8	20.5	3.9
Aug-01	22.8	21.6	5.2
Sep-01	22.4	22.9	1.9
Oct-01	23.7	24.1	1.7
Nov-01	23.6	24.3	3.0
Mar-02	20.1	21.3	5.6
Apr-02	20.2	20.2	0.0

Table 4.4: Comparison of Model and Data Averages for Salinity at NB1

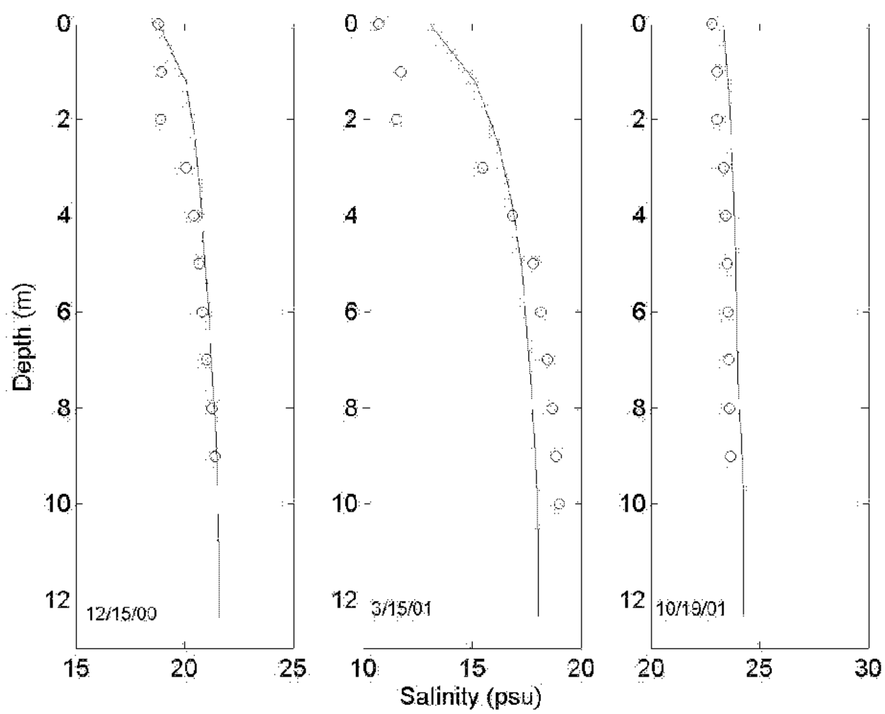


Figure 4.9: Profile Comparison of CTD and Model at NB1

4.4.3 Velocity

Hourly Velocity

The bottom panels of Figures 4.5 and 4.6 show the comparison of along-channel surface and bottom velocity for NB1 for the time periods of March-May 2001 and September-November 2001. Figure 4.10shows the agreement between depth-averaged along-channel velocity data and the model at NB1 for all time periods. These figures show the model velocity to be well correlated with the data. Similar figures are shown in Appendix E, and Table 4.5 summarizes the statistical comparison for along channel depth-averaged, near surface and near bottom velocity over all time periods where data is acceptable. Comparisons at KVK1 for April 2001 are not included because dredging operations prohibited the placement of the bottom mount near the channel. The average r^2 at NB1 for depth averaged velocity is 0.90, with an average RMS error of about 10% of the velocity range. Comparison at KVK1 for depth-averaged velocity is generally good, with an average r^2 of 0.88, and an average RMS error of 14% of the range. The average r^2 for AK1 is 0.85, with an average RMS error of about 14% of the range. For near surface and near bottom velocities, the average error at all stations is 13% and 14% of the range with an average r^2 of 0.86 and 0.80, respectively. Comparison of model-data velocity is not as good as Blumberg, et. al., (1999) where the mean r^2 for velocity at all levels was 0.96, but model velocities are still well correlated with data from the ADP.

Band-passed Velocity (periods between 34 hours and 5 days)

Figure 4.11 shows the comparison of model and data depth-averaged velocity at NB1 after applying a band-pass filter, which removed events occurring at a period greater than 34 hours, but less than 5 days (similar plots for all other locations can be found in Appendix E). The model appears to represent the data well. Statistical information for this type of comparison is included in Table 4.6. (Comparisons for September 2001 are not included because of the short sampling period.)

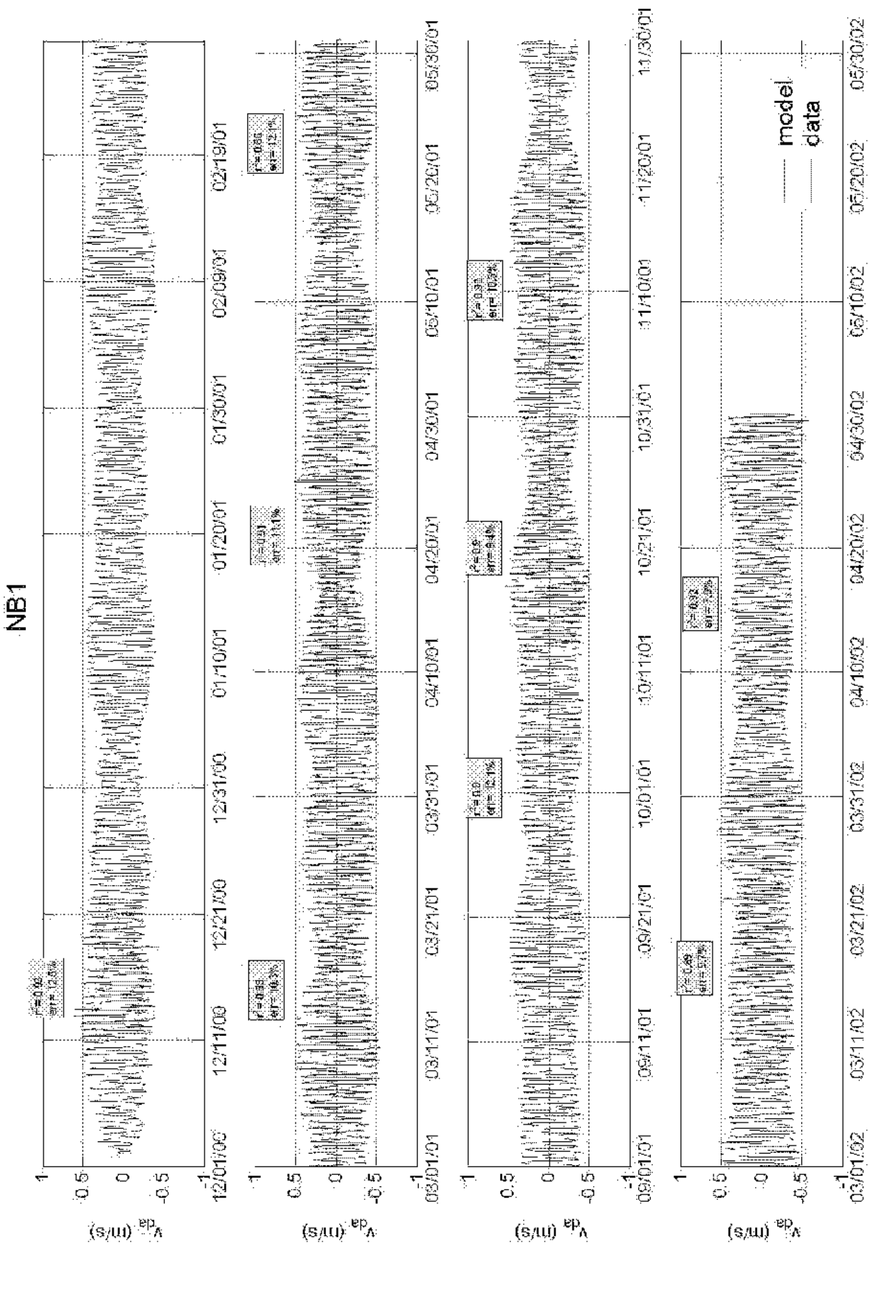


Figure 4.10: Model-Data Depth-Averaged Velocity Comparison at NB1

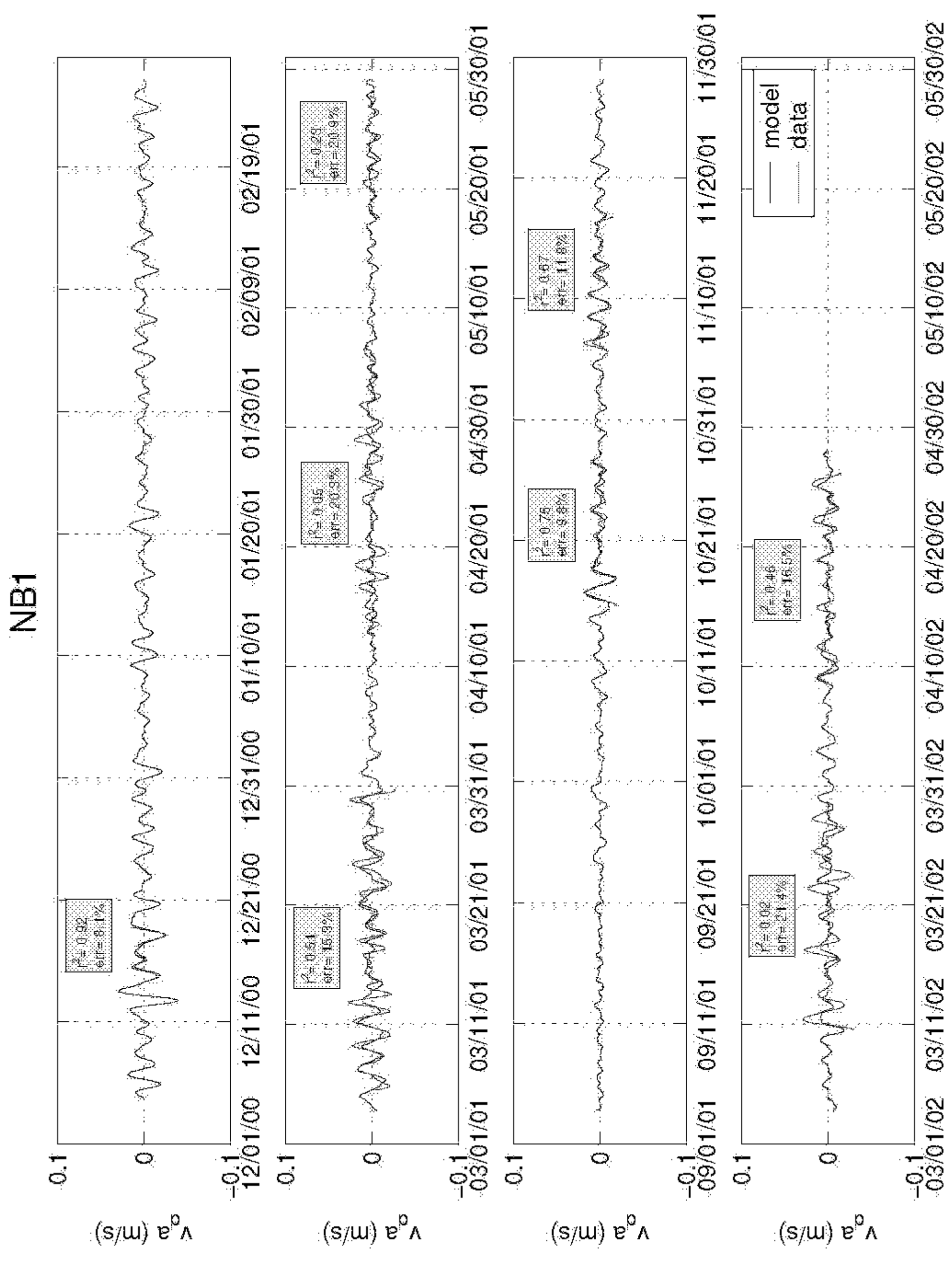


Figure 4.11: Model-Data Depth-Averaged Band-passed Velocity Comparison at NB1 for periods of greater than 34 hours and less than 5 days.

Low-passed Velocity (periods greater than 5 days)

Also included in Table 4.6 is a comparison of long-term velocity (longer than 5 days). This comparison shows low r^2 values (mean value of 0.29) and high errors (mean value of 91%). Poor agreement between the model and data for long-term velocity may be explained by the fact that the long-term water elevation at the boundaries is unknown, i.e. there is no existing datum. A slope in the datum between the ends would drive a long-term mean circulation. The boundaries for the model run in this report have a mean elevation of zero.

To better understand the effects of a potential slope, a sensitivity analysis was performed by changing the elevation at each end by 1 centimeter, with the results shown in Table 4.7, Table 4.8, and Table 4.9. Positive numbers represent fluxes entering the system, while negative numbers represent fluxes leaving the system. A mean elevation difference of zero results in essentially no flux of water through the system. The weak flow that does exist moves east through the Kill van Kull. When the water level at Arthur Kill boundary (Table 4.8) is higher, the mean flux in the Kills system is clockwise around Staten Island. When the water level at the Kill van Kull boundary is higher (Table 4.9), the mean flux in the Kills system is reversed and flows counter-clockwise around Staten Island. These sensitivity cases demonstrate that long-term flow around Staten Island is dependent on the mean slope between the boundaries.

Figure 4.12 shows the energy spectra for depth-averaged currents at NB1 for four different months. The model and data both show a peak in the velocity spectra at the M_2 period, which is much higher than the energy at any other frequency.

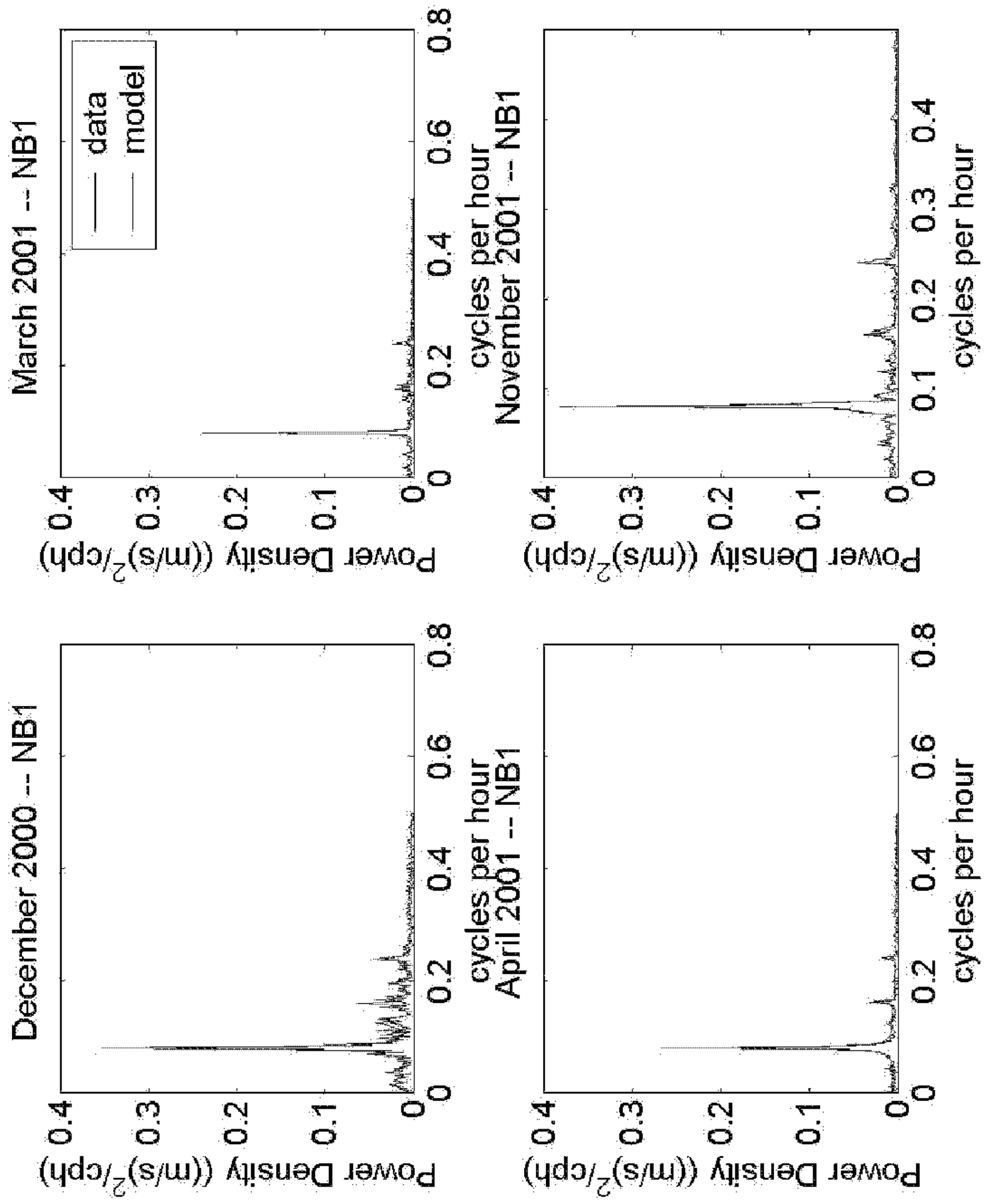


Figure 4.12: Monthly Power Spectral Density of Depth Averaged Currents at NB1

Time Period	Location		Depth-Averaged Velocity			Velocity Near Surface			Velocity Near Bottom		
		Number of points	Range (m/s)	RMS Error %	r^2	Range (m/s)	RMS Error %	r^2	Range (m/s)	RMS Error %	r^2
Dec-00	NB1	231	0.78	13	0.93	0.8	17	0.88	0.9	9	0.84
Mar-01	NB1	734	1.05	10	0.88	1.2	16	0.77	1.1	15	0.62
Apr-01	NB1	712	1.04	11	0.91	1.1	10	0.87	1.1	13	0.76
May-01	NB1	374	0.91	12	0.86	1.0	10	0.87	0.9	18	0.65
Sep-01	NB1	86	0.82	12	0.90	0.8	11	0.90	0.9	19	0.76
Oct-01	NB1	426	1.01	9	0.90	1.0	10	0.87	1.0	14	0.80
Nov-01	NB1	400	0.93	10	0.92	1.0	9	0.92	1.0	14	0.86
Mar-02	NB1	589	1.10	10	0.89	1.1	9	0.90	1.1	12	0.81
Apr-02	NB1	600	1.06	8	0.92	1.2	8	0.89	1.2	14	0.74
Dec-00	KVK1	232	2.32	6	0.96	2.7	6	0.96	2.0	8	0.93
Mar-01	KVK1	762	1.64	12	0.86	1.9	13	0.79	1.5	13	0.78
Apr-01	KVK1	-	-	-	-	-	-	-	-	-	-
May-01	KVK1	374	1.43	14	0.87	1.7	13	0.85	1.3	13	0.84
Sep-01	KVK1	180	1.12	21	0.80	1.3	19	0.83	1.1	18	0.75
Oct-01	KVK1	428	1.77	10	0.88	2.0	12	0.84	1.5	9	0.87
Nov-01	KVK1	400	1.18	20	0.91	1.3	23	0.84	1.1	15	0.90
Dec-00	AK1	230	1.62	14	0.89	1.7	14	0.87	1.5	17	0.84
Mar-02	AK1	485	1.33	17	0.75	1.4	17	0.69	1.2	18	0.78
Apr-02	AK1	600	1.38	15	0.90	1.4	15	0.88	1.4	20	0.87
Maximum	-	-	2.3	21	0.96	2.7	23	0.96	2.0	20	0.93
Minimum	-	-	0.8	6	0.75	0.8	6	0.69	0.9	8	0.62
Mean	-	-	1.2	12	0.88	1.4	13	0.86	1.2	14	0.80

Table 4.5: Comparison of Hourly Model and Data Velocity: Depth-averaged, near surface, and near bottom

Time Period	Location	Number of points	Between 34 hours and 5 days			Longer than 5 days		
			Range (m/s)	RMS Error %	r^2	Range (m/s)	RMS Error %	r^2
Dec-00	NB1	231	0.04	8	0.92	0.03	72	0.68
Mar-01	NB1	734	0.05	15	0.51	0.08	67	0.25
Apr-01	NB1	712	0.04	20	0.05	0.06	146	0.16
May-01	NB1	374	0.02	21	0.23	0.04	93	0.53
Oct-01	NB1	426	0.03	10	0.75	0.02	161	0.81
Nov-01	NB1	400	0.03	12	0.67	0.02	193	0.01
Mar-02	NB1	589	0.06	21	0.02	0.08	75	0.04
Apr-02	NB1	600	0.03	16	0.46	0.05	62	0.31
Dec-00	KVK1	232	0.10	17	0.65	0.10	52	0.24
Mar-01	KVK1	762	0.07	22	0.12	0.11	49	0.02
May-01	KVK1	374	0.03	19	0.41	0	146	0.08
Oct-01	KVK1	428	0.05	28	0.24	0.07	50	0.06
Nov-01	KVK1	400	0.04	19	0.45	0	181	0.14
Dec-00	AK1	230	0.29	18	0.87	0.28	37	0.77
Mar-02	AK1	485	0.17	20	0.03	0.31	35	0.38
Apr-02	AK1	600	0.12	13	0.07	0.11	31	0.14
Maximum	-	-	0.3	28	0.92	0.3	193	0.81
Minimum	-	-	0.0	8	0.02	0.0	31	0.01
Mean	-	-	0.1	17	0.40	0.1	91	0.29

Table 4.6: Comparison of Long-term Model and Data Velocity: Periods between 34 hours and 5 days, and periods longer than 5 days. Velocity information is depth-averaged and low-pass filtered.

Volume Flux into system via AK (m^3/s)	0
Volume Flux into system via KVK (m^3/s)	-28
Total Volume Flux into/out of system (m^3/s)	-28

Table 4.7: Volume Flux in Kills for 0 slope between boundaries

Volume Flux into system via AK (m^3/s)	102
Volume Flux into system via KVK (m^3/s)	-130
Volume Flux into/out of system (m^3/s)	-28

Table 4.8: Volume Flux in Kills for Arthur Kill boundary 1cm higher than Kill van Kull boundary

Volume Flux into system via AK (m^3/s)	-94
Volume Flux into system via KVK (m^3/s)	66
Volume Flux into/out of system (m^3/s)	-28

Table 4.9: Volume Flux in Kills for Kill van Kull boundary 1cm higher than Arthur Kill boundary

Chapter 5

Characterization of the Data

5.1 Tidal Propagation

The amplitude and phase for the major semidiurnal constituent (M_2, period of 12.42 hours) for elevation and depth-averaged velocity are shown in Table 5.1, as calculated from tide gages and bottom-mounted ADP data. (Note: All velocities are positive entering Newark Bay.) Column 1 lists the station locations, column 2 shows the M_2 component of amplitude for elevation, and columns 3 and 4 show the phase (referenced to the equilibrium tide) in both degrees and hours. The same is shown for depth-averaged velocity in columns 5 through 8. Column 9 lists the difference in phase (in hours) between the elevation and depth-averaged velocity where both sets of data exist. High tide for the M_2 component of the tide at PA occurs 0.2 hours earlier than at AK1, demonstrating the propagation of the tide north along the Arthur Kill. The phases of water elevation for the M_2 at AK1 and KVK1 are similar, and both lead NB1 slightly. The amplitude of the M_2 elevation is similar at all locations, but the amplitude for velocity varies over the region. Velocity amplitude is greatest at KVK1, followed in magnitude by AK1; amplitudes are lower at NB1 and PA.

The phase difference between velocity and elevation is important in understanding how water

Water Elevation M_2				**Depth-averaged velocity M_2**				
Sta.	**Amp.** (m)	**Phase** (deg)	(hrs)	**Amp.** (m/s)	**Φ** (deg)	**Phase** (deg)	(hrs)	**Δphase** (hrs)
CH	0.67	12	0.4					
PAYC	0.73	7	0.2					
PVSC	0.75	21	0.7					
NB1	0.76	24	0.8	0.35	78	314	10.8	-2.4
KVK1	0.71	20	0.7	0.60	173	288	9.9	-3.2
AK1	0.74	17	0.6	0.50	48	350	12.1	-0.9
PA	0.72	11	0.4	0.43	135	313	10.8	-2.0

Table 5.1: M_2 Constituents for Elevation and Velocity from Bottom Mounted ADPs and Tide Gages

moves through a system. In an estuary, a tidal wave will travel at the speed given by

$$c = \sqrt{gh} \tag{5.1}$$

where g is acceleration due to gravity, and h is the water depth. In a frictionless system, the wave would travel to the head of the estuary and be reflected back, where it would meet the next incoming wave. If the time of travel is equal to the tidal wave period, a standing wave system would be set up, where the high tide is 90 degrees out of phase with the maximum velocity. (For the M_2 tide component, this phase shift would be about 3.1 hours, one quarter of the 12.42 hour period.) Alternatively, if the energy of the tide wave is dissipated before reflection, then the tide becomes more progressive, and high tide and maximum velocity remain in phase. Table 5.1 shows that the tide wave is not purely progressive at any station; elevation and velocity are always out of phase. The wave is most like a standing wave at KVK1 where the flood current leads high tide by 3.2 hours. The depth averaged current in the Kill van Kull leads the current in Newark Bay by about 1 hour, which in turn leads the current in the Arthur Kill by about 1.3 hours. The depth-averaged current at Perth Amboy also leads the current at the Arthur Kill by about 1.3 hours.

5.2 Salinity

Salinity varies over the Newark Bay Complex in both time and space. Water tends to be fresher in the areas closer to the freshwater source of the Passaic River and more saline near the east end of the Kill van Kull and the south end of the Arthur Kill which are closer to ocean sources. The following discussion of salinity refers to the long-term measurements of salinity from the bottom-mounted CTDs. The average salinity at Perth Amboy (south end of the Arthur Kill) over all time periods of data collection is about 25 psu at the bottom. The minimum salinity in this area was about 16 psu at the bottom during April 2001, and the maximum was about 29 psu occurring during the same month. The average salinity from the north end of the Arthur Kill is fresher than at Perth Amboy at about 21 psu, with a maximum salinity of about 24 psu from March 2002, and a minimum salinity of 15 psu during December 2000. The average salinity in the Kill van Kull was about 23 psu, with a maximum salinity of about 28.5 psu in April 2002, and a minimum salinity of 10 psu in April 2001. Salinity is lower in the north end of Newark Bay, with an average values of 22 psu. Maximum salinity was about 25 psu (October 2001) with a minimum of 15 psu (surface) in April 2002.

5.3 Winds

Figure 5.1 shows histograms for 6 wind speed ranges for the time period of December 2000 to April 2002, where direction indicates where the wind is blowing from. Each histogram represents a speed range, with the number printed below (n=) showing the number of times the wind was in this speed range over the specified time period. Wind speeds and direction were taken from the NOAA/NOS meteorological station at Bergen Point. For wind speeds ranging from 10-20 m/s, the most commonly occurring wind directions are north, east and west. For wind speeds from 8-10 m/s, the most common directions are northeast and southwest. For all other wind speeds, wind comes from most all directions equally. The most commonly occurring wind speeds were from 0-4 m/s.

5.4 River flow from the Passaic

Figure 5.2 shows the river flow from the Passaic River as collected by the United States Geological Survey (USGS 01389500 Passaic River at Little Falls, NJ) (USGS, 2004). The average river flow for the entire 106 year span of USGS data is 29 m^3/s (1013 ft^3/s), and is shown with the red line. The maximum river flow ever recorded was 232 m^3/s (8200 ft^3/s), and was not reached during the time period for this investigation. The maximum for this time period was 126 m^3/s (4450 ft^3/s) which occurred during the higher river flows of spring of 2001. A storm event in December 2000 also caused some relatively high flow from the Passaic River. The spring of 2002 was a very dry period, with river flow remaining below average most of the time.

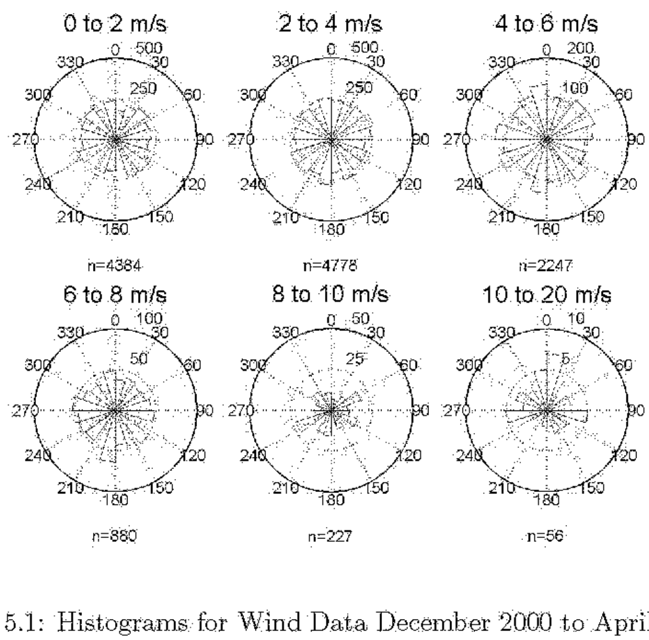


Figure 5.1: Histograms for Wind Data December 2000 to April 2002

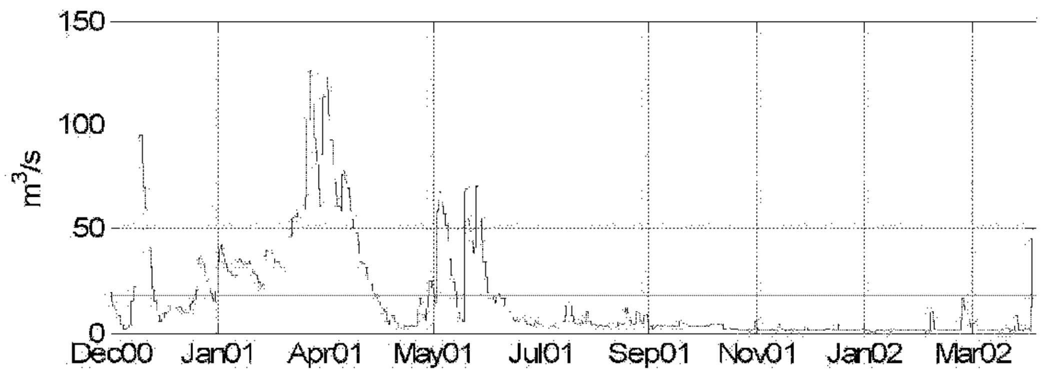


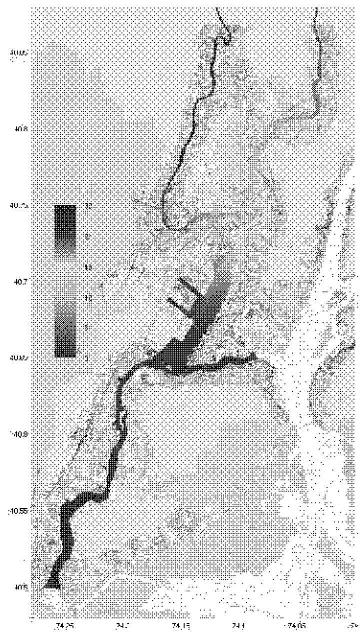
Figure 5.2: River Flow from the Passaic December 2000 to April 2002. Red line represents the average river flow for the entire 106 year span of USGS data (29 m^3/s).

Chapter 6

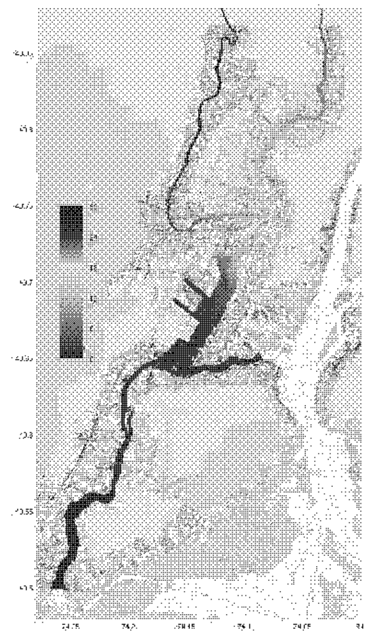
Model/Data Synthesis

6.1 Estuarine Circulation Dynamics

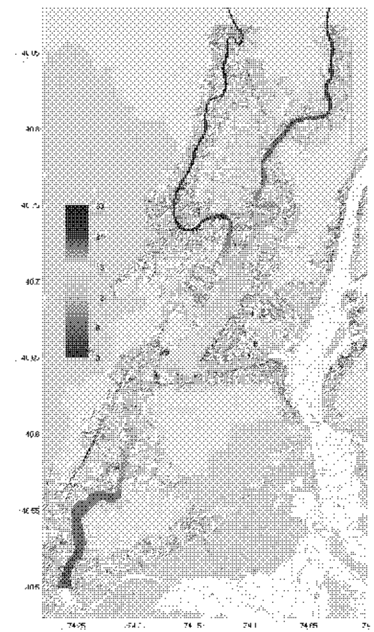
The water in the Newark Bay Complex moves under the influence of three main forcing mechanisms: tide, wind, and salinity differences between the head and the mouth. Salinity differences result from freshwater flows draining to New York Harbor and the Atlantic Ocean while saltier ocean water enters Newark Bay through tidal motion, in the process known as estuarine circulation. In Newark Bay, freshwater is supplied mainly by the Passaic River, while saltier ocean water enters through the Kill van Kull and the Arthur Kill. Figure 6.1 shows a one hour average of surface and bottom salinity (psu) from the model for a period of low freshwater flow (daily mean flow is about 2 m^3/s) as well as for a period of high freshwater flow (daily mean flow is about 60 m^3/s). Salinity is higher during the time of low freshwater flow, and is also more uniform throughout the system than during the time of higher freshwater flow. Freshwater flow from the Passaic River stays along the western edge of Newark Bay, as shown in Figure 6.1(c). There is more vertical stratification in Newark Bay when freshwater flow is higher, where the difference between the salinity at the surface and the bottom appears to be about 2 psu. Also, the salinity in the shipping channels appears to be higher than the salinity in the shallower areas.



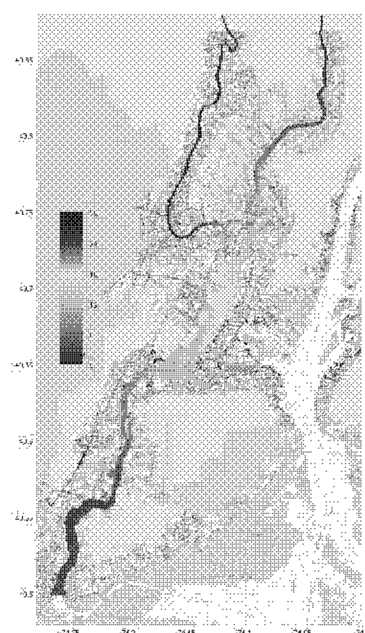
(a) Surface Salinity During Period of Low Freshwater Flow



(b) Bottom Salinity During Period of Low Freshwater Flow



(c) Surface Salinity During Period of High Freshwater Flow



(d) Bottom Salinity During Period of High Freshwater Flow

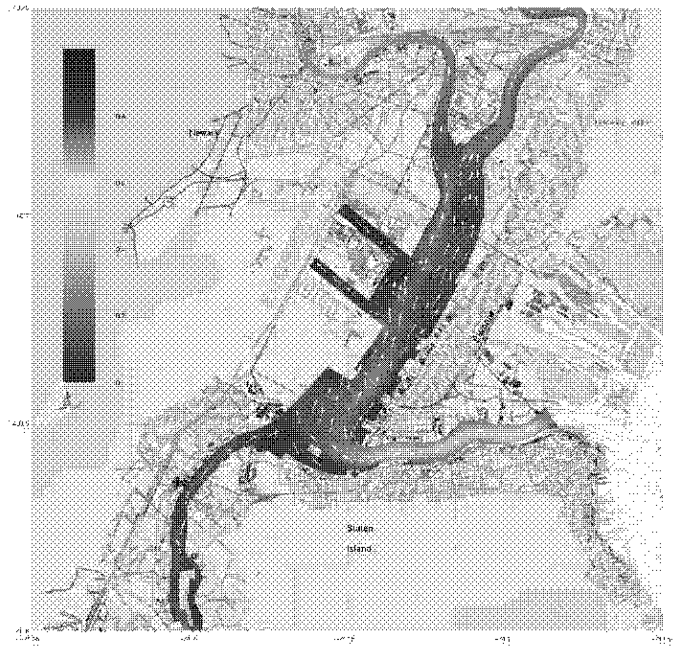
Figure 6.1: Surface and Bottom Salinity in the Newark Bay Complex (salinity is in psu)

Figures 6.2 and 6.3 show a one hour average of surface and bottom velocity for a peak flood and peak ebb tide in Newark Bay. The shading represents the magnitude of the velocity (m/s) and the arrows show direction. For both flood and ebb phases, the greatest velocities appear to be in the shipping channels. In general, both surface and bottom velocities are highest in the Kill van Kull.

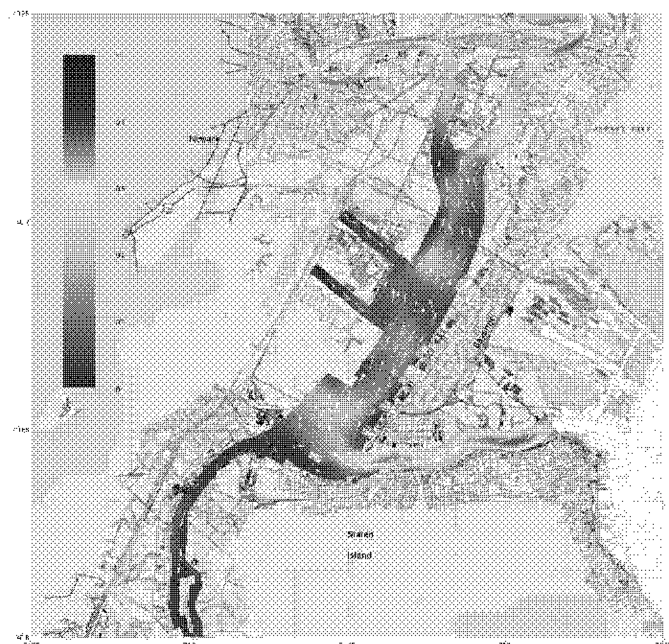
Figure 6.4 shows longitudinal profiles of salinity (psu) through the Newark Bay shipping channel during peak flood and ebb for a period of low freshwater flow, while Figure 6.5 shows the same section for a period of high freshwater flow. The vertical axis represents depth in meters and the horizontal axis shows latitude. The left side of the graph is the southern end of Newark Bay, and the right represents lower reaches of the Passaic River. Note that the salinity scales are different for the low freshwater case and the high freshwater case to show more detail. Conditions are more well mixed during the low freshwater period, and salinity decreases as latitude increases, meaning the water is fresher moving further into the Passaic River. When freshwater flow increases, stratification increases, and the average salinity decreases. Velocities tend to be higher in the deeper shipping channels than in the shallower areas. Surface velocity on the flood tide decreases when freshwater flow increases because it is being opposed by the freshwater flow attempting to drain to sea.

Figure 6.6 shows a vertical cross-section near NB1 of monthly averages of salinity (psu) and upstream along-channel velocity (m/s) for a month with low freshwater flow (daily mean flow is about 2 m^3/s), and Figure 6.7 shows the same section for a month with high freshwater flow (daily mean flow is about 60 m^3/s). Velocity is positive north (up-estuary) and negative to the south. Salinity is homogeneous (at about 24 psu) through the section during the period of low freshwater flow. Salinity through the water column is much lower during the month with high freshwater flow than the month with low freshwater flow. There is also more stratification during this month, with a difference of about 4 psu between the surface and bottom in the channel, while the difference during low freshwater conditions is less than 1 psu. The salinity tends to be lower along the side banks than in the channel.

During the month with low freshwater flow, the velocity in the channel is directed upstream at all depths. The velocity along the side banks is mostly moving downstream. During the month with

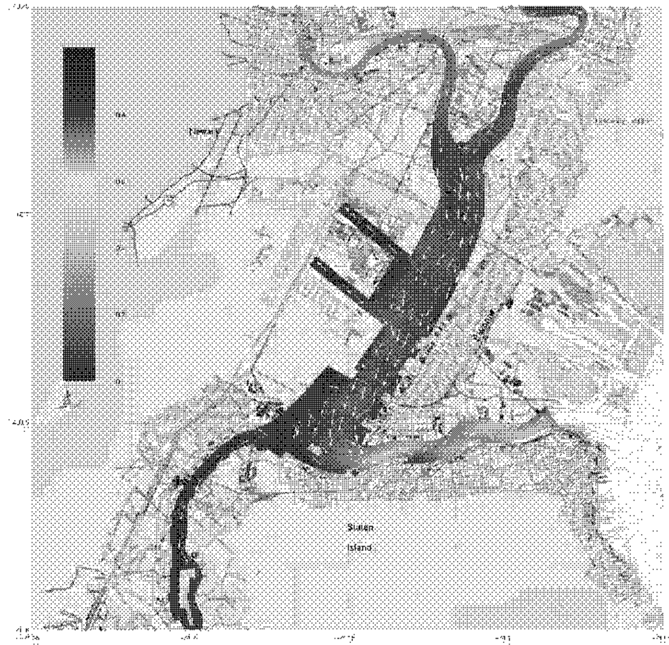


(a) Bottom Velocity During Peak Flood

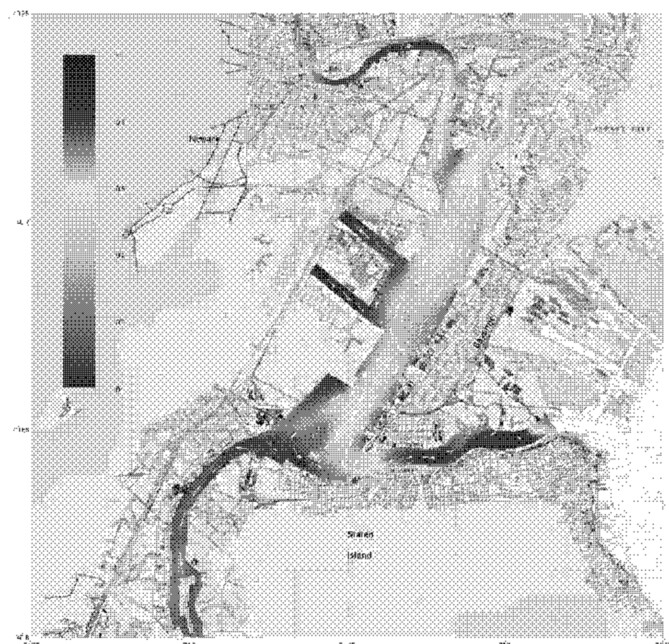


(b) Surface Velocity During Peak Flood

Figure 6.2: Surface and Bottom Velocity During Flood Tide (velocity is in meters per second).

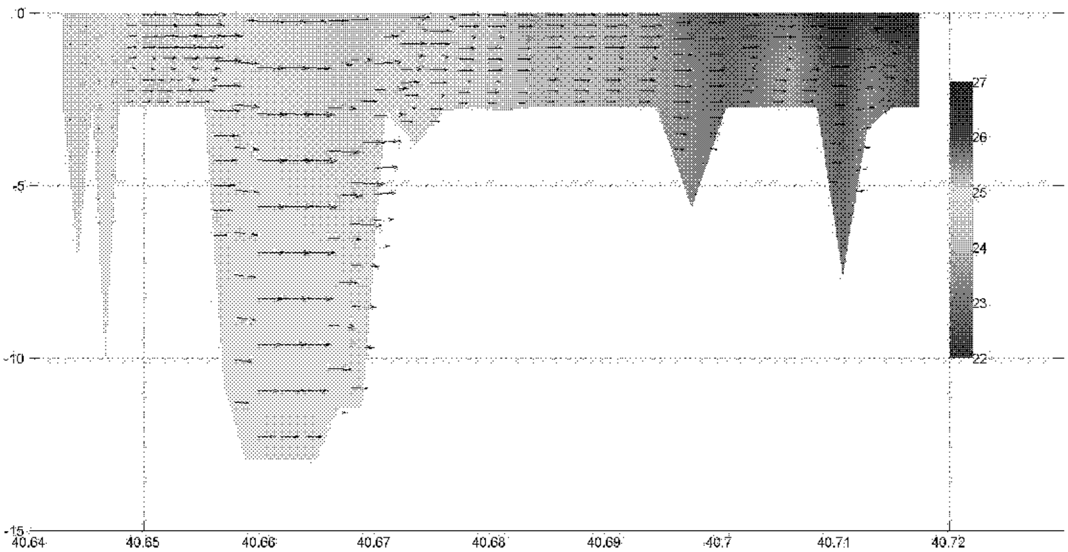


(a) Bottom Velocity During Peak Ebb

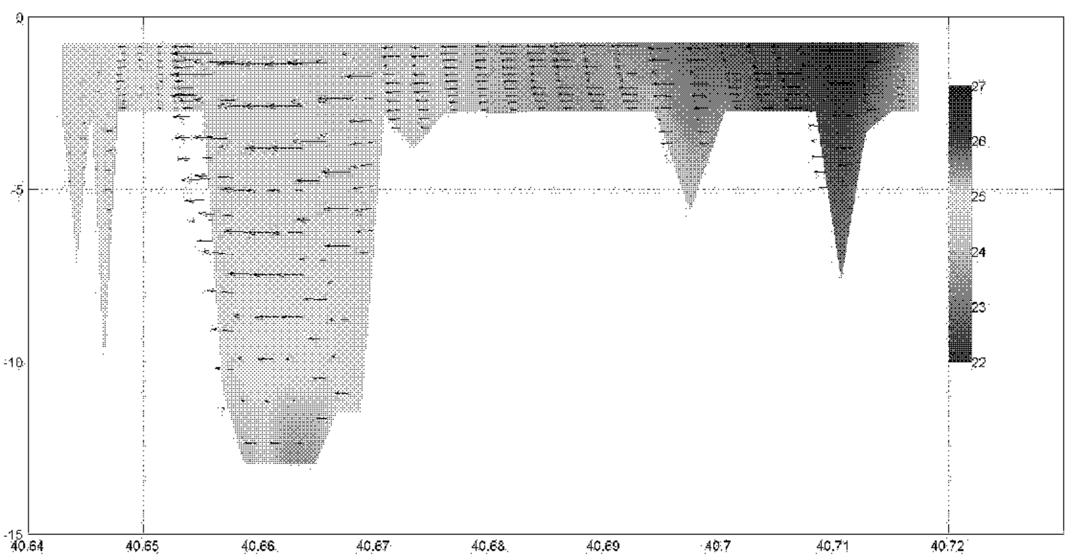


(b) Surface Velocity During Peak Ebb

Figure 6.3: Surface and Bottom Velocity During Ebb Tide (velocity is in meters per second.

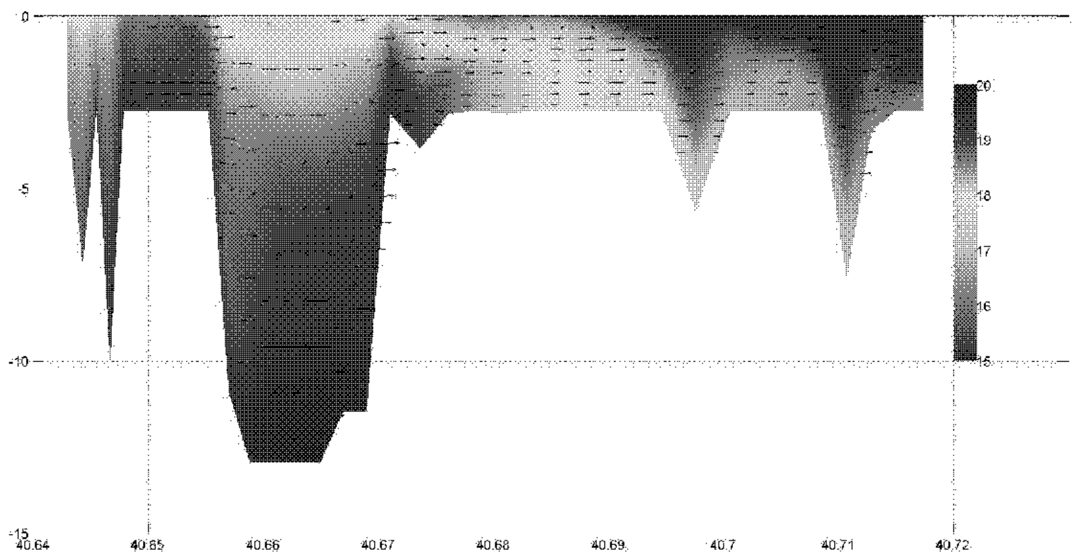


(a) Peak Flood During Period of Low Freshwater Flow

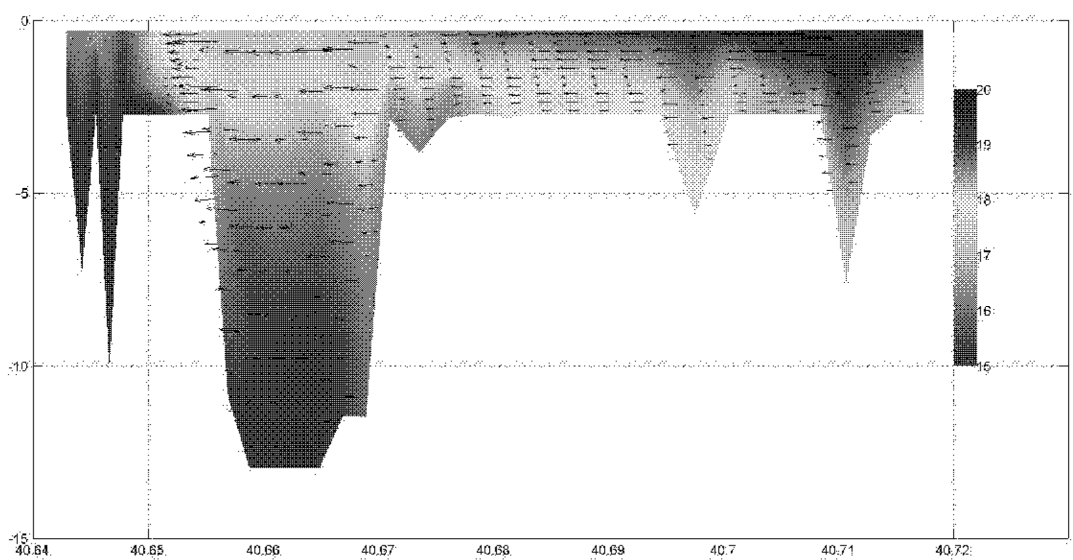


(b) Peak Ebb During Period of Low Freshwater Flow

Figure 6.4: Longitudinal salinity sections in Newark Bay for period of low freshwater flow during peak flood and peak ebb. Vertical axis shows depth in meters, horizontal axis shows latitude, and color indicates salinity in psu. Largest arrows correspond to a velocity magnitude of about 0.5 m/s for both flood and ebb.



(a) Peak Flood During Period of High Freshwater Flow



(b) Peak Ebb During Period of High Freshwater Flow

Figure 6.5: Longitudinal salinity sections in Newark Bay for period of high freshwater flow during peak flood and peak ebb. Vertical axis shows depth in meters, horizontal axis shows latitude, and color indicates salinity in psu. Largest arrows correspond to a velocity magnitude of about 0.5 m/s for both flood and ebb. Note that the salinity scale has shifted from Figure 6.4.

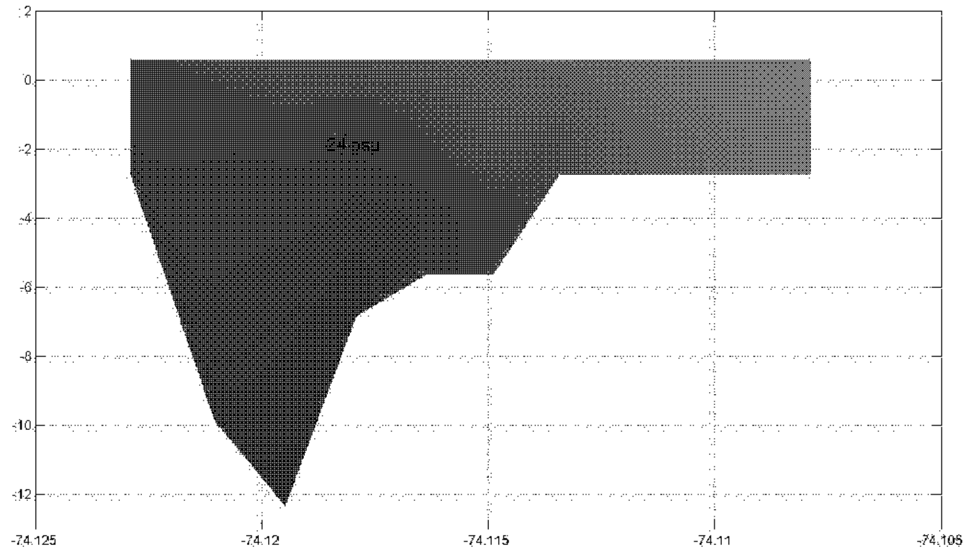
NJDEP00015880

high freshwater flow, classical two-layer estuarine circulation is observed, with surface velocity flowing seaward and bottom velocity flowing upstream. The net flow along the side banks is downstream, with an increased magnitude under higher freshwater flow conditions than during low freshwater conditions. For both cases, there is more inflow and saltier water in the deep channel, with fresher water flowing out along the side banks. Similar transverse structure has been observed in the Delaware Bay (Wong, 1994).

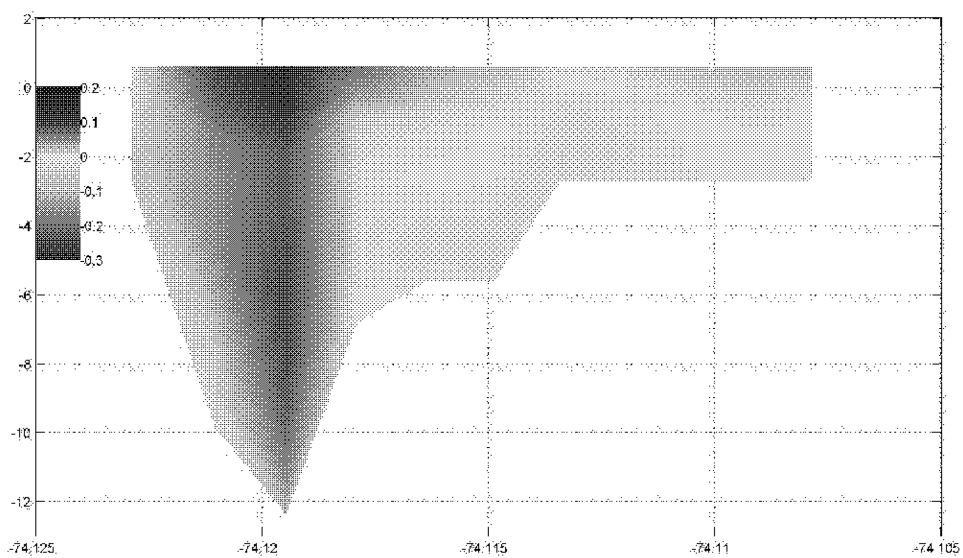
6.2 Meteorological Events

Large, persistent wind events in Newark Bay (longer than one day) can have a strong effect on the circulation in the estuary, and in some extreme cases can disrupt the expected pattern of estuarine circulation (Chant, et. al., 2002; Rankin, et.al., 2002; Pence, et.al., 2003). The east-west component of wind stress has an effect on the residual elevation in the estuary. Figures 6.9 and 6.10 show four panels which display 34-hour low-passed model output from December 2000 and March 2001, as well as some low-passed NOAA/NOS water level data. The top panel shows the wind velocity and direction, the second shows both volume flux into Newark Bay and the elevation change in time ($\frac{d\eta}{dt}$). The value of $\frac{d\eta}{dt}$ can be used as a proxy for the net volume flux entering Newark Bay if the horizontal area is assumed to be the same, which is shown by integrating the vertically integrated continuity equation over the horizontal surface area. The vertically integrated continuity equation is shown in Equation 6.1, where η is surface water level, t is time, $\bar{u}$ and $\bar{v}$ are the vertically integrated velocities, and D is the depth. This equation is based in a system of orthogonal Cartesian coordinates with x increasing to the east and y increasing northward. Equation 6.2 displays the results of integrating over the horizontal surface area (A is surface area and Q is volume flux), where $\frac{d\eta}{dt}$ is shown to be proportional to the net volume flux entering Newark Bay. Simply stated, if the horizontal area of the estuary stays the same, the only change in volume will be due to the change in surface elevation.

$$\frac{\partial\eta}{\partial t} + \frac{\partial\bar{u}D}{\partial x} + \frac{\partial\bar{v}D}{\partial y} = 0 \tag{6.1}$$

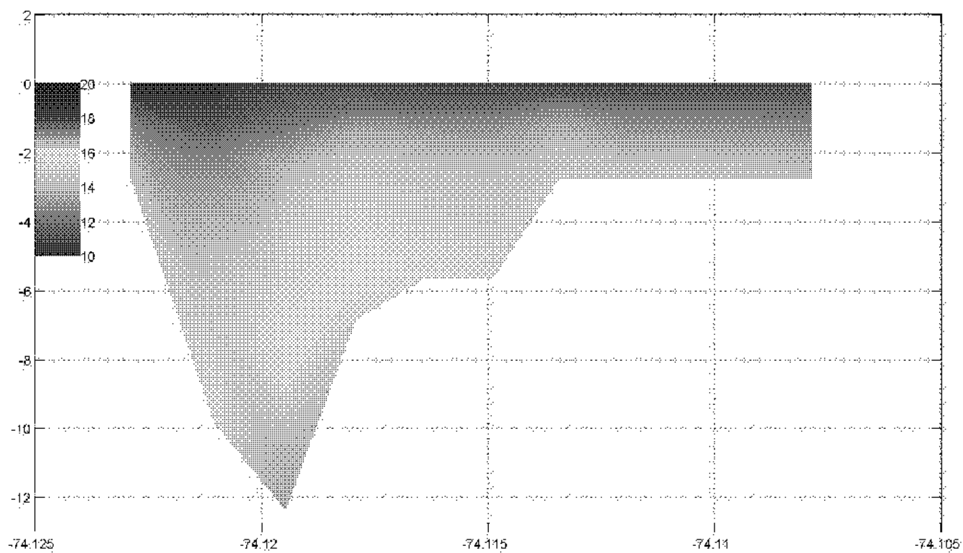


(a) Cross-section of monthly average of salinity (psu) in Newark Bay during period of low freshwater flow. Salinity is homogeneous through the section at about 24 psu during this time.

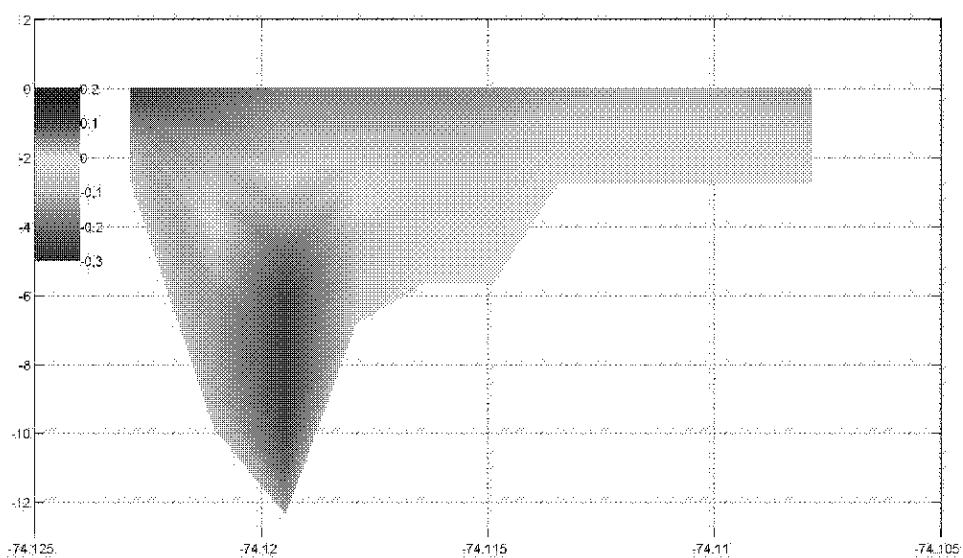


(b) Cross-section of monthly average of velocity upstream (m/s) in Newark Bay during period of low freshwater flow. Velocity is positive north (up-estuary) and negative to the south.

Figure 6.6: Monthly average cross-section of salinity (psu) and velocity upstream (m/s) in Newark Bay for period of low freshwater flow. Vertical axis shows depth in meters, horizontal axis shows longitude, and color indicates salinity/velocity.



(a) Cross-section of monthly average of salinity (psu) in Newark Bay during period of high freshwater flow.



(b) Cross-section of monthly average of velocity upstream (m/s) in Newark Bay during period of high freshwater flow. Velocity is positive north (up-estuary) and negative to the south.

Figure 6.7: Monthly average cross-section of salinity (psu) and velocity upstream (m/s) in Newark Bay for period of high freshwater flow. Vertical axis shows depth in meters, horizontal axis shows longitude, and color indicates salinity/velocity.

$$A\frac{\partial \eta}{\partial t} - Q_{in} + Q_{out} = 0 \tag{6.2}$$

The third panel in Figures 6.9 and 6.10 shows the flux in the upper Arthur Kill and the Kill van Kull (positive is into Newark Bay), and the bottom panel shows water level at Sandy Hook, the Battery and King's Point, all taken from NOAA/NOS water level stations (note: the Battery station was not operational for January through April 2001). The Sandy Hook station is located east of Raritan Bay in Sandy Hook Bay, the Battery is located in Upper New York Bay, and the King's Point Station is located in Long Island Sound. In the wind plot, the arrow shows direction the wind is blowing, while the arrow's position along the y-axis denotes speed.

When wind blows across the sea, the water surface flows to the right of the wind direction in the Northern Hemisphere due to the Coriolis effect. Water at levels below the surface flows to the right as well, though not as quickly as the surface layer. The net effect is that the mass transport of water is at a ninety degree angle to the wind, which is known as Ekman transport. Ekman transport due to strong winds from the west in the Newark Bay region will move water offshore (see diagram in Figure 6.8). This cause a lowering the sea level in the coastal ocean, which sets up a gradient between the water level in Newark Bay and the coastal ocean and causes water to flow out of the Bay. A wind event from the west that begins approximately December 17, 2000, results in flux out of Newark Bay, and a lowering of residual elevation (Figure 6.9). The lowering of water level in the coastal ocean is apparent in the water level plots in the Battery, at Sandy Hook, and King's Point. Figure 6.11 demonstrates the flushing mechanisms of this event as well, showing the daily average of surface salinity (in psu) and currents for December 17 and December 19, 2000. The salinity distribution on December 17 is typical of the daily salinity distribution of the previous week. The flushing due to the wind event on December 18 is apparent in the significantly fresher surface salinity shown on December 19.

Conversely, strong wind events from the east will cause a rise in water level in the coastal ocean. An example of this is a wind event that begins approximately March 21, 2001, results in flux into Newark Bay, and an ensuing increase in residual elevation (Figure 6.10). The rise in elevation in

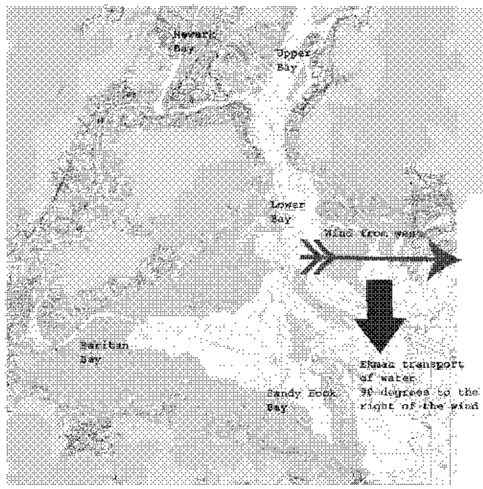


Figure 6.8: Diagram of Ekman transport in Newark Bay due to wind from west.

coastal waters is apparent in the Sandy Hook and King's Point water level stations.

During these events, it is possible for Newark Bay to fill or empty through the Kill van Kull or the Arthur Kill. It can fill and empty through both of these simultaneously("filling-emptying" event), or can fill through one while emptying through the other ("flow-through" event). From examination of Arthur Kill and Kill van Kull flux plots above, it is interesting to see that for March 2001, the Kill van Kull acts as the sink when Newark Bay empties, with residual flow in the Arthur Kill usually moving in the opposite direction with a smaller magnitude (Figure 6.10), while this is not generally true for December 2000, where Newark Bay seems to fill mostly through the Arthur Kill (Figure 6.10). Similar plots from other months (available in Appendix F), show trends similar to those of March 2001. Due to the apparent anomalous nature of December 2000, this month will be analyzed separately at the end of this section.

A correlation table was created for different hourly model output variables from January 2001 to April 2002 (Table 6.1). The variables chosen are: wind stress corresponding to wind from the east, wind stress corresponding to wind from the north, change in elevation in Newark Bay with time (at NB1, $d\eta/dt$), the flux at the north end of the Arthur Kill, the flux at the west end of the Kill van Kull, the elevation difference (slope) between the de-meaned elevations at either end of the Kills

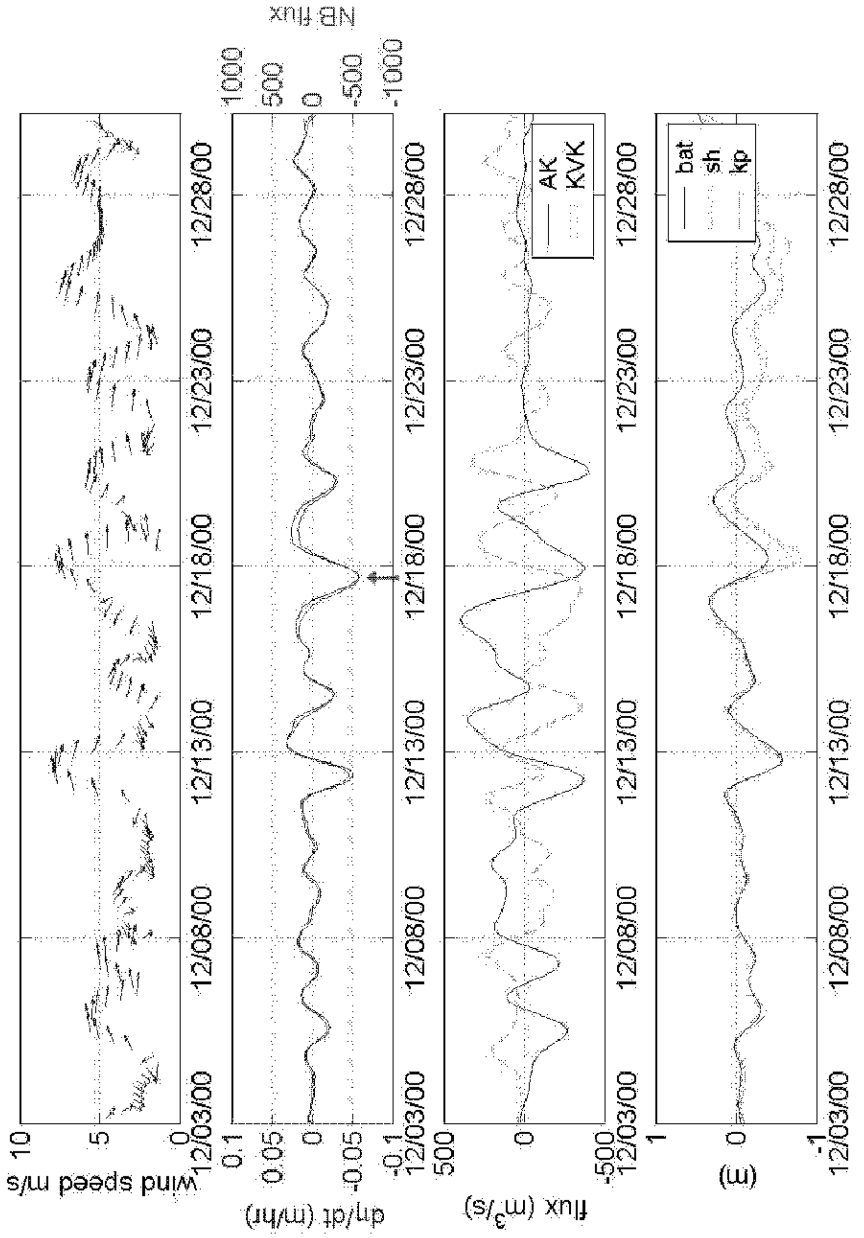


Figure 6.9: Low-passed data from December 2000. Top panel shows the wind velocity and direction (arrow indicates direction that wind is blowing to), second panel shows both flux into Newark Bay and the elevation change in time ($\frac{d\eta}{dt}$), third panel shows the flux in the upper Arthur Kill and the Kill van Kull (positive is into Newark Bay), and the bottom panel shows water level at Sandy Hook, the Battery and King's Point. North is along the positive vertical axis on the top panel.

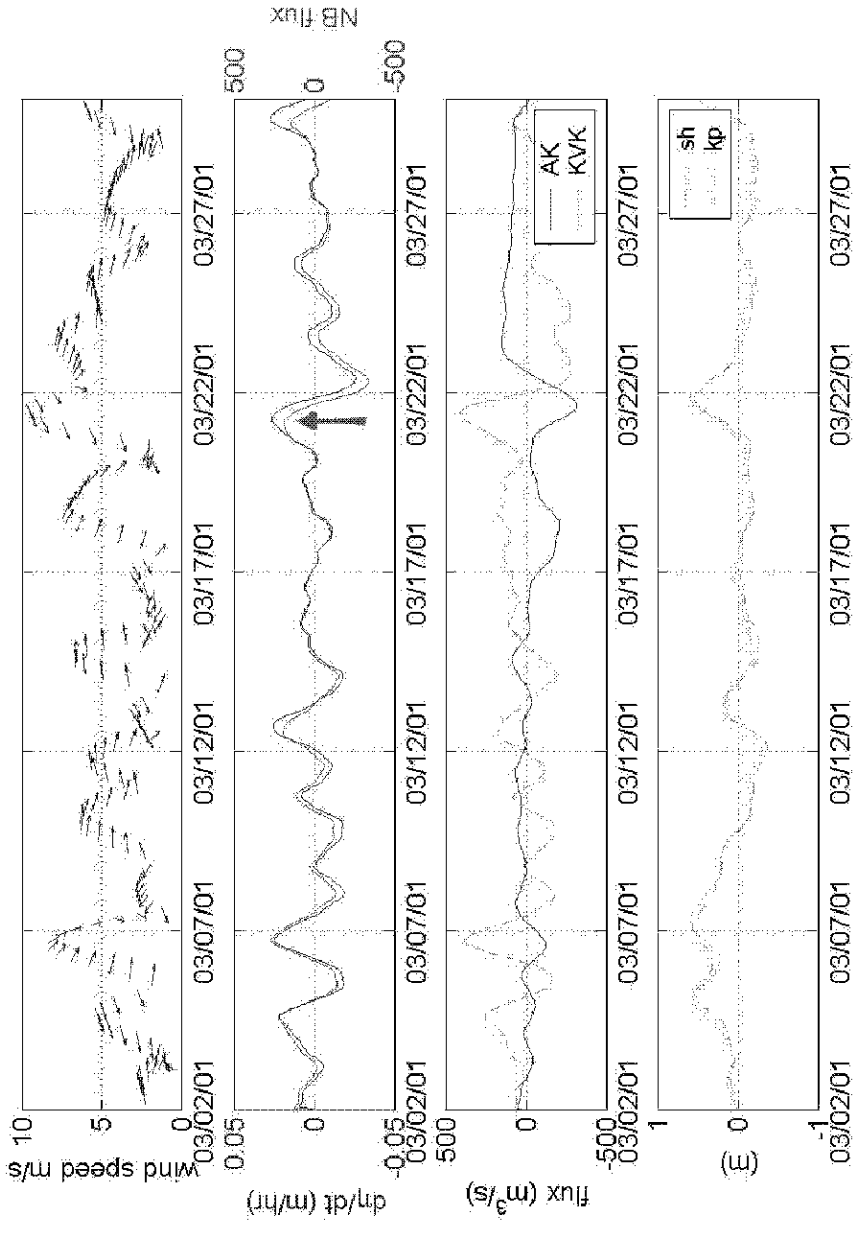
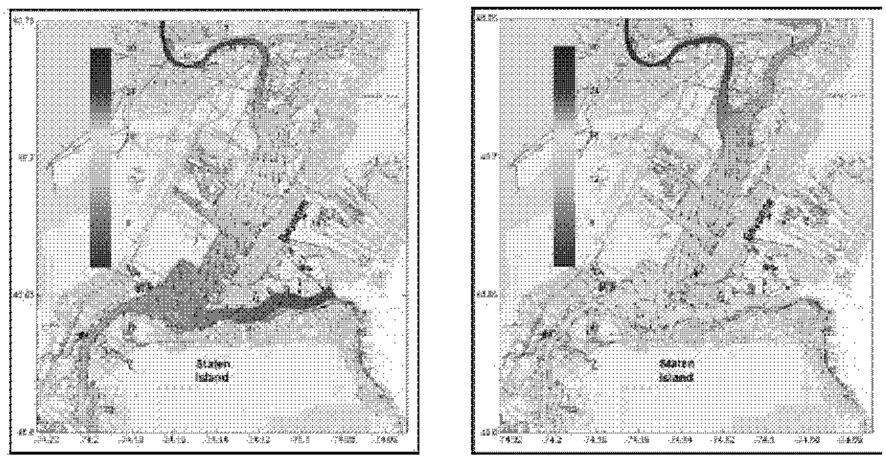


Figure 6.10: Low-passed data from March 2001. Top panel shows the wind velocity and direction (arrow indicates direction that wind is blowing to), second panel shows both flux into Newark Bay and the elevation change in time ($\frac{d\eta}{dt}$), third panel shows the flux in the upper Arthur Kill and the Kill van Kull (positive is into Newark Bay), and the bottom panel shows water level at Sandy Hook and King's Point. North is along the positive vertical axis on the top panel.



(a) December 17, 2000 (b) December 19, 2000

Figure 6.11: Surface Salinity (psu; colors) and Current Direction for December 2000

(elevation at Perth Amboy subtracted from the boundary of the Kill van Kull), elevation at Sandy Hook, and elevation at King's Point.

	wind from east	wind from west	dη/dt	AK flux	KVK flux	slope	η Sandy Hook	η King's Point
wind from east	1.00	-0.03	0.53	-0.35	0.54	-0.46	0.45	0.40
wind from north	-0.03	1.00	0.08	-0.63	0.38	-0.15	0.20	0.19
dη/dt	0.53	0.08	1.00	-0.22	0.83	-0.06	0.02	0.03
AK flux	-0.35	-0.63	-0.22	1.00	-0.69	0.06	-0.07	-0.05
KVK flux	0.54	0.38	0.83	-0.69	1.00	-0.02	0.01	0.01
slope	-0.46	-0.15	-0.06	0.06	-0.02	1.00	-0.83	-0.79
η Sandy Hook	0.45	0.20	0.02	-0.07	0.01	-0.83	1.00	0.95
η King's Point	0.40	0.19	0.03	-0.05	0.01	-0.79	0.95	1.00

Table 6.1: Correlation table for meteorological events for January 2001 to April 2002

Wind from the east is highly positively correlated with dη/dt, suggesting wind from the east causes volume in Newark Bay to increase, as stated above. Flux in the Kill van Kull is also highly positively correlated with wind from the east as well as with dη/dt, suggesting the Kill van Kull is the pathway for water filling the Bay. The flux in the Arthur Kill has a weaker negative correlation with

$d\eta/dt$, signifying that the Arthur Kill is likely not the conduit for the filling/emptying of Newark Bay. However, wind from the north was found to be highly negatively correlated with flux in the Arthur Kill. This would suggest that wind from the north would have a local effect on the Arthur Kill, creating a set-down at Perth Amboy and driving water out of Newark Bay. This may explain why Thomas (1993) found that westward wind stress is well correlated with sea surface elevation in the Arthur Kill, but that the transport was correlated to the north-south component of the wind. Slope does not appear to be well correlated with the change in volume in Newark Bay, nor with the direction of fluxes, suggesting that it is not likely the driving mechanism for the types of flushing modes. Water level at Sandy Hook and King's Point are highly positively correlated with east wind, which follows along with the assumptions stated above of east wind causing a lowering in the coastal ocean. Although the slope between elevation at Sandy Hook and King's Point is not highly correlated with $d\eta/dt$, it was not expected to be; that is it was expected that there would be a relationship between east/west wind and sea surface elevation in the coastal ocean, but that the $d\eta/dt$ and the water level in the coastal ocean would only be related when the wind event was strong enough to create a sufficient gradient between Newark Bay and the offshore areas.

Often, effects of meteorological forcing in an estuary are analyzed using empirical orthogonal function (EOF) analysis. The EOF method provides a compact description of the spatial and temporal variability in a large time series of data in terms of orthogonal "modes". Some examples of EOF analysis to interpret oceanographic data are Kundu and Allen (1975) and Elliot (1978). A detailed description of the theory of EOF analysis, along with an example, can be found in Emery and Thomson (2001).

Five variables were chosen to use in the EOF analysis: wind stress corresponding to wind from the east, wind stress corresponding to wind from the north, $d\eta/dt$, flux in the Arthur Kill, and flux in the Kill van Kull. These variables were demeaned, as well as normalized by their standard deviation prior to the analysis so that each variable had a variance of 1. The standard deviations as well as the results of the analysis are shown in Table 6.2 below. The column of variance explained

(%) is a percentage of the total energy that is explained by that mode (sum total of 100%), and the amplitude factors describe the magnitude and direction of each variable in that mode. The lower portion of the chart shows the correlation between each mode and variable (r^2).

		wind from east	**wind from north**	**dη/dt**	**AK flux**	**KVK flux**
SD		1.7E-05	1.4E-05	7.4E-03	49.8	94.1
units		m^2/s^2	m^2/s^2	m/hour	m^3/s	m^3/s
	Variance Explained (%)	**Amplitude Factors**				
mode 1	54.0	-0.36	-0.29	-0.46	0.47	-0.59
mode 2	27.2	0.48	-0.69	0.38	0.39	0.06
mode 3	12.9	0.65	-0.13	-0.59	-0.42	-0.21
mode 4	5.5	-0.46	-0.65	-0.12	-0.50	0.31
mode 5	0.4	-0.05	-0.06	0.53	-0.44	-0.72
		Variance explained				
mode 1		0.41	0.26	0.58	0.61	0.93
mode 2		0.25	0.62	0.22	0.23	0.01
mode 3		0.18	0.00	0.25	0.13	0.03
mode 4		0.06	0.14	0.00	0.07	0.03
mode 5		0.00	0.00	0.01	0.00	0.01

Table 6.2: EOF Analysis Results January 2001 to April 2002

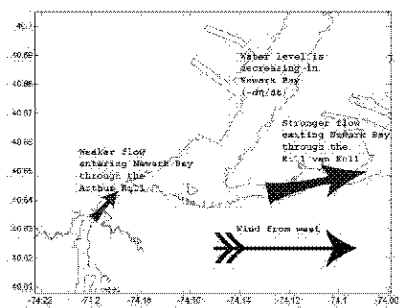
The results of the EOF analysis demonstrate some important points:

- The first three modes account for about 94 % of the total variance
- The first mode is most highly correlated with flux in the Kill van Kull (0.93), and was more correlated with east wind than north wind.
- The second mode is better correlated with wind from north than from the east, and better correlated with flux in the Arthur Kill than in the Kill van Kull (which had *zero* correlation with this mode).

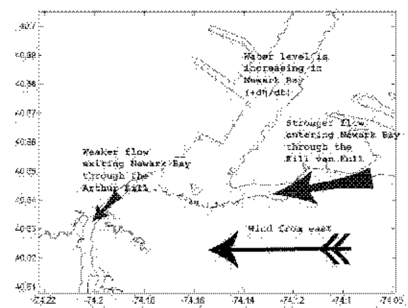
- The third mode is most correlated with wind from the east, dη/dt and flux in the Arthur Kill. In this mode, the direction of the flux is the same for both the Arthur Kill and the Kill van Kull.
- Modes 4-5 do not contribute significantly to the total variance.

The first mode describes the east-west wind events that were explained above. Wind from the west (which causes a lowering of the sea level in the coastal ocean) is accompanied by a lowering of the sea level in Newark Bay (-dη/dt). The water leaves Newark Bay through the Kill van Kull (negative flux means that the water is leaving Newark Bay), and slowly enters through the Arthur Kill. This is the dominant mode, accounting for 54 percent of the variance. A wind from the east would cause the signs of these variables to be opposite; sea level in Newark Bay would rise as water filled in through the Kill van Kull and slowly exited through the Arthur Kill. Figure 6.12(a) and 6.12(b) show sketches of the two cases of flow directions in the Kills for this mode. It is interesting to note the Kill van Kull is the conduit for draining and filling Newark Bay, which means that dredging this strait could have a profound effect on the circulation in the system. The reason for this is most likely due to the phase lag of currents in the system between the Kill van Kull, Newark Bay, and the Arthur Kill. The currents turn first in the Kill van Kull, turn one hour later at Newark Bay, and then 2 hours after that, they turn at the Arthur Kill. For most of the tidal cycle in Newark Bay, the velocities are flowing in the same direction as the Kill van Kull, making it easiest for the water to enter and leave this way. Additionally, the Kill van Kull is shorter and parallel to the wind forcing, making it the simplest path to the New York Bight. Examples of this mode can be seen in Figure 6.10 and the figures in Appendix F, specifically on March 21, 2001, April 13, 2002, and October 26, 2001.

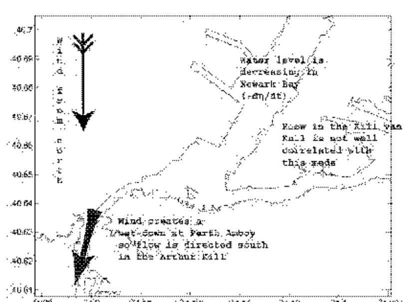
The second mode is most highly correlated with wind from the north. It appears that this mode is describing a local effect. Wind from the north causes a set-down at Perth Amboy, creating a gradient along the Arthur Kill. Water flows out of Newark Bay through the Arthur Kill; flow in the Kill van Kull is not correlated with this mode. Figure 6.12(c) and 6.12(d) show sketches of the two cases of flow directions in the Kills for this mode. This mode is not as prevalent as the first since it



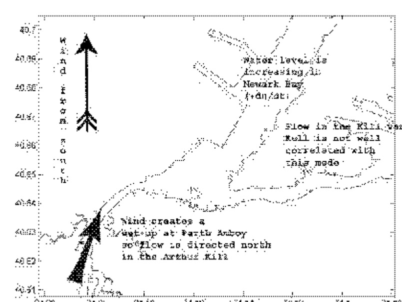
(a) Mode 1 - Wind from west



(b) Mode 1 - Wind from east



(c) Mode 2 - Wind from north



(d) Mode 2 - Wind from south

Figure 6.12: Flow Directions in the Kills During Modes 1 and 2

only accounts for 27.2 percent of the variance. An example of this mode can be seen in Figure 6.9 on December 18, 2000, where winds from the north causes water to flow out of Newark Bay through the Arthur Kill.

The third mode is less correlated with the variables than the first two modes, but seems to describe a filling-emptying phenomenon that can be observed from the data. This mode suggests that wind from the northwest causes flow into Newark Bay through both the Arthur Kill and the Kill van Kull and wind from the southeast would cause the opposite. This does not make physical sense since (as described above) wind from the west causes flow out of Newark Bay, nor does it follow with examples from the data. For example, on June 21, 2001, both the Arthur Kill and the Kill van Kull are filling Newark Bay, but wind is from the southeast (Appendix F). On June 18, 2001, both the Arthur Kill and the Kill van Kull are emptying Newark Bay, and wind is from the northwest. It could be that there is some noise in the data that obscures the true wind direction for mode 3, or that the filling-emptying mode is actually a combination of 2 higher order modes. Mode 3 could be the same as mode 2, but a more easterly or westerly component of the wind causes the flow in the Kill van Kull to be larger. (In mode 2, the flux amplitude factors have the same sign, but the Kill van Kull flux is small.) Compared to the first two modes, this mode is not significant since it accounts for only about 13% of the total variance. Also, the correlation of each variable in this mode is less than 0.25.

The EOF analysis described above was performed on all events, whether they were filling or emptying Newark Bay. To ensure that neither was dominating the signal of the other, an EOF analysis was performed on this data again in two separate sets: filling events ($d\eta/dt > 0$) and emptying events ($d\eta/dt < 0$). The modes and amplitude factors were similar for both sets, and similar to EOF analysis of the entire data set, demonstrating that both filling and emptying events have been properly represented.

Results from the EOF analysis of this data set suggest that the flushing modes in Newark Bay respond to both remote wind effects where east-west winds cause a lowering of water level offshore and local wind effects which create a setup or setdown in the Arthur Kill. This makes it necessary to have knowledge of both to predict and understand the circulation in this complex system. The most common flushing mode is a "flow-through" mode, followed by a filling/emptying mode through the Arthur Kill due to local effects. The general filling/emptying mode exists, but it not completely clear from the EOF analysis.

As mentioned above, the meteorological events that occurred in December 2000 appear to be quite different than the events that occur in the subsequent months. A correlation table similar to Table 6.1 was created for December 2000, shown in Table 6.3 below. For this data set, elevation is again highly positively correlated with wind from the east, as it was with the rest of the data. However, wind from the east is now highly positively correlated with flux in the Arthur Kill, not the Kill van Kull as it was previously, with a weak negative correlation between wind from the east and flux in the Kill van Kull. In fact, from Figure 6.9, it seems that flux into and out of Newark Bay (panel 2) follows the pattern of flux in the Arthur Kill (panel 3) very closely. As before, water level at Sandy Hook and King's Point is highly positively correlated with wind from the east. Additionally, these water levels are highly negatively correlated with flux in the Kill van Kull, as well as with slope between the ends of the Kills.

	wind from east	**wind from north**	**dη/dt**	**AK flux**	**KVK flux**	**slope**	**η Sandy Hook**	**η King's Point**
wind from east	1.00	0.10	0.61	0.63	-0.14	-0.76	0.62	0.67
wind from north	0.10	1.00	0.32	0.31	0.05	-0.41	-0.03	-0.01
dη/dt	0.61	0.32	1.00	0.58	0.34	-0.57	0.13	0.18
AK flux	0.63	0.31	0.58	1.00	-0.55	-0.93	0.41	0.49
KVK flux	-0.14	0.05	0.34	-0.55	1.00	0.44	-0.34	-0.38
slope	-0.76	-0.41	-0.57	-0.93	0.44	1.00	-0.49	-0.56
η Sandy Hook	0.62	-0.03	0.13	0.41	-0.34	-0.49	1.00	0.97
η King's Point	0.67	-0.01	0.18	0.49	-0.38	-0.56	0.97	1.00

Table 6.3: Correlation table for meteorological events December 2000

EOF analysis was also performed on the December 2000 data using the same method as above, with the results shown in Table 6.4. Important points from this analysis are as follows:

- The first mode accounts for 47.4 percent of the total variance.

		wind from east	wind from north	dη/dt	AK flux	KVK flux
SD		2.6E-05	1.1E-05	1.4E-02	153.1	138.7
units		m^2/s^2	m^2/s^2	m/hour	m^3/s	m^3/s
	Variance Explained (%)	**Amplitude Factors**				
mode 1	47.4	0.54	0.28	0.51	0.59	-0.15
mode 2	27.9	0.00	0.23	0.45	-0.29	0.81
mode 3	18.2	0.41	-0.88	0.16	-0.05	0.14
mode 4	6.2	0.74	0.29	-0.45	-0.41	0.02
mode 5	0.3	-0.02	0.05	0.55	-0.63	-0.54
		Variance explained				
mode 1		0.68	0.19	0.63	0.82	0.05
mode 2		0.00	0.07	0.28	0.12	0.93
mode 3		0.15	0.71	0.02	0.00	0.02
mode 4		0.17	0.03	0.06	0.05	0.00
mode 5		0.00	0.00	0.00	0.01	0.00

Table 6.4: EOF Analysis Results December 2000

• The first mode is highly correlated with wind from the east, change in water elevation and flux in the Arthur Kill. It is weakly negatively correlated with flux in the Kill van Kull. This is exactly the opposite of the first mode in the Arthur Kill.

• Though the first mode only accounts for 47.4 percent of the total variance, the other modes do not appear to describe naturally occurring phenomena. From an examination of the data, it appears that the events are mostly described by wind from the west emptying the Bay, and east wind filling.

The pattern described by the first mode is similar to mode 1 of all of the other data, but here the conduit for emptying Newark Bay is through the Arthur Kill. Wind from the west again causes a lowering of the coastal sea level, with water leaving Newark Bay through the Arthur Kill, and a weaker flux of water entering Newark Bay through the Kill van Kull. The reason for the change of flux direction is most visible in the event beginning around December 17 (Figure 6.9). West wind lowers the elevation at the Battery, Sandy Hook and King's Point. This sets up the gradient driving water out of Newark Bay, where at first water flows out of both the Arthur Kill and the Kill van Kull. Soon, water level at King's Point and Sandy Hook are much lower than at the Battery, on the order of about 0.4 m. The reason for this lowering is most likely the persistence of the wind from the southwest which blows shallow waters of Raritan Bay offshore and to the right, through the Sandy Hook-Rockaway Transect as a result of Ekman Transport. The water in the Battery is less responsive because it has nowhere to go; it could possibly travel northeast through the East River, but it is a narrow passage not conducive to accommodating large volumes of water as is the Sandy Hook-Rockaway Transect. This sets up a large gradient between the ends of the Kills, so that water level is much higher at the mouth of the Kill van Kull than at Perth Amboy causing water to flow downhill out through the Arthur Kill. Strong west winds are prevalent for most of the rest of December maintaining the gradient between Sandy Hook/King's Point and the Battery. Winds from the west are large and prevailing during themonth of December causing the emptying of Newark Bay to be primarily through the Arthur Kill. One event of west wind blowing stronger than 2 meters per second lasts 4 days during December 2000; the next longest event during the 18 month study period occurs in March 2001 and lasts for only 3 days.

Most of the flushing events during this time period are "flow-through" events, and can be described by a west (or east) wind which drives water out of (or into) Newark Bay out (or in) through the Kill van Kull, with a weak flow in (or out) through the Arthur Kill. These events have been previously characterized through the work of Chant, et. al., (2002) and Rankin, et. al., (2002). Extreme and persistent winds from the west can cause the Arthur Kill to be the filling/emptying conduit, but these events are exceptional. A second mode, though not as prevalent, is a result of north-south wind affecting the Arthur Kill locally, causing a north-south flux.

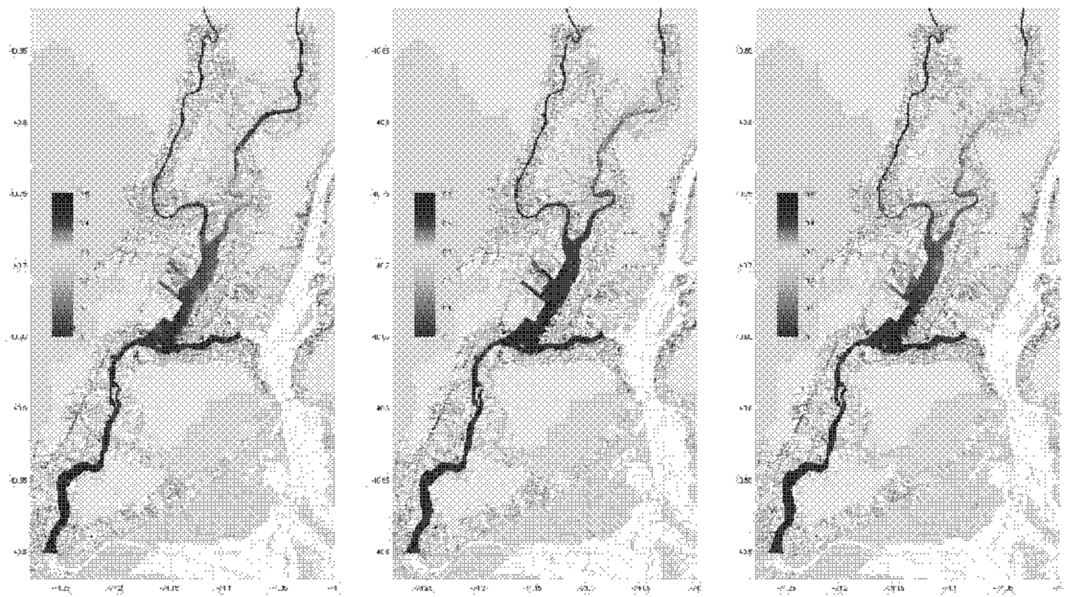
These flushing events disrupt the expected patterns of estuarine circulation, and play an important role in determining the fate and transport of contaminants. The average flux over a day in the Arthur Kill for the time period of sampling was about 60 m3/s, while the average flux in the Kill van Kull was about 120 m3/s. A strong wind event can drive a flux of up to 400 m3/s in the Kills lasting longer than 34 hours, and driving a considerable amount of possibly contaminated water out of Newark Bay, most likely transporting contaminated sediments with it, into Upper New York Bay or Raritan Bay. As these events are not uncommon (fluxes achieved levels greater than 200 m3/s on 22 days in the Arthur Kill, and 85 days in the Kill van Kull during the time period of December 2000 to April 2002), this could be an important factor in the water quality in New York Harbor, as well as in Raritan Bay. An interesting investigation would be to see what the currents are like in New York Harbor during this time, to determine if the sediment would settle here, or be flushed from this system as well.

6.3 Fate of Suspended Sediment in the Passaic River

At the beginning of each month of the model run, a suspended sediment concentration of 1 mg/L was specified in each grid box through the water column and along the length of the Passaic River. The sediment was given a settling rate of 0.0001 m/s, typical of estuarine sediments (Wang, 2002), but was not permitted to settle into the bed, i.e. the sediment remained in suspension for the length of the run. The physics describing scour and settling of estuarine sediments are not yet fully understood which makes it difficult to model these processes accurately. This method allowed for a simple sediment transport model. The fate of suspended sediment in the Passaic River is important to the sediment quality in Newark Bay because it is a source of some of the most highly contaminated sediments in the Newark Bay Complex. Many hazardous substances, including dioxin, PCBs, pesticides and metals, have been found near the land-based part of the Diamond Alkali Superfund Site located on this river (USEPA, 2004).

Examination of the sediment distribution in the bottom layer over the Newark Bay Complex at the end of each month shows varying results for different months (Figure 6.13). At the end of March 2001, some sediment has travelled up the Hackensack River, while some is present in Newark Bay. At the end of April 2001, some sediment resides in the Hackensack, and there seems to be no sediment present in Newark Bay; much of the sediment appears to have exited the system entirely. At the end of May 2001, sediment has travelled further north into the Hackensack and in higher concentrations than in either March or April. Overall, the Hackensack appears to be acting as a sink for the sediment of the Passaic River.

Table 6.5 shows the amount of sediment remaining as a percentage of the initial mass concentration in the separate areas of Newark Bay at the end of month. Only months when good salinity boundary conditions were available are part of the analysis. The total loss from the system is the sum of all areas subtracted from 100%, meaning the total sediment that has been lost across the model boundaries. Also included in the table are the sum, maximum and mean values for river flow from the Passaic for that month. Several mechanisms are combining to determine the fate of sediment from the Passaic, including the magnitude of river flow, the tide forcing, the gravitational circulation, and episodic wind events. River flow will tend to flush the sediment into Newark Bay, where it can be acted on by the tide, the gravitational circulation, and possibly wind events. Gravitational circulation is a result of the salinity gradient that exists between the fresher water of the Passaic and the Hackensack and the boundaries at the Kill van Kull and the Arthur Kill. The river water flows seaward along the surface, while the saltier water from the boundaries moves up river along the bottom layer, carrying sediment with it. Gravitational circulation moves salt water up



(a) March 2001 (b) April 2001 (c) May 2001

Figure 6.13: Sediment Distribution in Bottom Layer at End of Month (mg/L)

into the Passaic, but since the opposing river flow in the Passaic is usually much higher than in the Hackensack, it is more likely the water will travel up the Hackensack and bring sediment along with it.

The table shows that the highest loss of sediment was during the two months of high river flow, April and March 2001, where more than 65% of the sediment was lost in one month. This is not to suggest that the river flow alone is responsible for flushing the sediment out of the system entirely, but rather that the river flow brings the sediment into Newark Bay, where it has a better chance of being flushed from the system than if it remained in the Passaic. Also, the river flow would create higher velocities in the Passaic River in the upper water column, keeping the sediment in suspension longer, so it would remain free from being acted upon by gravitational circulation in the bottom layer. This reasoning makes sense since the smallest losses were during the months that most of the sediment remained in the Passaic (September, October, and November 2001).

The percentage of original sediment that becomes trapped in the Arthur Kill and the Kill van

Time Period	River Flow Sum m^3/s	Max m^3/s	Mean m^3/s	Final Concentration Pass. %	Hack. %	NB %	KVK %	AK %	Total loss from system %
Dec-00	802	95	27	0.3	22.6	19.5	0.8	7.2	49.5
Mar-01	1885	126	61	0.1	16.8	14.6	0.9	0.3	67.2
Apr-01	1678	123	56	0.3	15.4	6.3	0.3	0.2	77.5
May-01	264	25	9	2.8	42.4	17.3	0.7	1.4	35.4
Sep-01	154	12	5	34.1	32.6	11.6	0.0	0.7	21.0
Oct-01	107	6	3	35.9	26.9	10.1	0.0	0.2	26.9
Nov-01	64	5	2	51.9	21.4	6.0	0.0	0.1	20.6

Table 6.5: Sediment Distribution at the End of Month

Kull is usually quite low, suggesting that once the sediment that originated from the Passaic River reaches these points, it gets flushed out of the system in under one month. The highest remaining concentrations in the Hackensack occurred during May, September and October 2001. These months seem to have had enough river flow to move sediment into a location in Newark Bay where it could be transported up into the Hackensack, but not past the point where they could be flushed out of the system entirely. Also, the river flows may have been enough to keep the sediment in suspension in the Passaic so that it would be flushed, but not enough to keep it in suspension in Newark Bay so that it could be flushed from the system entirely. The sediment would then have settled into the bottom layers of Newark Bay where it could be transported upriver. Figure 6.14 shows the monthly average of bottom currents for May 2001. The strongest currents are seen in the shipping channel, moving upstream, which would carry sediment with it.

To investigate the effect of the different forces separately, three month-long synthetic runs were constructed. These are:

1. tide, no salinity, no freshwater inflow
2. tide, no salinity, low freshwater inflow (daily average = $1m^3/s$)
3. tide, with salinity, low freshwater inflow (daily average = $1m^3/s$)
4. tide, with salinity, high freshwater inflow(daily average = $20m^3/s$)

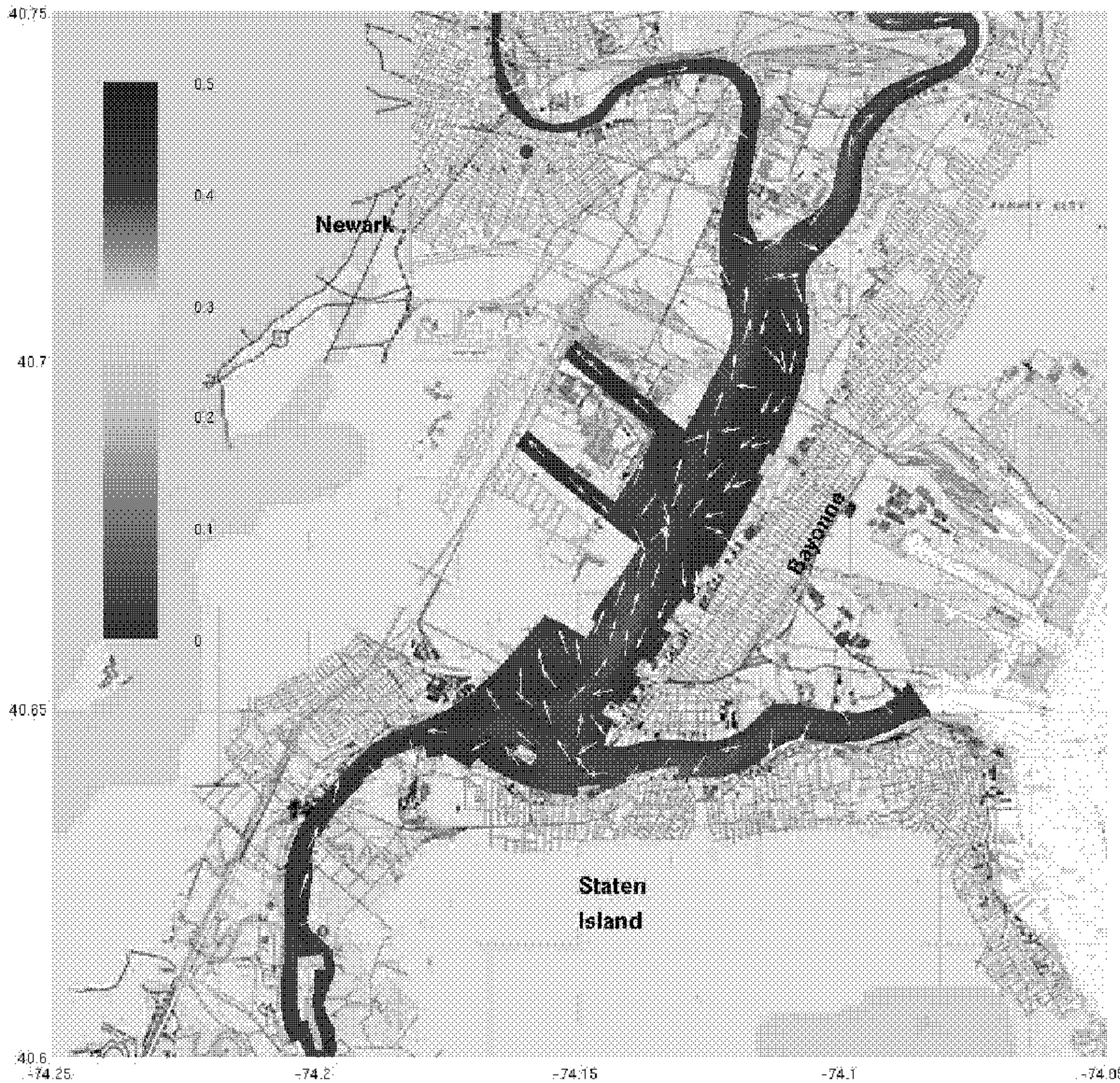
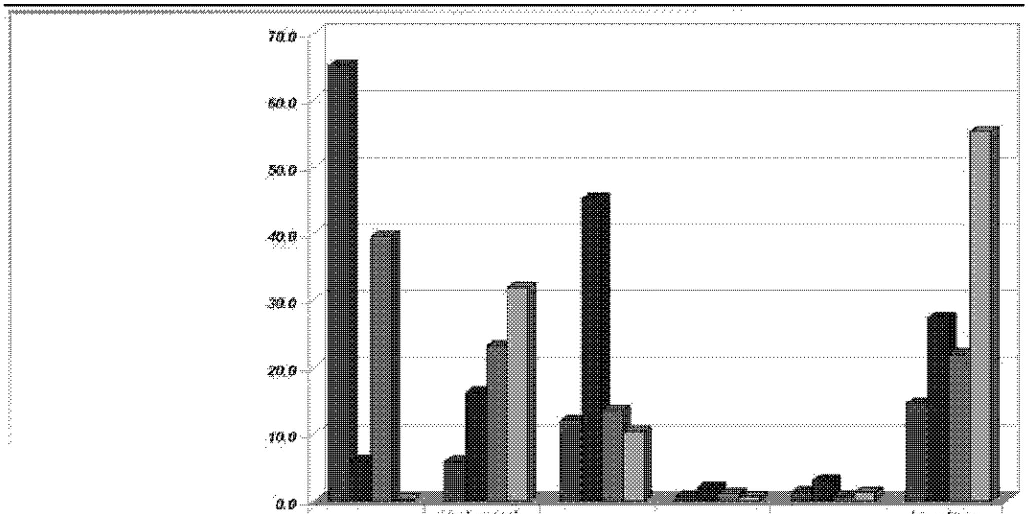


Figure 6.14: Monthly Average of Bottom Currents for May 2001 (m/s)

These runs do not include effects of either local or remote wind forcing; the water level at the boundary consists of the typical tide forcing only. The salinity boundary values were taken from December 2000, and were the same for both cases 3 and 4. The results are shown in Figure 6.15.For case 1, which includes only tide forcing, little sediment leaves the Passaic River. A small percentage of sediment ends up in the Hackensack, likely due to the phase shift in tidal currents between the two rivers. For low freshwater inflow (case 2), only 6% of the sediment remains in the Passaic. Some sediment travels up into the Hackensack, but most is flushed into Newark Bay and remains there. Case 3 demonstrates the addition of the salinity gradient. Here, more sediment remains in the Passaic, and more travels up into the Hackensack. Very little remains in Newark Bay when compared to case 2 (difference of more than 30%). Also less total sediment is lost from the system. This would suggest that the salinity gradient works to keep sediment in the system, and keeps it further upstream. Case 4 shows the results from having a higher freshwater flows, similar to the conditions of Spring 2001. Under these conditions more than 50% of the initial sediment is lost from the system. This may be explained by a shifting of the turbidity maximum in Newark Bay. The turbidity maximum is a zone of high suspended sediment concentration located near the head of the salt intrusion (Dyer, 1997). The position of the maximum varies with river discharge, and will move further downstream in the estuary with increasing river flow (Dyer, 1997). The greater freshwater flows from the Passaic in this case will move the turbidity maximum further south in Newark Bay, where the sediment is more available to be carried out of the estuary by tidal action than during times of lower freshwater flow. Geyer et. al. (2001) observed the same processes in the Hudson River Estuary, where there was more seaward transport of sediment during freshet conditions and landward transport during times of lower freshwater flows. Castaing and Allen (1980) also observed this in the Gironde Estuary where maximum sediment escape occurred during high river flow. This case also has the most sediment remaining in Hackensack at the end of the month. This is because the larger freshwater flows from the Passaic River are compensated for by a stronger salinity intrusion along the bottom, which moves about 32% (see Figure 6.15) of the sediment upstream into the Hackensack. It is important to note here that this simplified model did not include deposition. If it had, sediment may have fallen out of suspension before reaching the points it did in this simplified model.



	Passaic (%)	Hackensack (%)	Newark Bay (%)	Kill van Kull (%)	Arthur Kill (%)	Loss from system (%)
1. tide, no salinity, no freshwater inflow	65.3	5.8	12.1	0.7	1.4	14.6
2. tide, no salinity, low freshwater inflow	6.0	16.2	45.3	2.1	3.1	27.4
3. tide, with salinity, low freshwater inflow	39.6	23.2	13.7	1.0	0.7	21.9
4. tide, with salinity, high freshwater inflow	0.3	32.0	10.5	0.6	1.3	55.4

Sediment Percentage Remaining in Each Region

Figure 6.15: Sediment Distribution at the End of Month for Synthetic Cases

In summary, under most conditions a significant amount of suspended sediment from the Passaic ends up in the Hackensack River. These results agree with the findings of Suszkowski (1978). The sediment carried there is partially due to a phase shift in the tidal currents between the two rivers, but mostly due to gravitational circulation. In order for the gravitational circulation to pick up the sediment, it must first be flushed into Newark Bay via freshwater flow. Increasing freshwater flow increases the amount of sediment that is transported into the Hackensack in two ways: one because more is flushed into Newark Bay, and two, because more freshwater flowing seaward along the surface causes a greater salinity intrusion along the bottom to compensate.

6.4 Effects of Channel Deepening

Two model runs were developed to simulate the future conditions of the Newark Bay Complex, where the depth of some shipping channels will be deepened to 50 feet. In the first case, only the shipping channels of the Kill van Kull were deepened to 50 feet, and in the second case, all shipping channels in the Newark Bay Complex were deepened to 50 feet. Though the depth of all channels will not necessarily be that great, this will provide an indication of the consequences of dredging. Since deeper channels would also allow more salinity to enter, the salinity boundary conditions were increased by 2 psu at the deepened boundaries.

Table 6.4 shows the change in the M_2 tidal constituents for both elevation and velocity over the entire time period for both the regular and deepened channel runs. There is very little difference in the elevation amplitude and phase between the original and deeper runs. A closer examination of the time series plots shows slight phase differences of less than an hour, which do not show up here since the tide analysis was performed on hourly averages of model output. The velocities at KVK1 and AK1 show greater differences between the regular and deepened channel runs. When only the Kill van Kull is deepened, only the velocity amplitude in the Kill van Kull is affected, decreasing by about 7%. When all the channels are deepened, the velocity amplitudes at KVK1 and NB1 both decrease, by about 8% and 20%, respectively. The velocity at AK1 does not change. The phase does not change significantly at any station due to any type of deepening, and the relative phase between the stations remains the same.

Figure 6.16 shows the monthly tidal flux on the flood tides for the regular case and the two deepened cases. The flux in Newark Bay does not change significantly (less than about 1%) for any case as expected, since the elevation does not change. In the Arthur Kill, the flux decreases from the regular run when only the Kill van Kull is deepened, with an overall decrease of about 7% in flux for the year. Flux in the Arthur Kill increases from the regular run when all of the channels are deepened by about 17 % for the entire year. In the Kill van Kull, the flux increases from the regular run by about 4% when only the Kill van Kull is deepened. It also increases when all the channels are dredged, though only by about 2 %. Changes in flux on the ebb tide are similar. Since both

	M_2 (η original)			M_2 (η KVK deep)			M_2 (η all deep)		
	amp. (m)	**phase (deg)**	**phase (hours)**	**amp. (m)**	**phase (deg)**	**phase (hours)**	**amp. (m)**	**phase (deg)**	**phase (hours)**
PA	0.70	7.3	0.3	0.70	7.1	0.2	0.70	8.1	0.3
AK1	0.70	13.8	0.5	0.70	12.9	0.4	0.70	12.8	0.4
KVK1	0.68	14.2	0.5	0.67	13.4	0.5	0.67	13.3	0.5
NB1	0.71	17.5	0.6	0.71	16.5	0.6	0.71	15.6	0.5
	M_2(v_{along} original)			M_2(v_{along} KVK deep)			M_2(v_{along} all deep)		
	amp. (m/s)	**phase (deg)**	**phase (hours)**	**amp. (m/s)**	**phase (deg)**	**phase (hours)**	**amp. (m/s)**	**phase (deg)**	**phase (hours)**
AK1	0.28	354.5	12.2	0.27	3.4	0.1	0.28	0.1	0
KVK1	0.62	277.6	9.6	0.58	277.4	9.6	0.57	272.8	9.4
NB1	0.30	301.1	10.4	0.30	299.6	10.3	0.24	298.0	10.3

Table 6.6: Change in M_2 Tide Constituents As a Result of Channel Deepening

flux in the Arthur Kill and in the Kill van Kull are increasing, with no significant change in the flux in Newark Bay, there is more flow-through in the Kills when the channels are deepened when the velocities in the Kills are out of phase.

Changes in bathymetry also affect the percentage of total flux delivered to Newark Bay by the Kill van Kull and the Arthur Kill. In the original run, the Arthur Kill contributes about 22% of the flood tide, while the Kill van Kull contributes 78% over the entire run. If the Kill van Kull is deepened, the percentage contributed by the Kill van Kull increases to about 80%, dropping the Arthur Kill contribution to 20%. When all the channels are deepened, the contribution of the Arthur Kill increases to about 24%, while the contribution of the Kill van Kull decreases to about 76%.

When all channels are deepened, both tidal flux and the cross-sectional area in the Kill van Kull are greater than in the original case, but tidal velocity decreases, so over time the mass of water entering (or leaving) Newark Bay remains similar to the original mass. In the Arthur Kill, flow and cross-sectional area increase while velocity remains constant, so the actual mass of water entering Newark Bay through the Arthur Kill increases. When only the channels in the Kill van Kull are deepened, the flux through the Kill van Kull still increases, but by a slightly larger percentage, and the velocity decreases in a fashion similar to the other case. Since more flux is permitted through the Kill van Kull, and since the Kill van Kull leads the Arthur Kill in tidal currents by about three

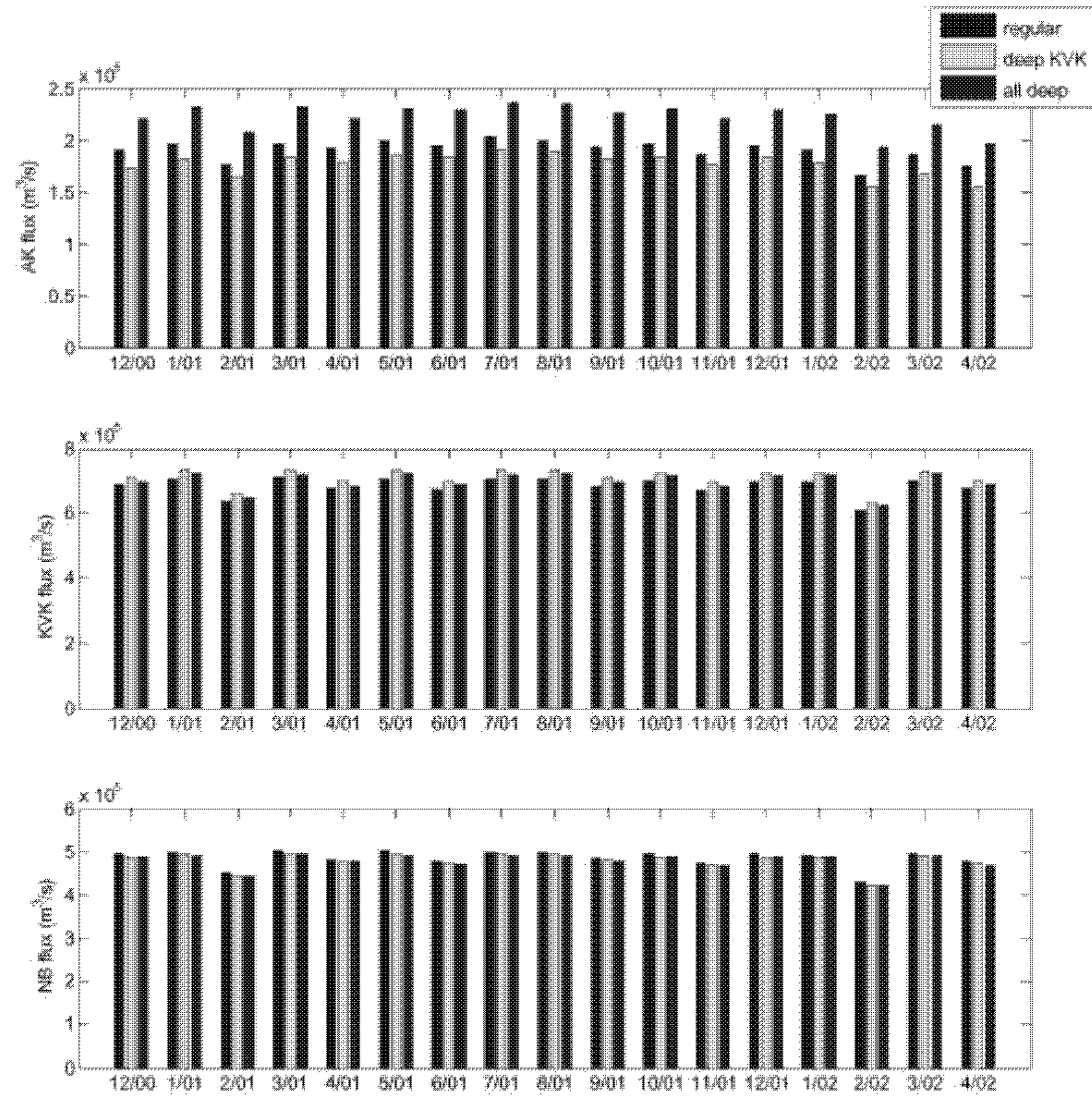


Figure 6.16: Tidal Flux Comparison for Flood Tide

hours, less mass is needed from the Arthur Kill to fill Newark Bay.

Tidal changes due to channel deepening are important, but changes in the low-passed portion of flow in the system can also be significant. Figure 6.17 shows the the time series of low-passed flux at NB1, AK1, and KVK1 for May 2001 for all cases. Though the flux magnitude in the Arthur Kill and the Kill van Kull change, the directions appeared unaffected. An EOF analysis similar to the one discussed in Section 6.2 was performed on both sets of the deepened channel runs, and verified that the direction and frequency of the modes remained the same, with only the magnitude of the fluxes changing. This is significant because it could cause Newark Bay to be flushed more thoroughly during one of these events, or to fill more quickly, having an effect on the episodic transport of sediments.

Deeper channels in the Kill van Kull and the Arthur Kill will likely allow more salinity to intrude along the bottom. In the case of deepening on the Kill van Kull, the salinity will only intrude to the inner boundary of the Kill van Kull, where the deepening stops. In the case of dredging all channels, the salinity can intrude much further. A change of 2 psu at the boundary translates to a change in salinity of about 2 psu at the NB1 station. The effects of the greater intrusion of salinity can be seen in Figure 6.18, which shows the distribution of bottom salinity (psu) in May 2001 for the regular run, and the run with all channels deepened.

Deepening various channels in Newark Bay has a marked effect on the fluxes and velocities throughout the system, which will in turn affect sediment transport. If the channels in Kill van Kull are deepened more significantly than Arthur Kill, the lowered flux in the Arthur Kill would cause the AK to flush even more slowly. This may need to be taken into account when determining the order of dredging operations in the system. Also, the increased tidal flux in the Kills when both are deepened creates the possibility of bringing more sediment in from the Upper Harbor and Raritan Bay, or out from Newark Bay into these bodies of water. The magnitude of flux moving through the Kills is also greater during the episodic events. These increases are not only important to the quantity of sediment, but to the quality of sediment that is deposited in both regions. Lower velocities in Newark Bay as a result of deepening all channels may have an effect on keeping sediment

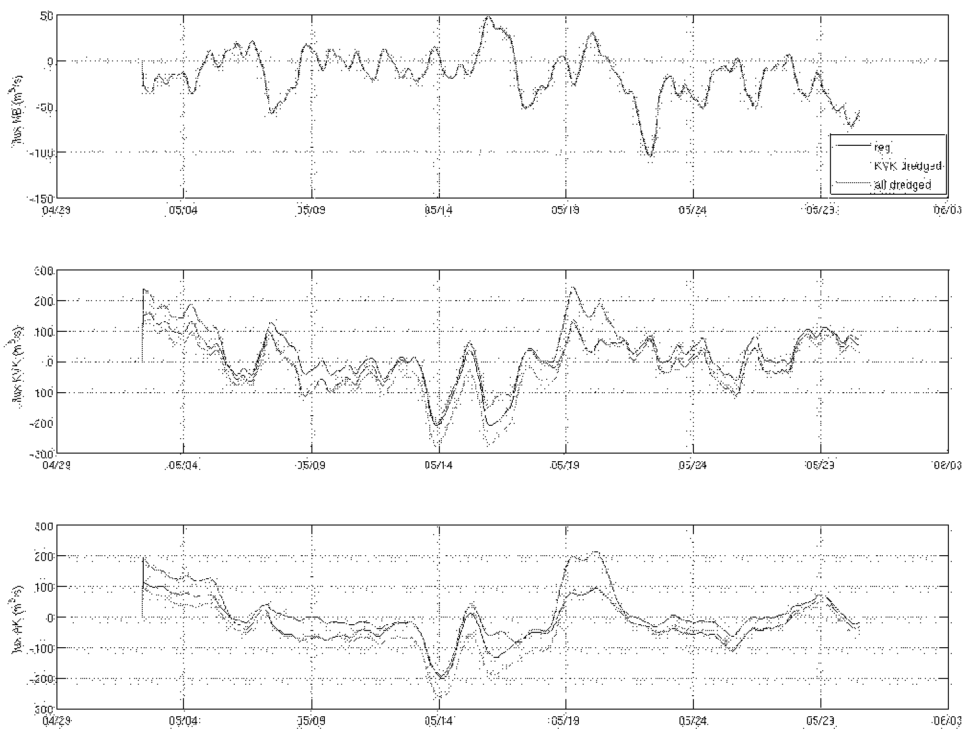
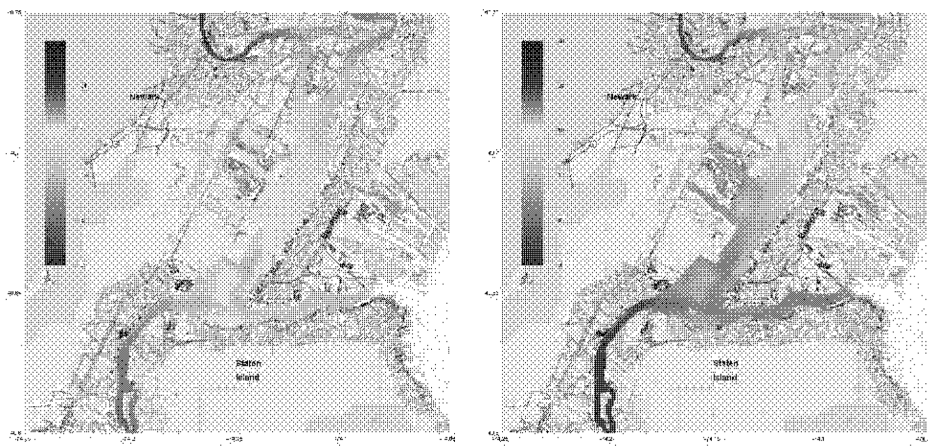


Figure 6.17: Low-pass Flux Comparison of Regular and Deepened Channel Runs May 2001



(a) Regular (b) All Channels Deepened

Figure 6.18: Bottom Salinity May 2001 (psu)

in suspension. More sediment may fall out of suspension in this area, and the lower tidal velocities will also pick up less sediment from the bottom to be transported to other areas. Finally, greater salt intrusion into the system due to deepening all channels could trap more sediment in the system due to gravitational circulation.

Chapter 7

Conclusions

The analysis of a very comprehensive hydrodynamic data set and results from a well calibrated three-dimensional circulation model have revealed the Newark Bay system to be highly complex, with many outside forces affecting and disrupting the expected tidal flow patterns in the system. One of the greatest accomplishments of this work has been the development of the high-resolution hydrodynamic model of the area with its ability to replicate the data. This tool has proven itself to be useful in filling the temporal and spatial gaps in the data, as well as in isolating the different forcing mechanisms and providing the ability to investigate the effects of changes in the system.

Using both the model and data, strong wind events were shown to create large episodic flushing events for the time period studied, described mostly as "flow-through" events. Most of these events are driven by a west (or east) wind which forces water out of (or into) Newark Bay out (or in) through the Kill van Kull, with a weak flow in (or out) through the Arthur Kill. Extreme and persistent winds from the west can cause the Arthur Kill to be the filling/emptying conduit instead, but these events are exceptional and only appeared in December 2000. Other events, though not as prevalent, are a result of north-south wind affecting the Arthur Kill locally, causing a north-south flux. All of these episodic events disrupt the expected patterns of tidal circulation, and play an important role in determining the fate and transport of contaminants.

Gravitational circulation played a big part in determining the fate of suspended sediment in the Passaic River. Higher river flows caused a greater percentage of sediment to be flushed from the system entirely by keeping sediment in suspension, while lesser river flows brought sediment into the bottom layers of Newark Bay where most of it was transported into the Hackensack River via gravitational circulation. Under most conditions, the Hackensack River seemed to act as a sink for suspended sediment in the Passaic River.

Deepening the shipping channels had an effect on tidal velocities and fluxes, as well as the longer term flushing events. Deeper channels throughout the system allow greater flows through the Kills, both tidally and due to meteorological events, which creates the possibility of bringing more sediment in from the Upper Harbor and Raritan Bay, or out from Newark Bay into these bodies of water. The deepening of the channels also caused the tidal velocities in Newark Bay to be lower, which may allow more sediment to fall out of suspension, as well as prevent new sediment from being scoured off the bottom. Greater salt intrusion into the system due to deepening of the channels at the boundaries could also trap more sediment in the system due to gravitational circulation.

Results from this study support findings from previous studies of this area. Analysis of the model output and data from this study showed that wind from the north could have a local effect on the Arthur Kill, creating a set-down at Perth Amboy and driving water out of Newark Bay, which followed with the results of Thomas (1993). Strong wind events were shown to create large episodic flushing events in the Newark Bay Complex for the time period studied which followed with the findings of Chant (2002) and Rankin (2002).

This study was the most comprehensive in the Newark Bay Complex, with the longest data set. This data set made it possible to evaluate the longer-term effects of tides, wind, freshwater inflow on the transport patterns of suspended sediments and the chemicals of concern within all estuarine areas of the Complex. This study also made it possible to create a dependable hydrodynamic model of the Newark Bay Complex, and in more detail than previous models of the area.

Chapter 8

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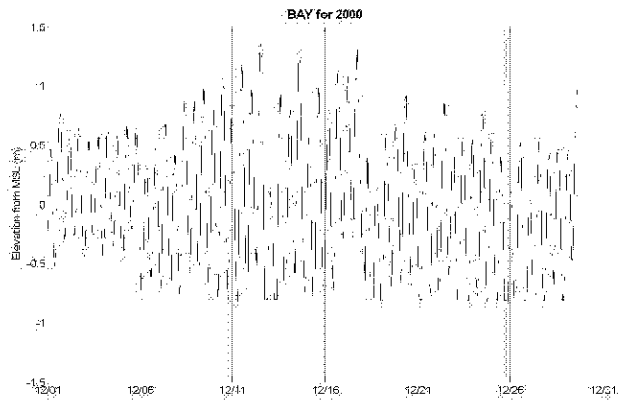
Appendix A

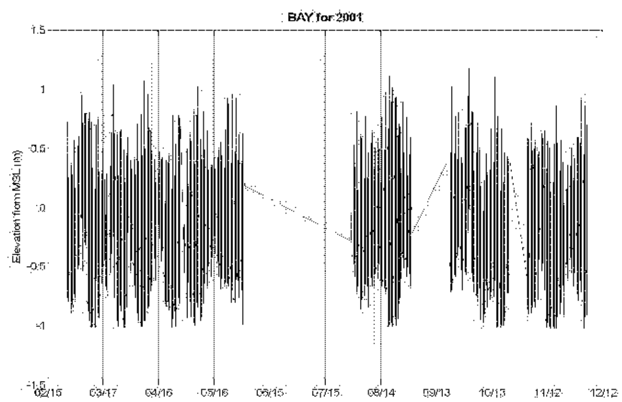
Water Level Data

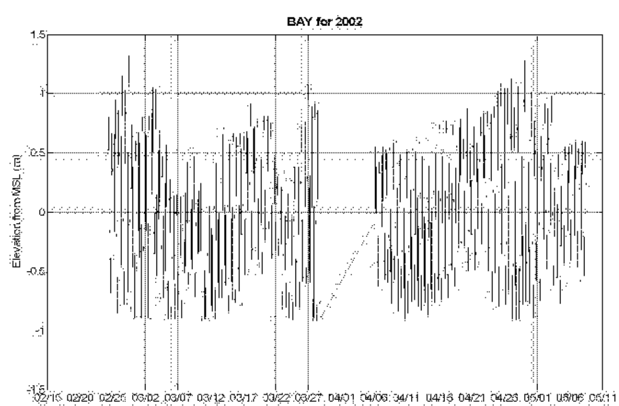
Appendix A Key

Bergen Point - BP (40° 38.4'N, 74° 8.8'W)
Passaic Valley Sewerage Commission -PVSC (40° 43'N, 74° 8'W)
Constable Hook in Bayonne - BAY (40° 40.2'N, 74° 4.2'W)
Perth Amboy Yacht Club PAYC (40° 30'N, 74° 15'W)
Hackensack River -HACK (N/A)
Perth Amboy - PA (40° 30.6'N, 74° 15.6'W)
North end of the Arthur Kill -AK1 (40° 37.8'N, 74° 12'W)
Western end of the Kill van Kull -KVK1 (40° 38.4'N, 74°7.5'W)
North end of Newark Bay -NB1(40° 42'N, 74° 7.2'W)
South end of Newark Bay -NB3 (40° 40'N, 74° 8.4'W)
Raritan River - RR (40° 24'N, 74° 18'W)

All times are GMT







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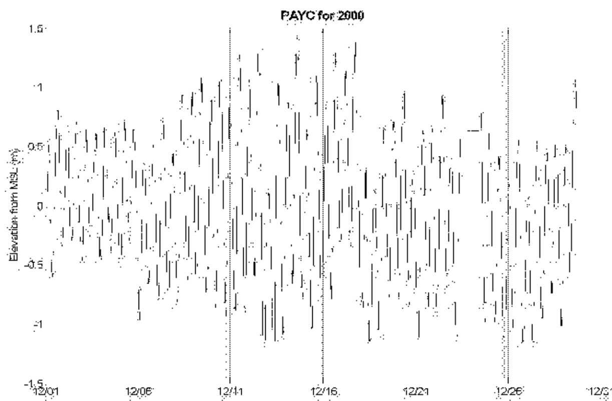
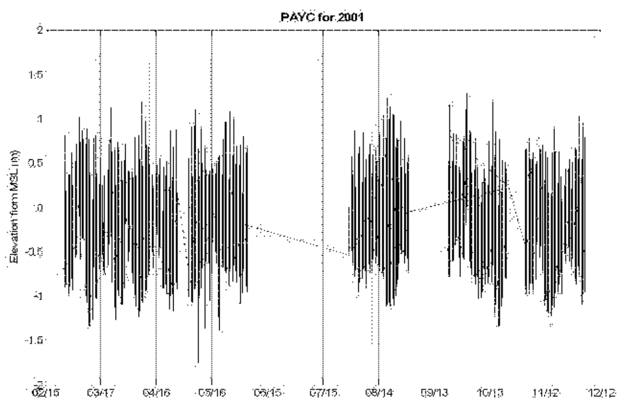
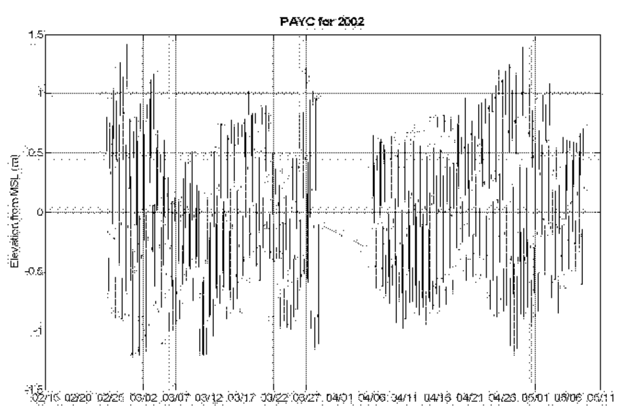

PAYC for 2000
Elevation from MSL (m)
12/01
12/06
12/11
12/16
12/21
12/26
12/31


PAYC for 2001
Elevation from MSL (m)
02/15
03/17
04/16
05/16
06/15
07/15
08/14
09/13
10/13
11/12
12/12


PAYC for 2002
Elevation from MSL (m)
02/15
02/20
02/25
03/02
03/07
03/12
03/17
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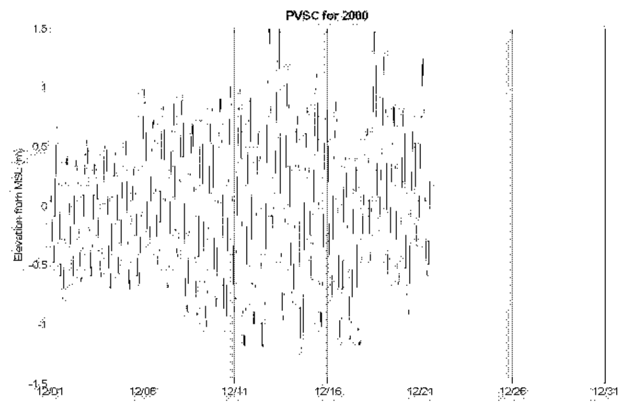
05/01
05/06
05/11


PVSC for 2000
Elevation from MSL (m)
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0.5
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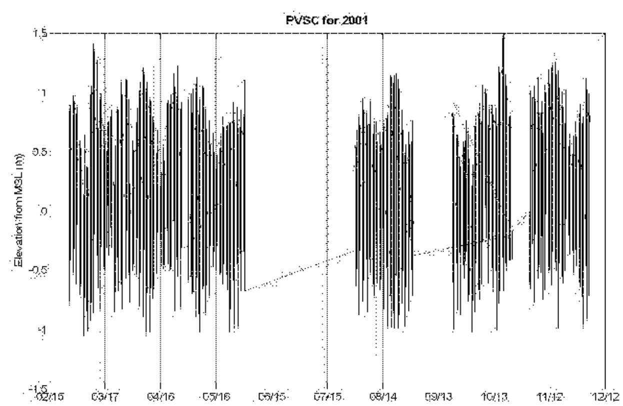
-0.5
-1
-1.5
12/01
12/06
12/11
12/16
12/21
12/26
12/31


PVSC for 2001
Elevation from MSL (m)
1.5
1
0.5
0
-0.5
-1
-1.5
02/15
03/17
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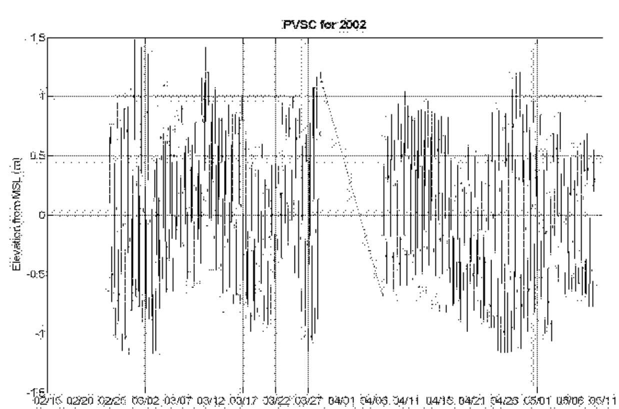
10/13
11/12
12/12


PVSC for 2002
Elevation from MSL (m)
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1
0.5
0
-0.5
-1
-1.5
02/15
02/20
02/25
03/02
03/07
03/12
03/17
03/22
03/27
04/01
04/06
04/11
04/16
04/21
04/26
05/01
05/06
05/11

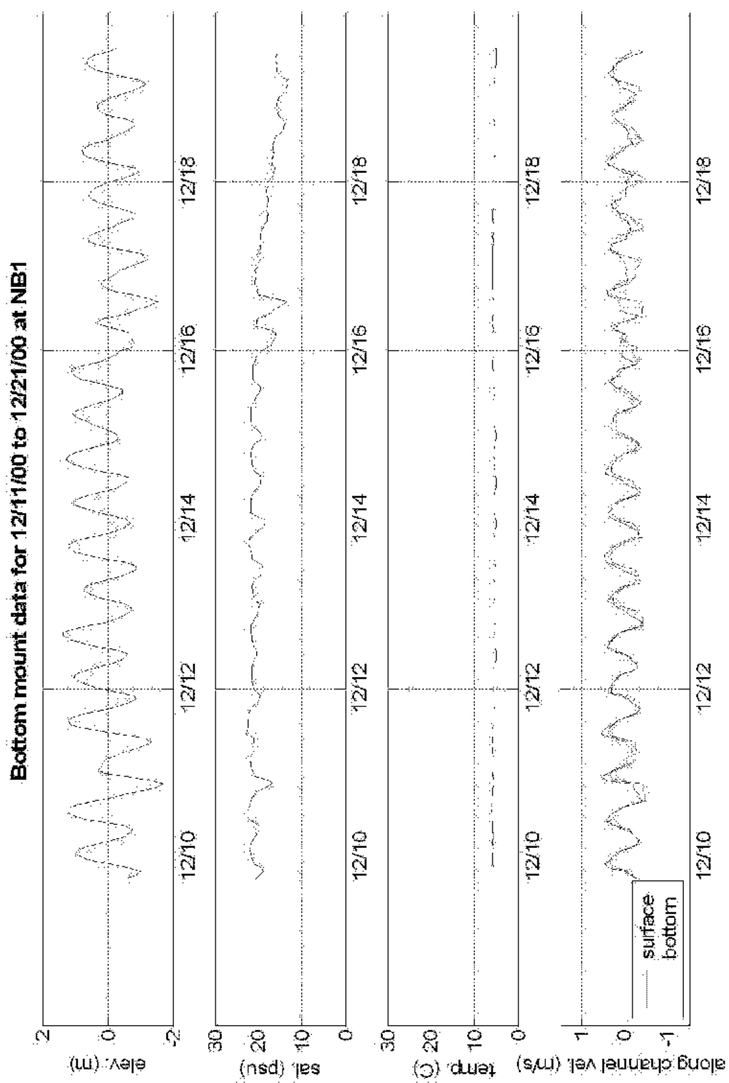
Appendix B

Bottom Mount Data

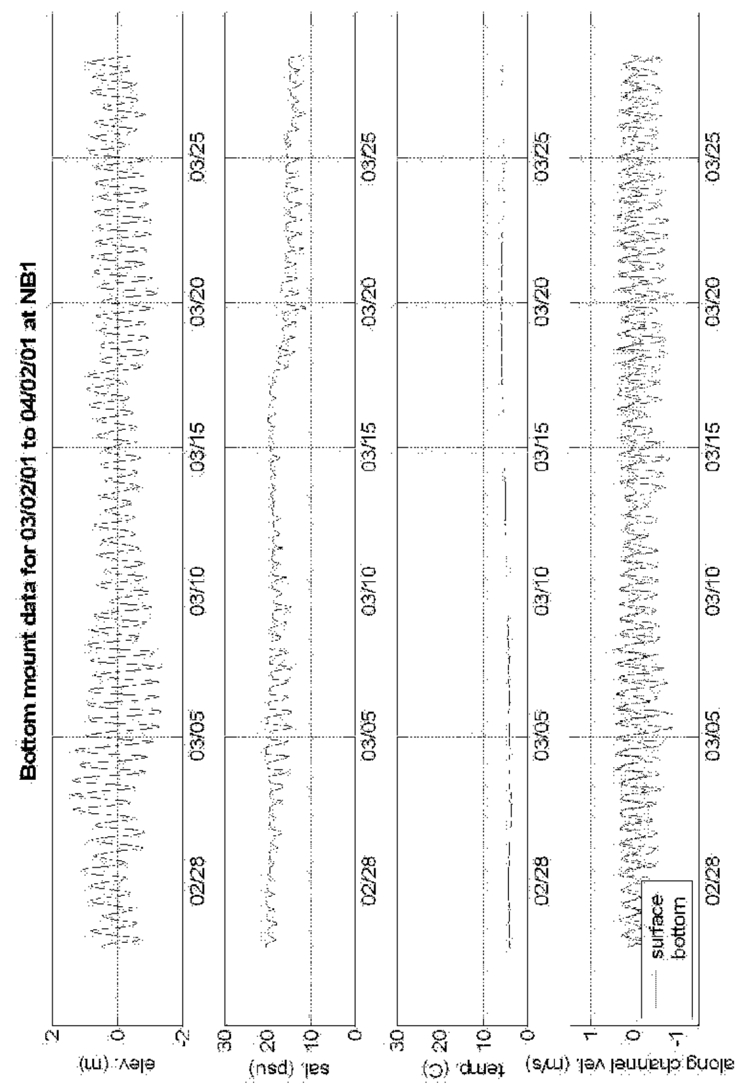
Appendix B Key

Bergen Point - BP (40° 38.4'N, 74° 8.8'W)
Passaic Valley Sewerage Commission -PVSC (40° 43'N, 74° 8'W)
Constable Hook in Bayonne - BAY (40° 40.2'N, 74° 4.2'W)
Perth Amboy Yacht Club PAYC (40° 30'N, 74° 15'W)
Hackensack River -HACK (N/A)
Perth Amboy - PA (40° 30.6'N, 74° 15.6'W)
North end of the Arthur Kill -AK1 (40° 37.8'N, 74° 12'W)
Western end of the Kill van Kull -KVK1 (40° 38.4'N, 74°7.5'W)
North end of Newark Bay -NB1(40° 42'N, 74° 7.2'W)
South end of Newark Bay -NB3 (40° 40'N, 74° 8.4'W)
Raritan River - RR (40° 24'N, 74° 18'W)

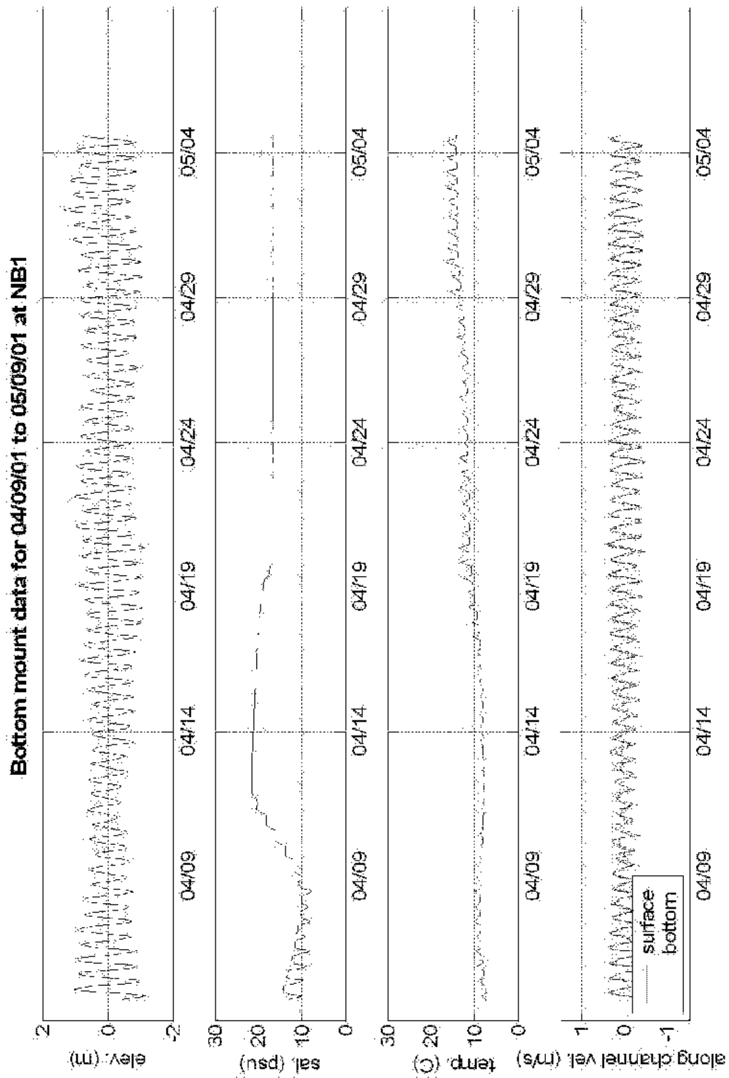
All times are in GMT.



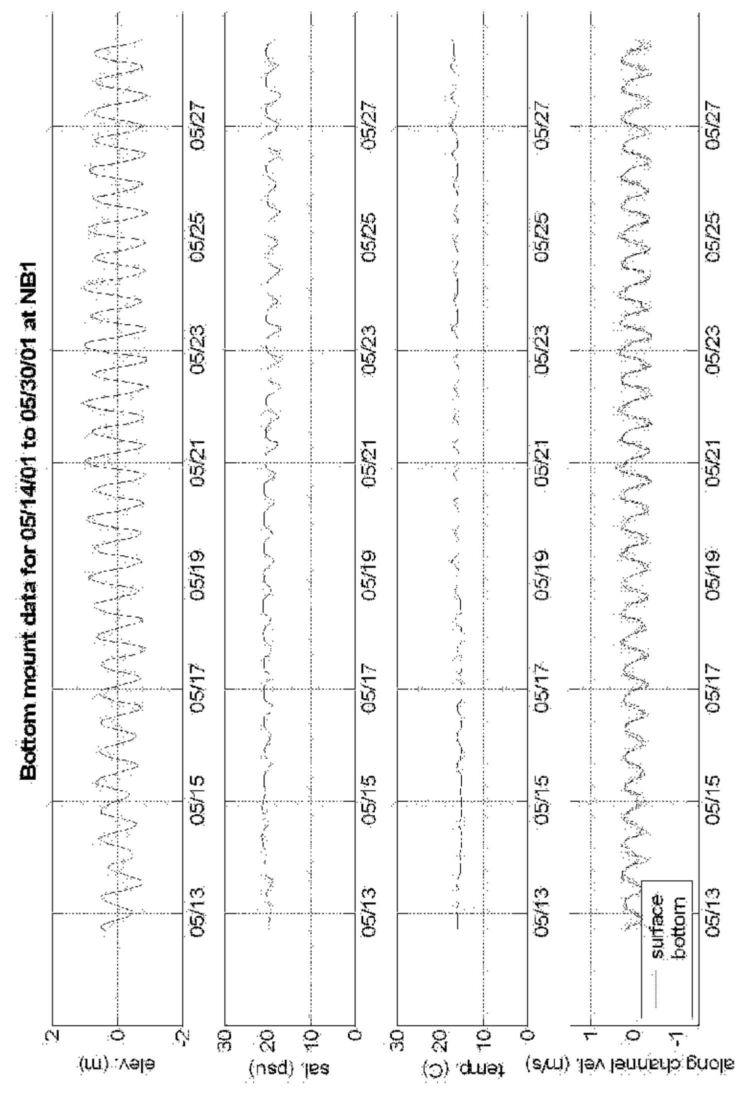
Note: Bottom velocity is measured 1.9 m from bottom and surface velocity is measured 8.4 m from bottom



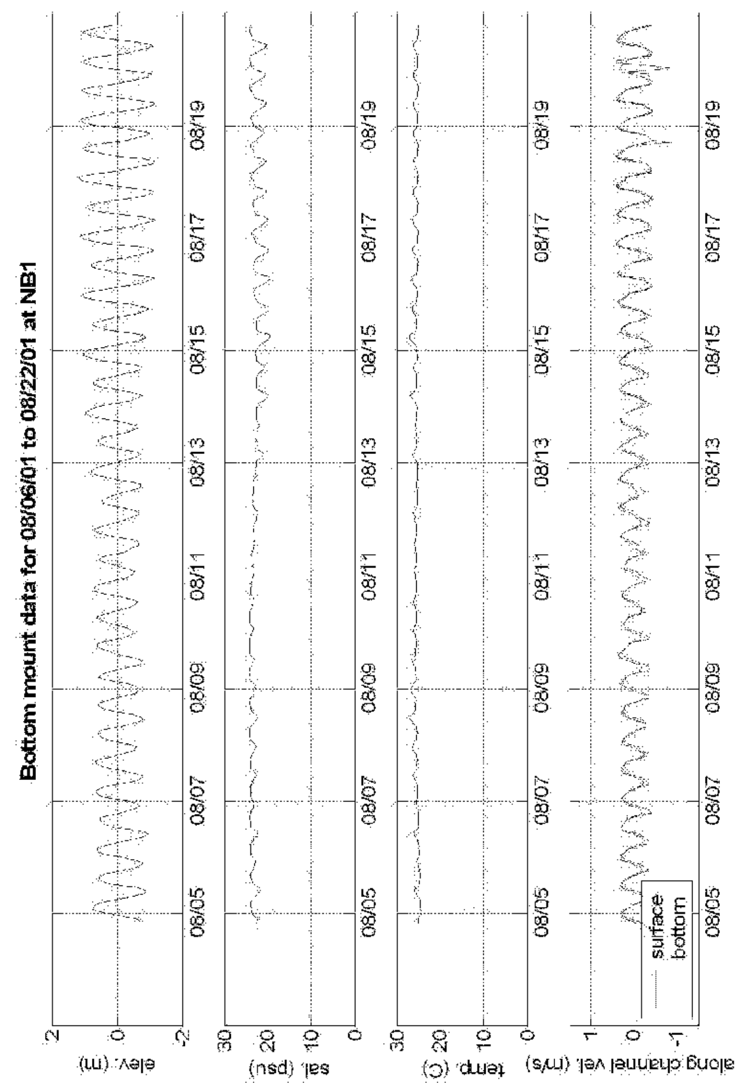
Note: Bottom velocity is measured 1.9 m from bottom and surface velocity is measured 8.4 m from bottom



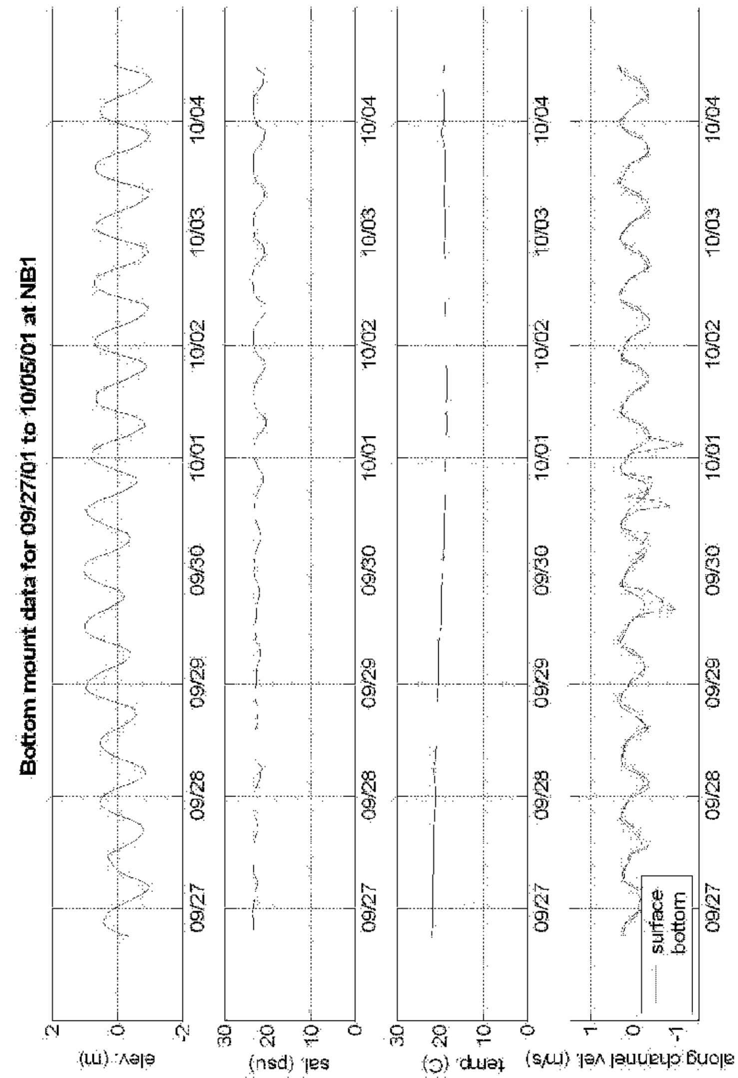
Note: Bottom velocity is measured 1.9 m from bottom and surface velocity is measured 8.4 m from bottom



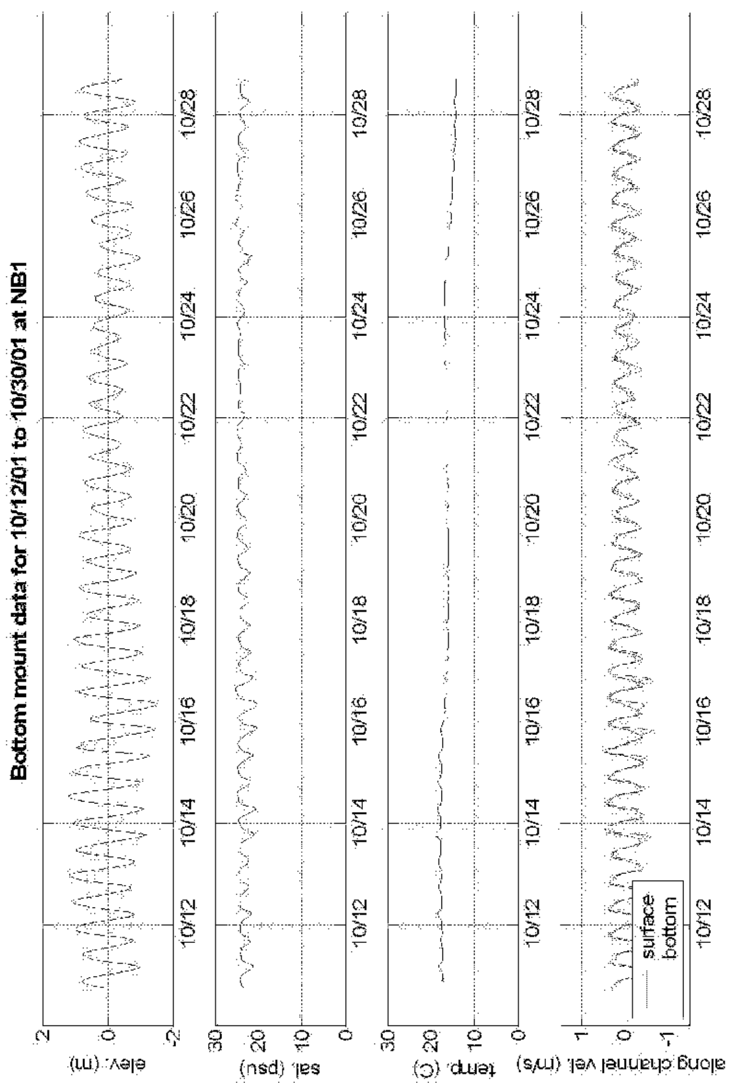
Note: Bottom velocity is measured 1.9 m from bottom and surface velocity is measured 8.4 m from bottom



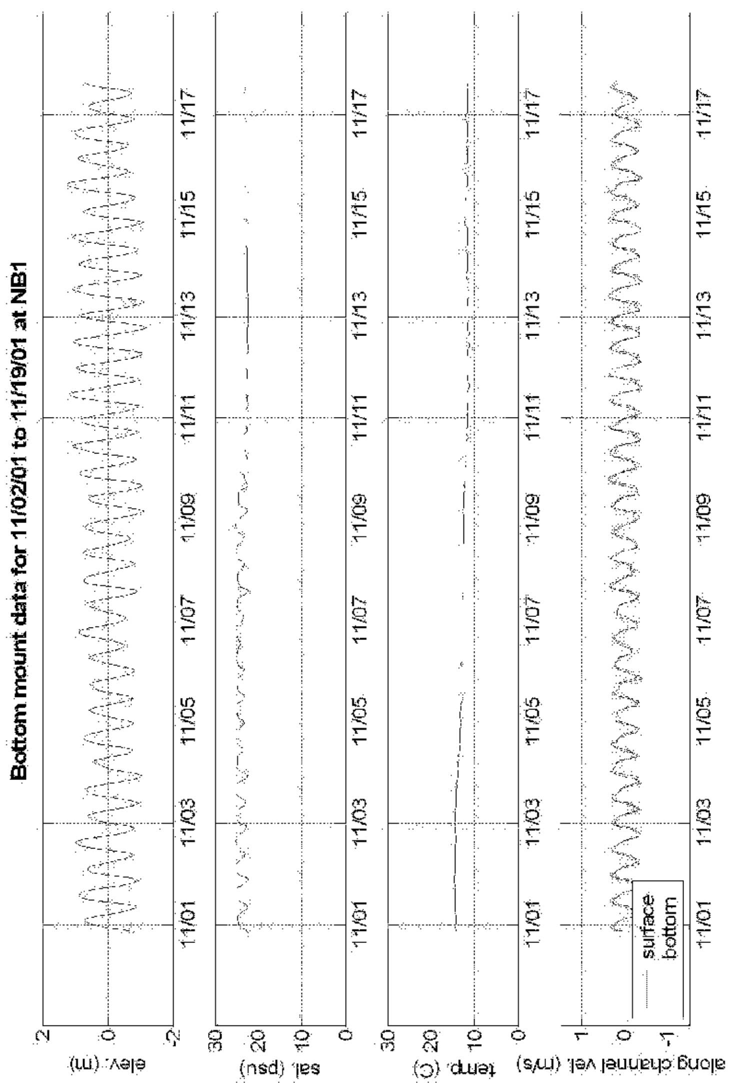
Note: Bottom velocity is measured 1.9 m from bottom and surface velocity is measured 8.4 m from bottom



Note: Bottom velocity is measured 1.9 m from bottom and surface velocity is measured 8.4 m from bottom

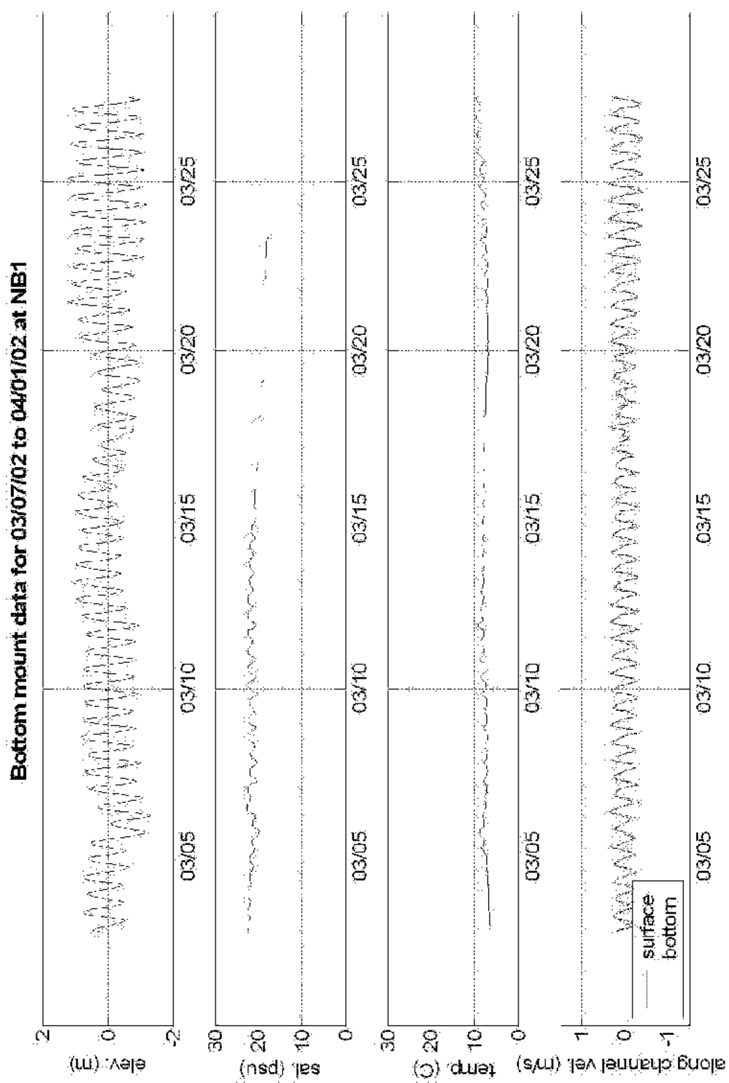


Note: Bottom velocity is measured 1.9 m from bottom and surface velocity is measured 8.4 m from bottom

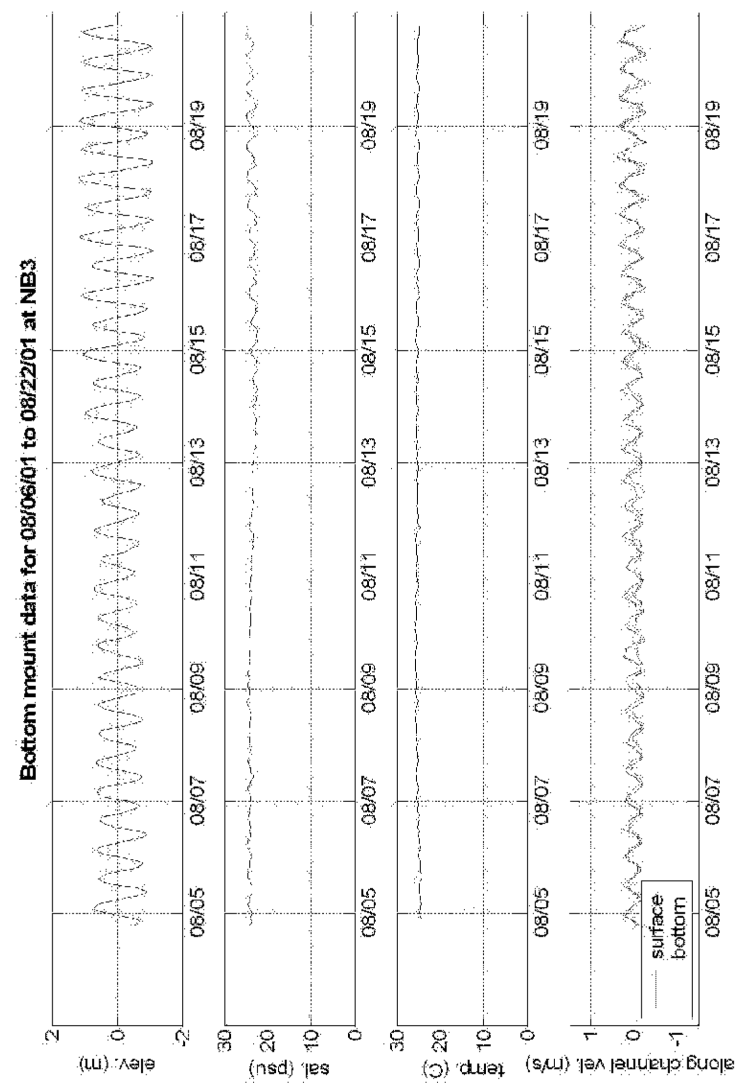


Note: Bottom velocity is measured 1.9 m from bottom and surface velocity is measured 8.4 m from bottom

NJDEP00015930



Note: Bottom velocity is measured 1.9 m from bottom and surface velocity is measured 8.4 m from bottom



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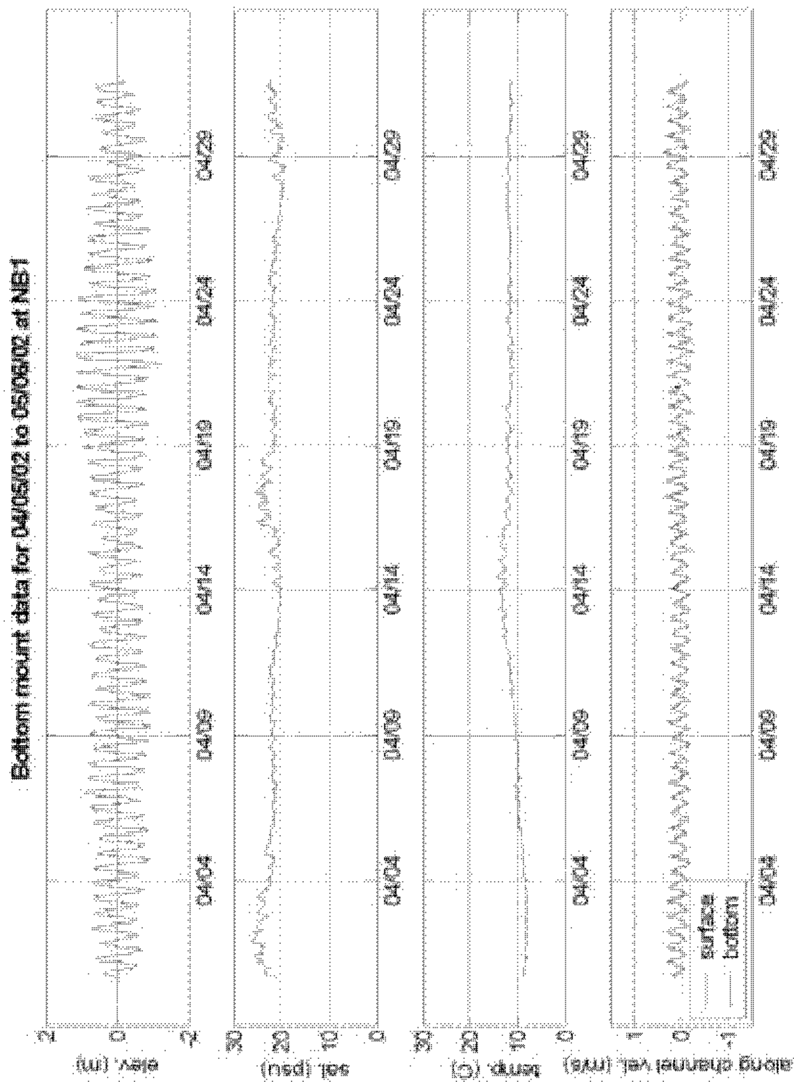
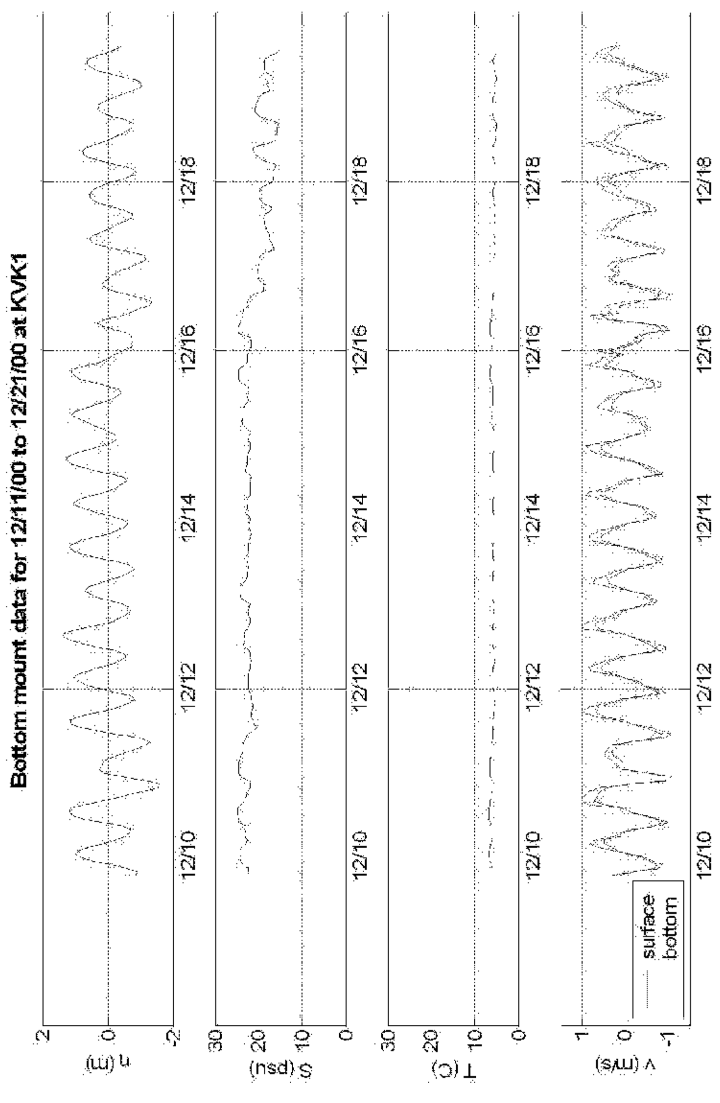
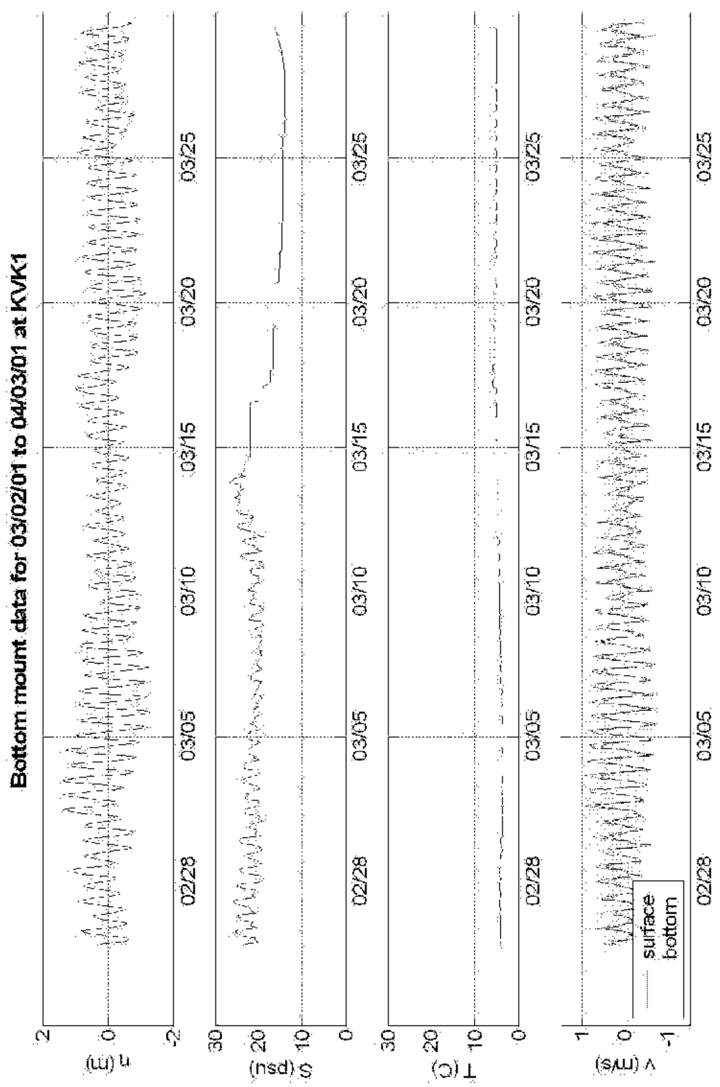


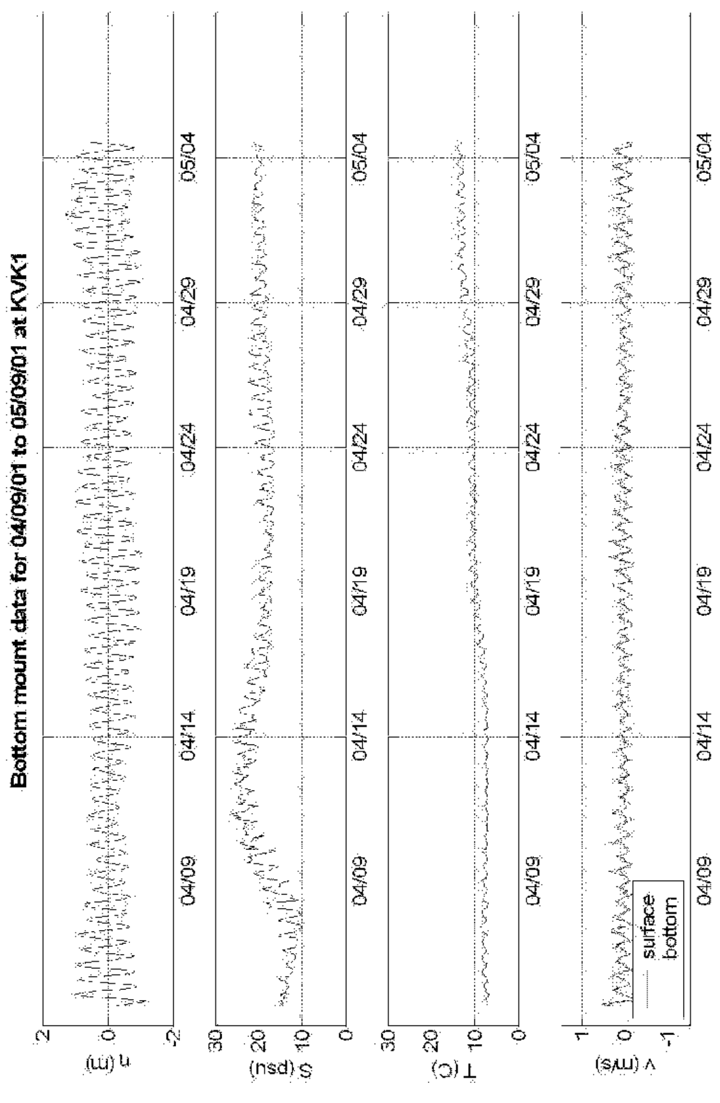
Note: Bottom velocity is measured 1.9 m from bottom and surface velocity is measured 8.4 m from bottom



Note: Bottom velocity is measured 1.9 m from bottom and surface velocity is measured 10.9 m from bottom

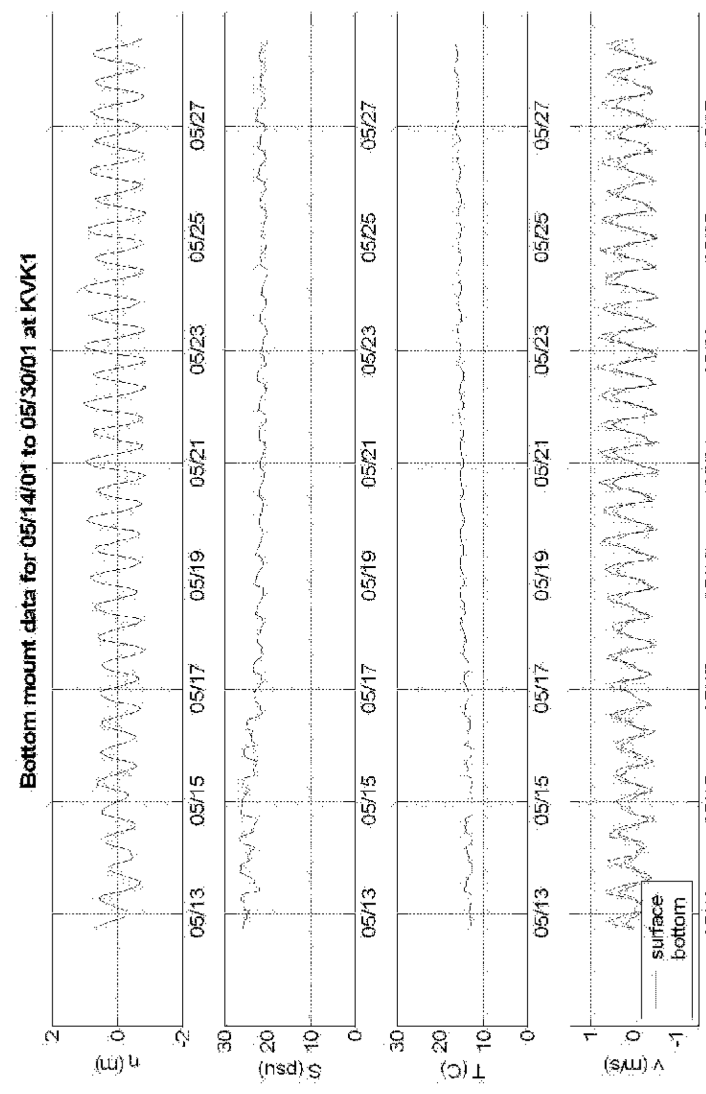


Note: Bottom velocity is measured 1.9 m from bottom and surface velocity is measured 10.9 m from bottom



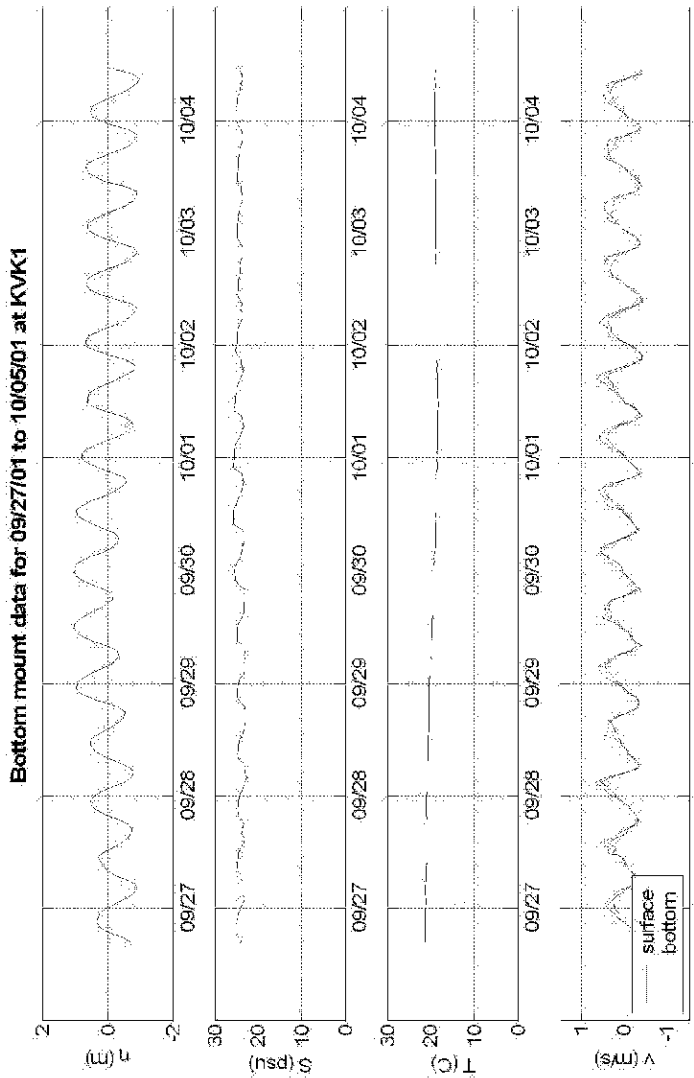
Note: Bottom velocity is measured 1.9 m from bottom and surface velocity is measured 10.9 m from bottom

NJDEP00015936

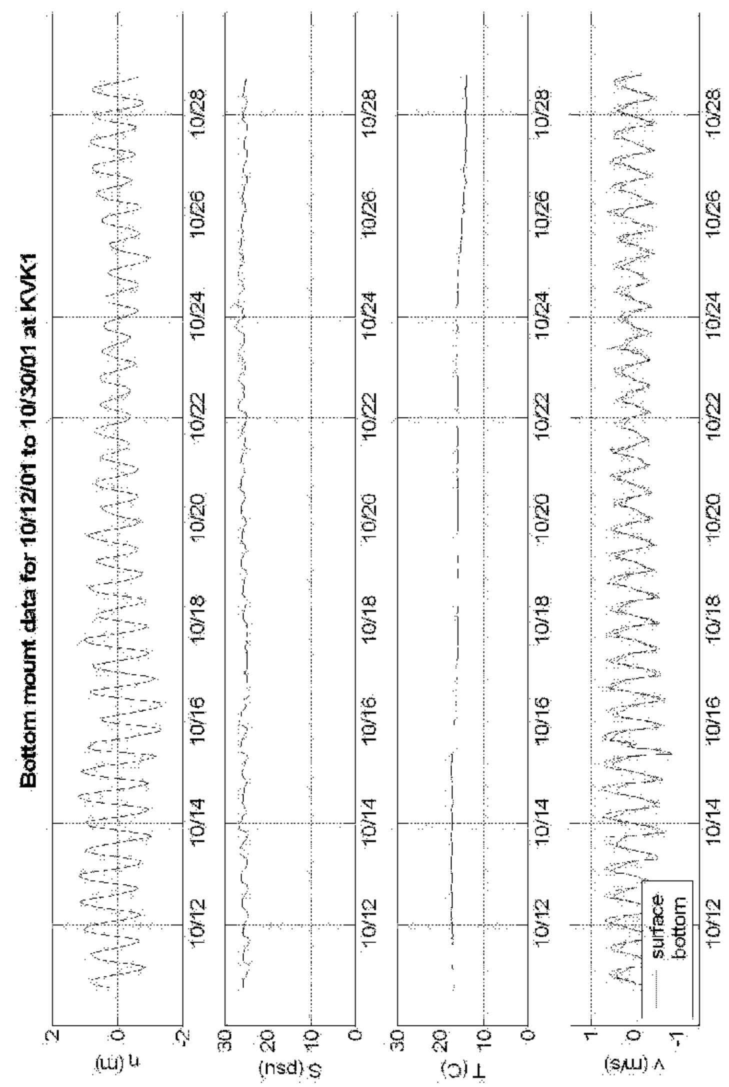


Note: Bottom velocity is measured 1.9 m from bottom and surface velocity is measured 10.9 m from bottom

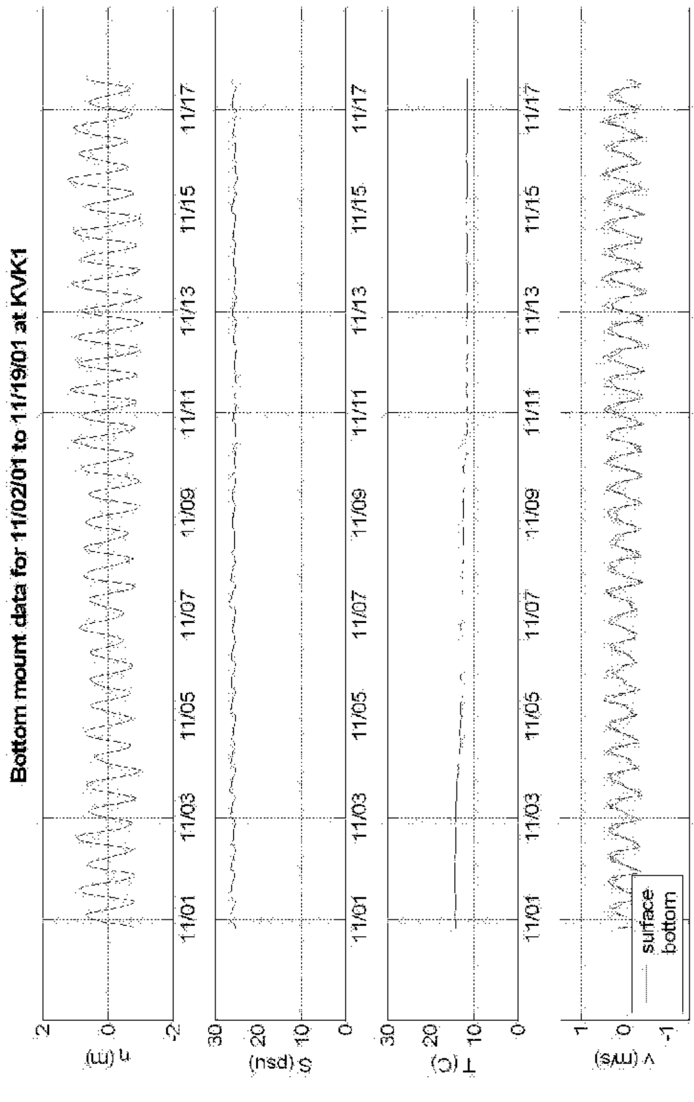
NJDEP00015937



Note: Bottom velocity is measured 1.9 m from bottom and surface velocity is measured 10.9 m from bottom



Note: Bottom velocity is measured 1.9 m from bottom and surface velocity is measured 10.9 m from bottom



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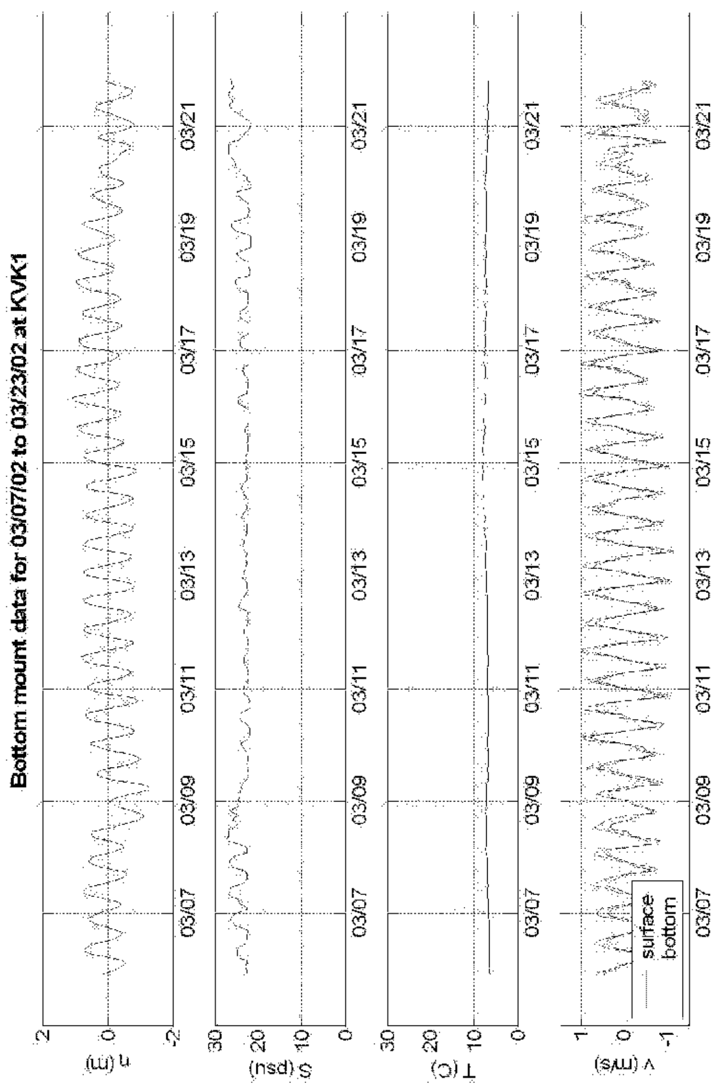
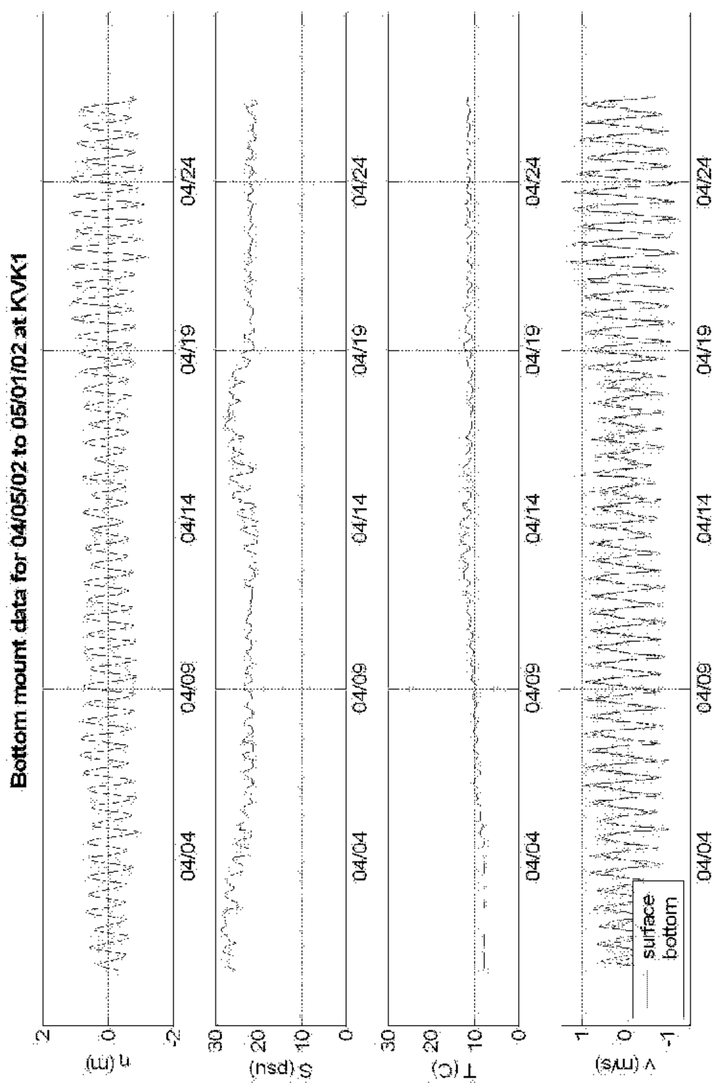
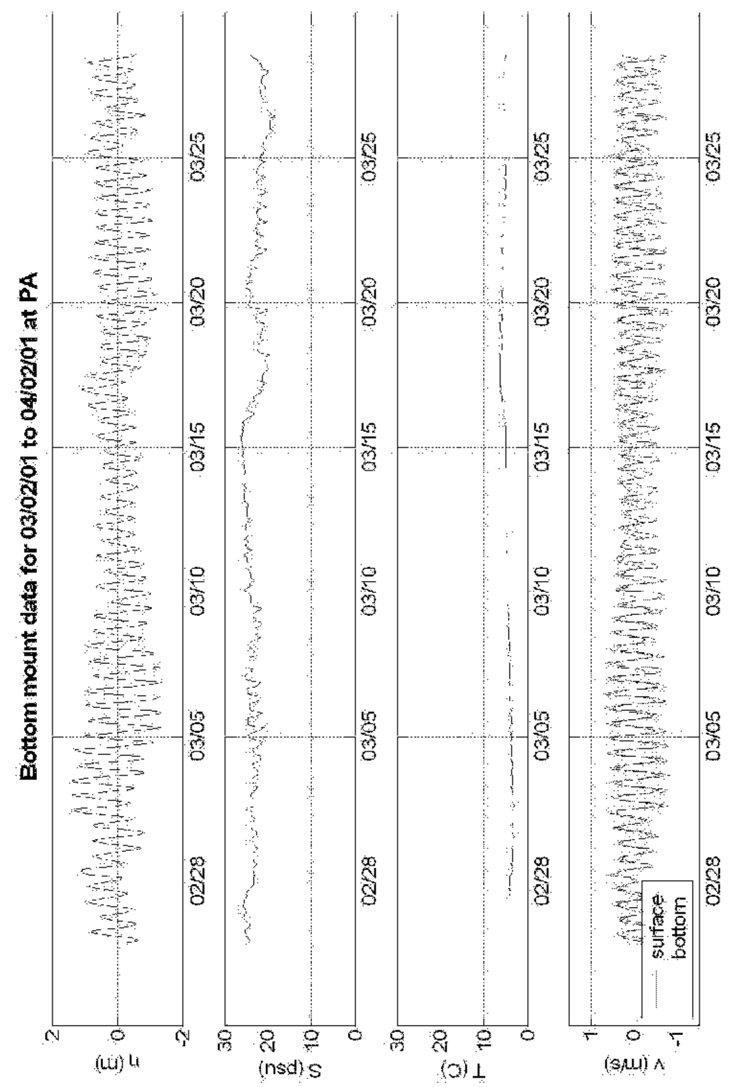


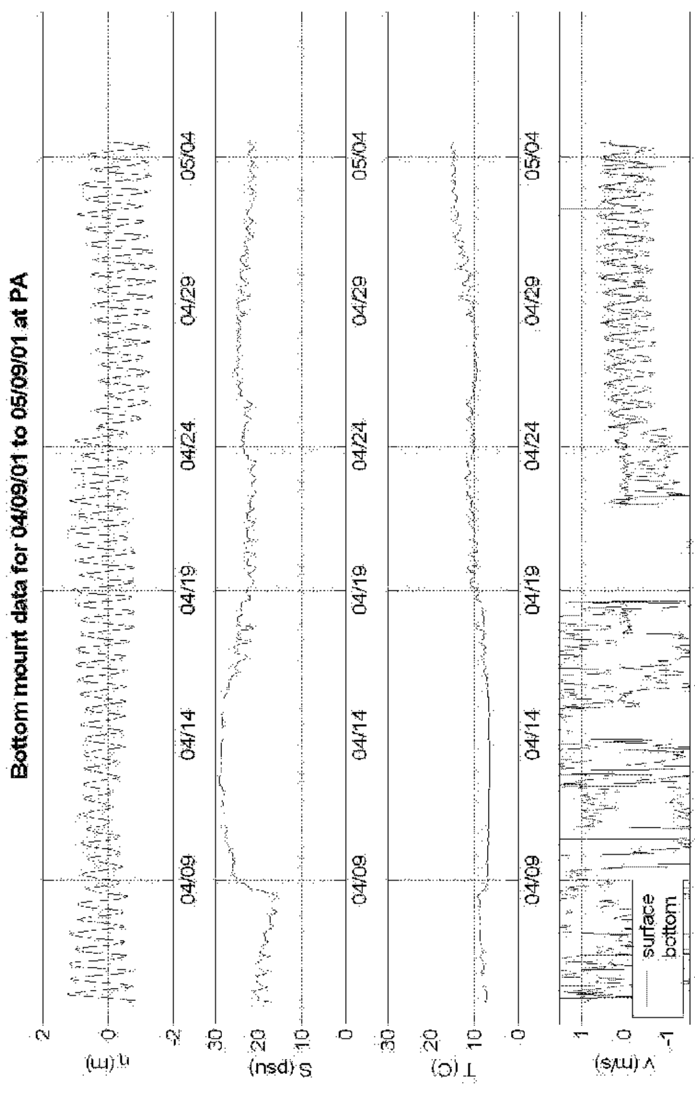
Note: Bottom velocity is measured 1.9 m from bottom and surface velocity is measured 10.9 m from bottom



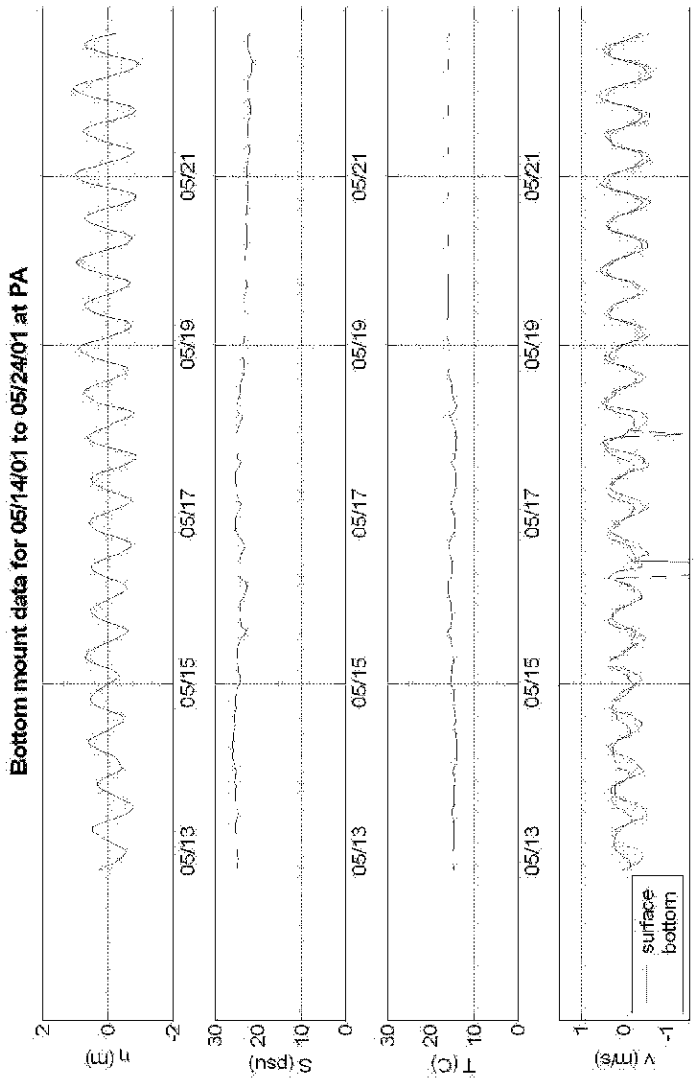
Note: Bottom velocity is measured 1.9 m from bottom and surface velocity is measured 10.9 m from bottom



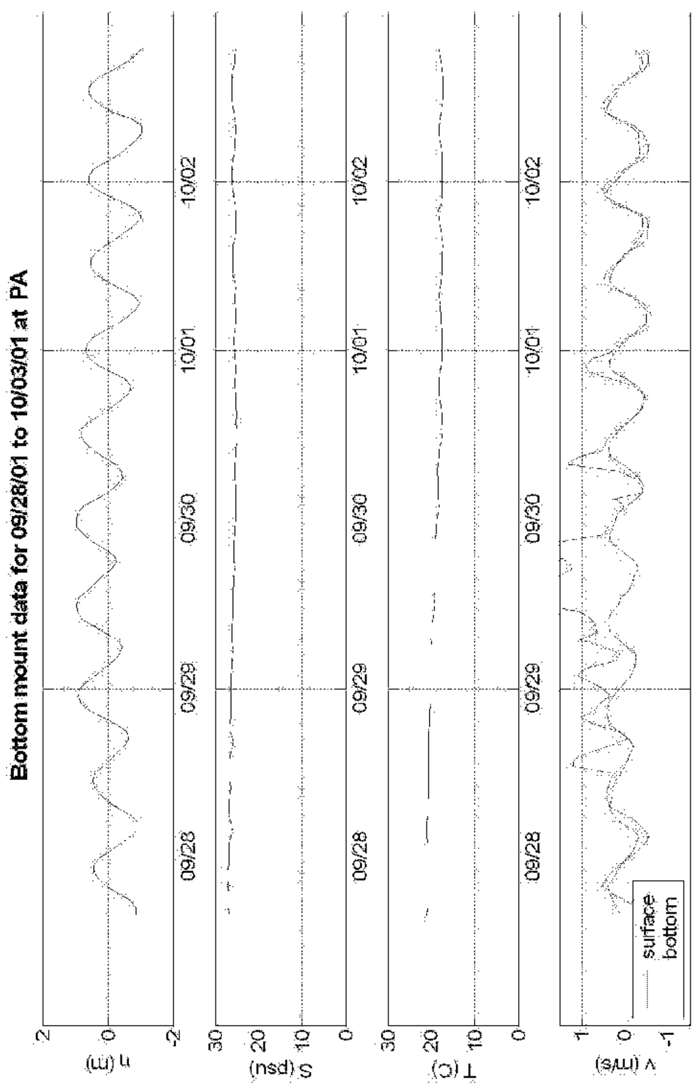
Note: Bottom velocity is measured 1.9 m from bottom and surface velocity is measured 10.9 m from bottom



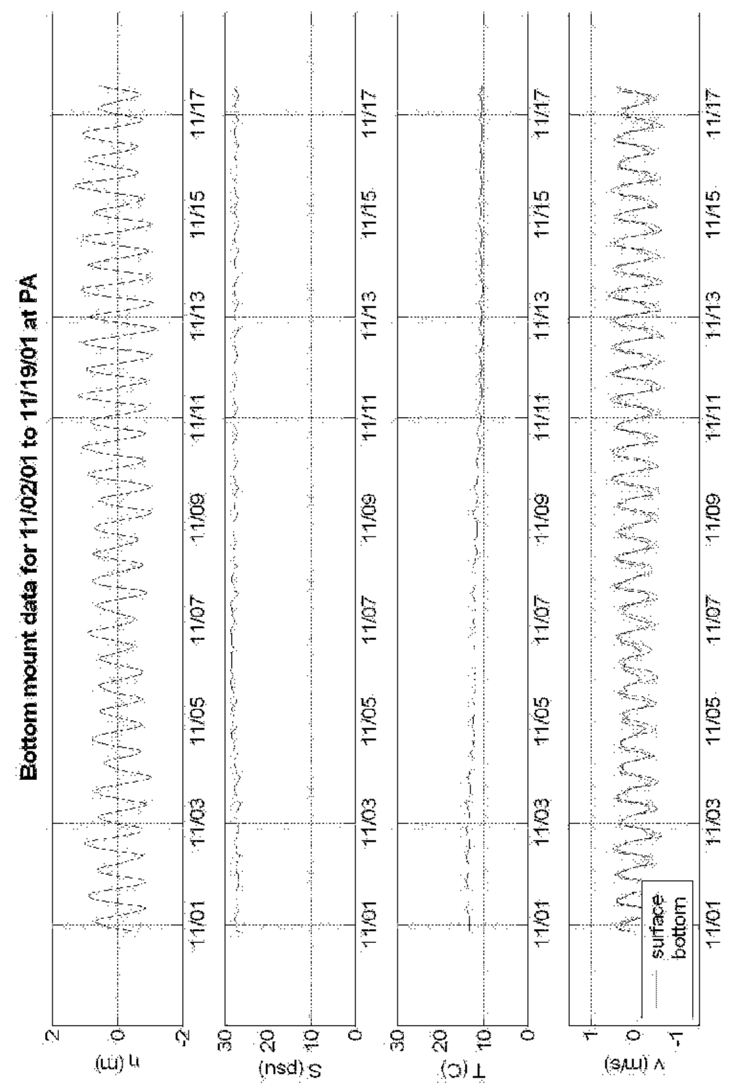
Note: Bottom velocity is measured 1.9 m from bottom and surface velocity is measured 10.9 m from bottom. Data is incorrect until about April, 25, 2001 due to rolling of instrument.



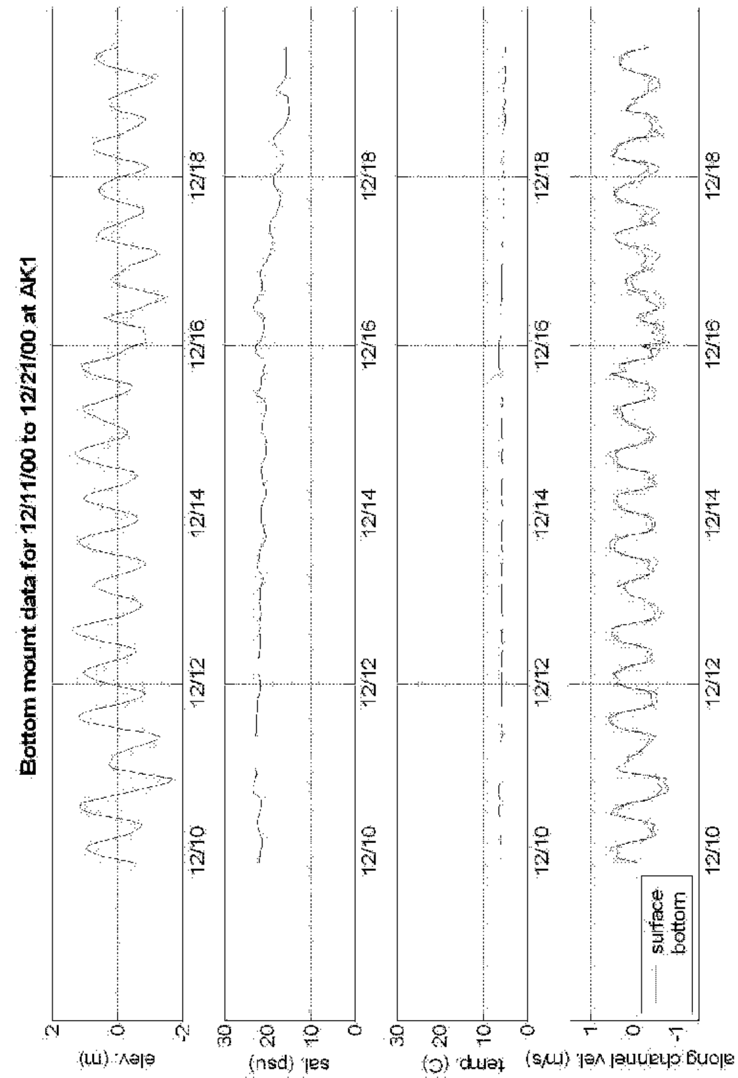
Note: Bottom velocity is measured 1.9 m from bottom and surface velocity is measured 10.9 m from bottom



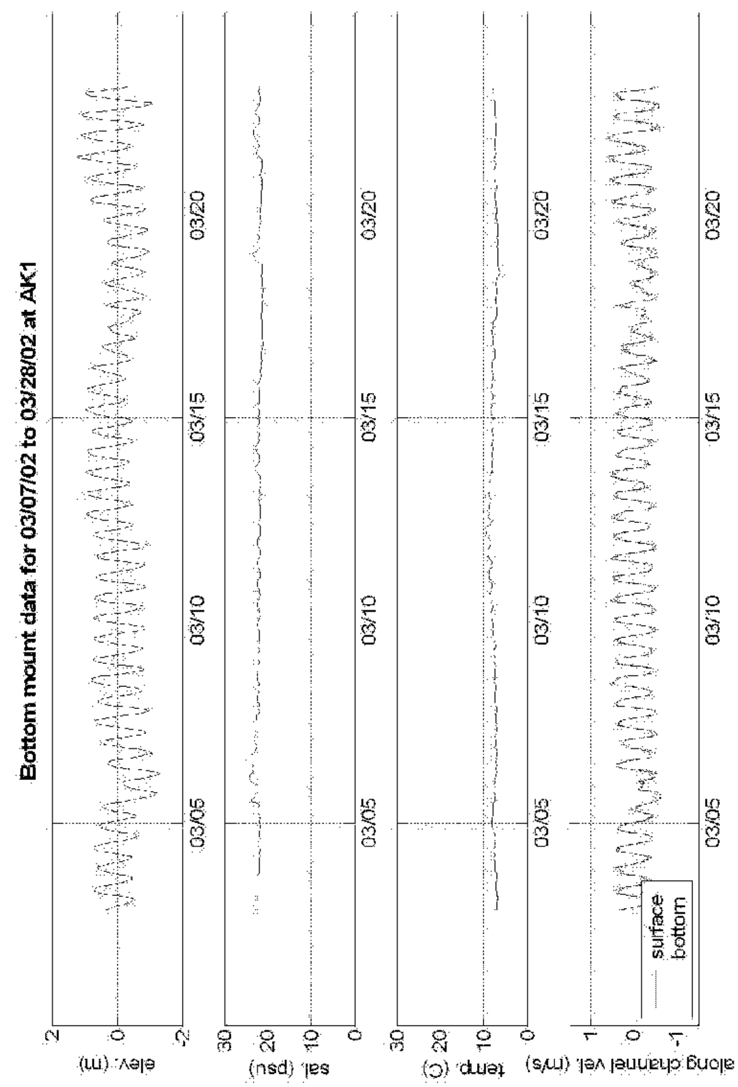
Note: Bottom velocity is measured 1.9 m from bottom and surface velocity is measured 10.9 m from bottom



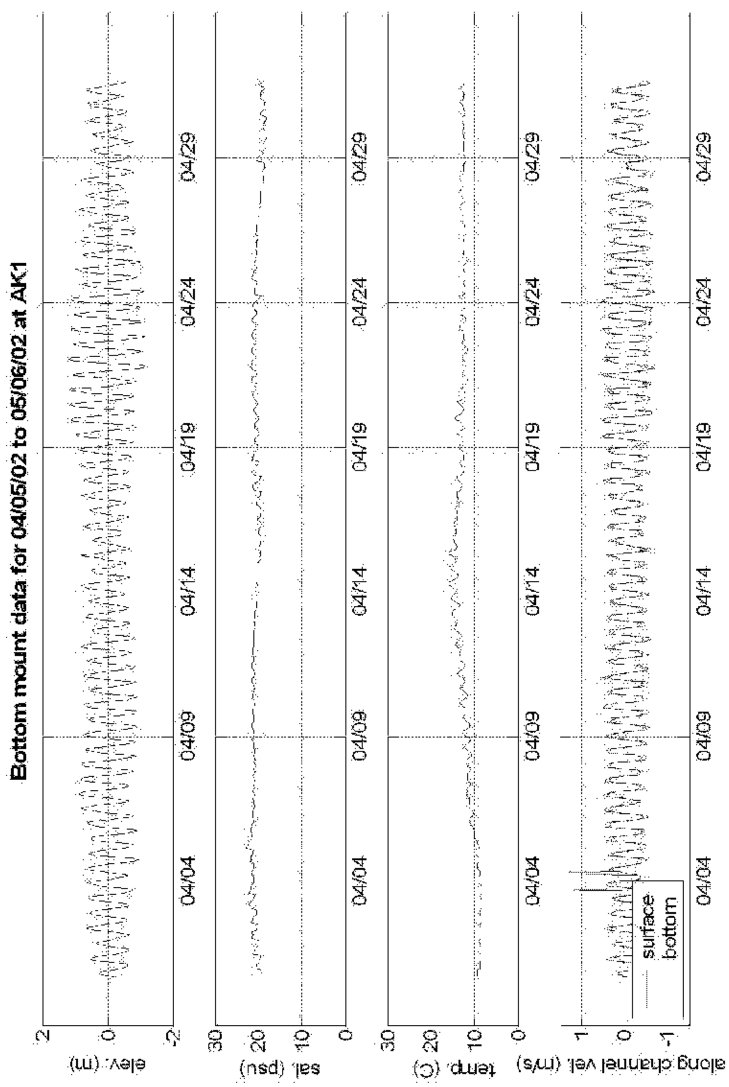
Note: Bottom velocity is measured 1.9 m from bottom and surface velocity is measured 10.9 m from bottom



Note: Bottom velocity is measured 1.9 m from bottom and surface velocity is measured 9.4 m from bottom



Note: Bottom velocity is measured 1.9 m from bottom and surface velocity is measured 9.4 m from bottom



Note: Bottom velocity is measured 1.9 m from bottom and surface velocity is measured 9.4 m from bottom

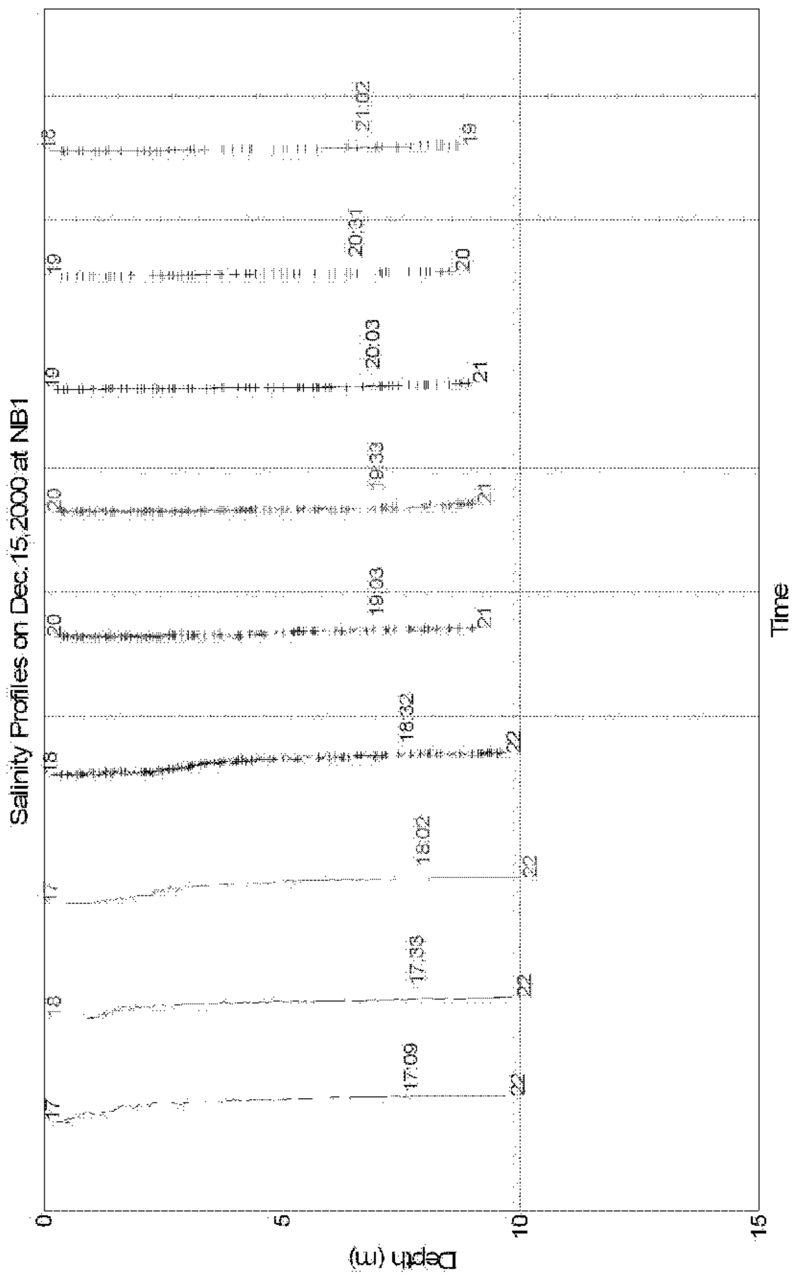
Appendix C

Moored Vessel Salinity Profiles

Appendix C Key

Bergen Point - BP (40° 38.4'N, 74° 8.8'W)
Passaic Valley Sewerage Commission -PVSC (40° 43'N, 74° 8'W)
Constable Hook in Bayonne - BAY (40° 40.2'N, 74° 4.2'W)
Perth Amboy Yacht Club PAYC (40° 30'N, 74° 15'W)
Hackensack River -HACK (N/A)
Perth Amboy - PA (40° 30.6'N, 74° 15.6'W)
North end of the Arthur Kill -AK1 (40° 37.8'N, 74° 12'W)
Western end of the Kill van Kull -KVK1 (40° 38.4'N, 74°7.5'W)
North end of Newark Bay -NB1(40° 42'N, 74° 7.2'W)
South end of Newark Bay -NB3 (40° 40'N, 74° 8.4'W)
Raritan River - RR (40° 24'N, 74° 18'W)

All times are in GMT.
Salinity is in psu.


Salinity Profiles on Dec.15,2000 at NB1
Depth (m)
Time
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5
10
15
17:09
17:33
18:02
18:32
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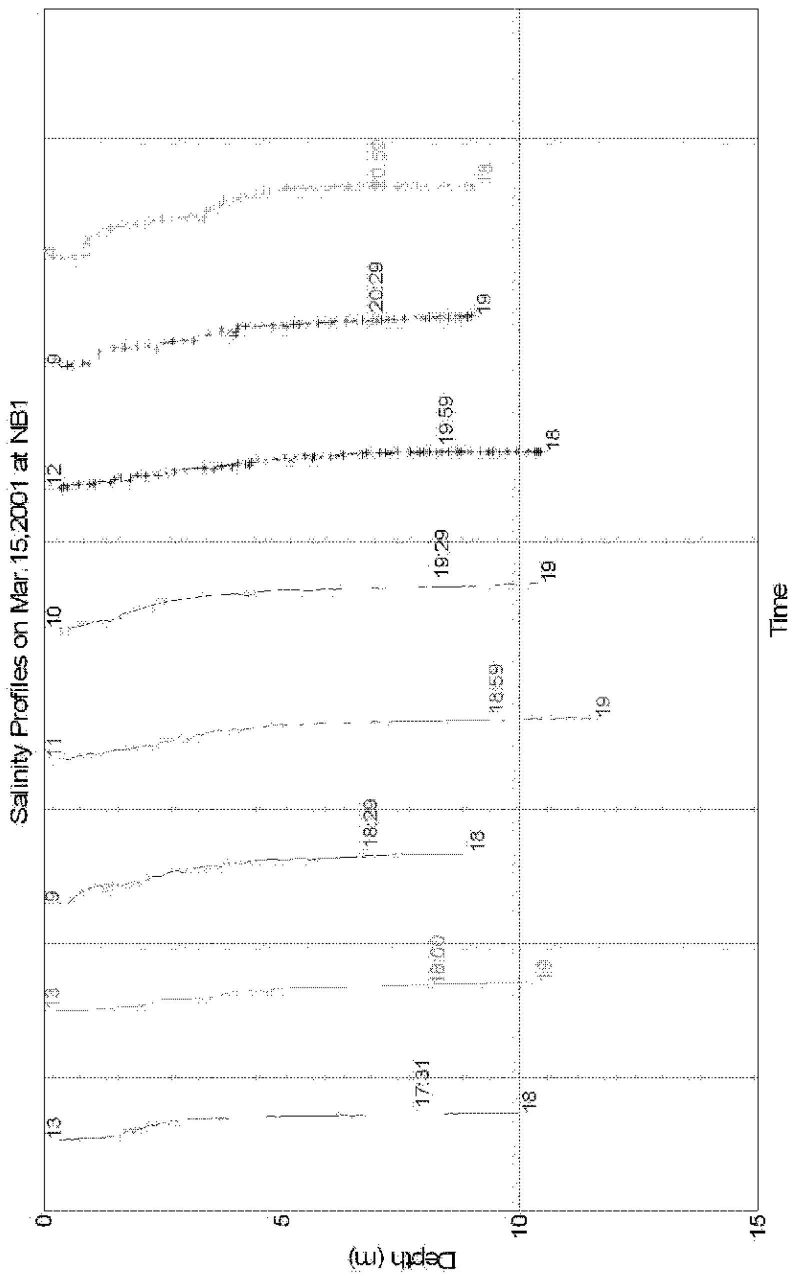
20:03
20:31
21:02


Salinity Profiles on Mar.15,2001 at NB1
Time
Depth (m)
0
5
10
15
17:31
18:00
18:29
18:59
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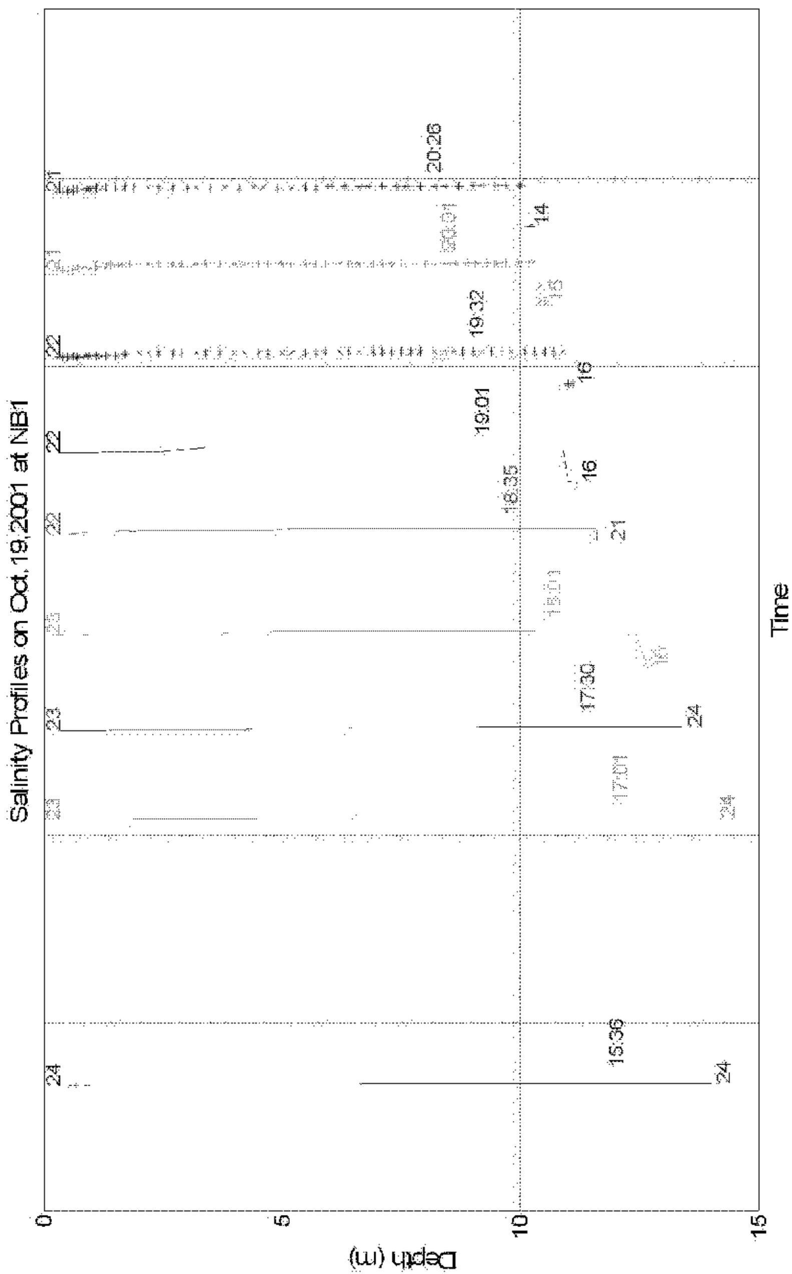
19:59
20:29
20:59


Salinity Profiles on Oct.19,2001 at NB1
Depth (m)
Time
0
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10
15
15:36
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18:01
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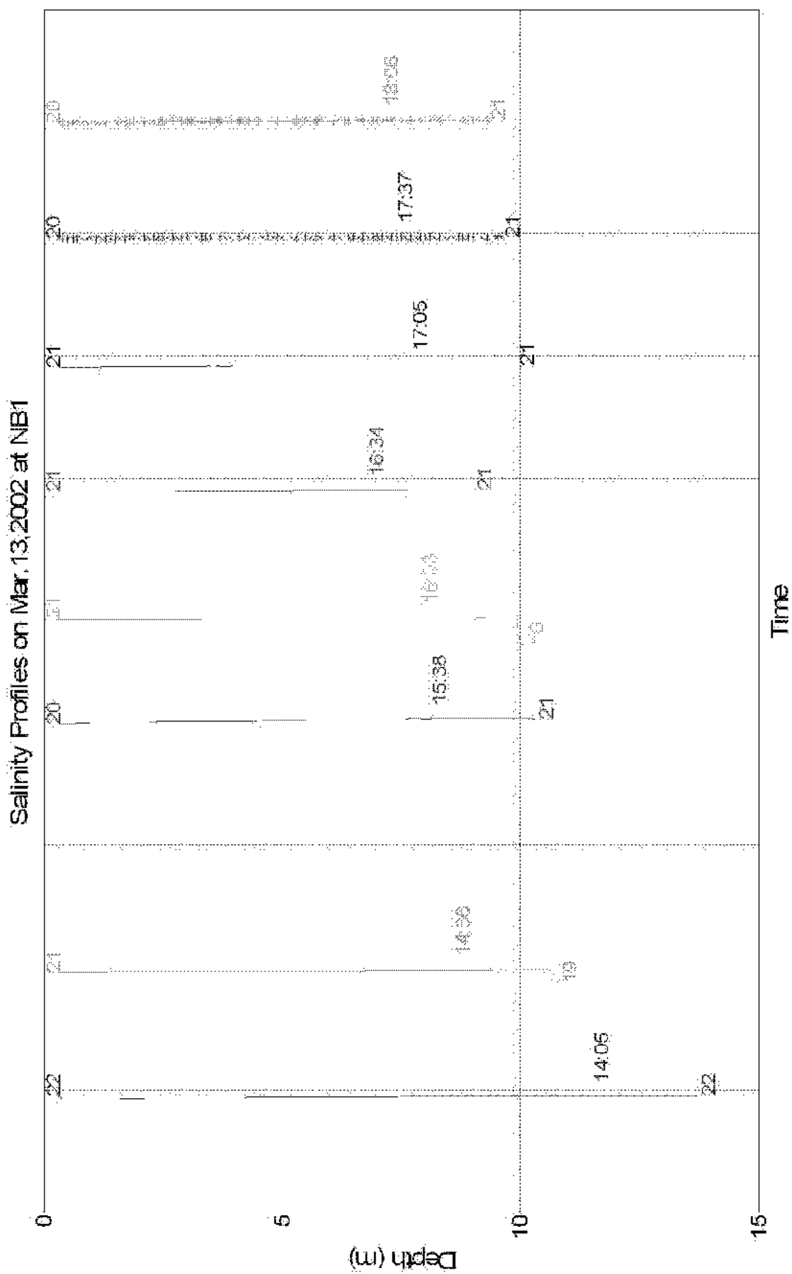
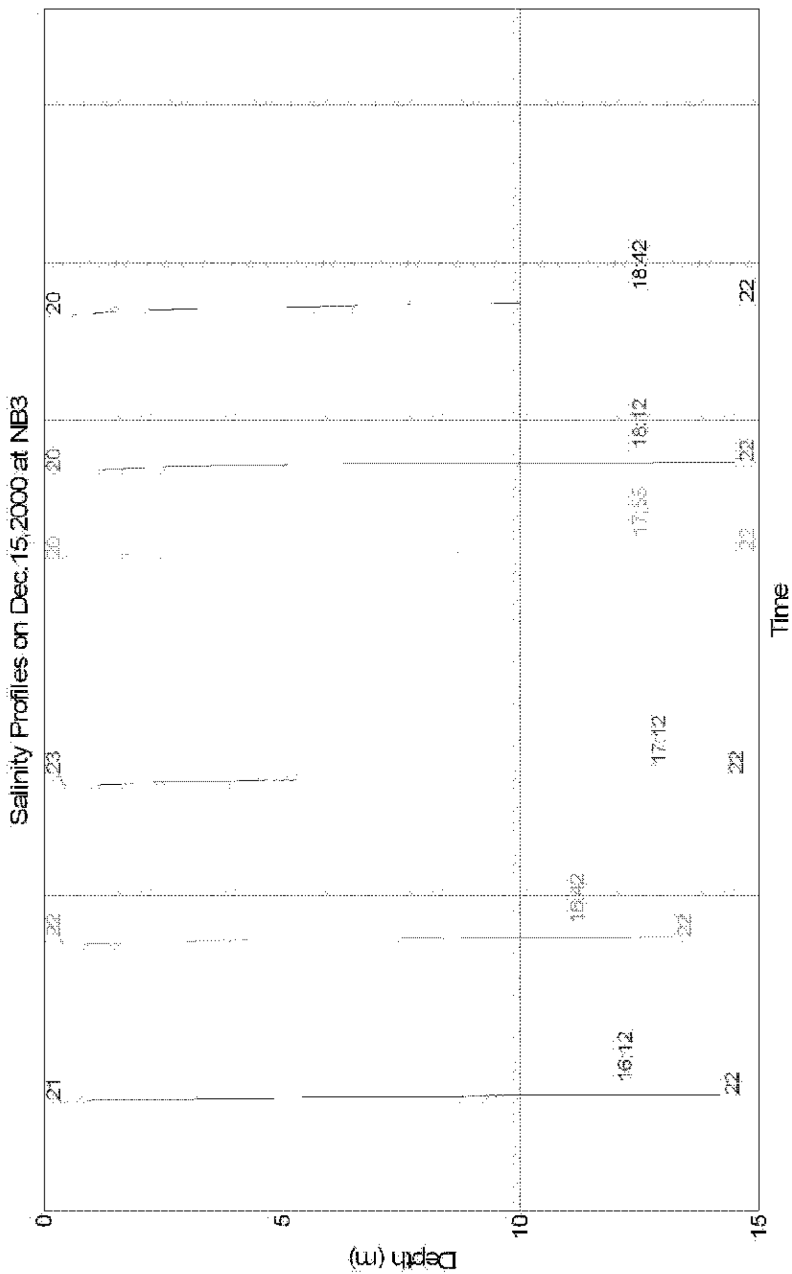
19:32
20:01
20:26


Salinity Profiles on Mar,13,2002 at NB1
Depth (m)
Time
0
5
10
15
14:05
15:38
16:34
17:05
17:37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Depth (m)
Time
0
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10
15
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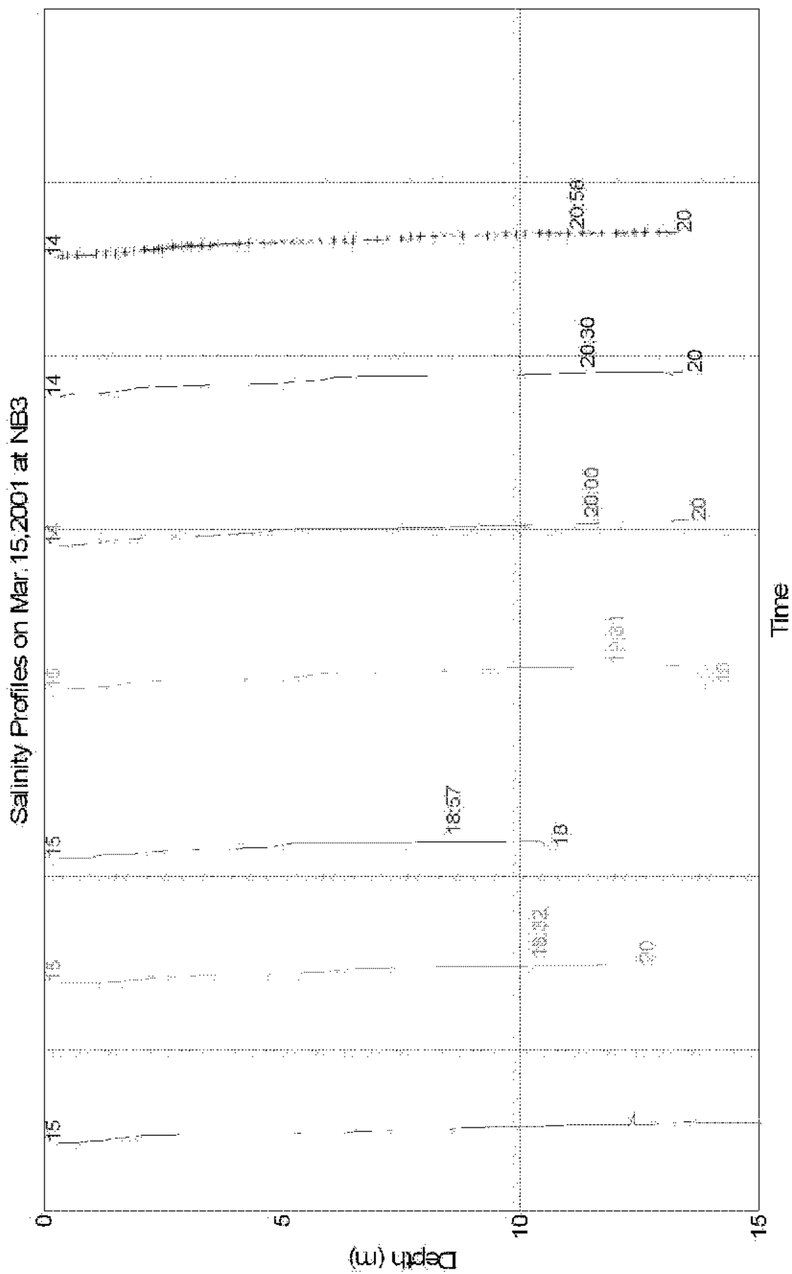
18:42


Salinity Profiles on Mar.15,2001 at NB3
Time
Depth (m)
0
5
10
15
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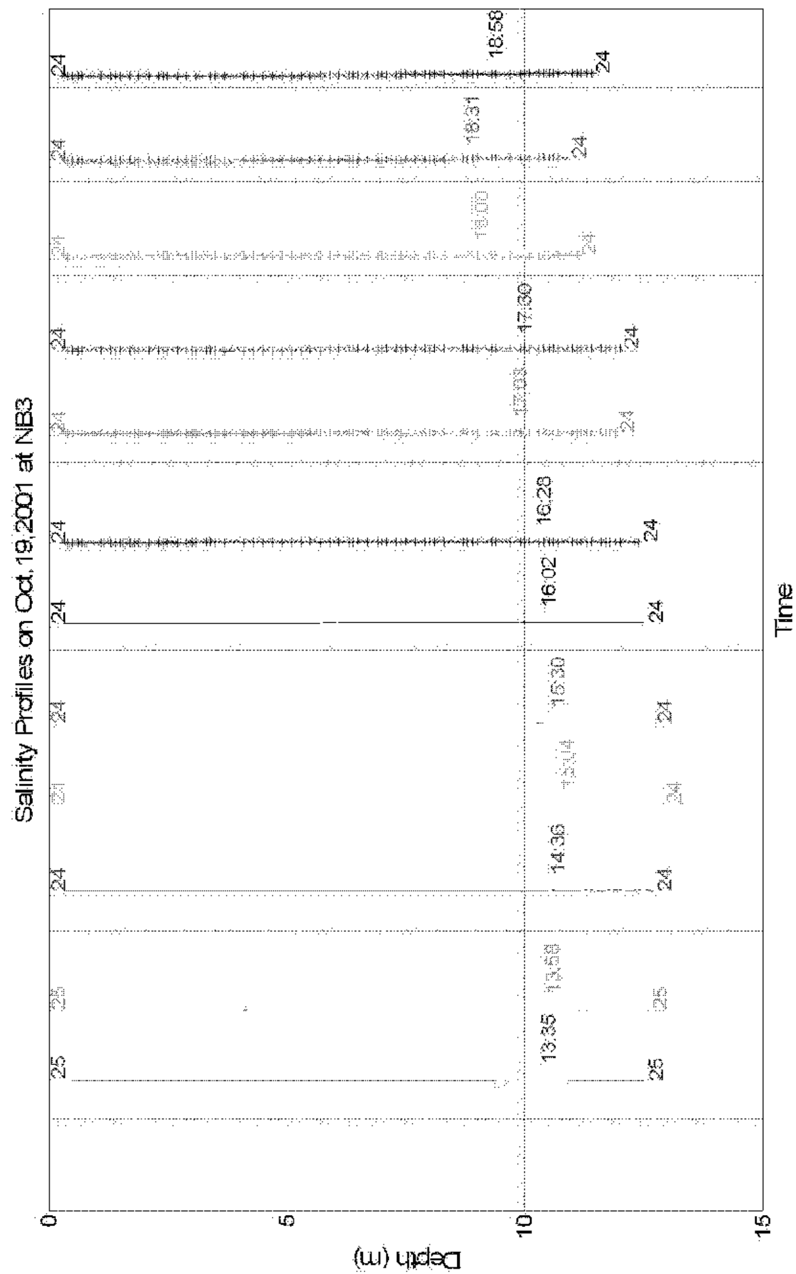
20:00
20:30
20:58


Salinity Profiles on Oct.19,2001 at NB3
Depth (m)
Time
0
5
10
15
13:35
13:58
14:36
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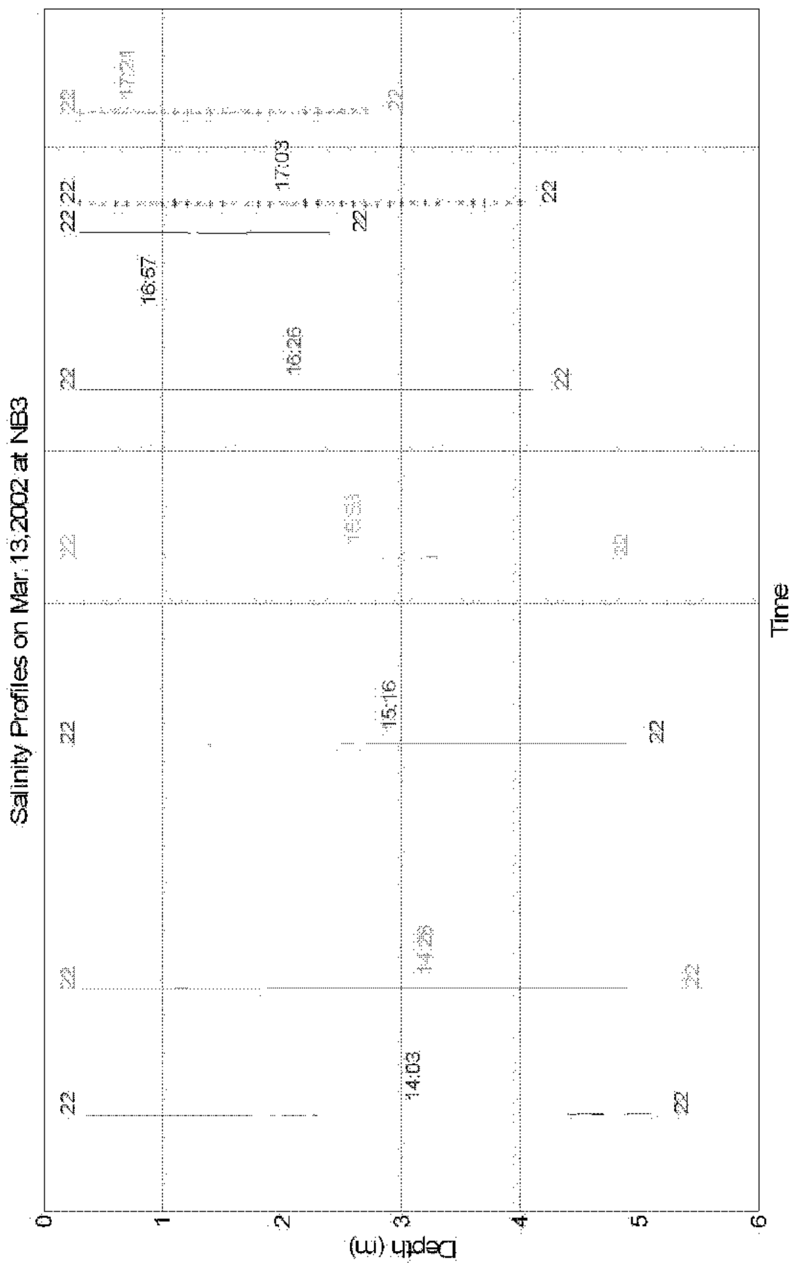
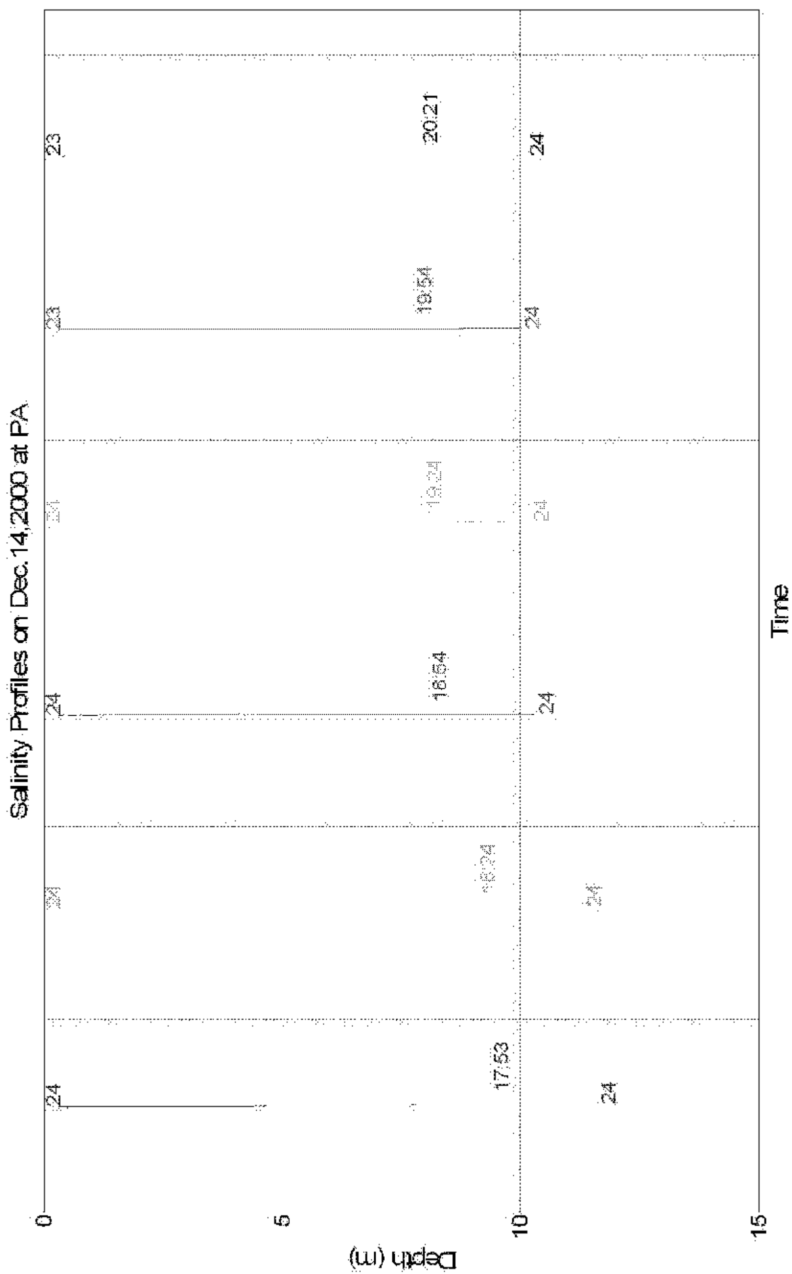
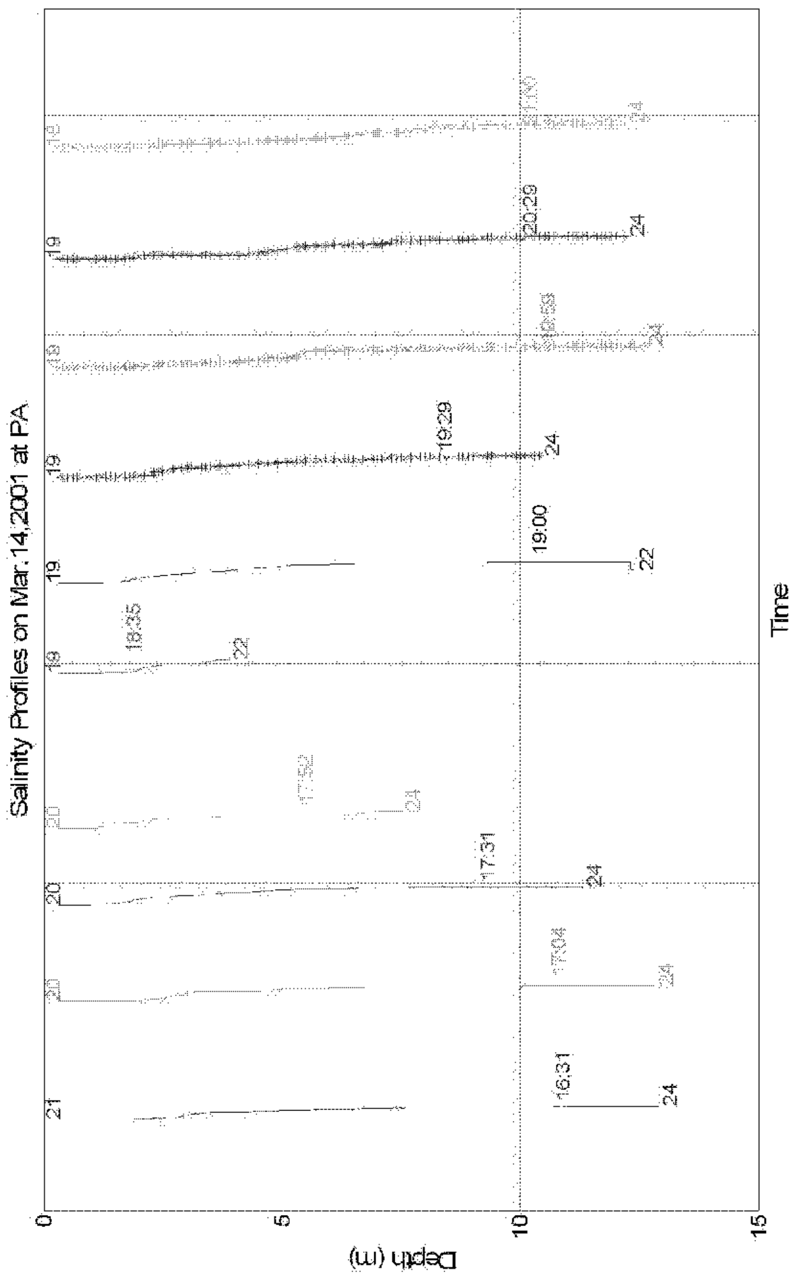
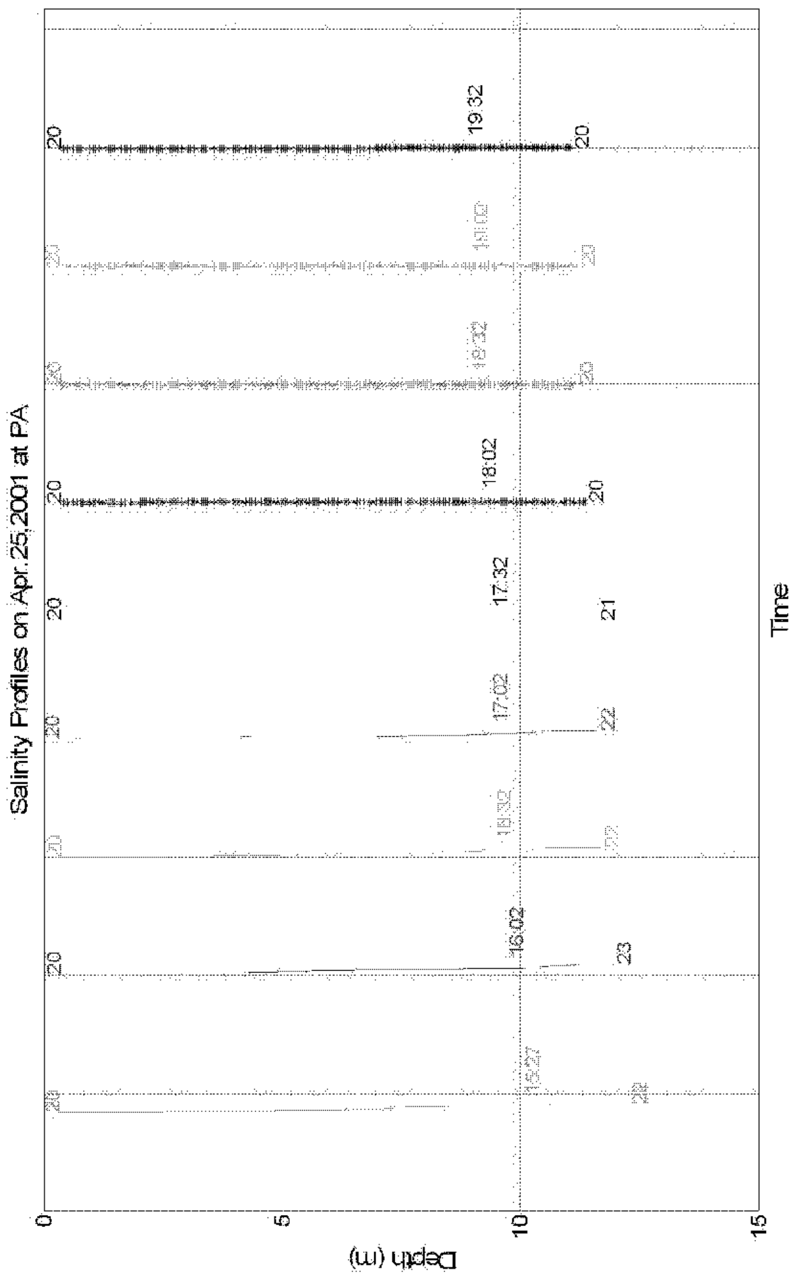
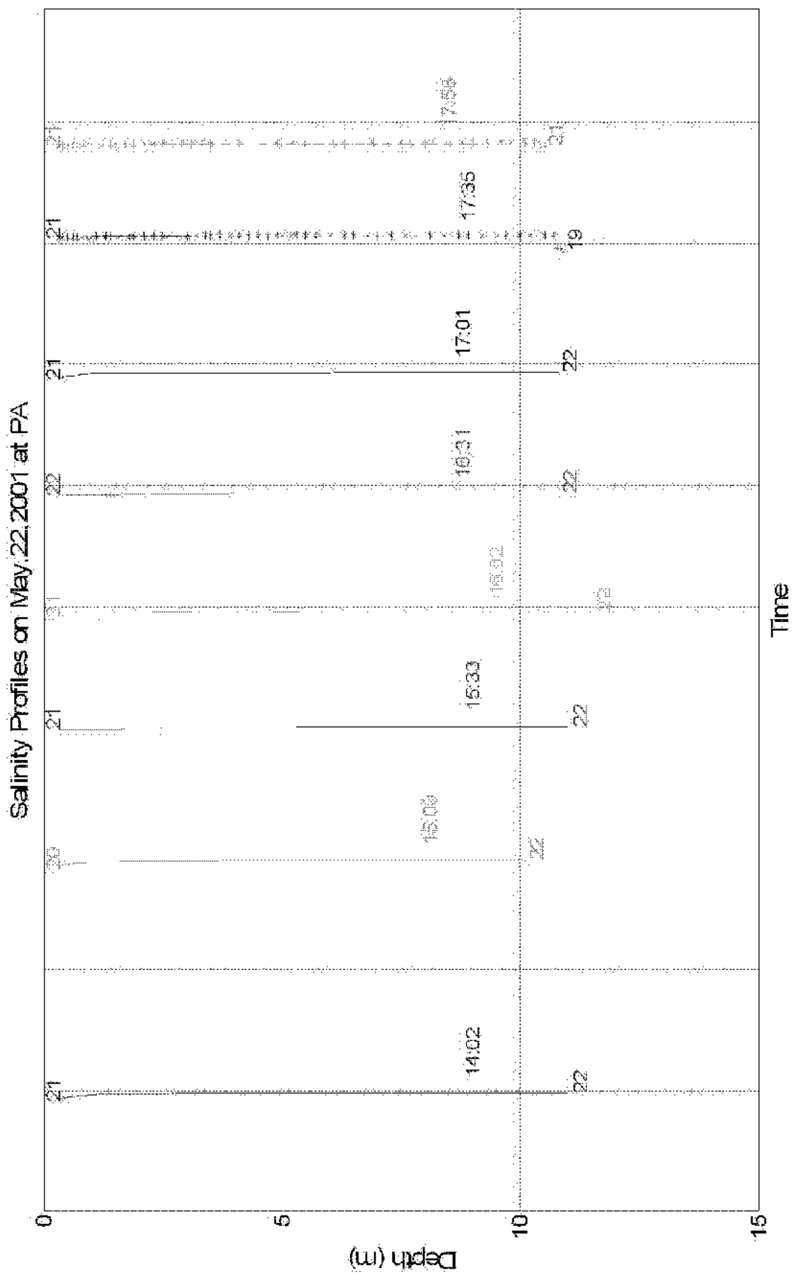
16:02
16:28
17:03
17:30
18:00
18:31
18:58


Salinity Profiles on Mar 13,2002 at NB3
Time
Depth (m)
0
1
2
3
4
5
6
14:03
15:16
16:26
16:57
17:03
22


Salinity Profiles on Dec. 14,2000 at PA
Time
Depth (m)
0
5
10
15
17:53
18:24
18:54
19:24
19:54
20:21
24
23


Salinity Profiles on Mar. 14,2001 at PA
Depth (m)
0
5
10
15
Time
16:31
17:04
17:31
17:52
18:35
19:00
19:29
19:59
20:29
21:00
21
20
20
20
19
19
19
19
19
19
24
24
24
24
22
22
24
24
24
24


Salinity Profiles on Apr.25,2001 at PA
Depth (m)
0
5
10
15
Time
16:02
17:02
17:32
18:02
19:32
20
21
22
23



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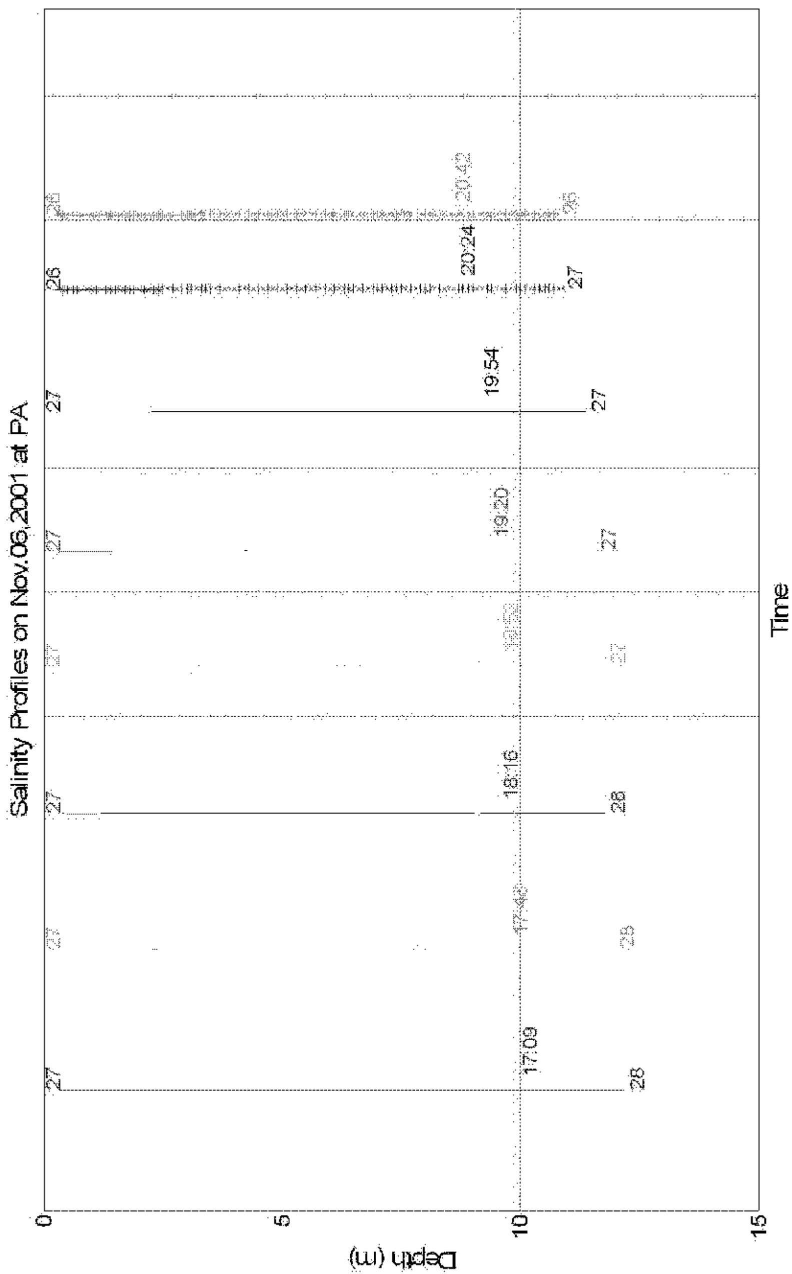
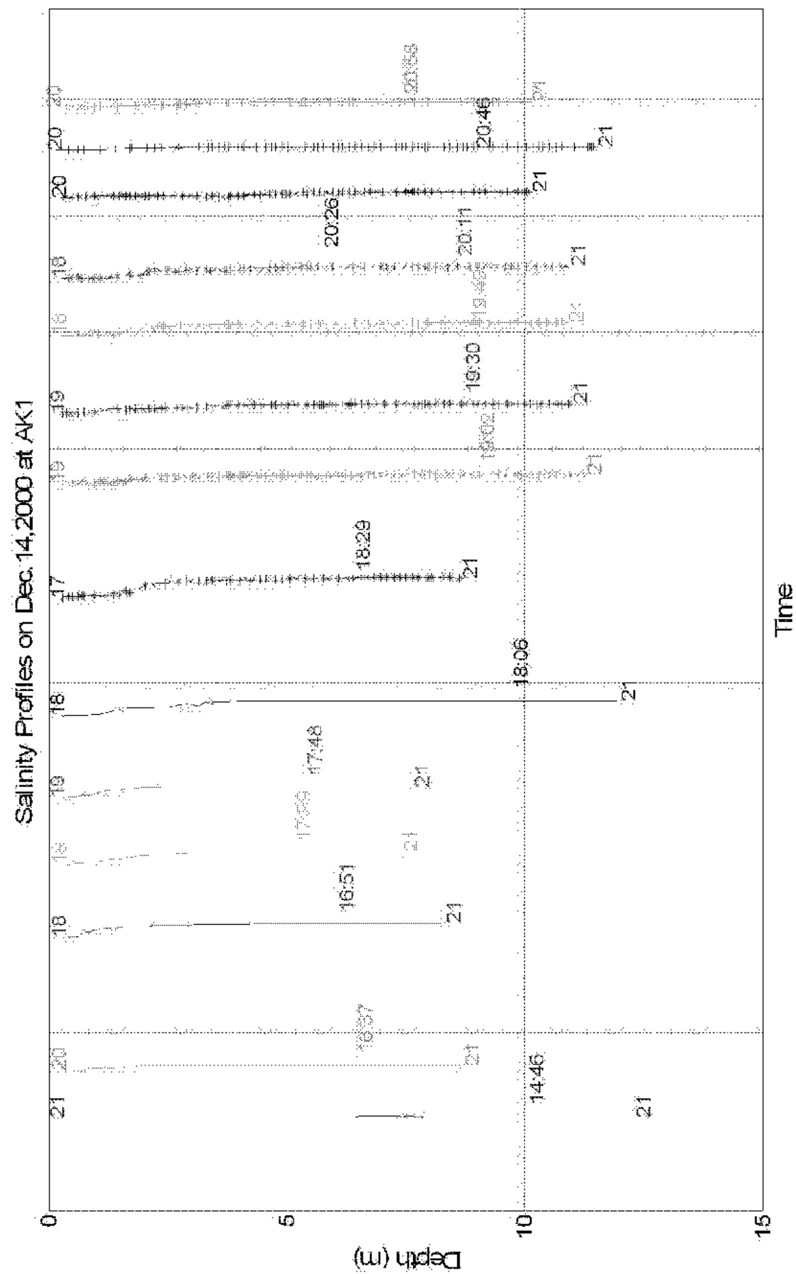
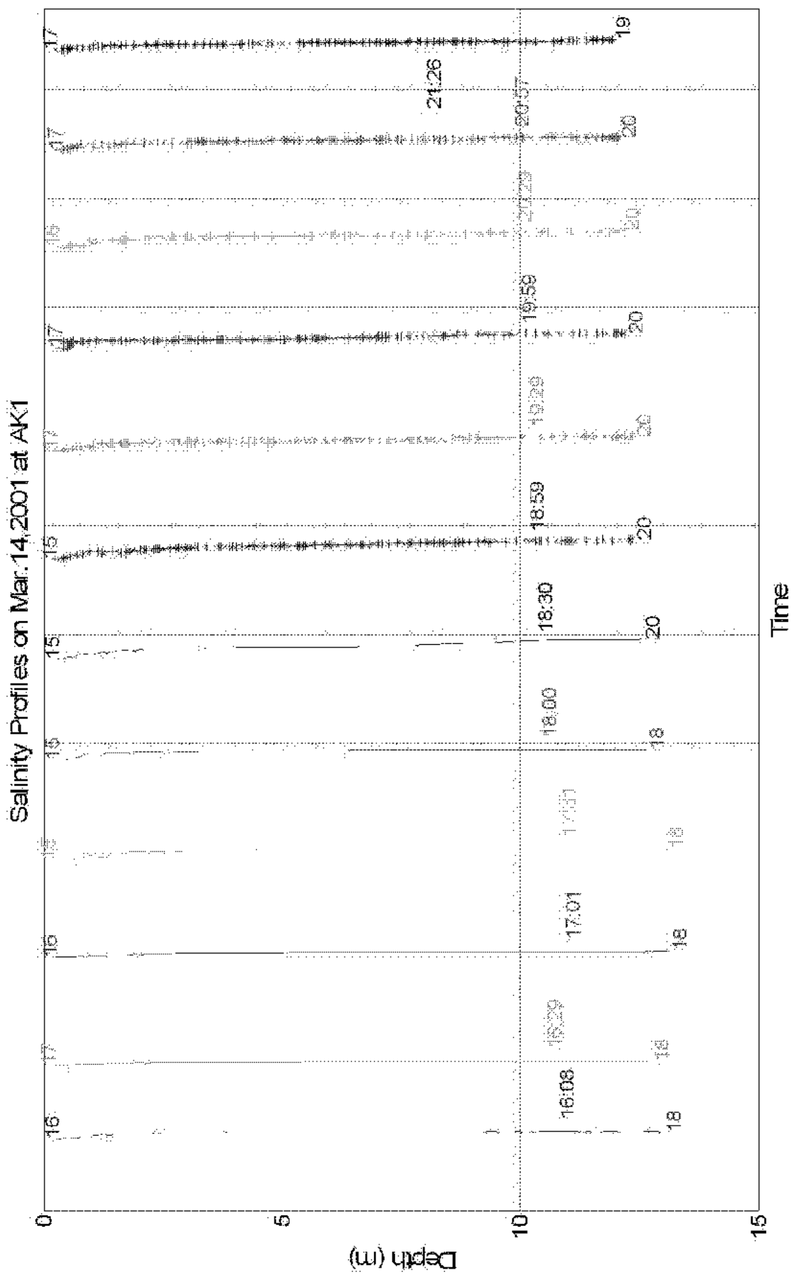
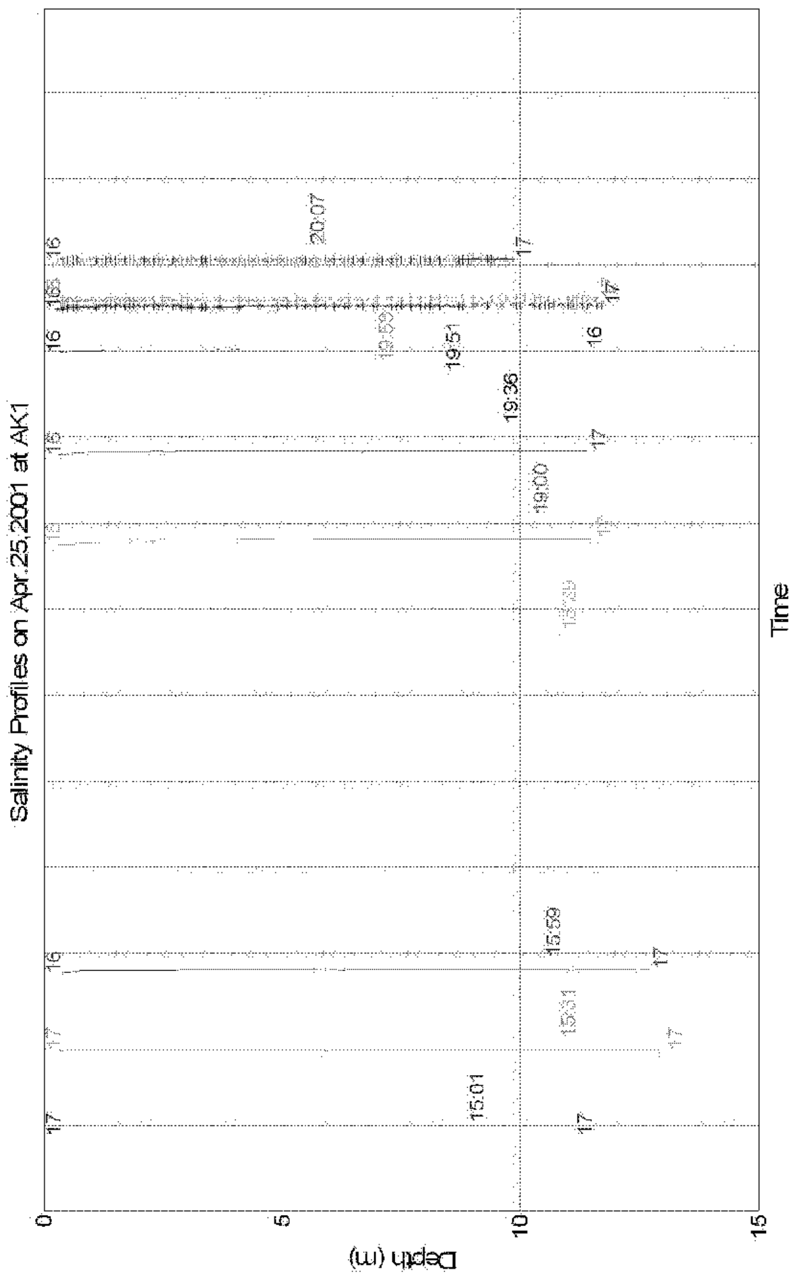
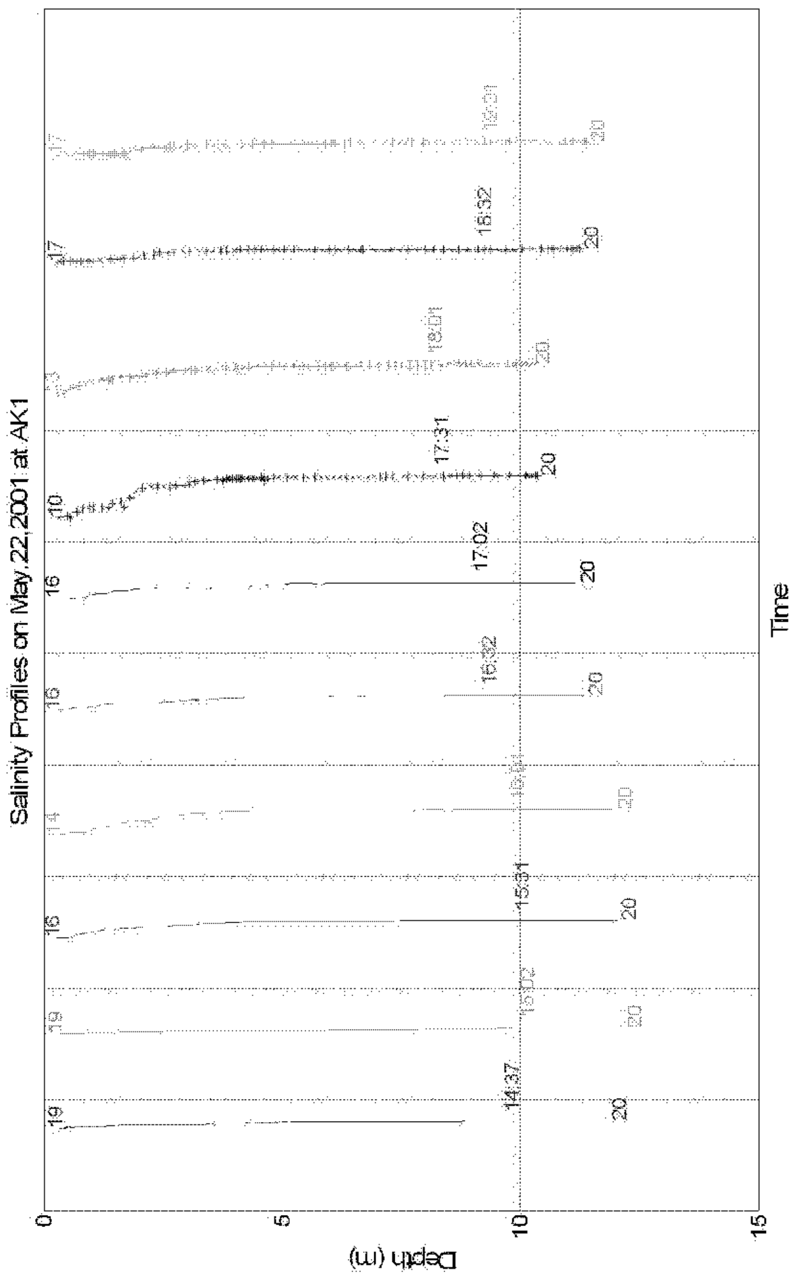
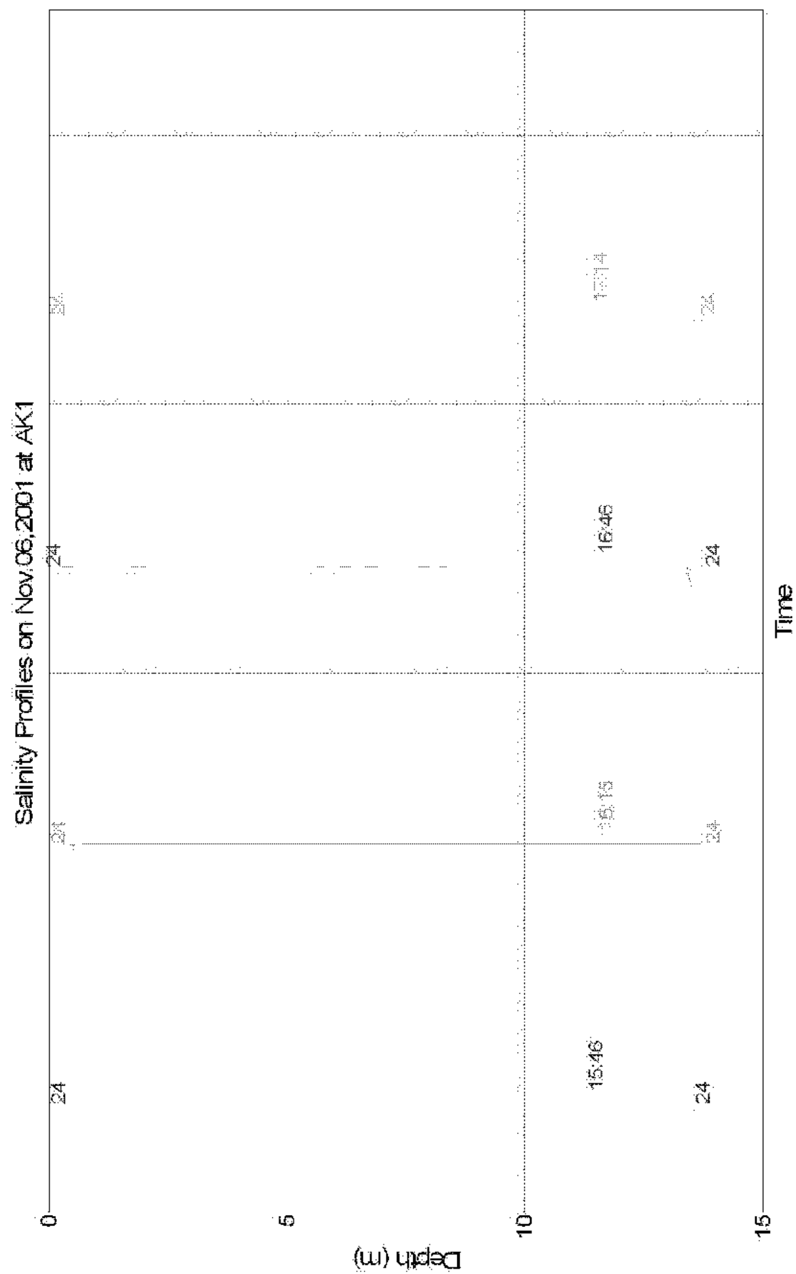

Salinity Profiles on Nov.06,2001 at PA
Depth (m)
Time
0
5
10
15
17:09
17:48
18:16
18:52
19:20
19:54
20:24
20:42
27
28
26


Salinity Profiles on Dec. 14,2000 at AK1
Depth (m)
Time
0
5
10
15
14:46
16:51
17:48
18:06
18:29
19:30
20:11
20:26
20:46

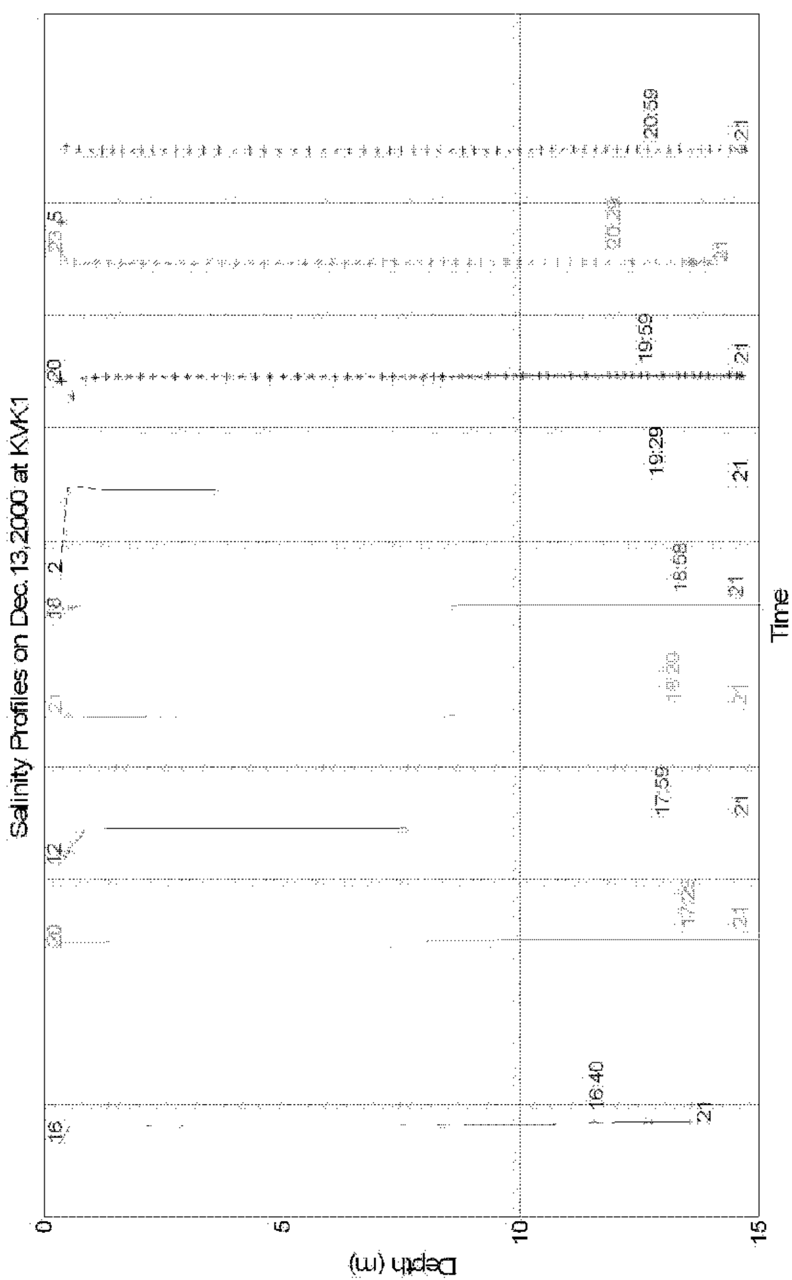

Salinity Profiles on Mar.14,2001 at AK1
Depth (m)
Time
0
5
10
15
16:08
16:29
17:01
18:00
18:30
18:59
19:29
19:58
20:29
20:57
21:26

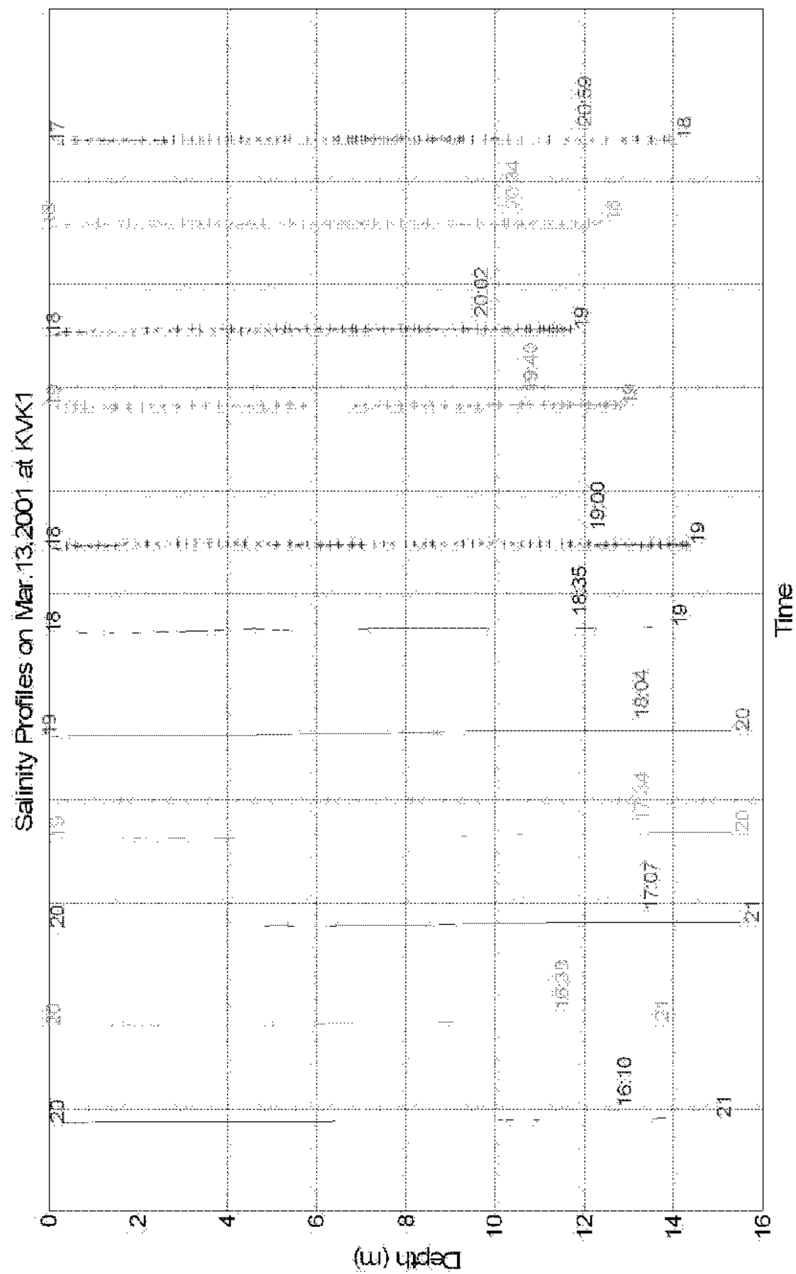

Salinity Profiles on Apr.25,2001 at AK1
Time
Depth (m)
0
5
10
15
15:01
15:31
15:59
19:00
19:36
19:51
20:07

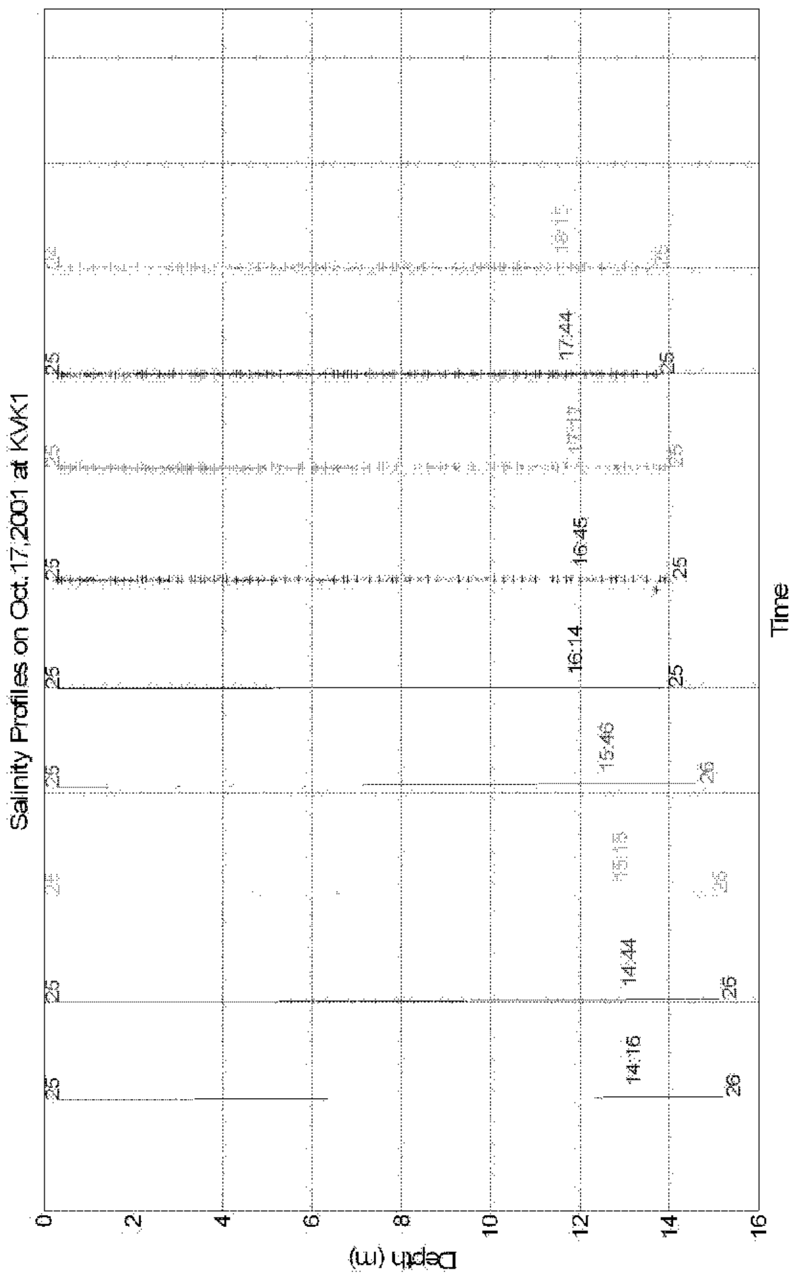

Salinity Profiles on May 22,2001 at AK1
Time
Depth (m)
0
5
10
15
14:37
16:32
17:02
17:31
20

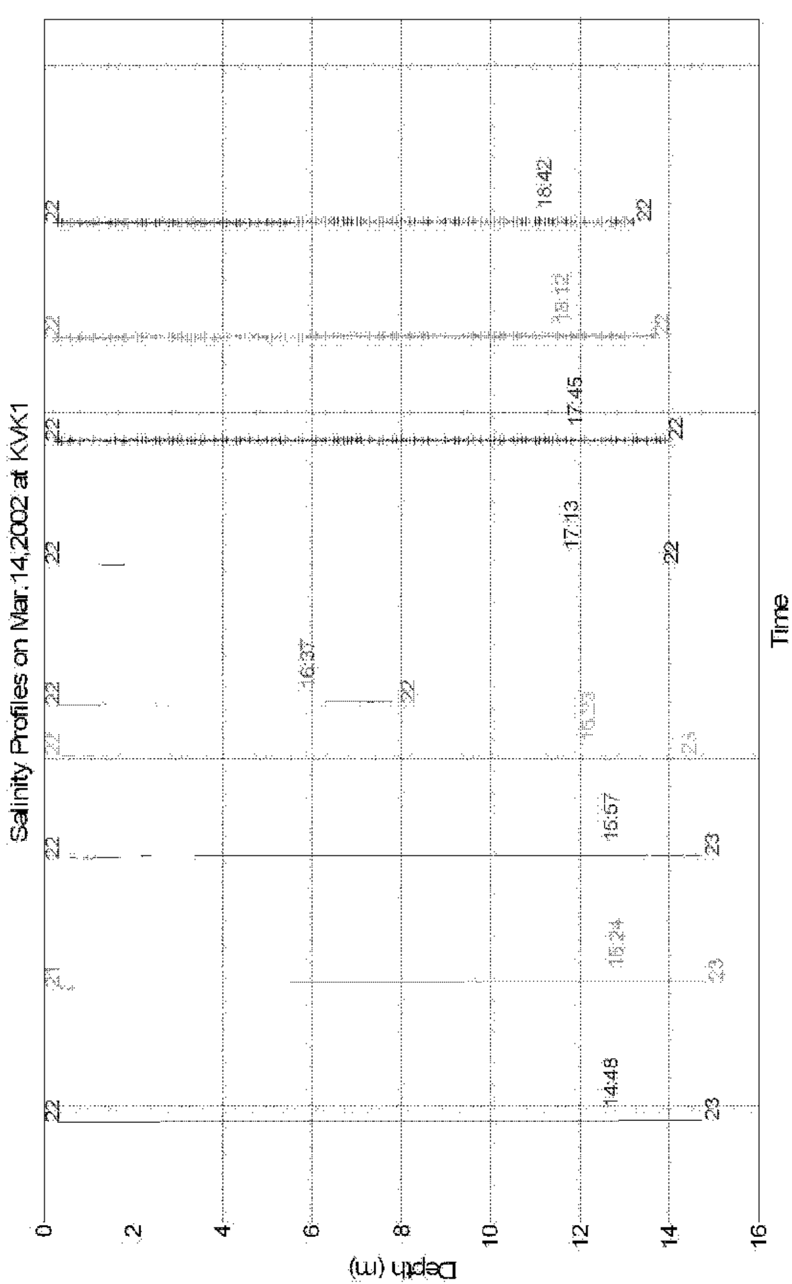


Salinity Profiles on Nov.06,2001 at AK1
Time
Depth (m)
0
5
10
15
15:46
16:46
24


Salinity Profiles on Dec. 13,2000 at KVK1
Depth (m)
Time
0
5
10
15
16:40
17:29
17:59
18:29
18:58
19:29
19:59
20:29
20:59
21
20
12
21
18
2
20
20.5
16


Salinity Profiles on Mar.13,2001 at KVK1
Depth (m)
Time
0
2
4
6
8
10
12
14
16
16:10
17:07
18:04
18:35
19:00
20:02
20:59


Salinity Profiles on Oct.17,2001 at KVK1
Time
Depth (m)
0
2
4
6
8
10
12
14
16
14:16
14:44
15:15
15:46
16:14
16:45
17:44
25
26


Salinity Profiles on Mar.14,2002 at KVK1
Depth (m)
Time
14:48
15:24
15:57
16:37
17:13
17:45
18:42

Appendix D

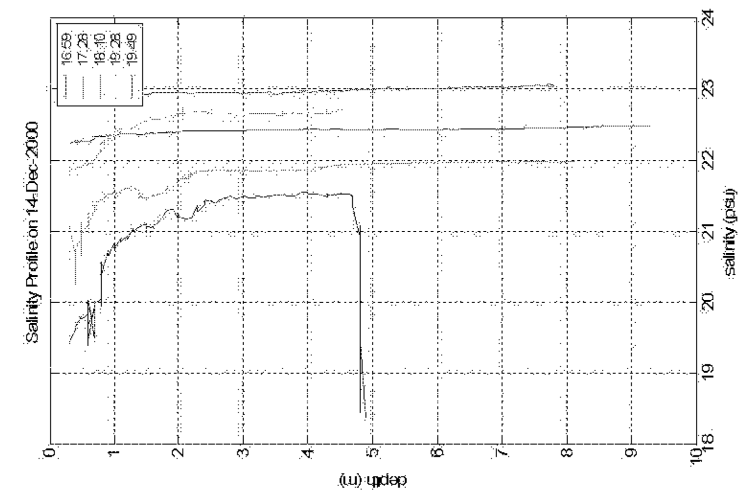
Vessel Transect Salinity Profiles

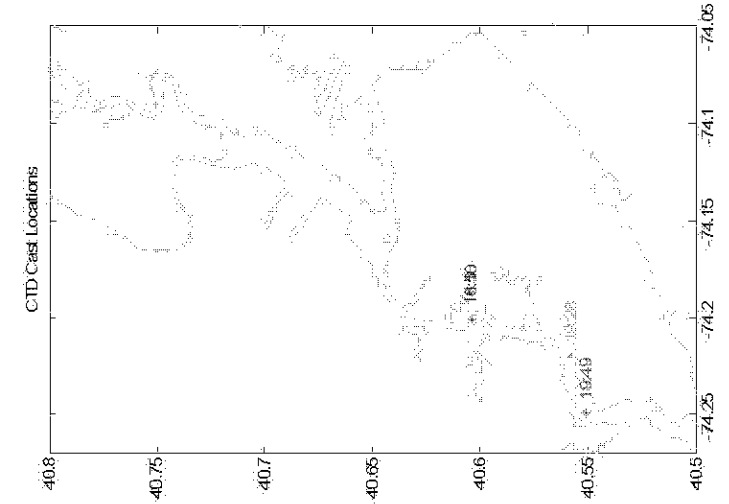
Appendix D Key

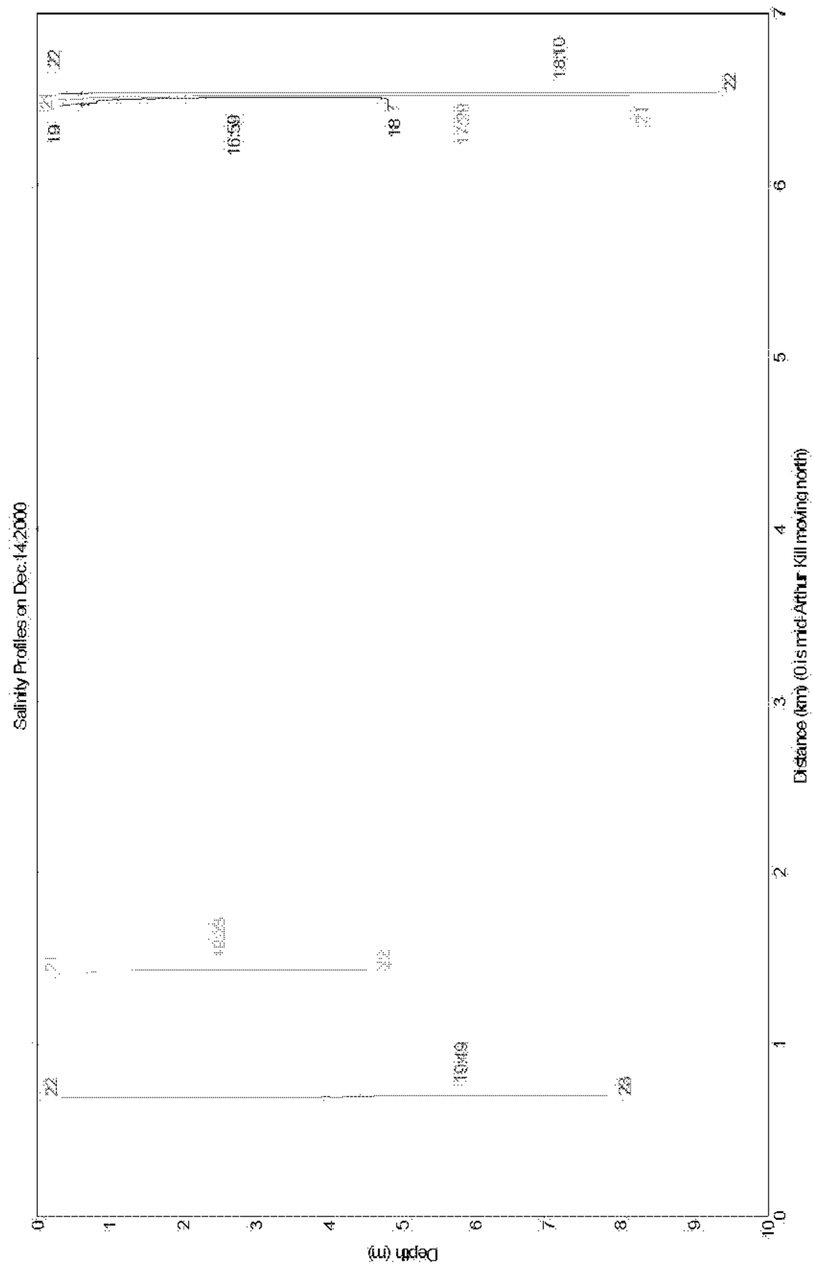
Bergen Point - BP (40° 38.4'N, 74° 8.8'W)
Passaic Valley Sewerage Commission -PVSC (40° 43'N, 74° 8'W)
Constable Hook in Bayonne - BAY (40° 40.2'N, 74° 4.2'W)
Perth Amboy Yacht Club PAYC (40° 30'N, 74° 15'W)
Hackensack River -HACK (N/A)
Perth Amboy - PA (40° 30.6'N, 74° 15.6'W)
North end of the Arthur Kill -AK1 (40° 37.8'N, 74° 12'W)
Western end of the Kill van Kull -KVK1 (40° 38.4'N, 74°7.5'W)
North end of Newark Bay -NB1(40° 42'N, 74° 7.2'W)
South end of Newark Bay -NB3 (40° 40'N, 74° 8.4'W)
Raritan River - RR (40° 24'N, 74° 18'W)

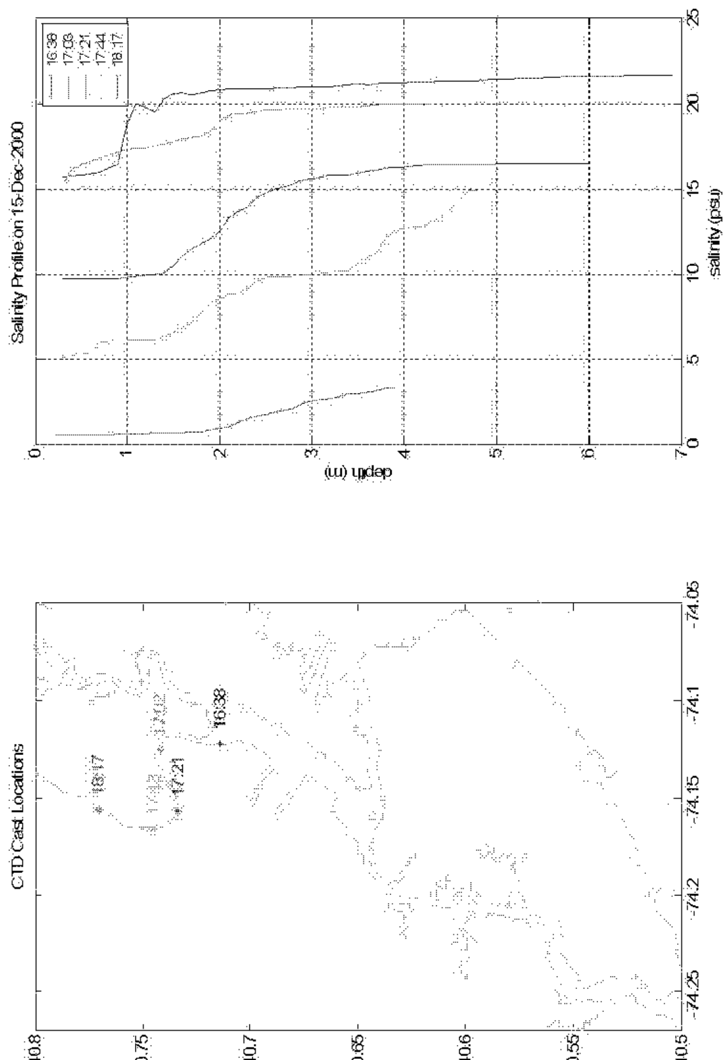
All times are in GMT.
Salinity is in psu.

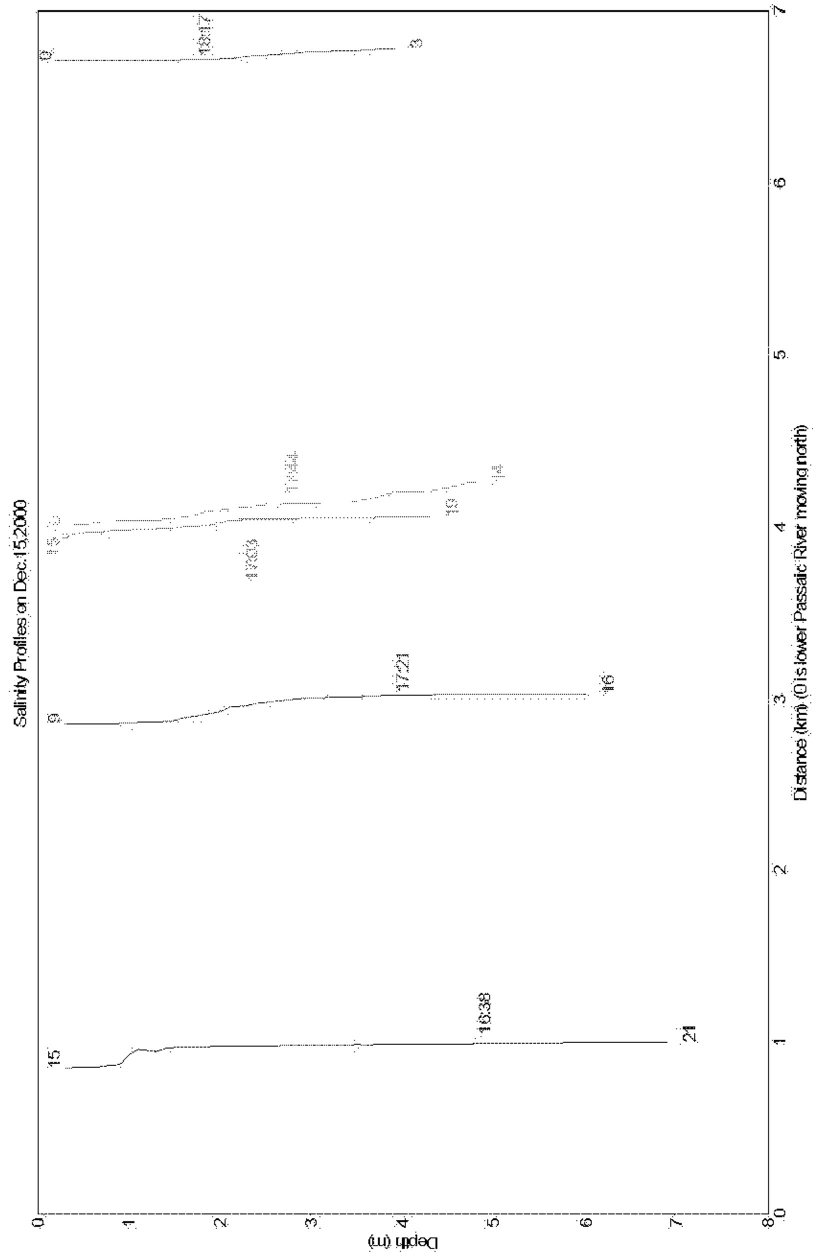
NB = transect in Newark Bay
NB1 to P = transect from NB1 into the Passaic River
NB1 to H = transect from NB1 into the Hackensack River
NB1 to PA = transect from NB1 to Perth Amboy
AK1 to P1 = transect from AK1 into the Passaic River
RAR = transect through the Raritan River
KVK1 to P = transect from KVK1 into the Passaic River
KVK1 to H = transect from KVK1 into the Hackensack River
AK to PA = transect from the north end of the Arthur Kill to Perth Amboy

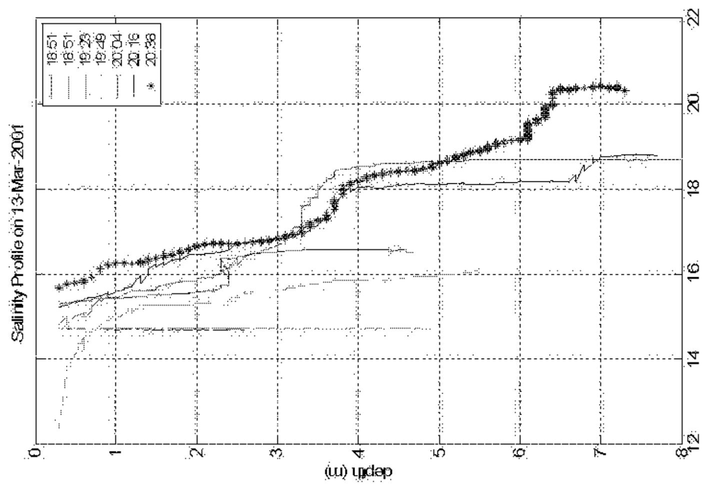

Salinity Profile on 14-Dec-2000
16:59
17:28
18:10
19:28
19:49
depth (m)
salinity (psu)
0
1
2
3
4
5
6
7
8
9
10
18
19
20
21
22
23
24

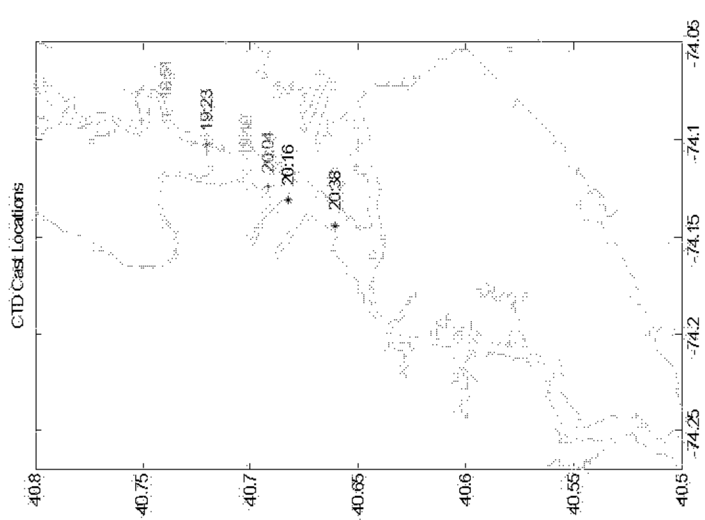

CTD Cast Locations
40.8
40.75
40.7
40.65
40.6
40.55
40.5
-74.25
-74.2
-74.15
-74.1
-74.05
19:49

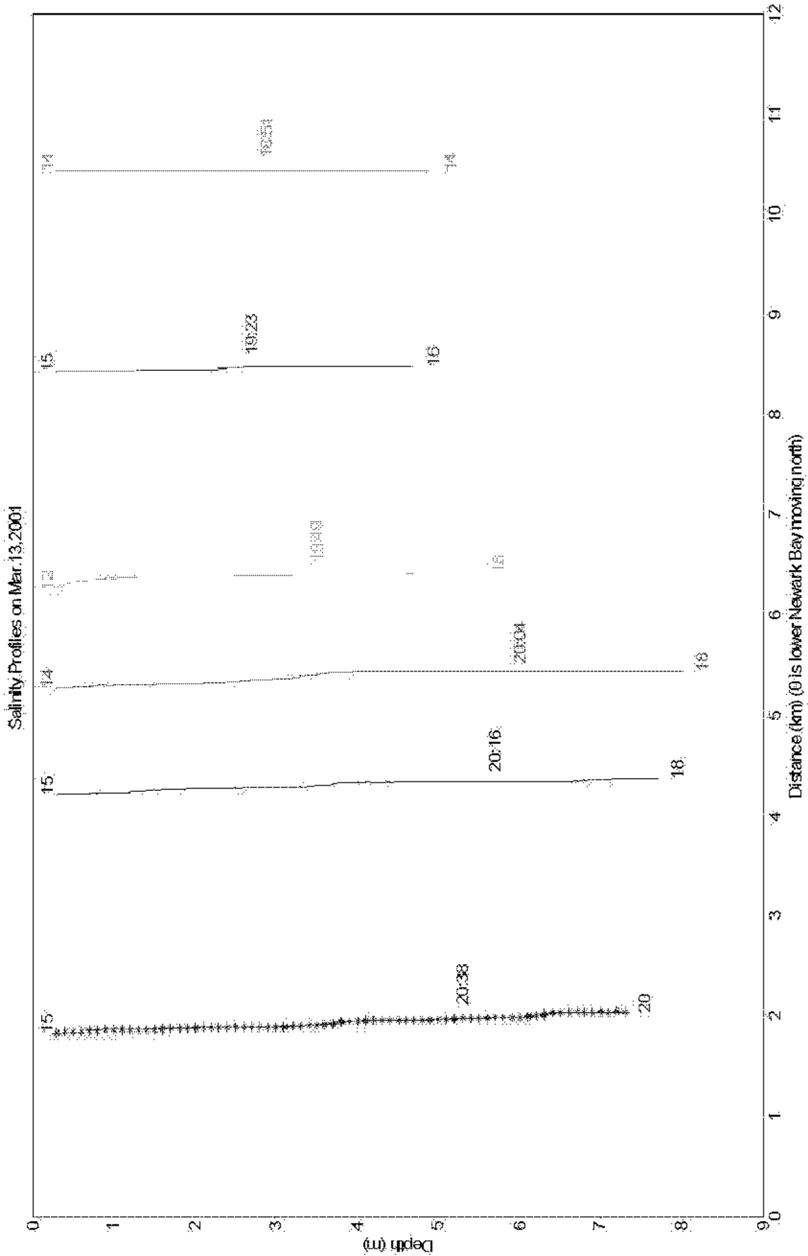

Salinity Profiles on Dec.14,2000
Depth (m)
Distance (km) (0 is mid-Arthur Kill moving north)
19:49
16:59
18:10

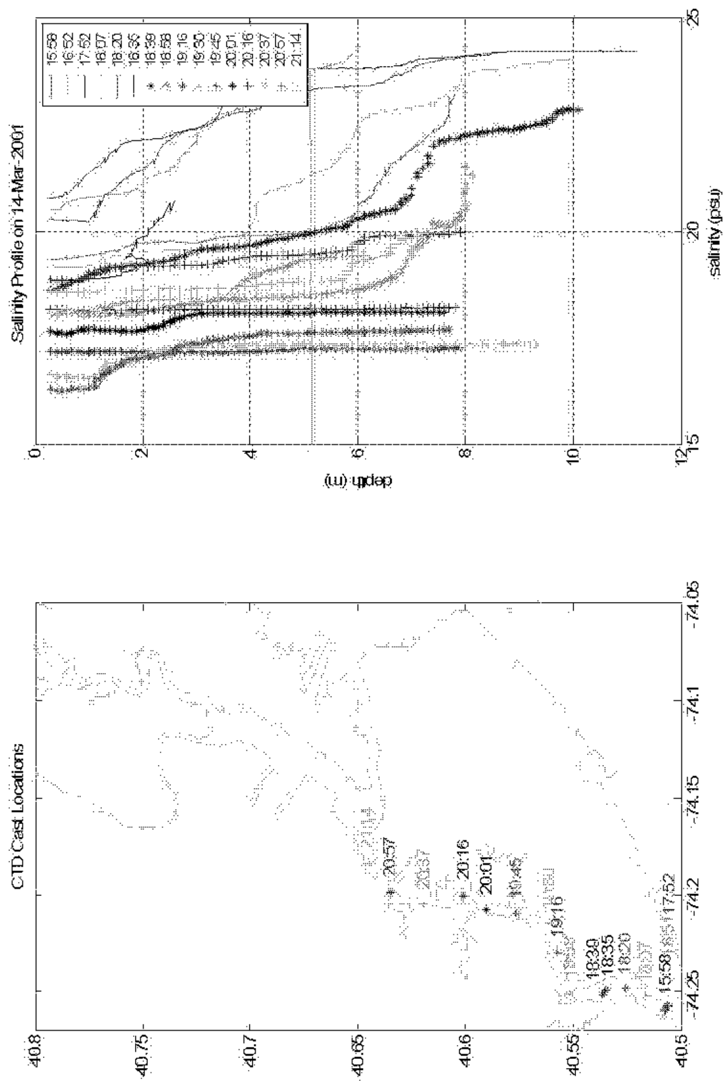

Salinity Profile on 15-Dec-2000
16:38
17:03
17:21
17:44
18:17
depth (m)
salinity (psu)
CTD Cast Locations
16:38
17:21
18:17
-74.25
-74.2
-74.15
-74.1
-74.05
40.5
40.55
40.6
40.65
40.7
40.75
40.8

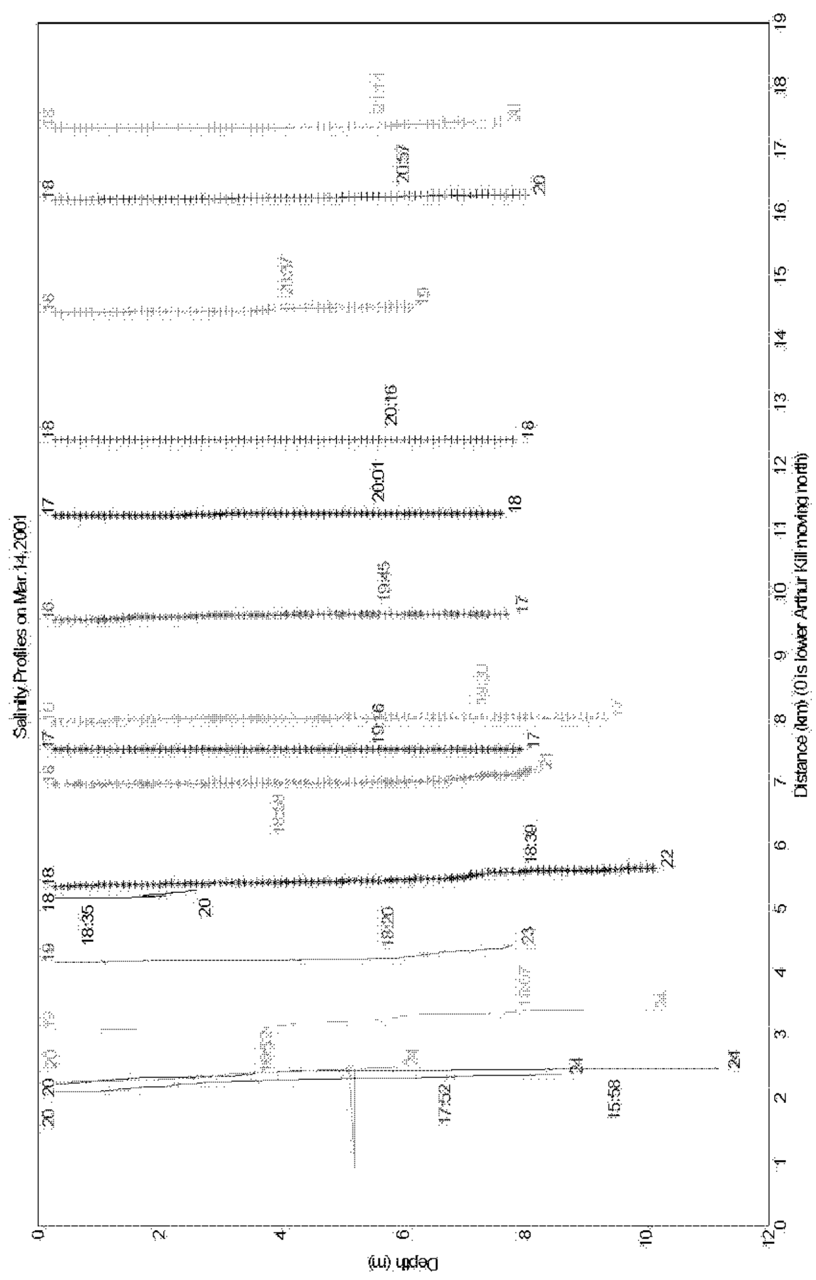

Salinity Profiles on Dec 15,2000
Depth (m)
Distance (km) (0 is lower Passaic River moving north)
16:38
17:21
18:17
17:44
18:03
15
21
9
16
13
14
0
3

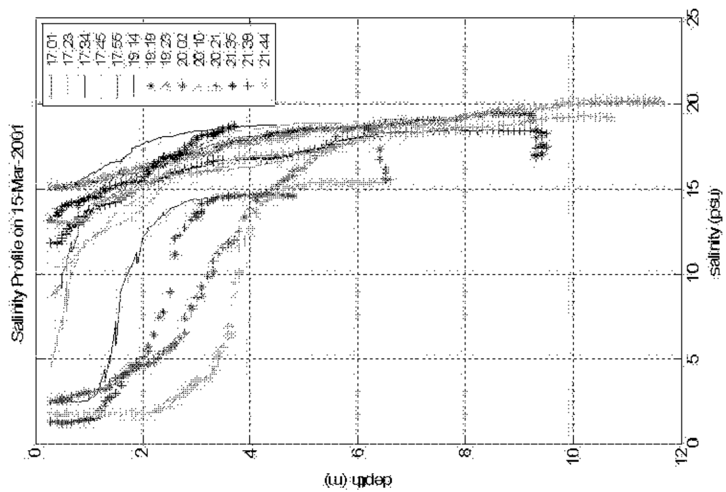

Salinity Profile on 13-Mar-2001
18:51
18:51
19:23
19:49
20:04
20:16
20:38
depth (m)
salinity (psu)
0
1
2
3
4
5
6
7
8
12
14
16
18
20
22

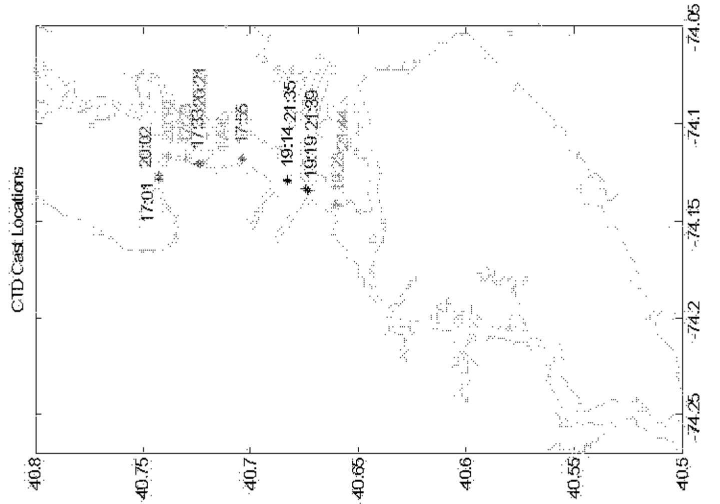

CTD Cast Locations
18:51
19:23
19:49
20:04
20:16
20:38
40.8
40.75
40.7
40.65
40.6
40.55
40.5
-74.25
-74.2
-74.15
-74.1
-74.05

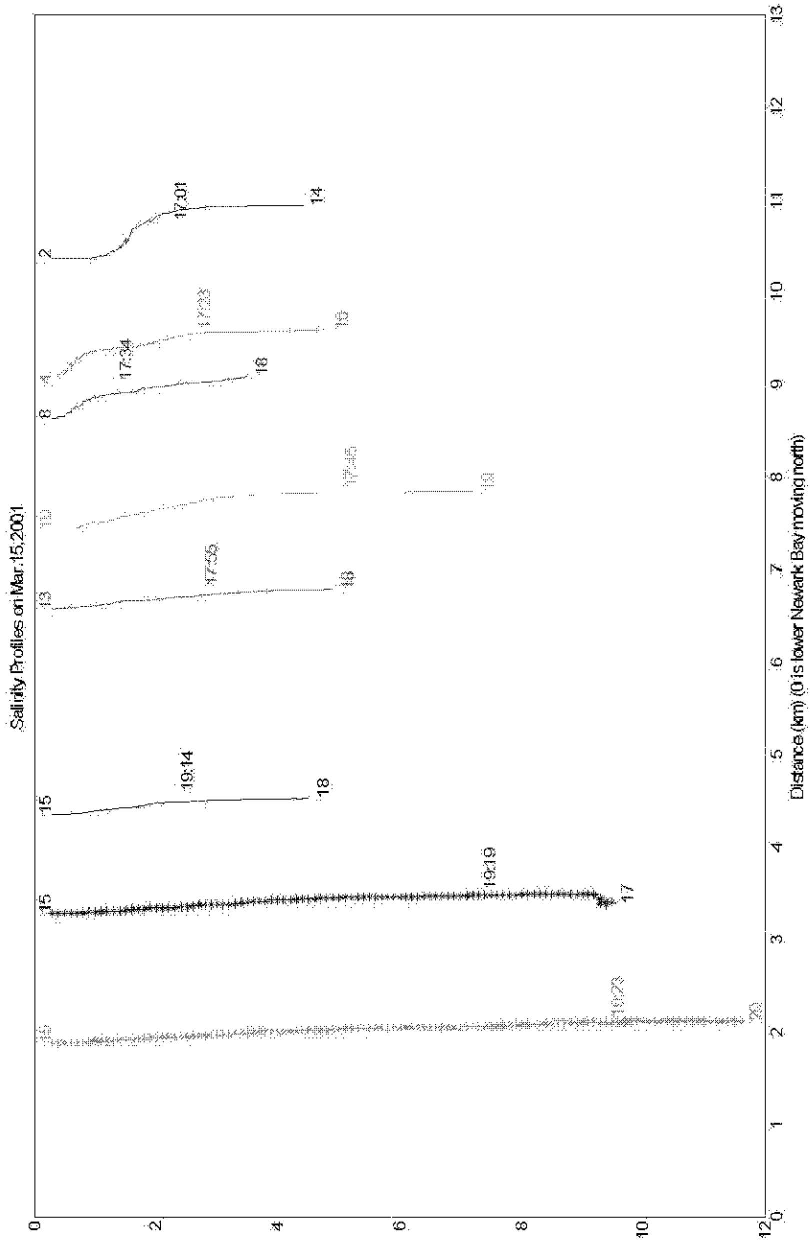

Salinity Profiles on Mar.13,2001
Distance (km) (0 is lower Newark Bay moving north)
Depth (m)
20:38
20:16
20:04
19:23


Salinity Profile on 14-Mar-2001
depth (m)
salinity (psu)
CTD Cast Locations

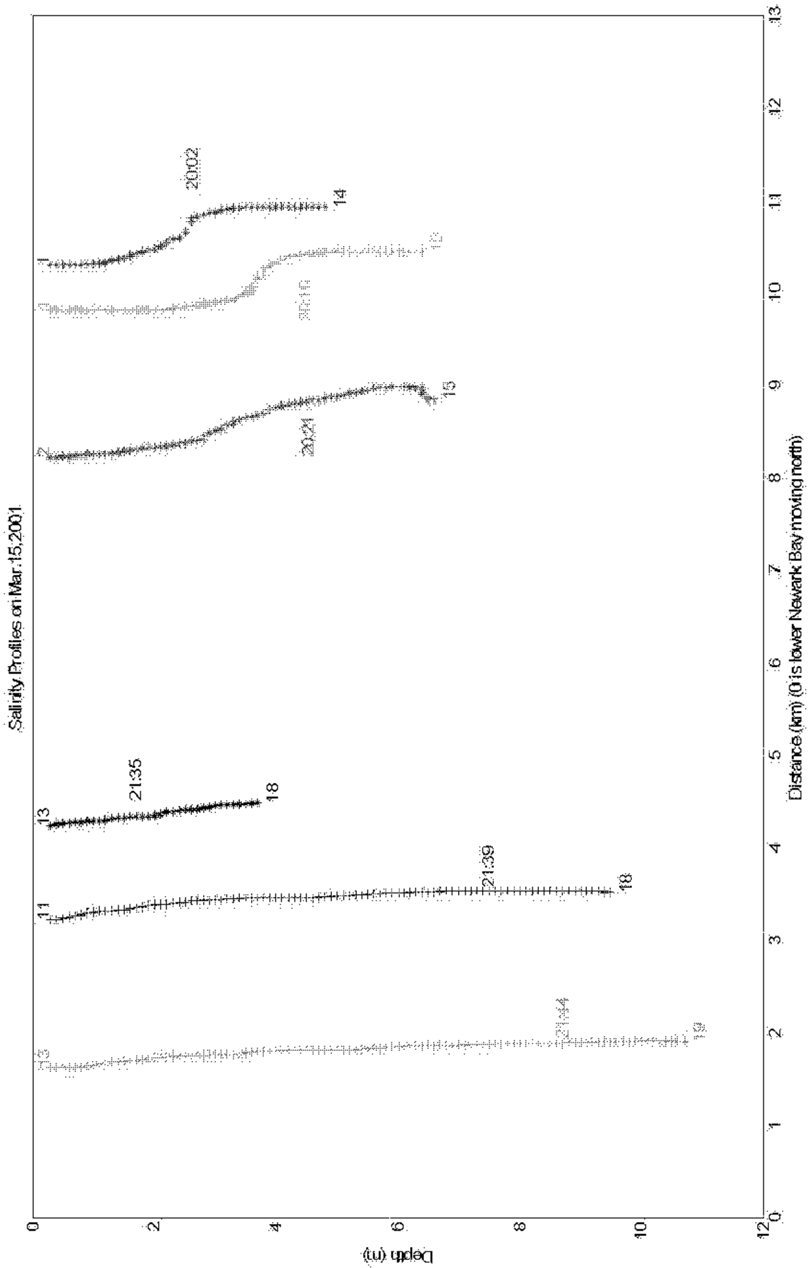

Salinity Profiles on Mar.14,2001
Distance (km) (0 is lower Arthur Kill moving north)
Depth (m)


Salinity Profile on 15-Mar-2001
depth (m)
salinity (psu)
17:01
17:23
17:34
17:45
17:55
19:14
19:19
19:23
20:02
20:10
20:21
21:35
21:39
21:44

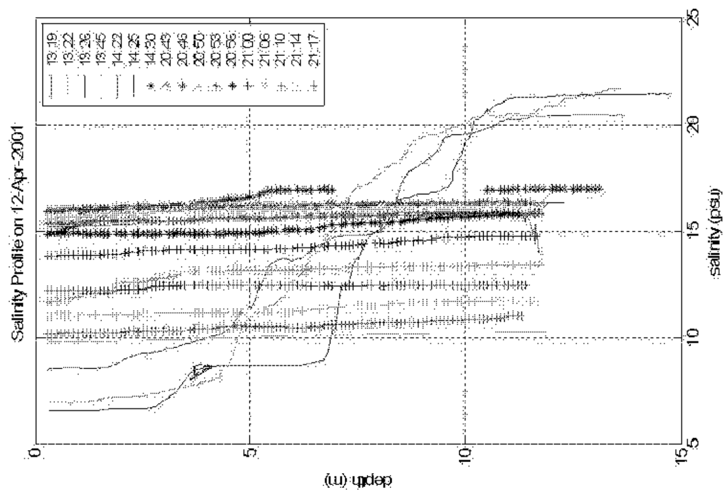

CTD Cast Locations
17:01
20:02
17:33
20:21
17:55
19:14 21:35
19:19 21:39

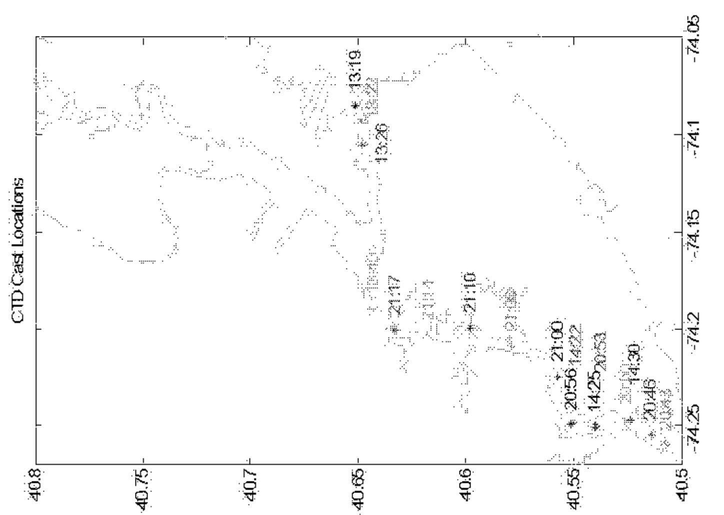

Salinity Profiles on Mar.15,2001
Distance (km) (0 is lower Newark Bay moving north)
Depth (m)
19:23
19:19
19:14
17:55
17:45
17:34
17:23
17:01

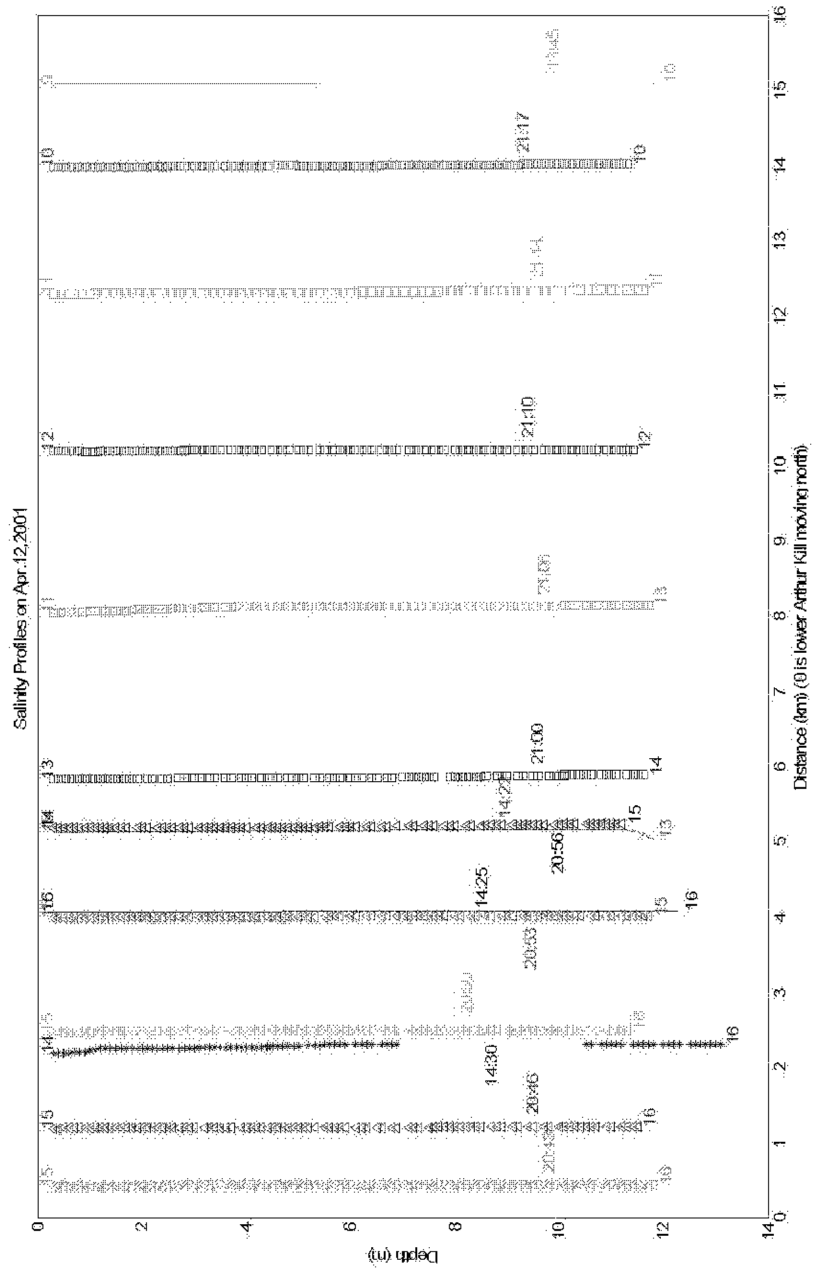
Transect 1


Salinity Profiles on Mar.15,2001
Depth (m)
Distance (km) (0 is lower Newark Bay moving north)
20:02
21:35
21:39
20:24

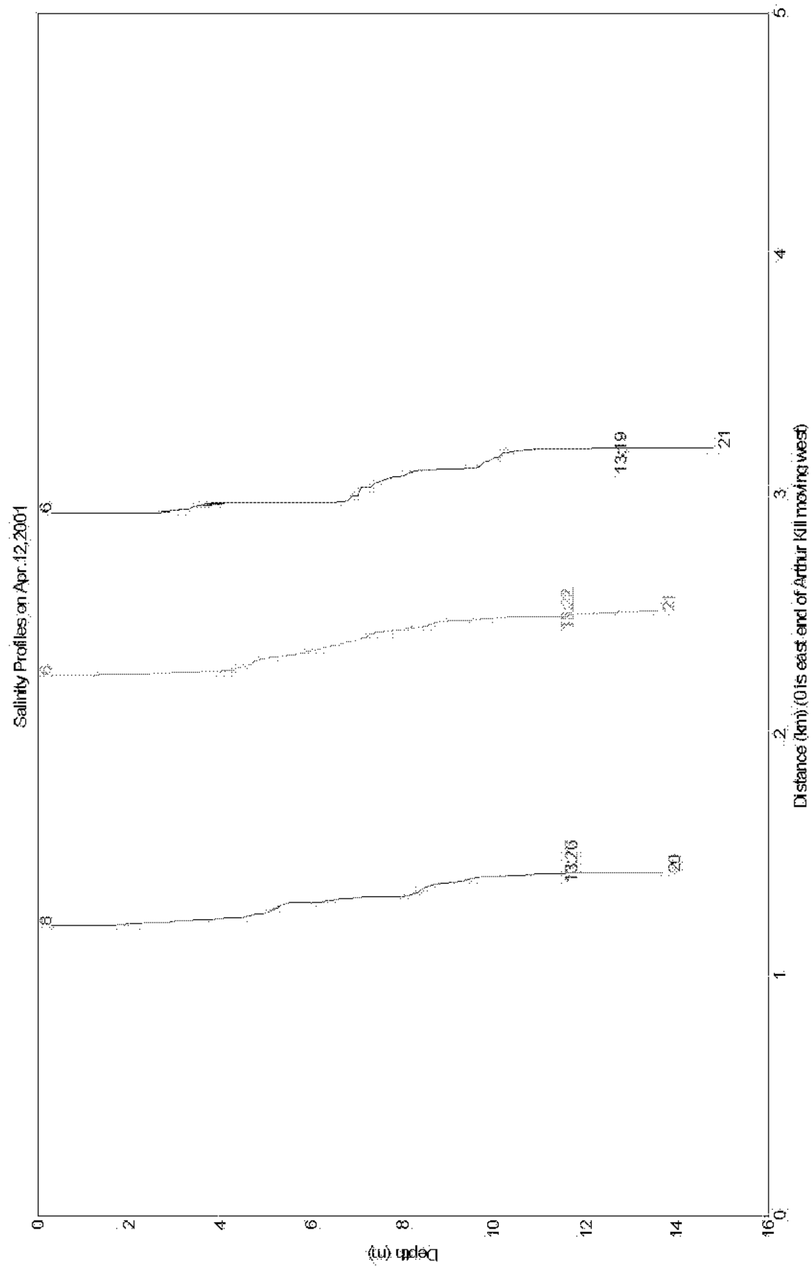
Transect 2


Salinity Profile on 12-Apr-2001
depth (m)
salinity (psu)

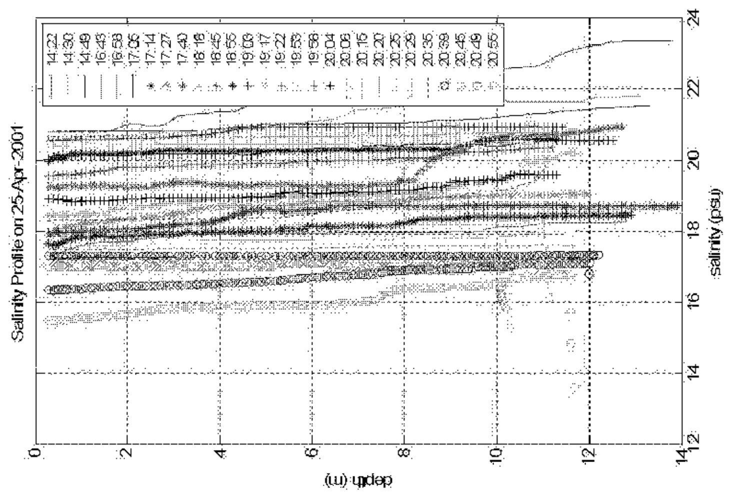

CTD Cast Locations

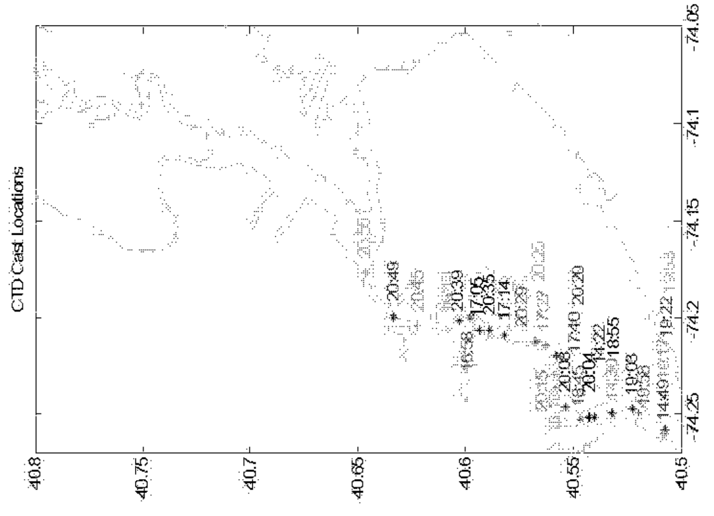


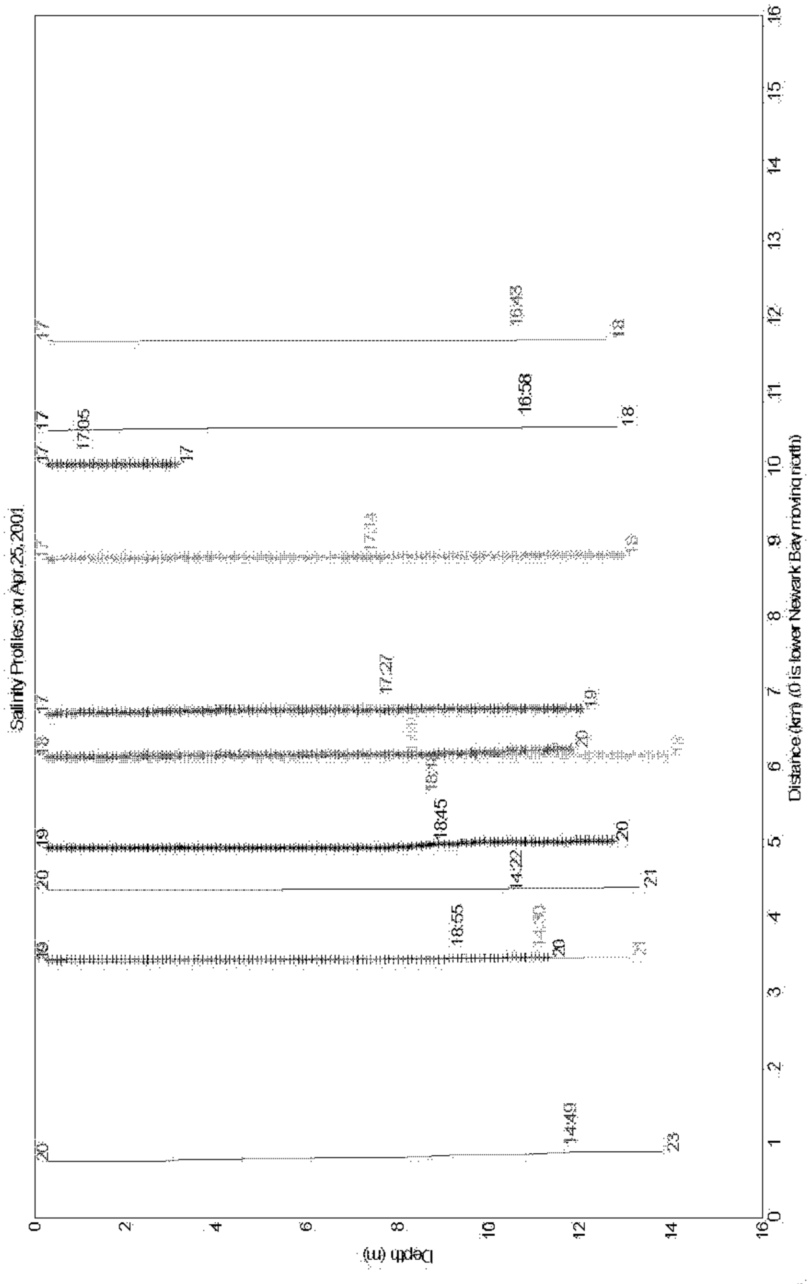
Arthur Kill Transects



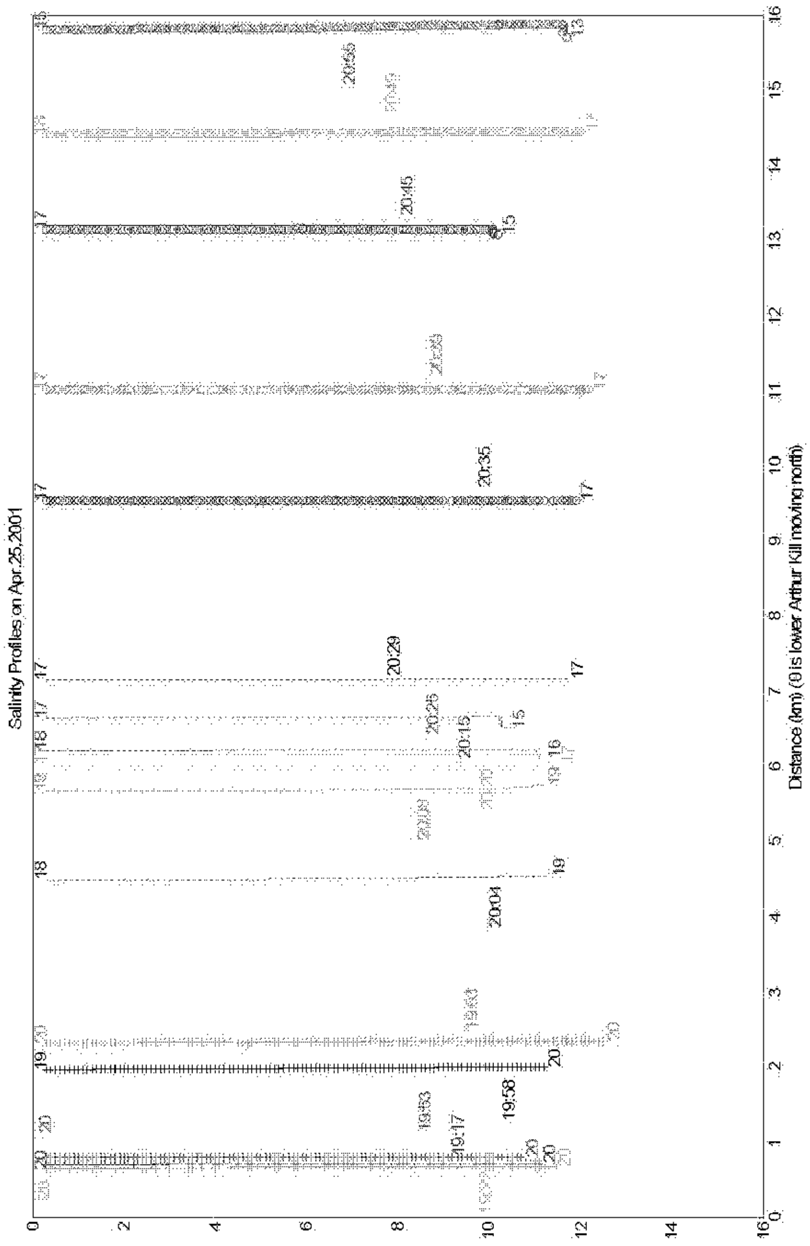
Kill van Kull Transects


Salinity Profile on 25-Apr-2001
depth (m)
salinity (psu)

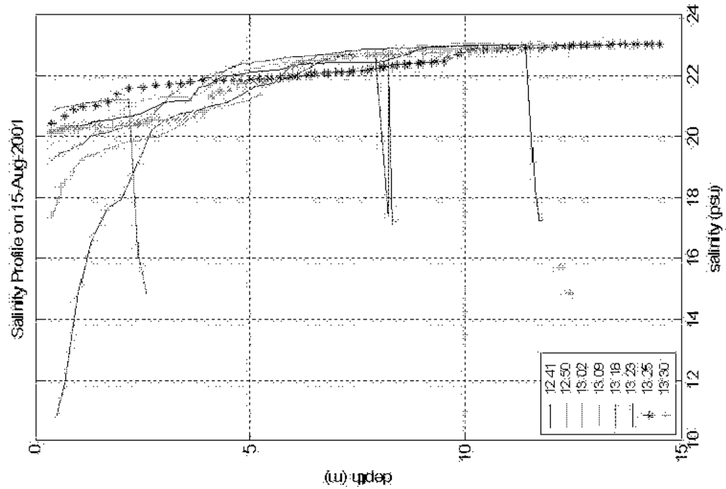

CTD Cast Locations

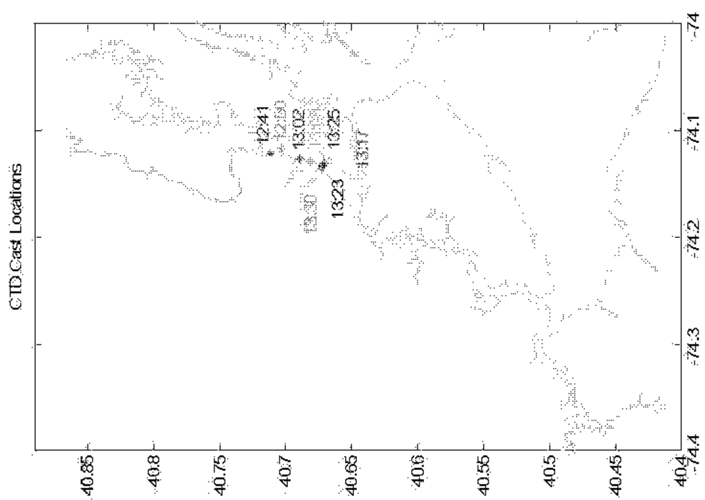

Salinity Profiles on Apr 25,2001
Depth (m)
Distance (km) (0 is lower Newark Bay moving north)

Transect 1

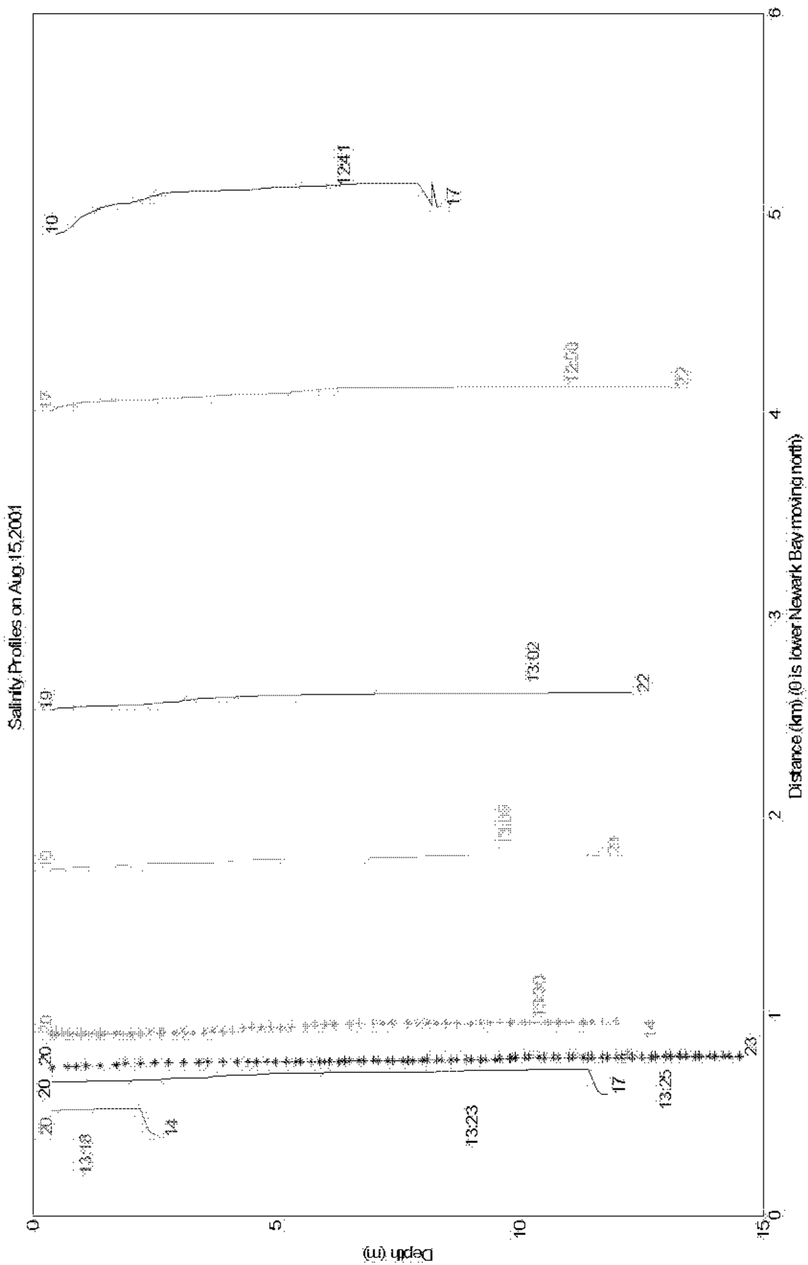

Salinity Profiles on Apr. 25,2001
Depth (m)
Distance (km) (0 is lower Arthur Kill moving north)

Transect 2





Transect 1 Note: Transects were split between 2 vessels on August 15, 2001. These transects were taken from the R/V Phoenix.



Transect 1 Note: Transects were split between 2 vessels on August 15, 2001. These transects were taken from the R/V Phoenix.

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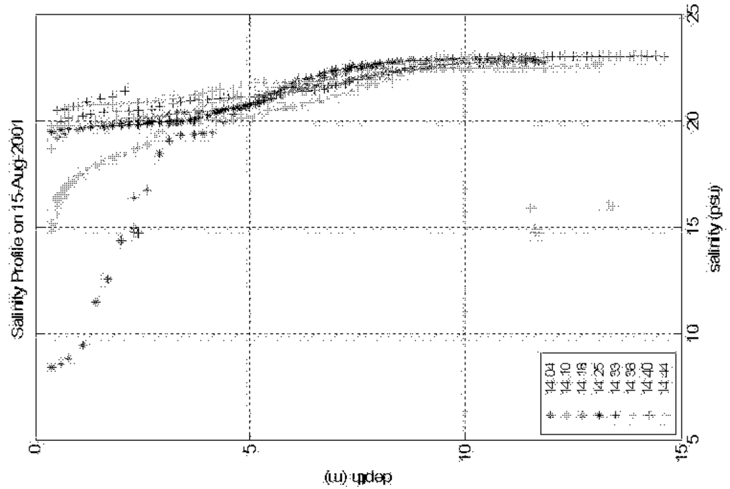
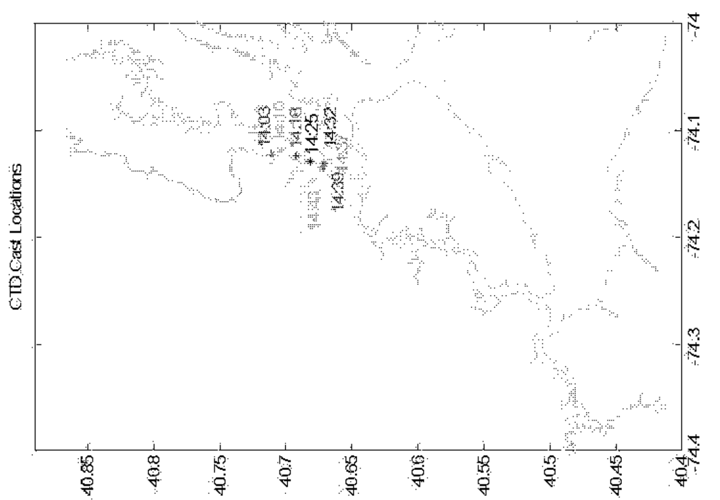
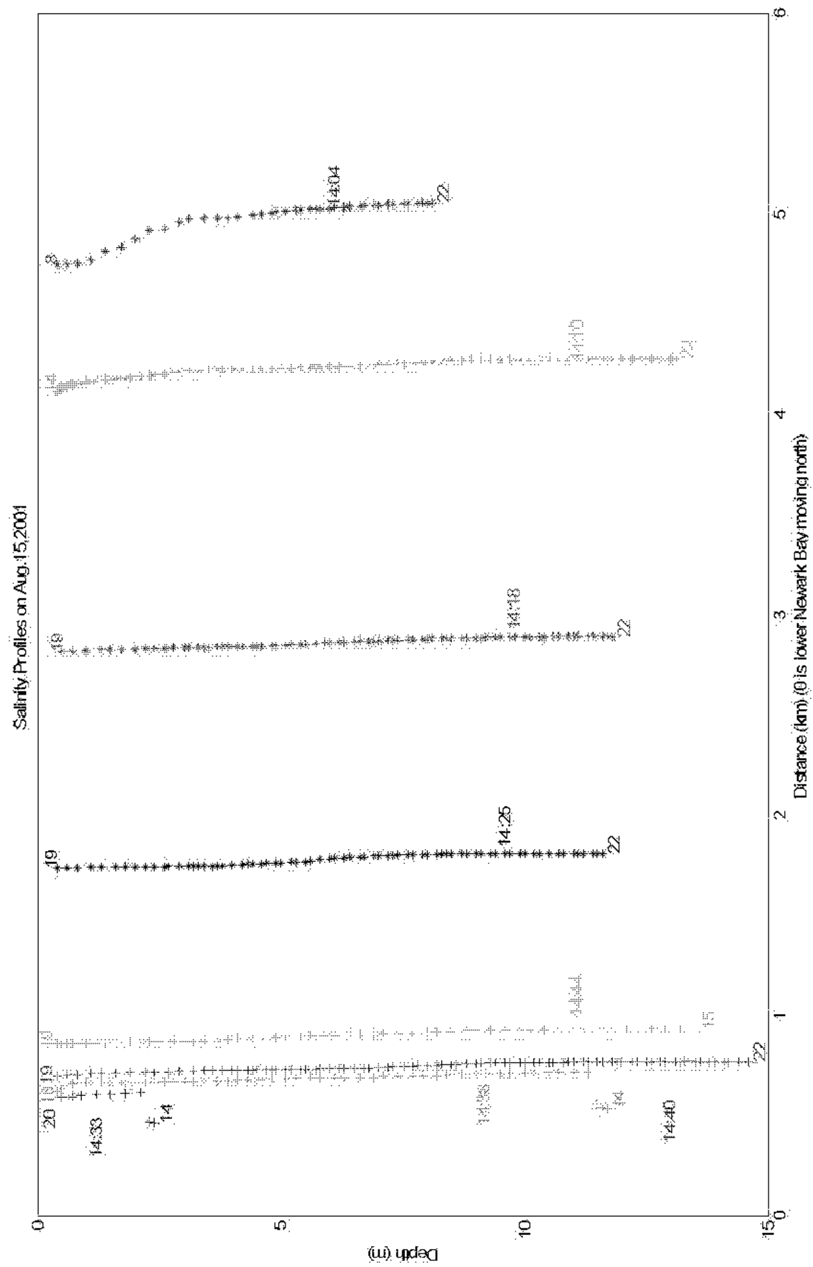
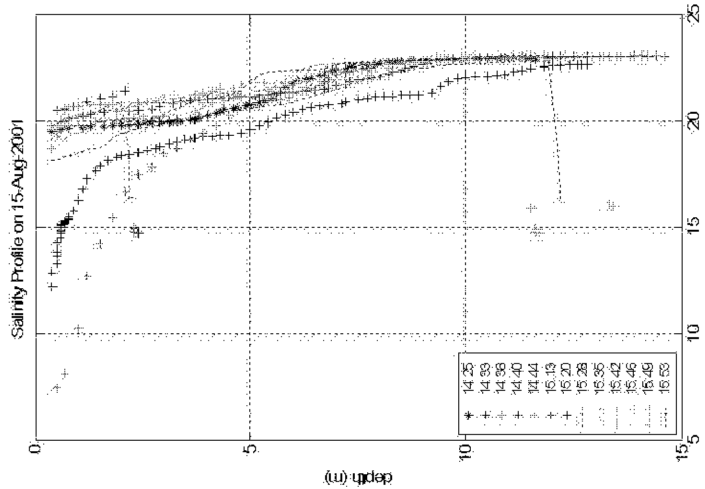


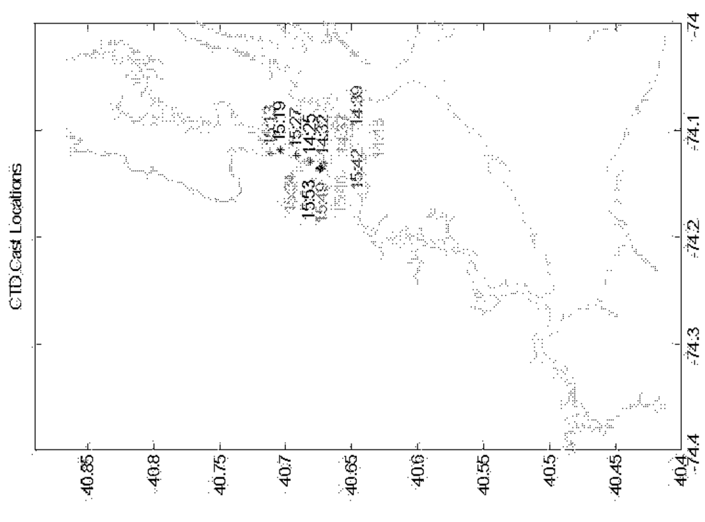


Transect 2 Note: Transects were split between 2 vessels on August 15, 2001. These transects were taken from the R/V Phoenix.

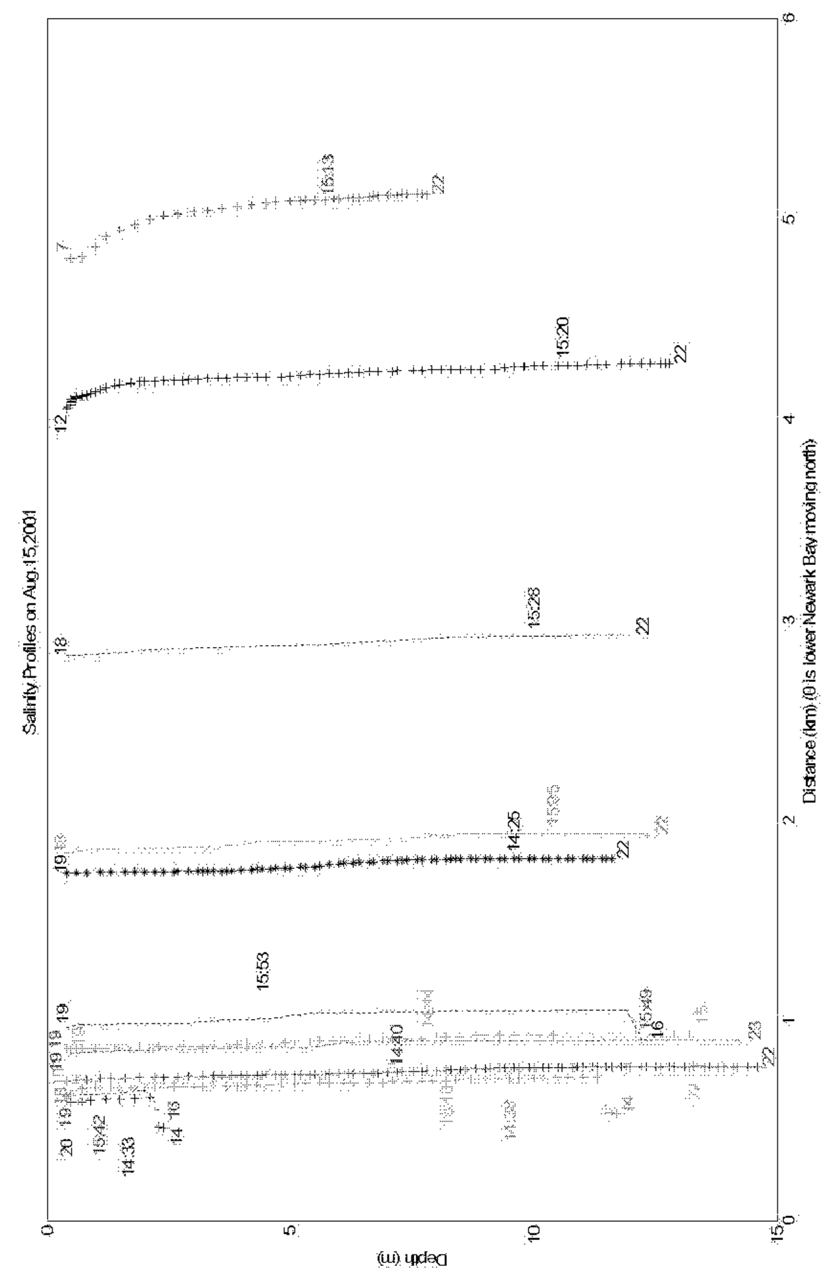


Transect 2 Note: Transects were split between 2 vessels on August 15, 2001. These transects were taken from the R/V Phoenix.

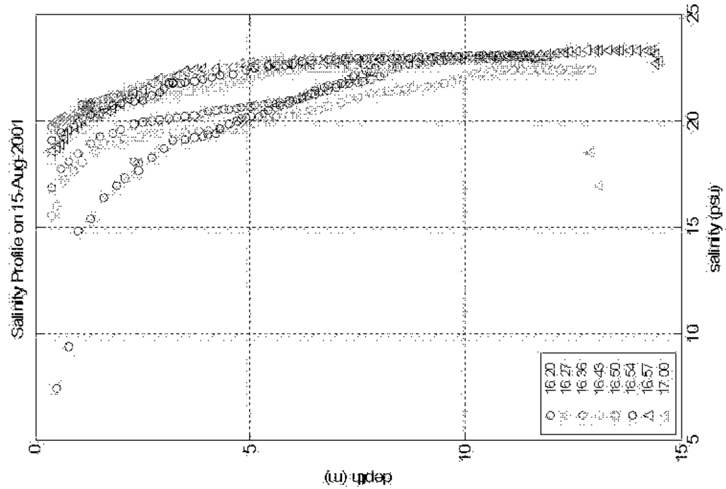


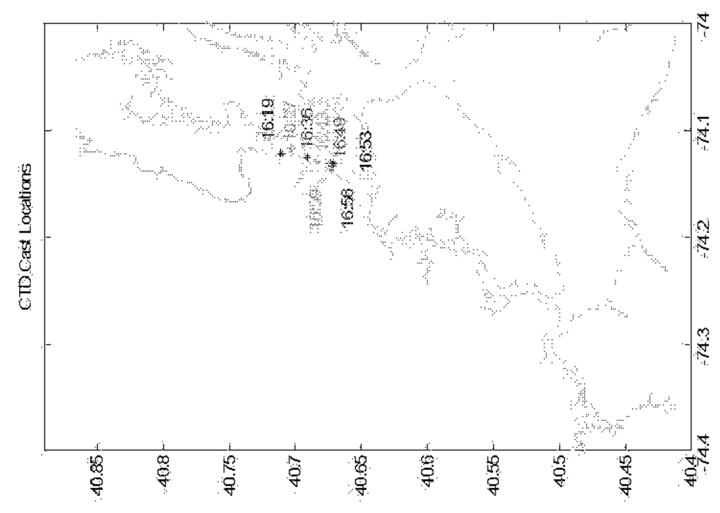


Transect 3 Note: Transects were split between 2 vessels on August 15, 2001. These transects were taken from the R/V Phoenix.

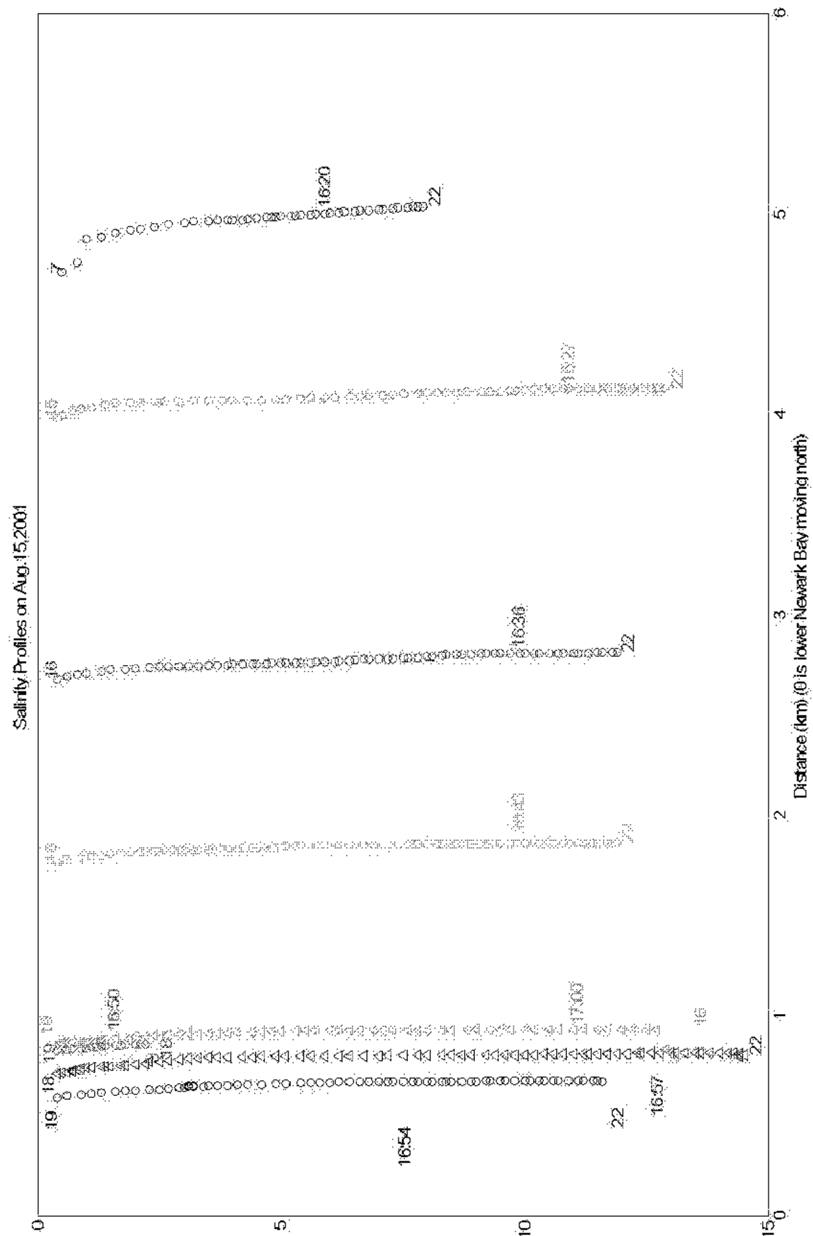


Transect 3 Note: Transects were split between 2 vessels on August 15, 2001. These transects were taken from the R/V Phoenix.

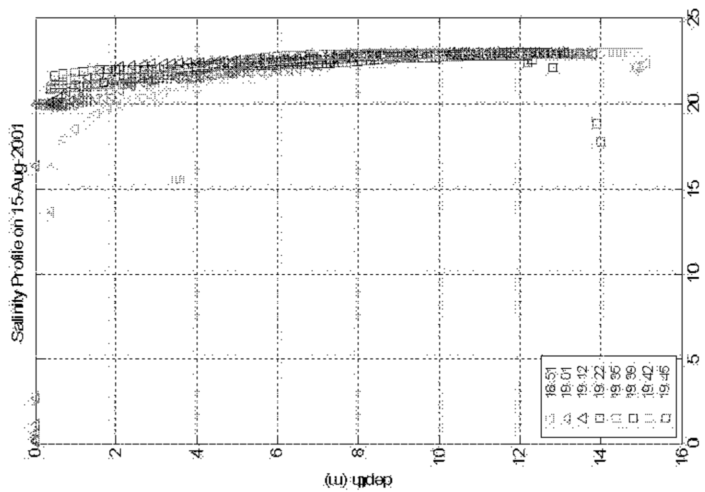


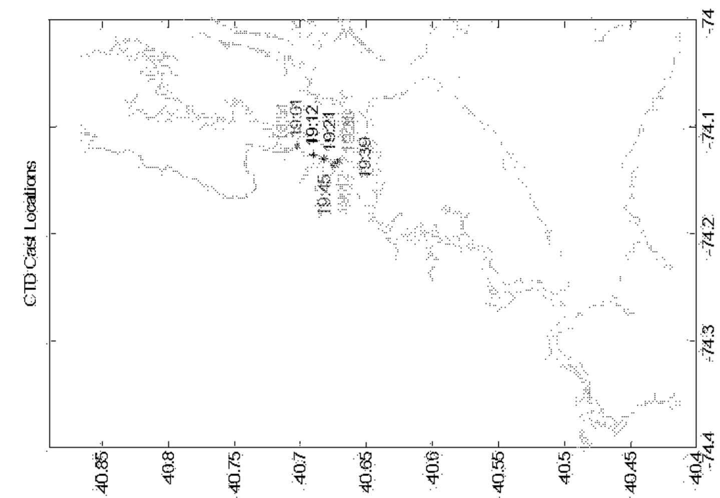


Transect 4 Note: Transects were split between 2 vessels on August 15, 2001. These transects were taken from the R/V Phoenix.

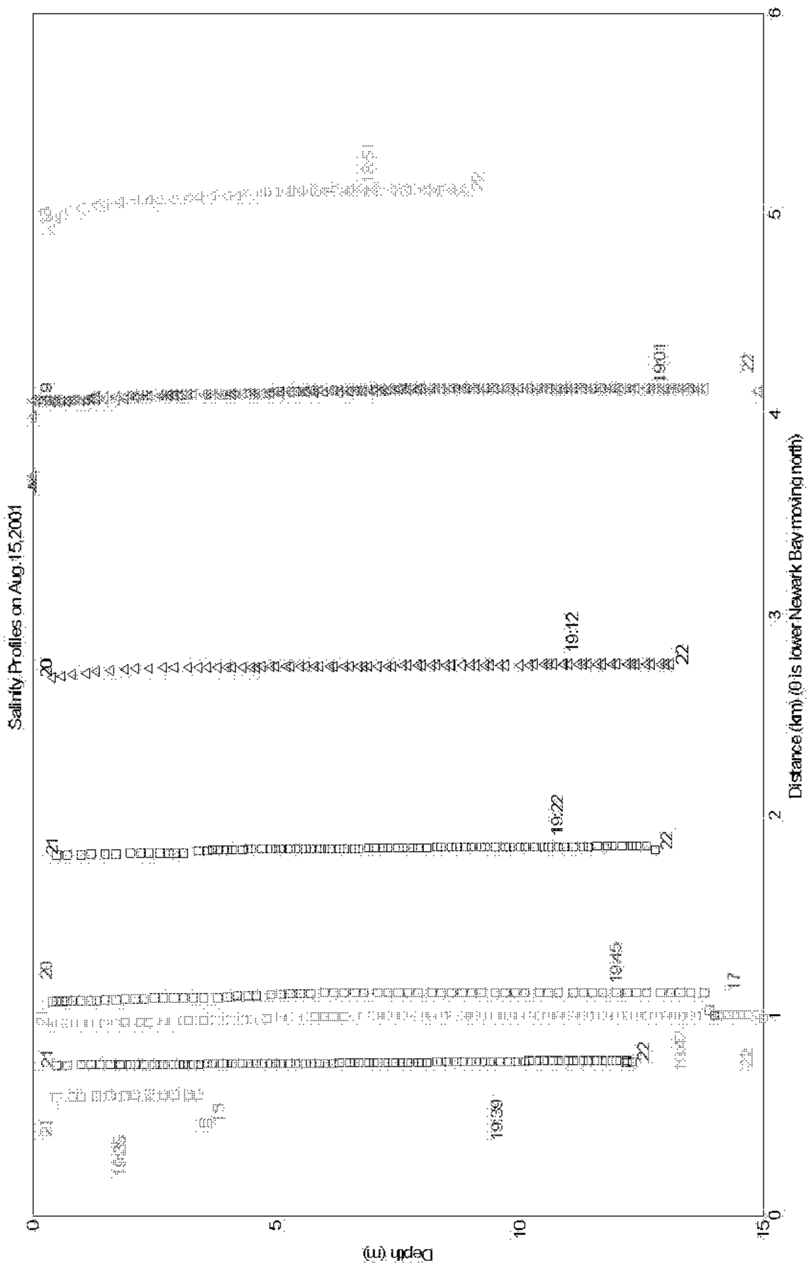


Transect 4 Note: Transects were split between 2 vessels on August 15, 2001. These transects were taken from the R/V Phoenix.

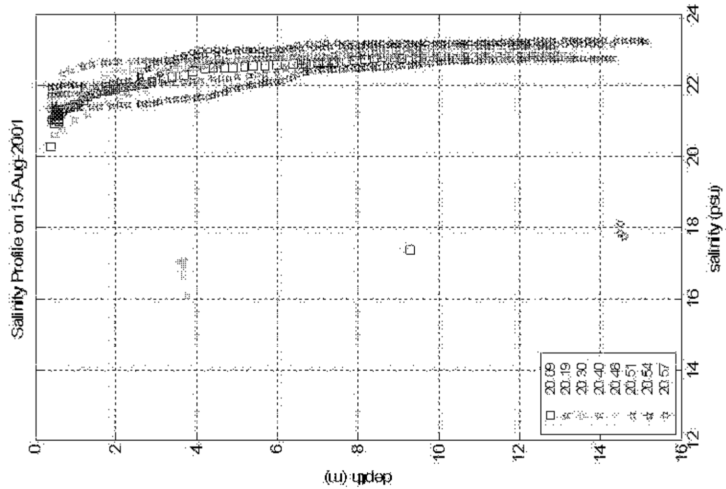

Salinity Profile on 15-Aug-2001
salinity (psu)
depth (m)
18:51
19:01
19:12
19:22
19:36
19:39
19:42
19:45

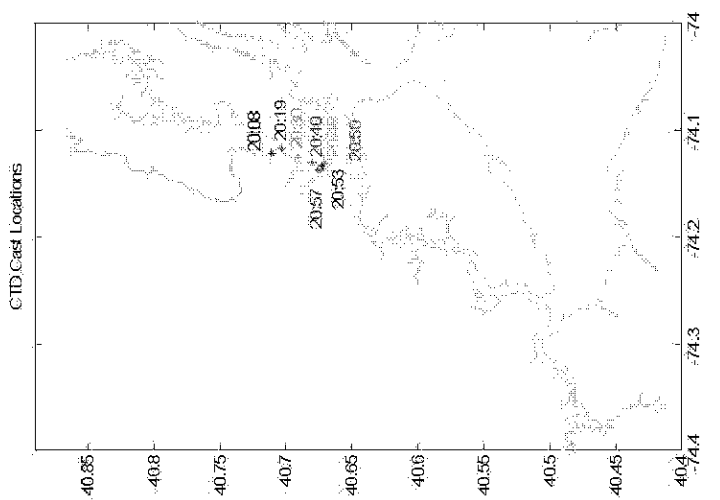

CTD Cast Locations
19:01
19:12
19:21
19:39
19:45

Transect 6 (Transect 5 data was not recovered from the instrument) Note: Transects were split between 2 vessels on August 15, 2001. These transects were taken from the R/V Phoenix.

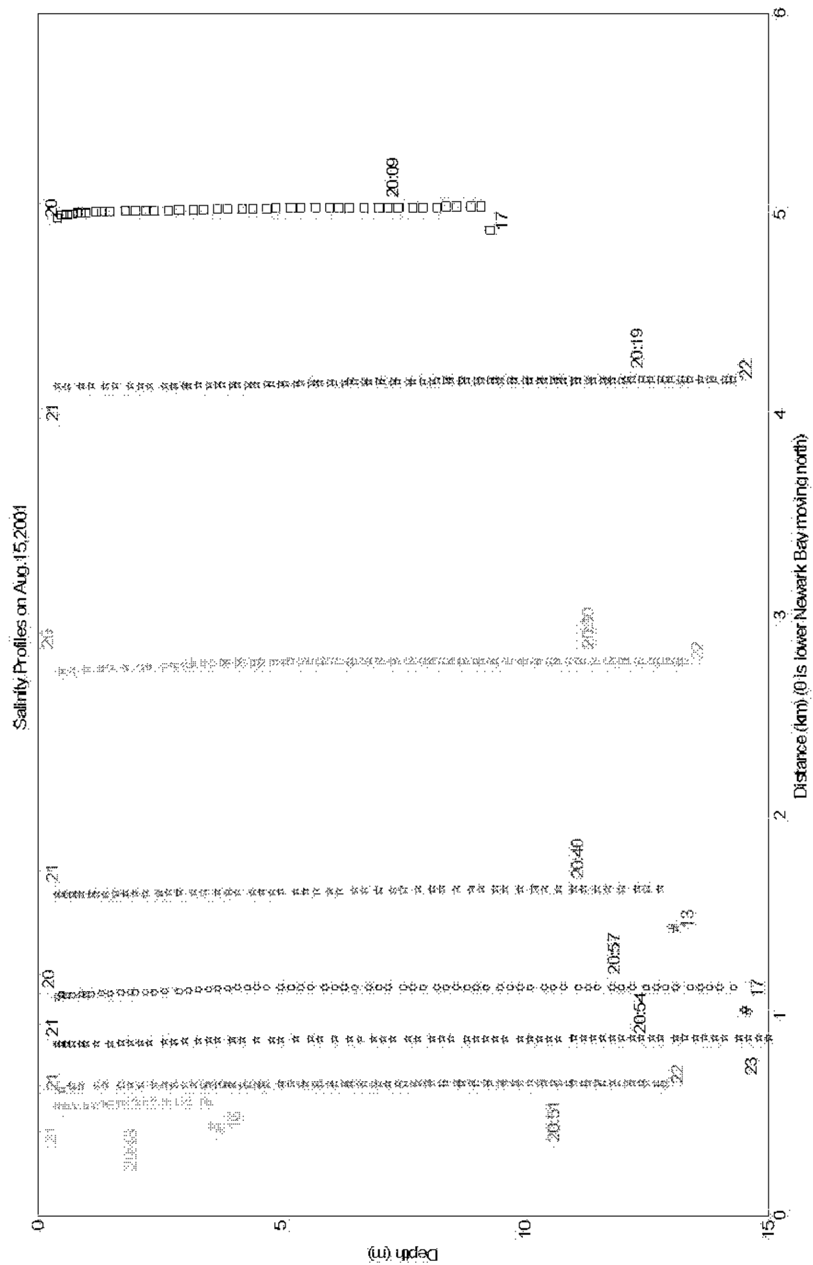


Transect 6 Note: Transects were split between 2 vessels on August 15, 2001. These transects were taken from the R/V Phoenix.

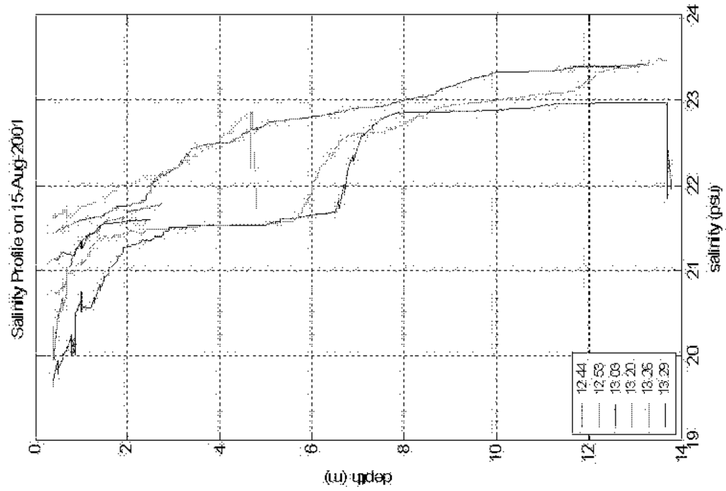


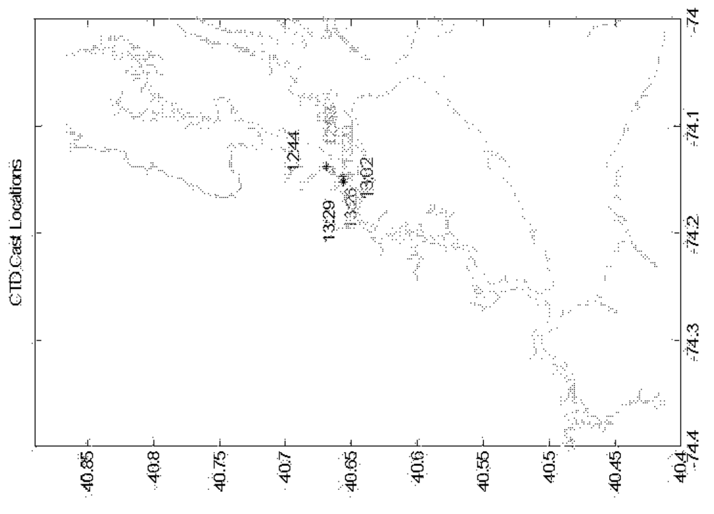


Transect 7 Note: Transects were split between 2 vessels on August 15, 2001. These transects were taken from the R/V Phoenix.

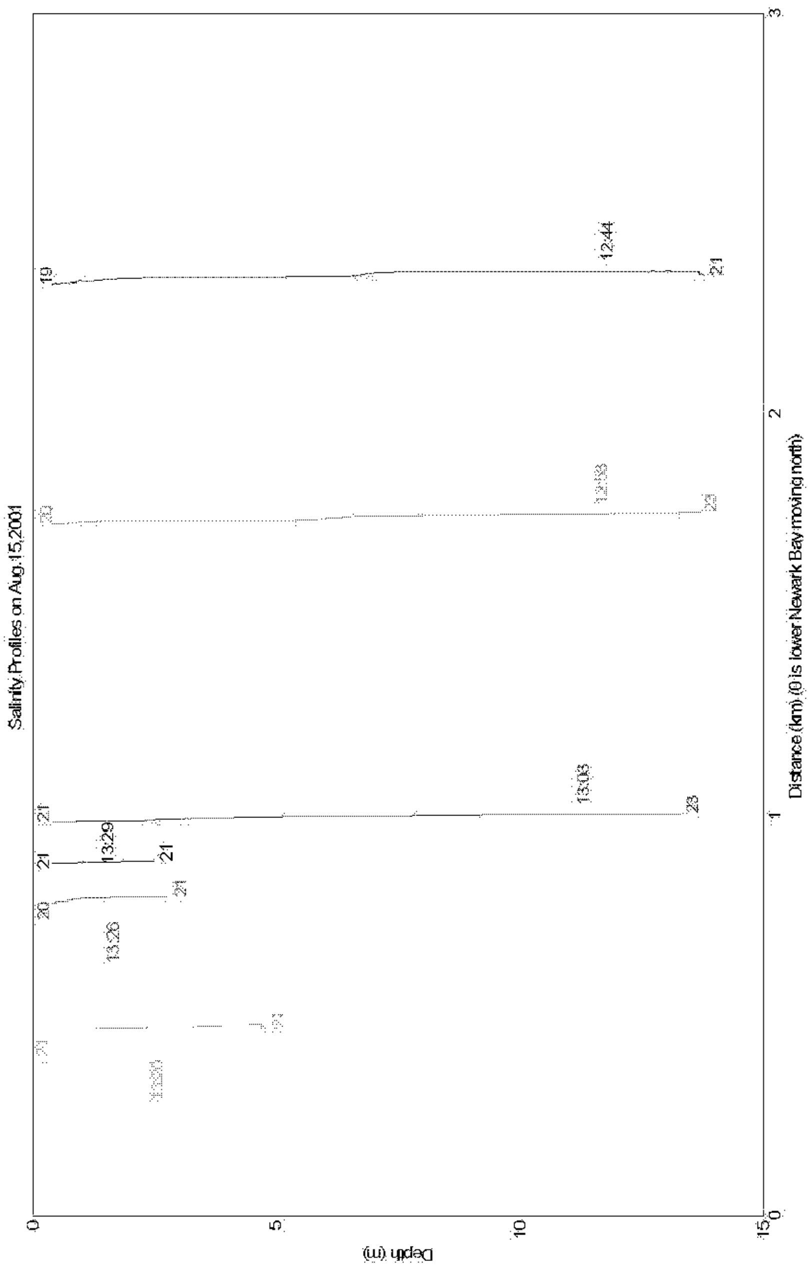


Transect 7 Note: Transects were split between 2 vessels on August 15, 2001. These transects were taken from the R/V Phoenix.

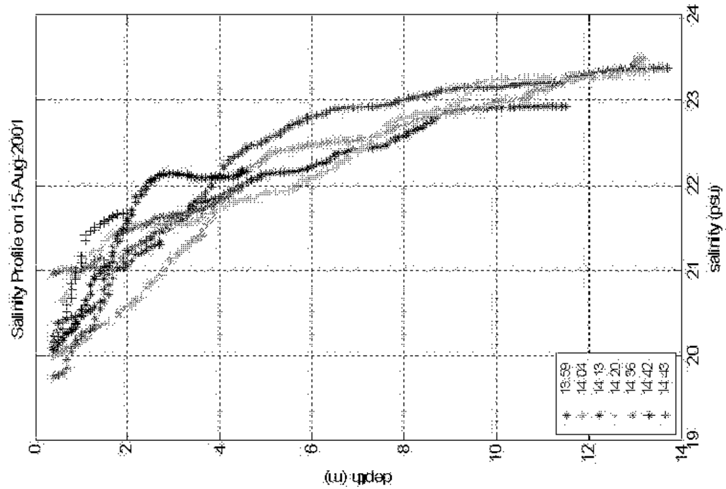


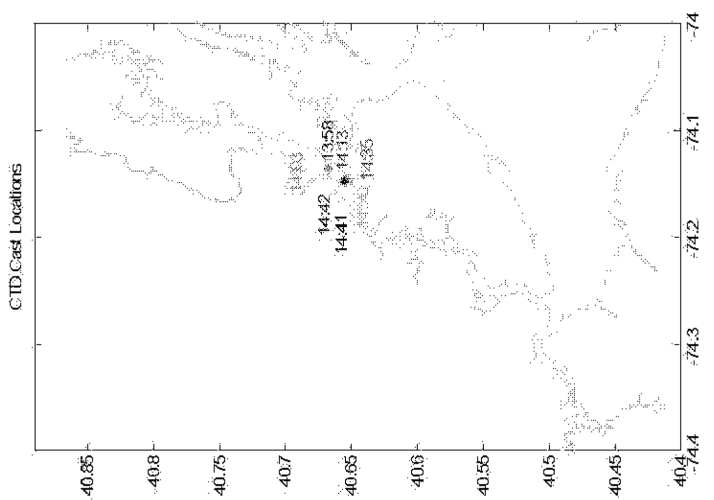


Transect 1 Note: Transects were split between 2 vessels on August 15, 2001. These transects were taken from the R/V Deep Explorer.

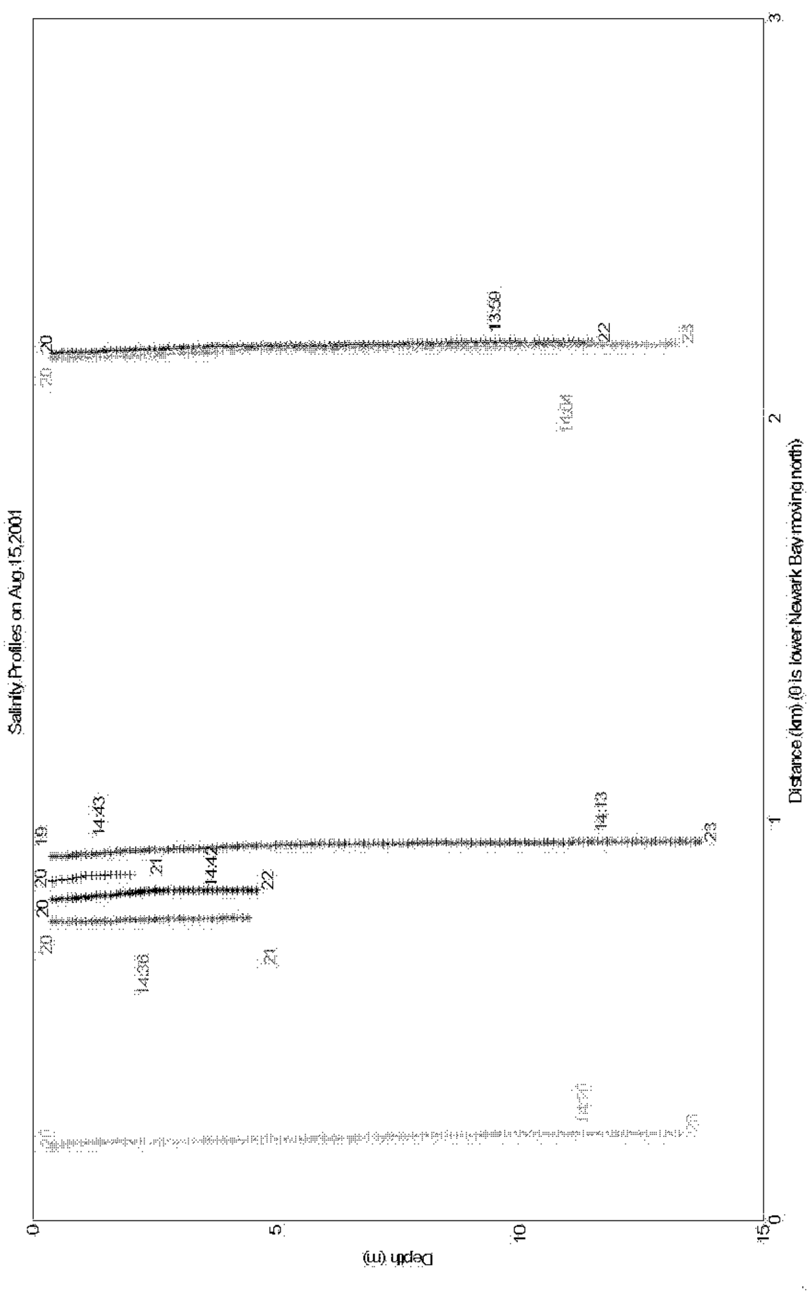


Transect 1 Note: Transects were split between 2 vessels on August 15, 2001. These transects were taken from the R/V Deep Explorer.

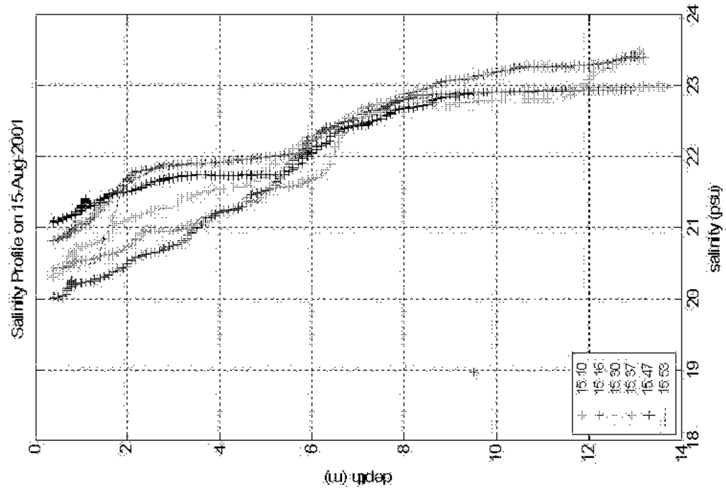


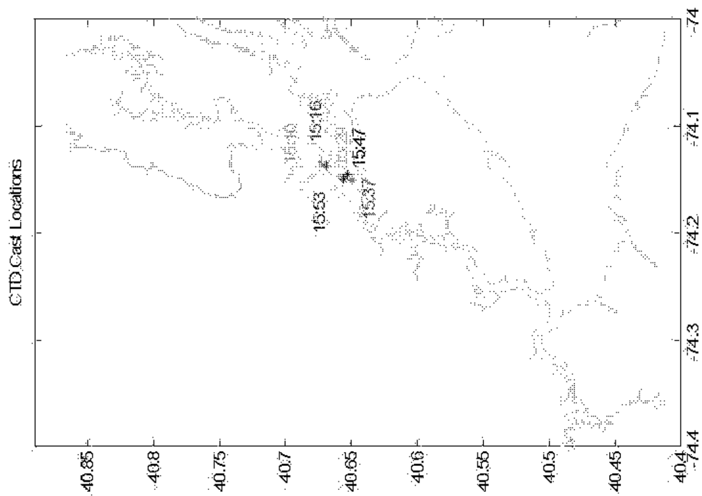


Transect 2 Note: Transects were split between 2 vessels on August 15, 2001. These transects were taken from the R/V Deep Explorer.

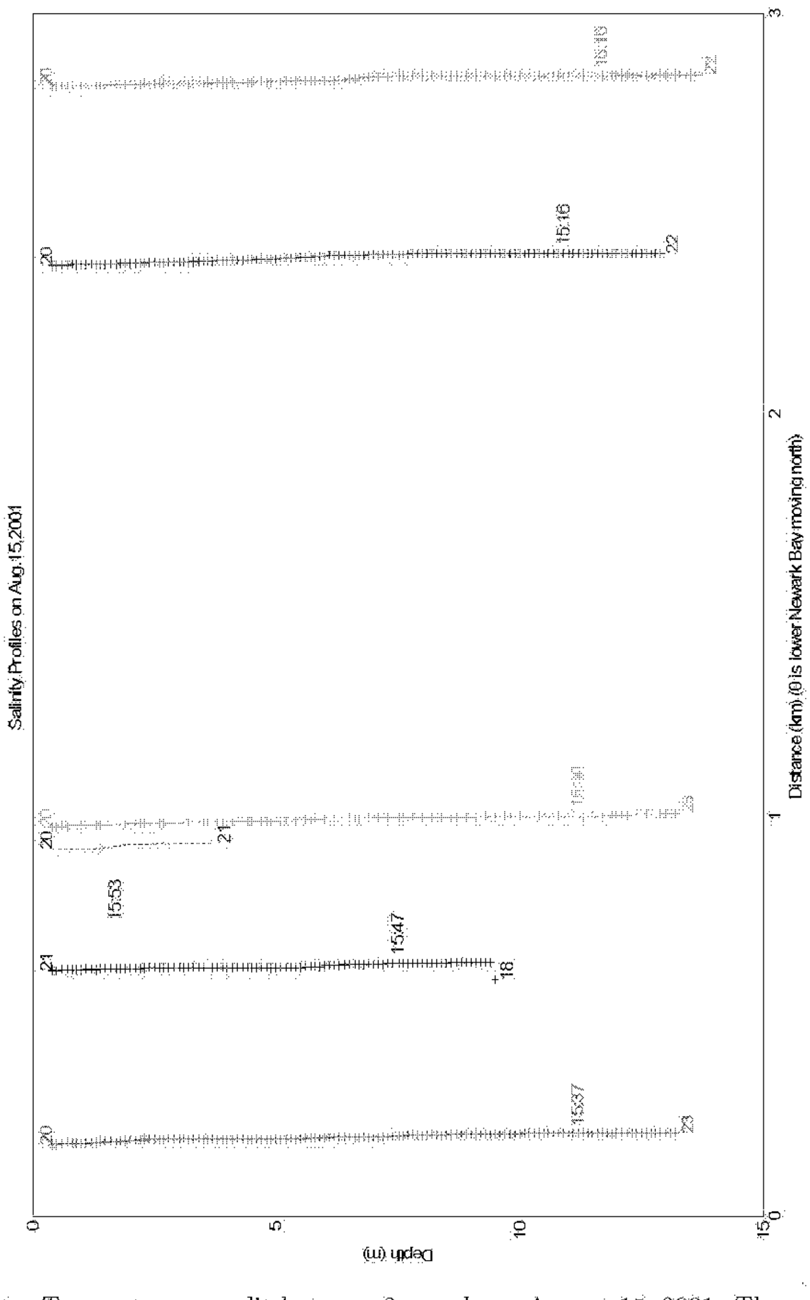


Transect 2 Note: Transects were split between 2 vessels on August 15, 2001. These transects were taken from the R/V Deep Explorer.

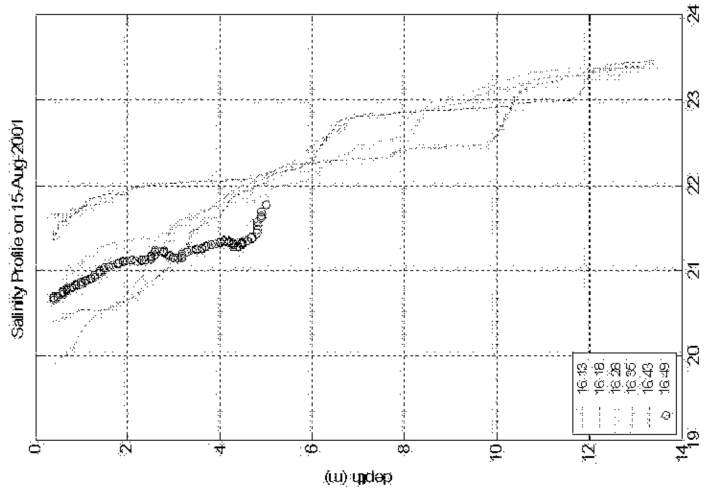


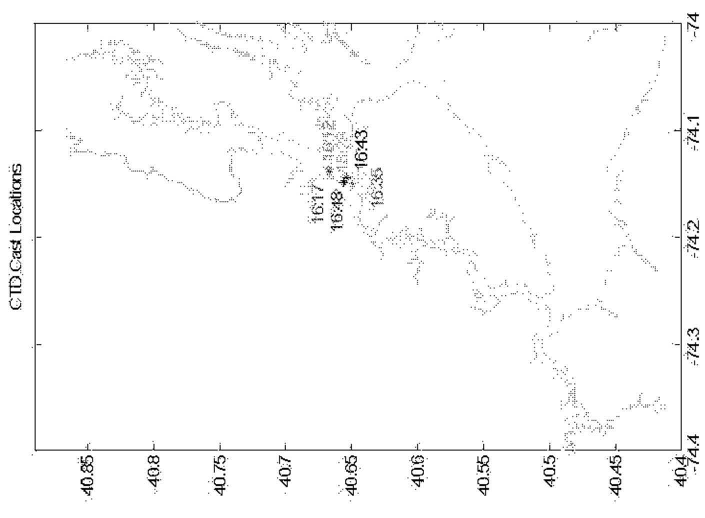


Transect 3 Note: Transects were split between 2 vessels on August 15, 2001. These transects were taken from the R/V Deep Explorer.

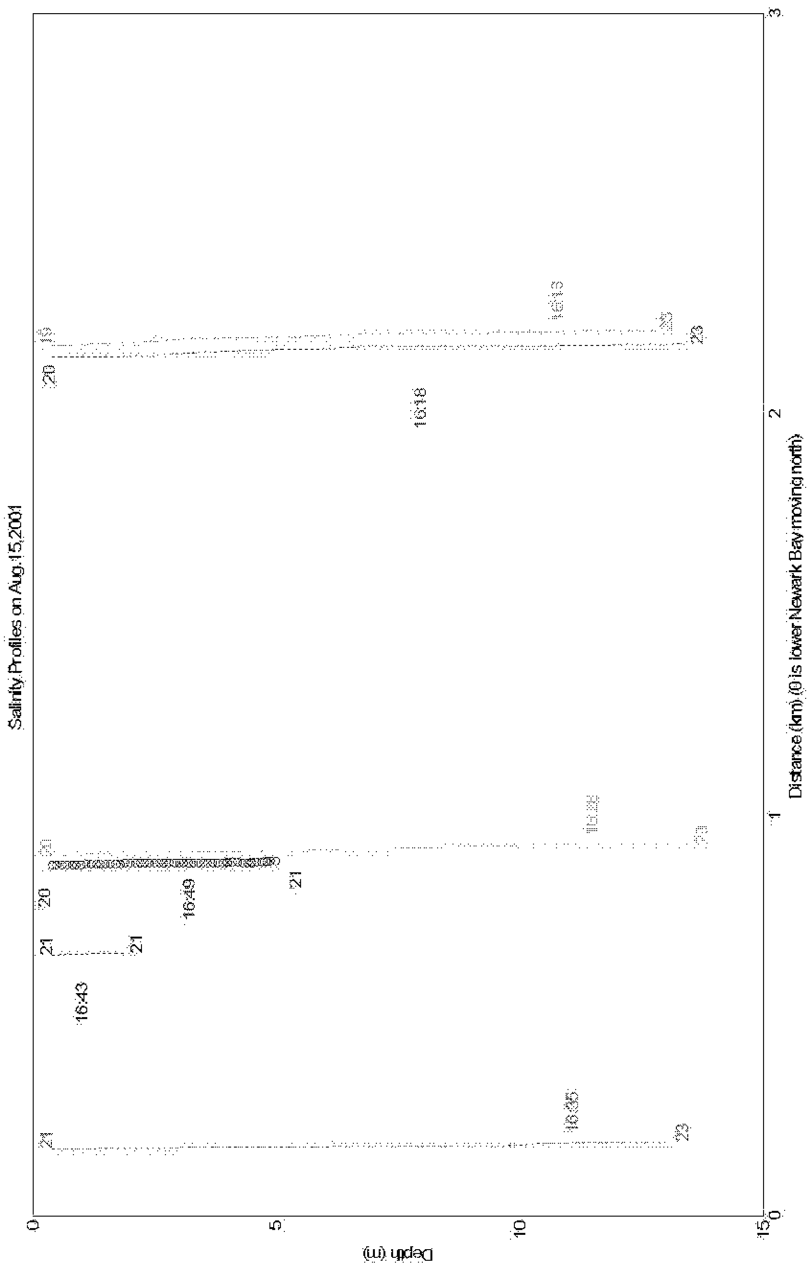


Transect 3 Note: Transects were split between 2 vessels on August 15, 2001. These transects were taken from the R/V Deep Explorer.

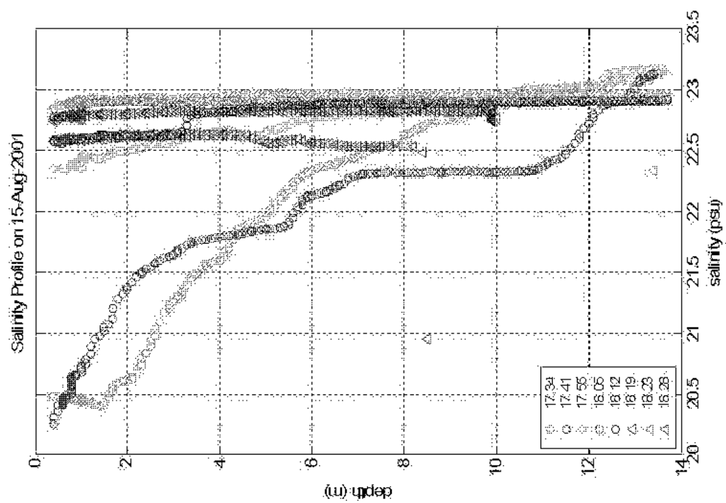


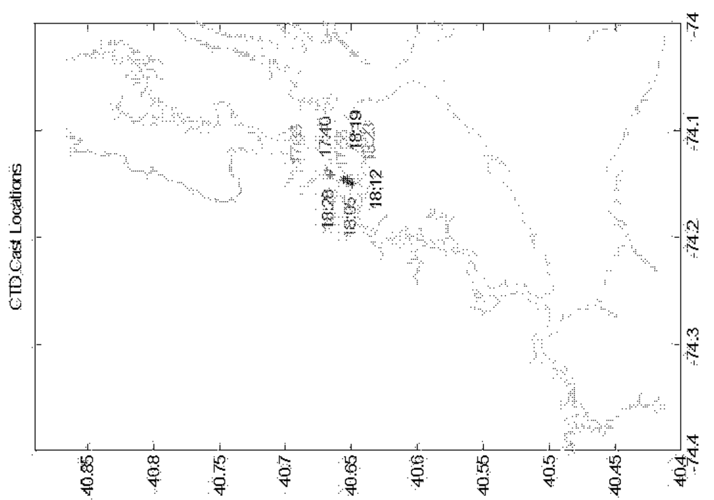


Transect 4 Note: Transects were split between 2 vessels on August 15, 2001. These transects were taken from the R/V Deep Explorer.

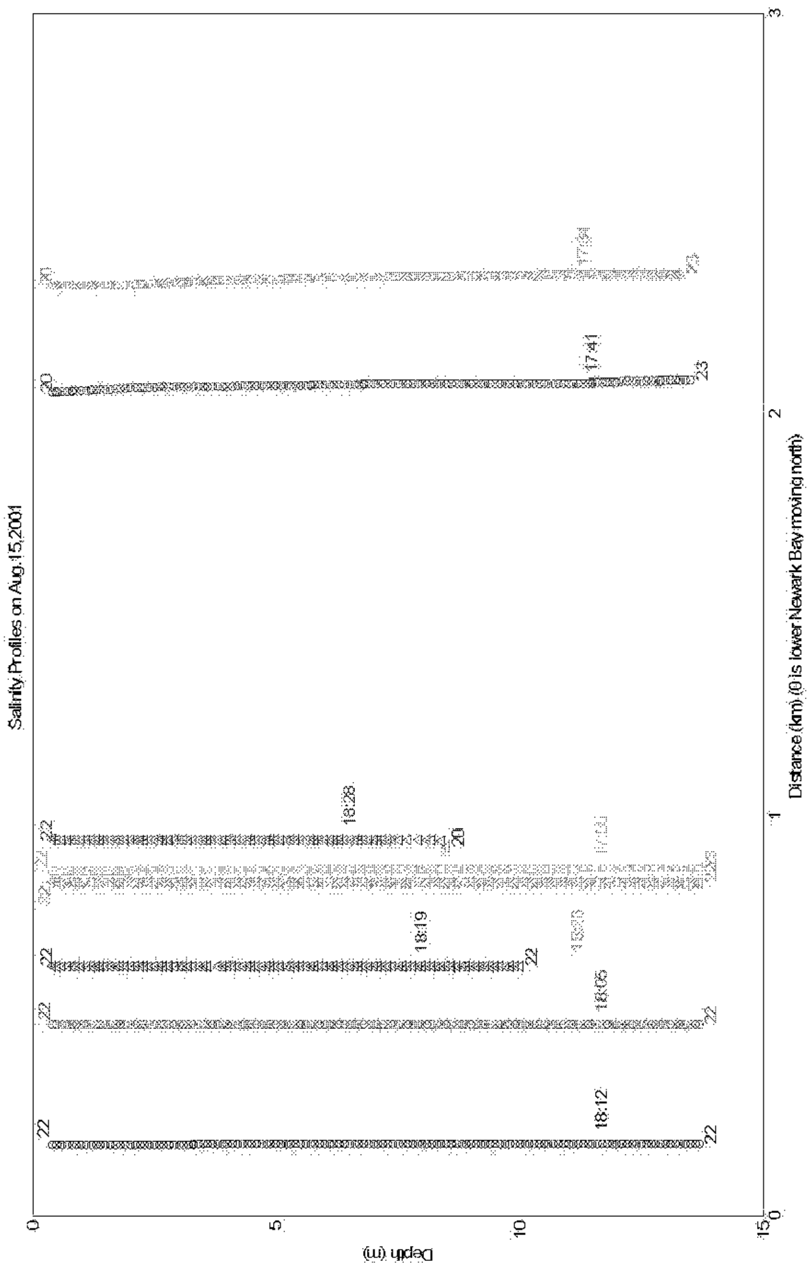


Transect 4 Note: Transects were split between 2 vessels on August 15, 2001. These transects were taken from the R/V Deep Explorer.

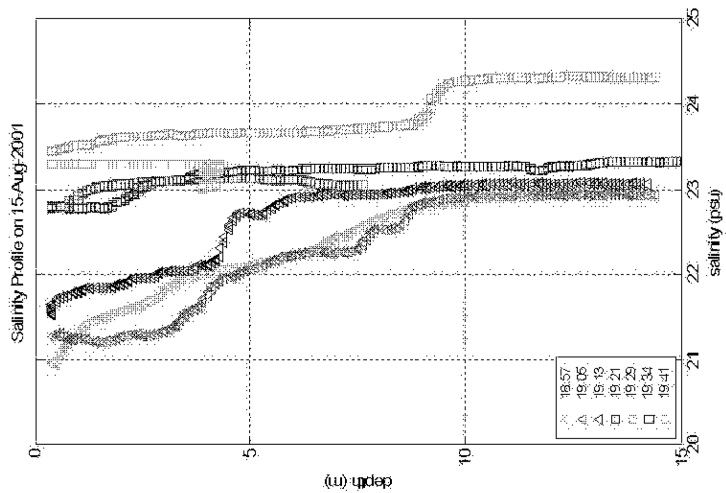


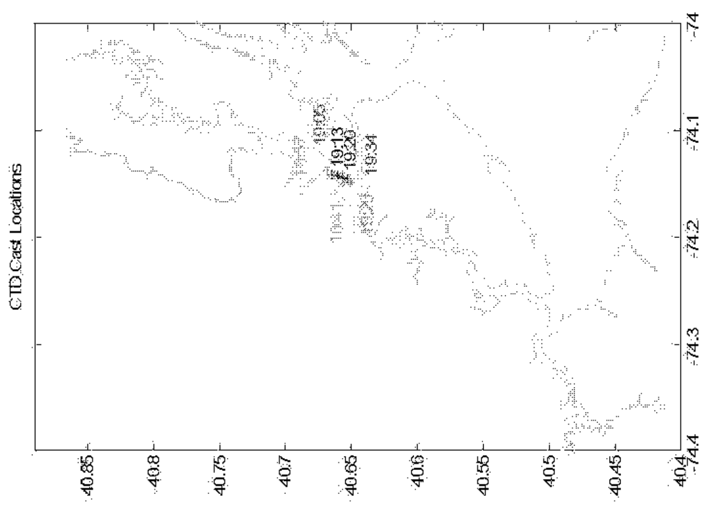


Transect 5 Note: Transects were split between 2 vessels on August 15, 2001. These transects were taken from the R/V Deep Explorer.

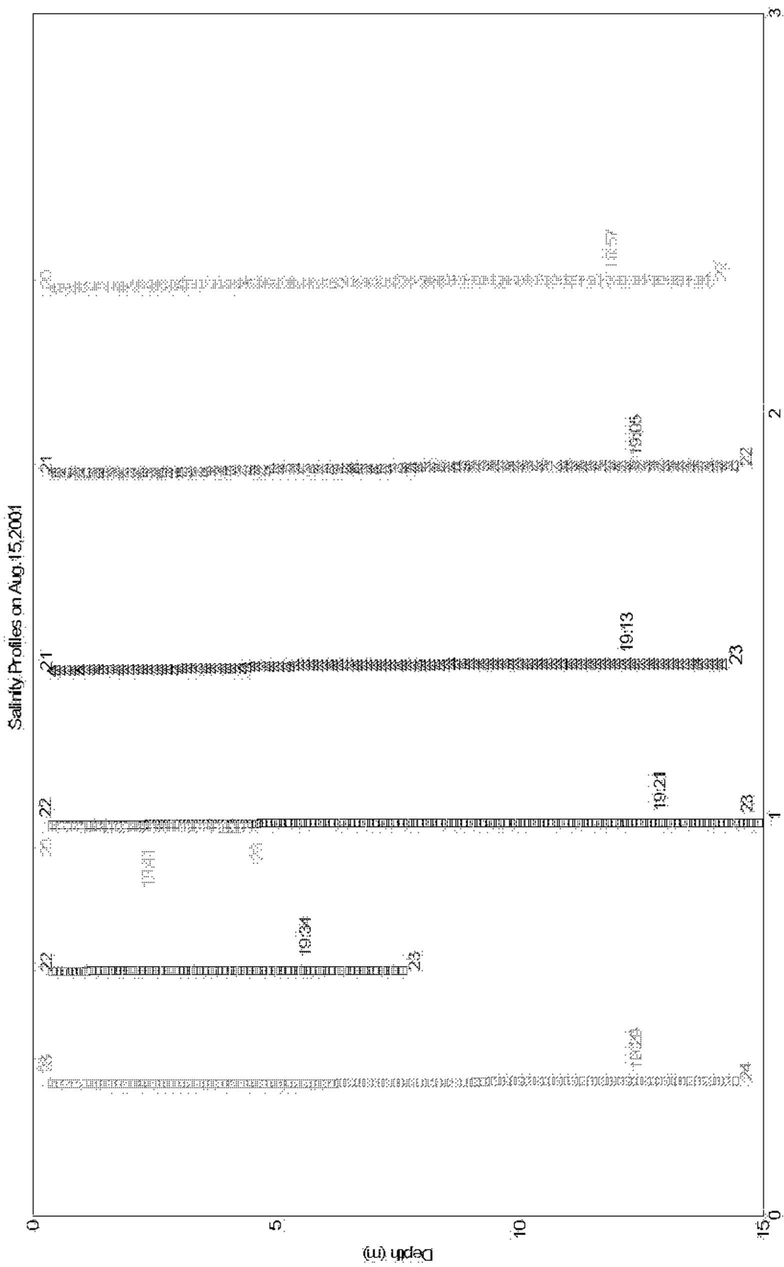


Transect 5 Note: Transects were split between 2 vessels on August 15, 2001. These transects were taken from the R/V Deep Explorer.

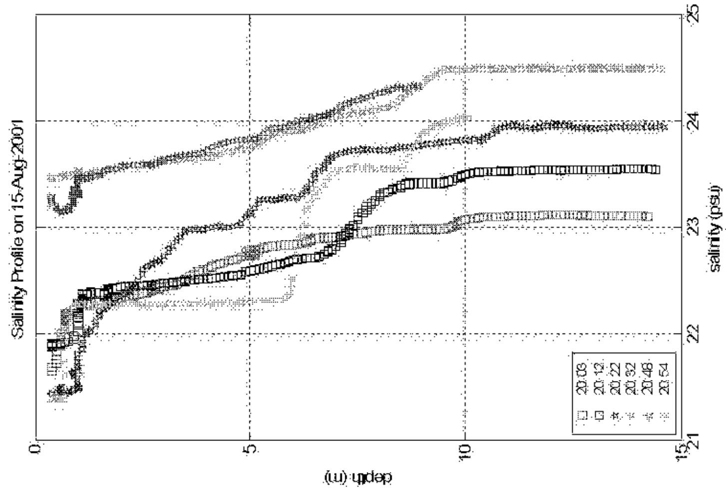


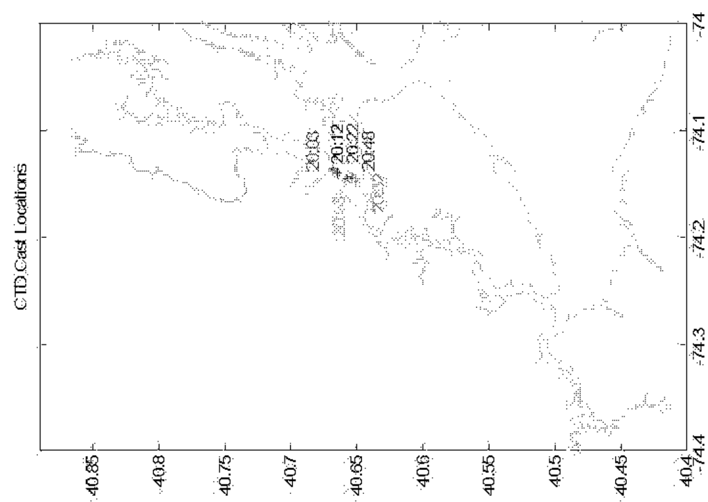


Transect 6 Note: Transects were split between 2 vessels on August 15, 2001. These transects were taken from the R/V Deep Explorer.

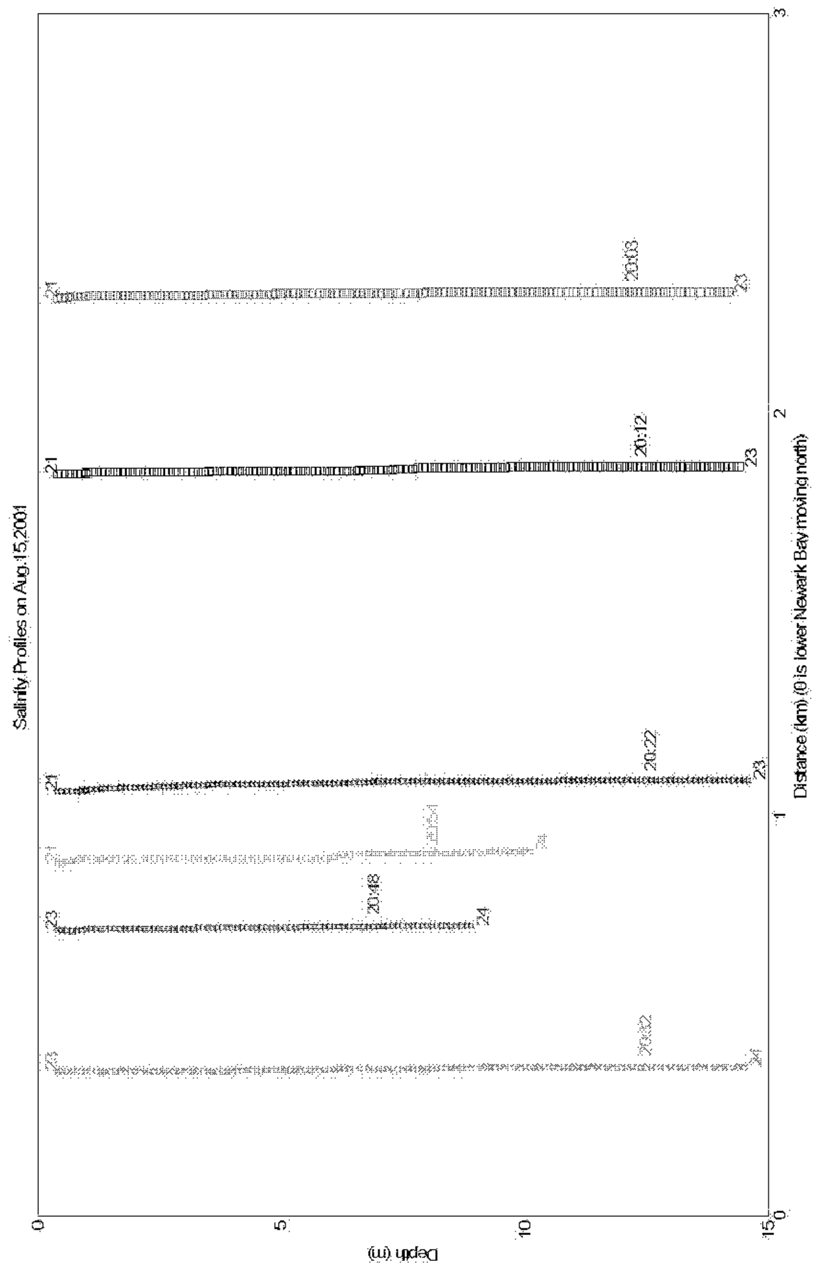


Transect 6 Note: Transects were split between 2 vessels on August 15, 2001. These transects were taken from the R/V Deep Explorer.

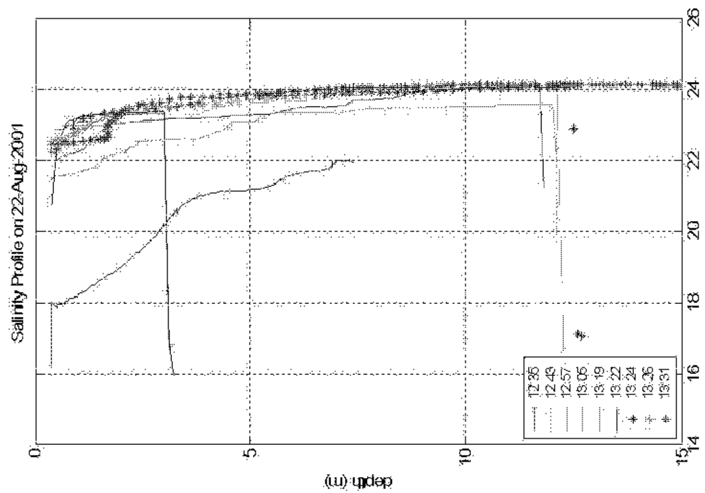


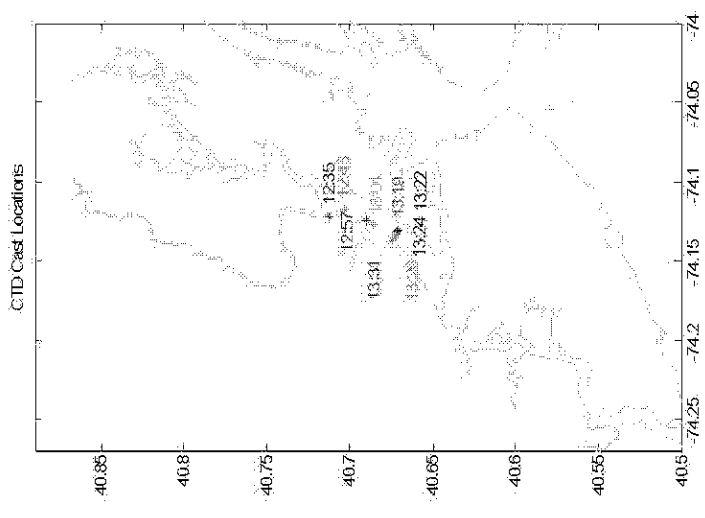


Transect 7 Note: Transects were split between 2 vessels on August 15, 2001. These transects were taken from the R/V Deep Explorer.

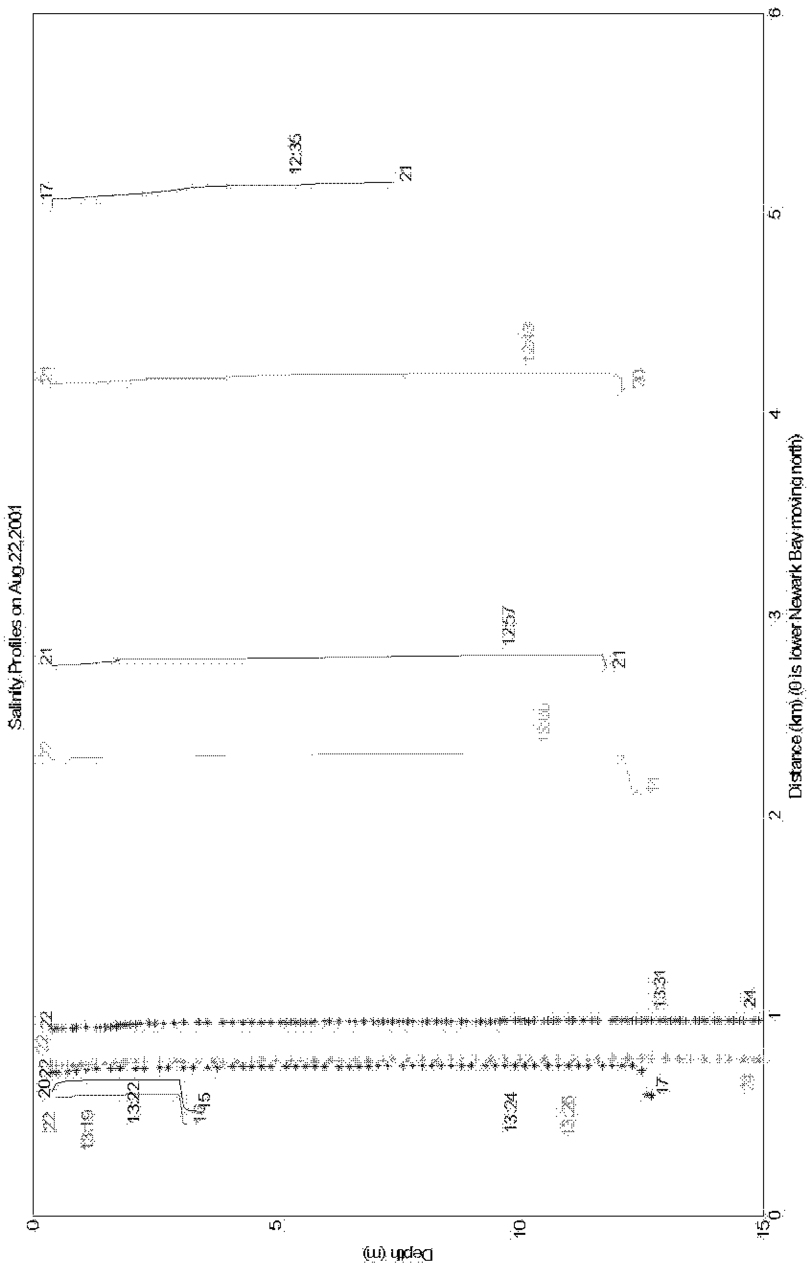


Transect 7 Note: Transects were split between 2 vessels on August 15, 2001. These transects were taken from the R/V Deep Explorer.

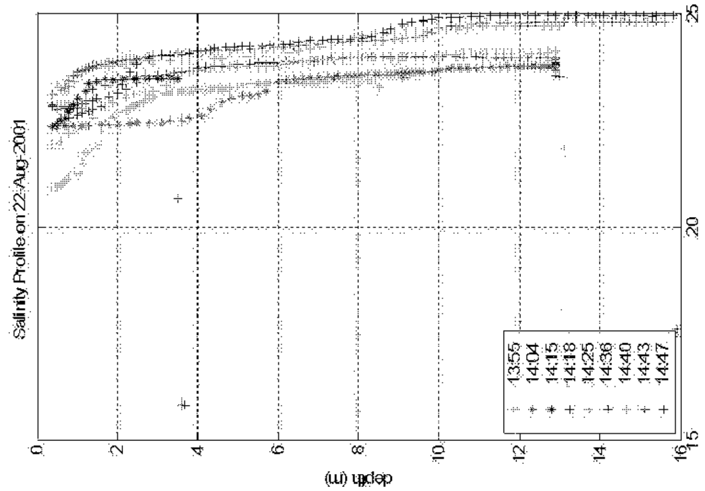


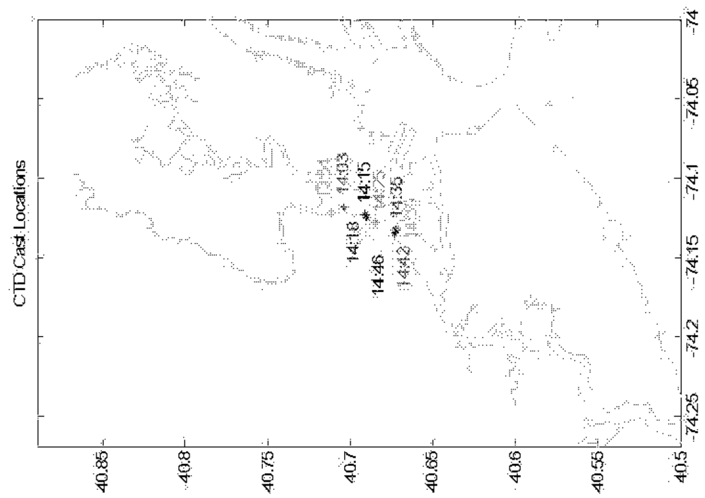


Transect 1 Note: Transects were split between 2 vessels on August 22, 2001. These transects were taken from the R/V Phoenix.

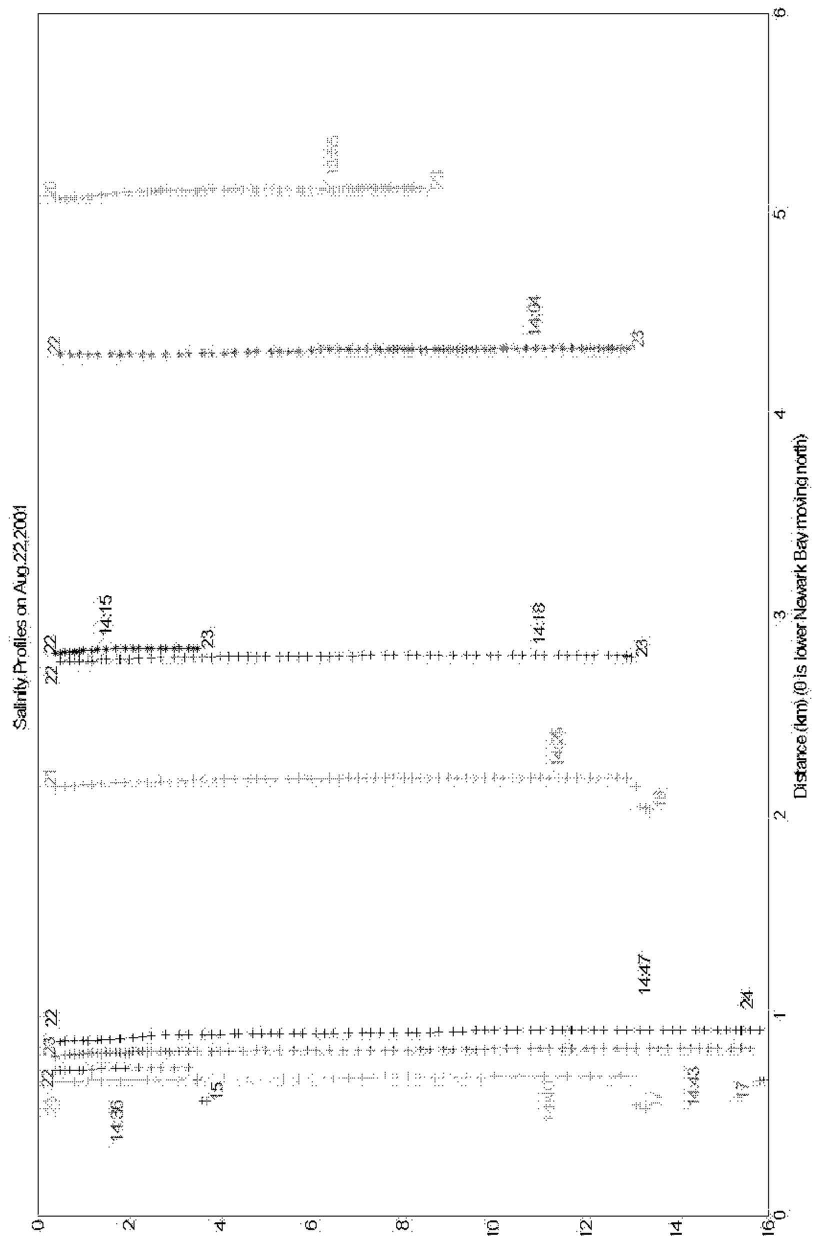


Transect 1 Note: Transects were split between 2 vessels on August 22, 2001. These transects were taken from the R/V Phoenix.

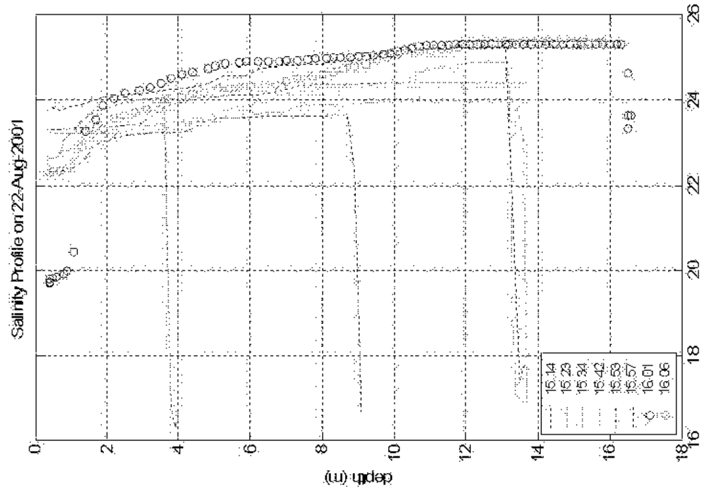


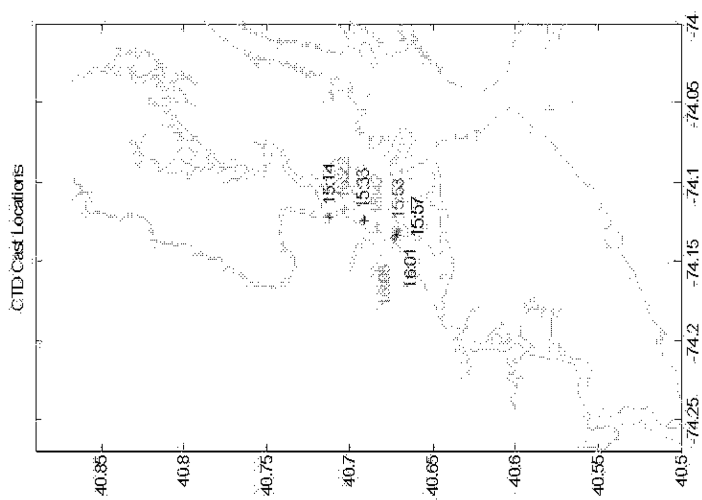


Transect 2 Note: Transects were split between 2 vessels on August 22, 2001. These transects were taken from the R/V Phoenix.

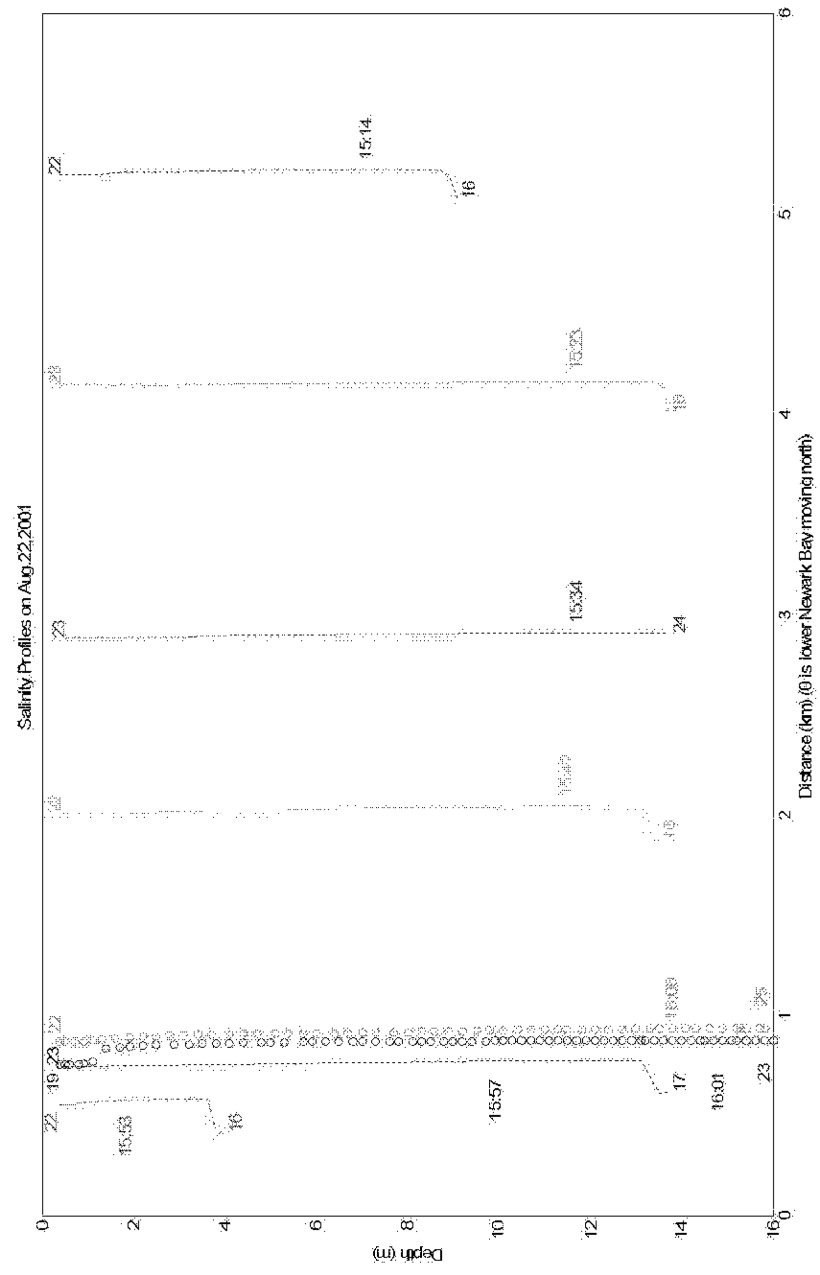


Transect 2 Note: Transects were split between 2 vessels on August 22, 2001. These transects were taken from the R/V Phoenix.

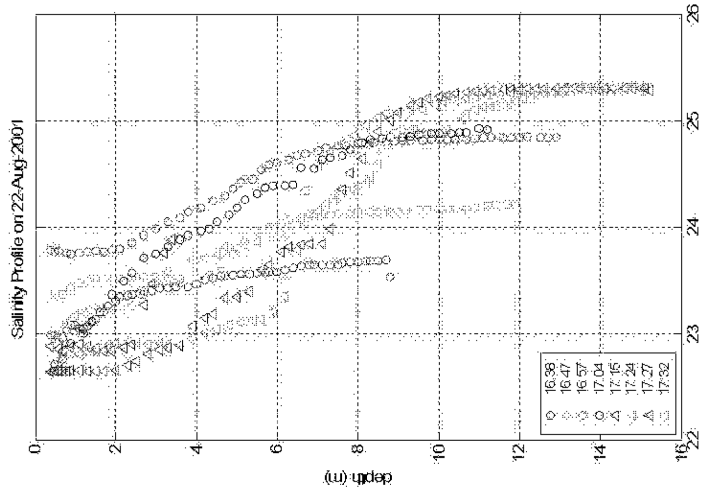


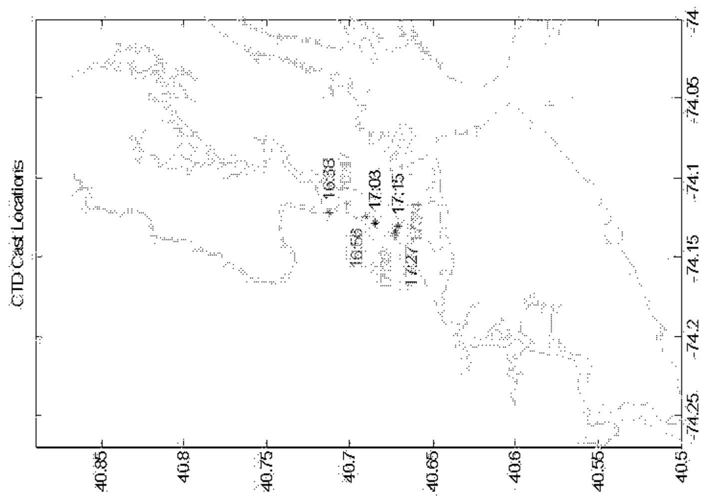


Transect 3 Note: Transects were split between 2 vessels on August 22, 2001. These transects were taken from the R/V Phoenix.

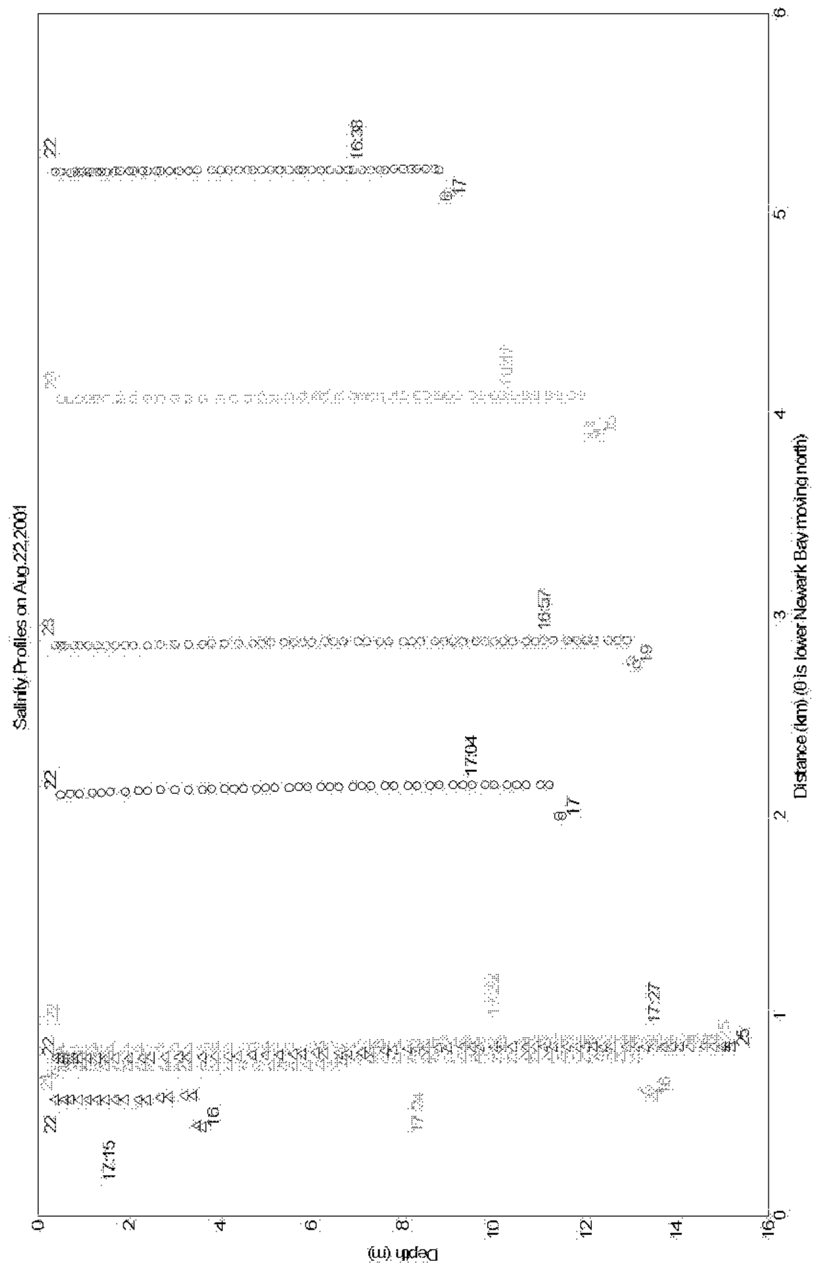


Transect 3 Note: Transects were split between 2 vessels on August 22, 2001. These transects were taken from the R/V Phoenix.

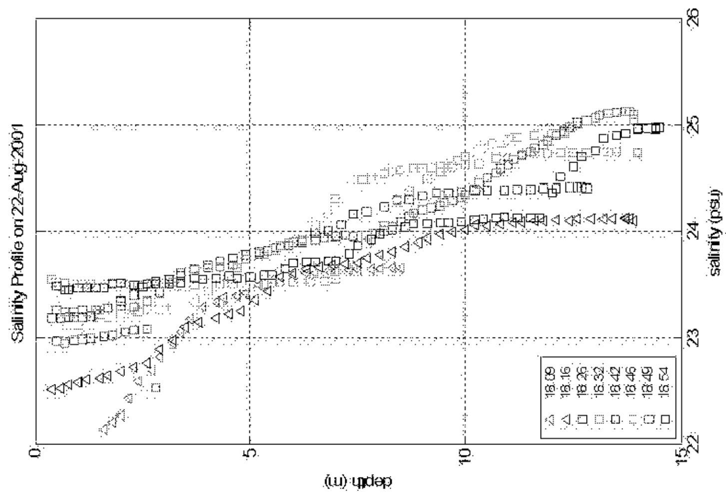


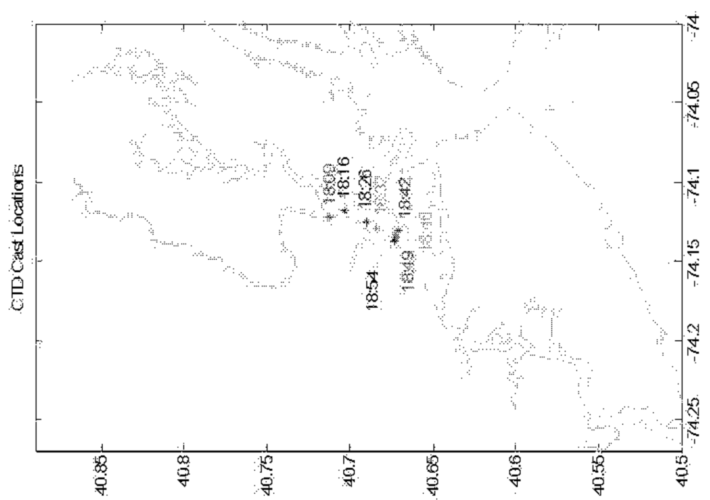


Transect 4 Note: Transects were split between 2 vessels on August 22, 2001. These transects were taken from the R/V Phoenix.

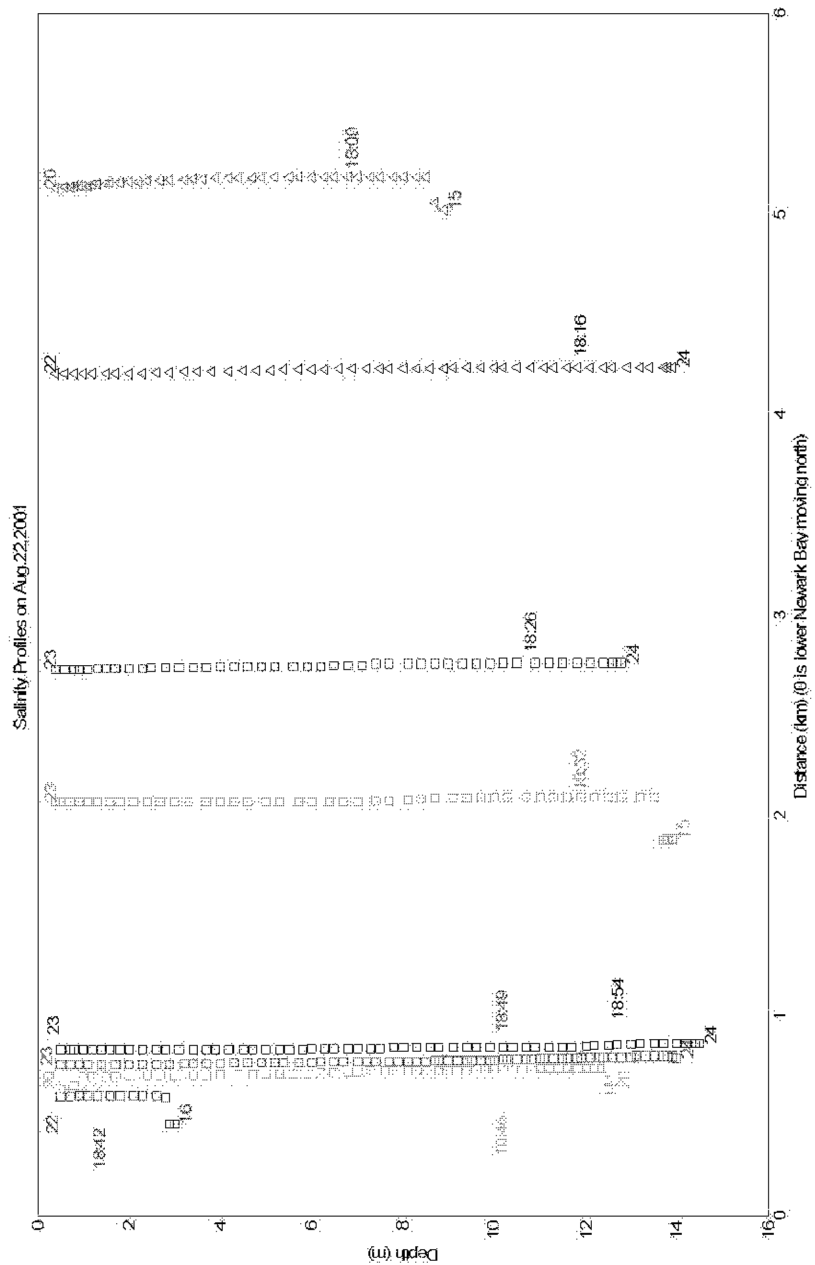


Transect 4 Note: Transects were split between 2 vessels on August 22, 2001. These transects were taken from the R/V Phoenix.

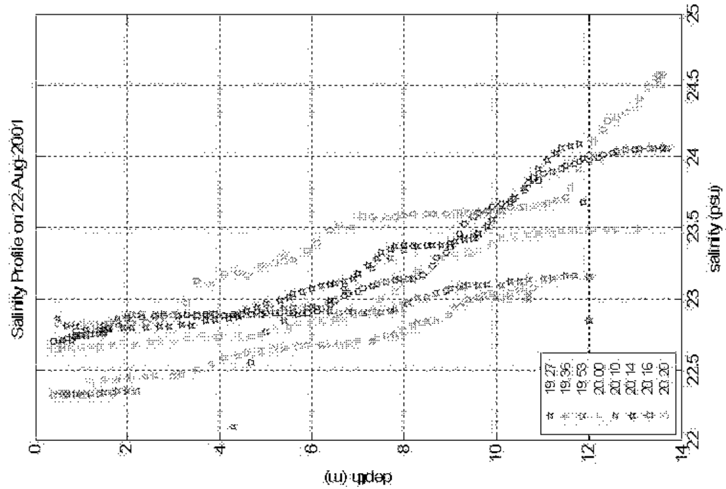


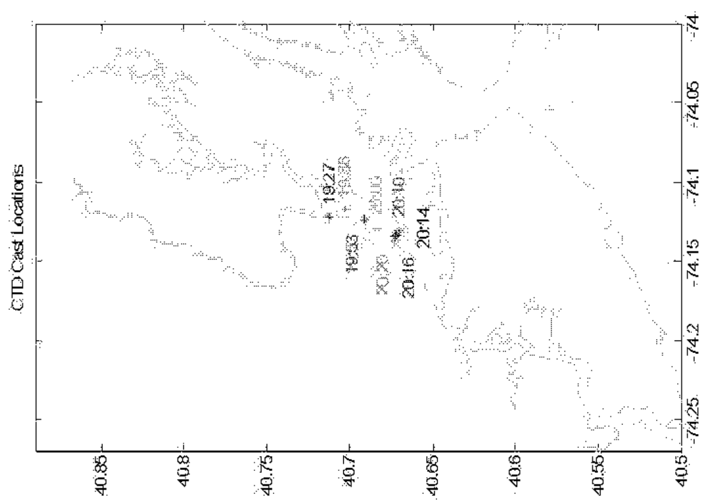


Transect 5 Note: Transects were split between 2 vessels on August 22, 2001. These transects were taken from the R/V Phoenix.

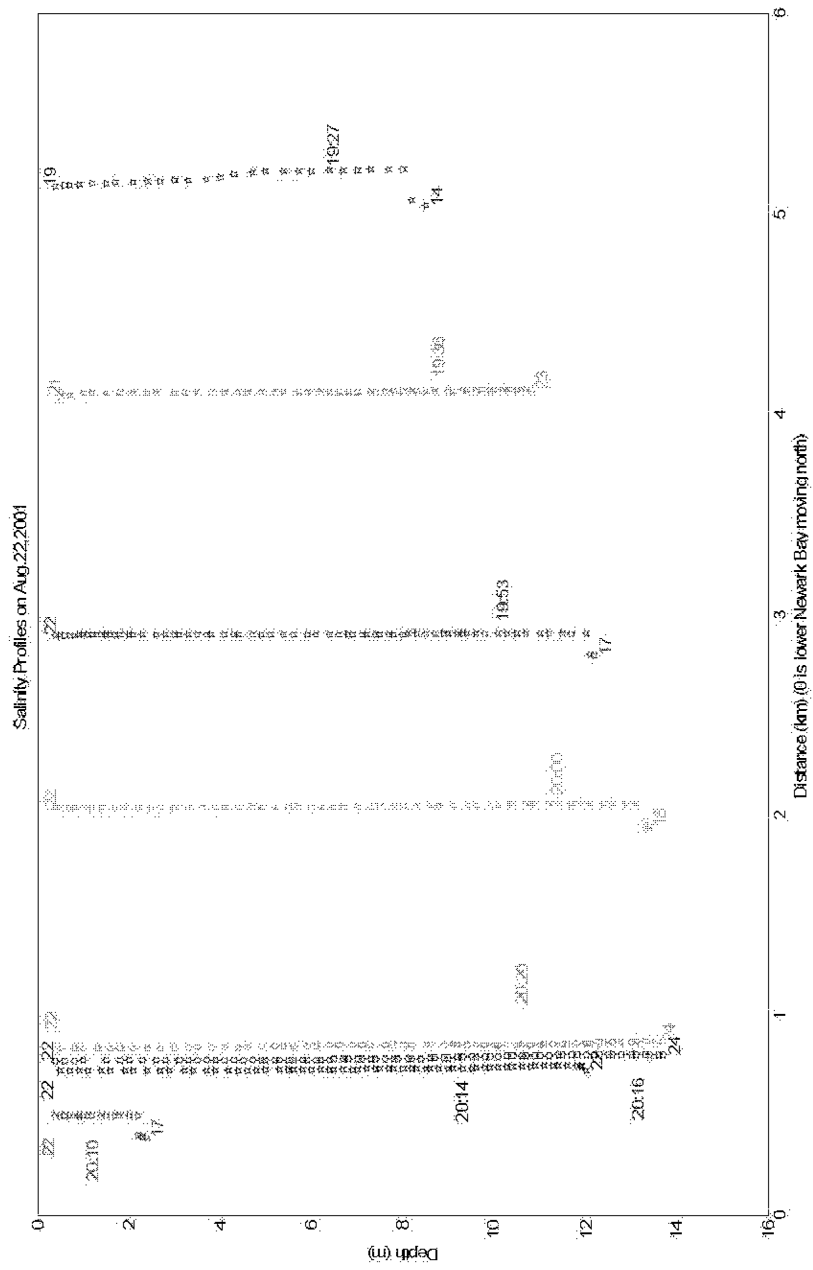


Transect 5 Note: Transects were split between 2 vessels on August 22, 2001. These transects were taken from the R/V Phoenix.

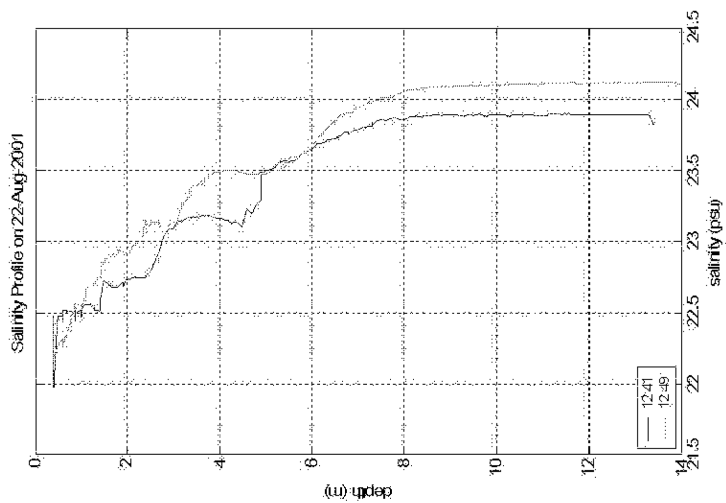


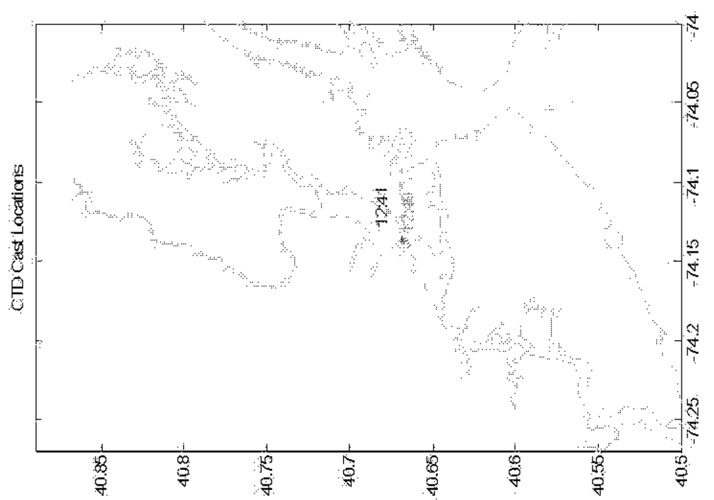


Transect 6 Note: Transects were split between 2 vessels on August 22, 2001. These transects were taken from the R/V Phoenix.

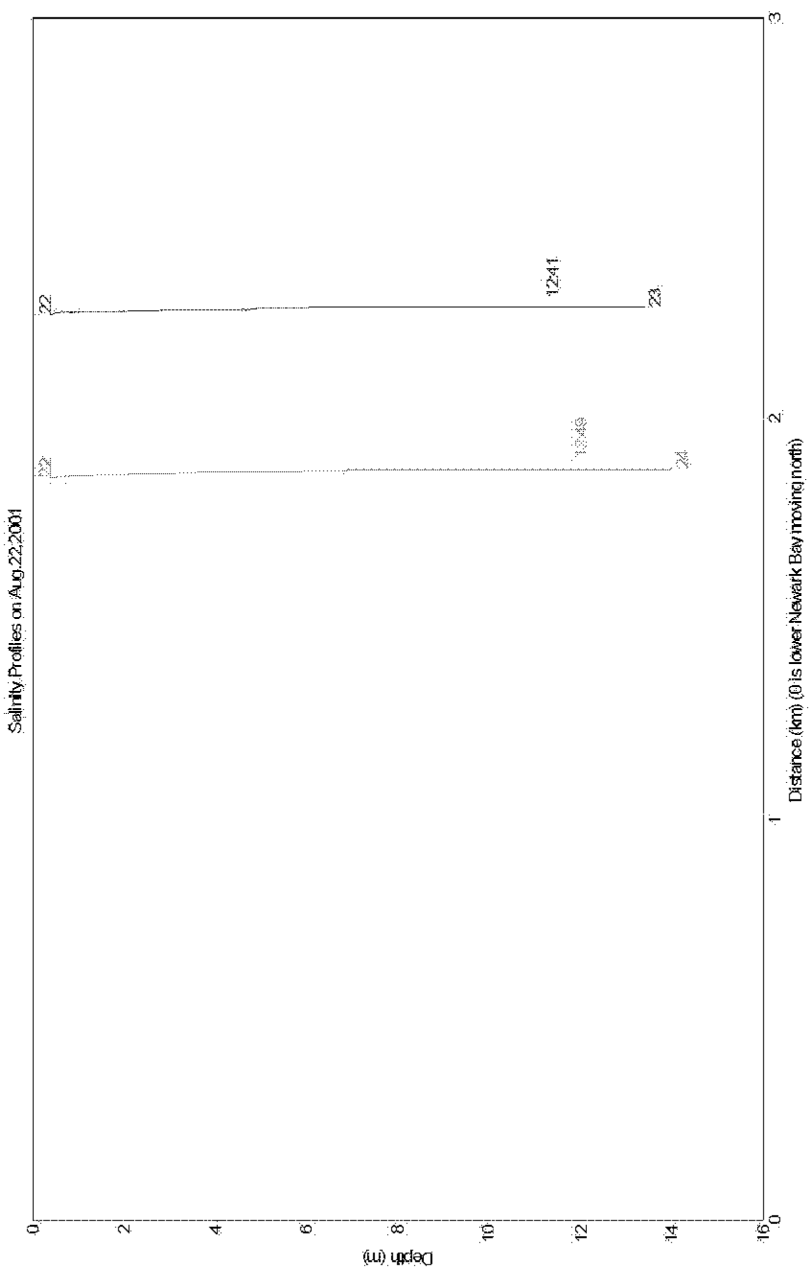


Transect 6 Note: Transects were split between 2 vessels on August 22, 2001. These transects were taken from the R/V Phoenix.

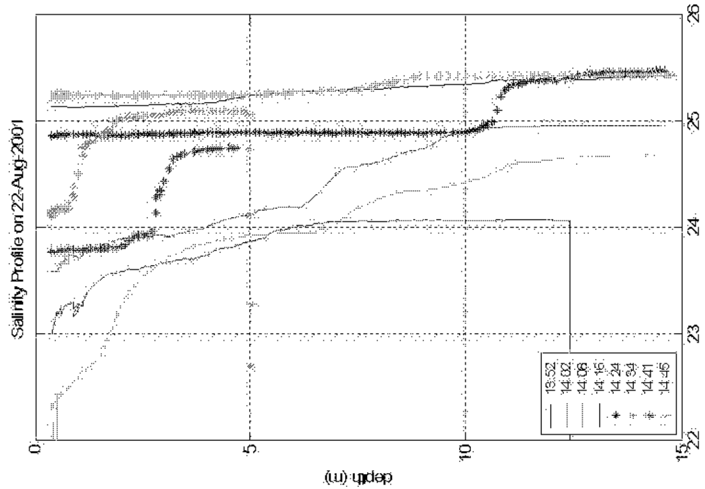


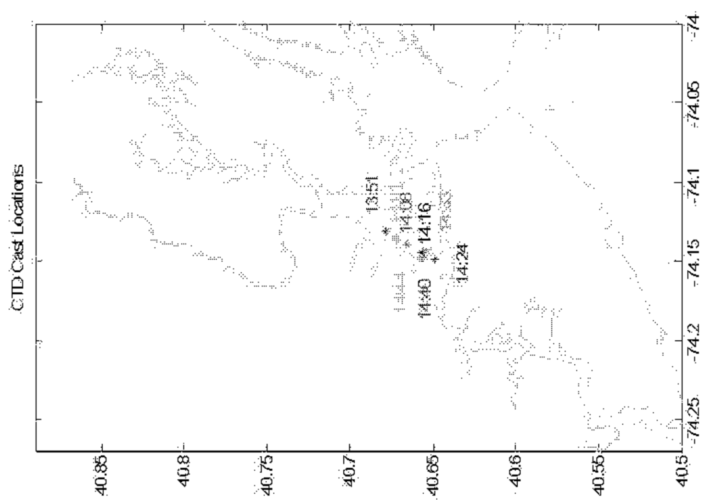


Transect 1 Note: Transects were split between 2 vessels on August 22, 2001. These transects were taken from the R/V Deep Explorer. Some data was unrecoverable from this transect.

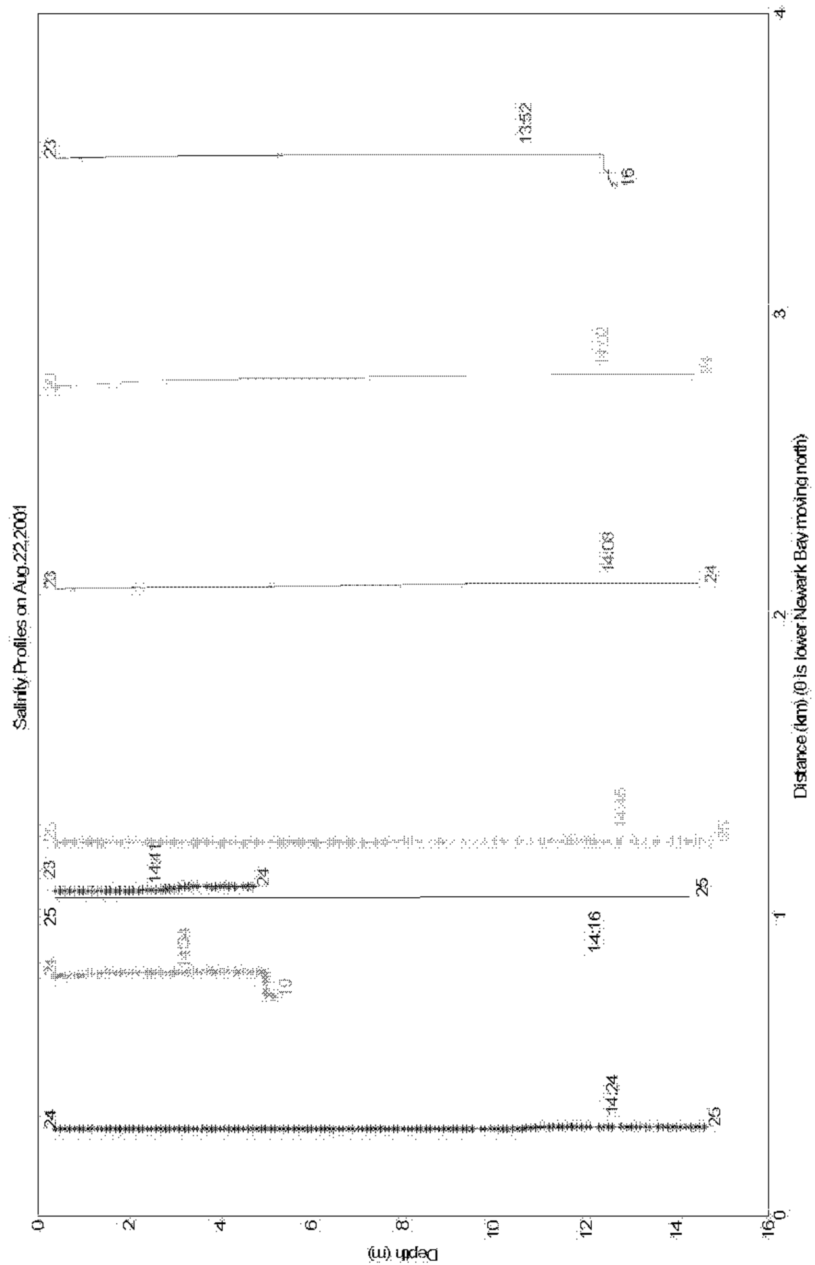

Salinity Profiles on Aug.22,2001
Depth (m)
0
2
4
6
8
10
12
14
16
Distance (km) (0 is lower Newark Bay moving north)
0
1
2
3
22
24
12:49
22
23
12:41

Transect 1 Note: Transects were split between 2 vessels on August 22, 2001. These transects were taken from the R/V Deep Explorer. Some data was unrecoverable from this transect.

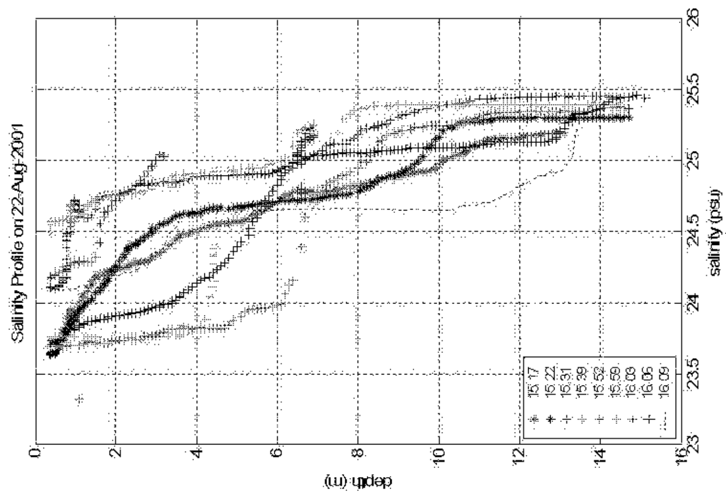


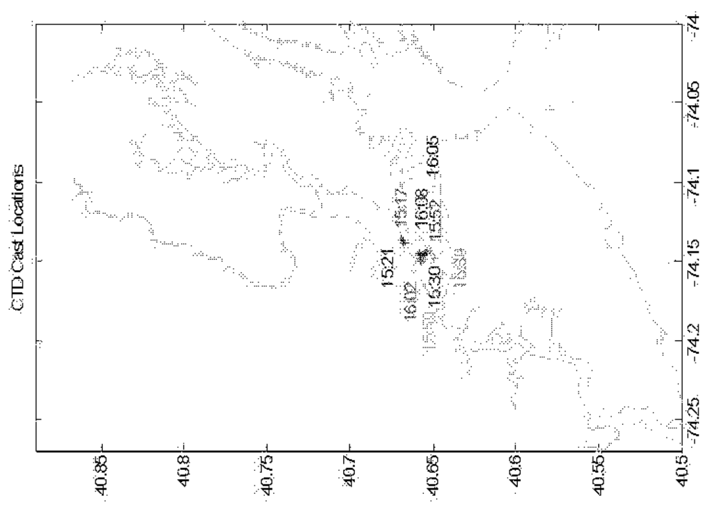


Transect 2 Note: Transects were split between 2 vessels on August 22, 2001. These transects were taken from the R/V Deep Explorer.

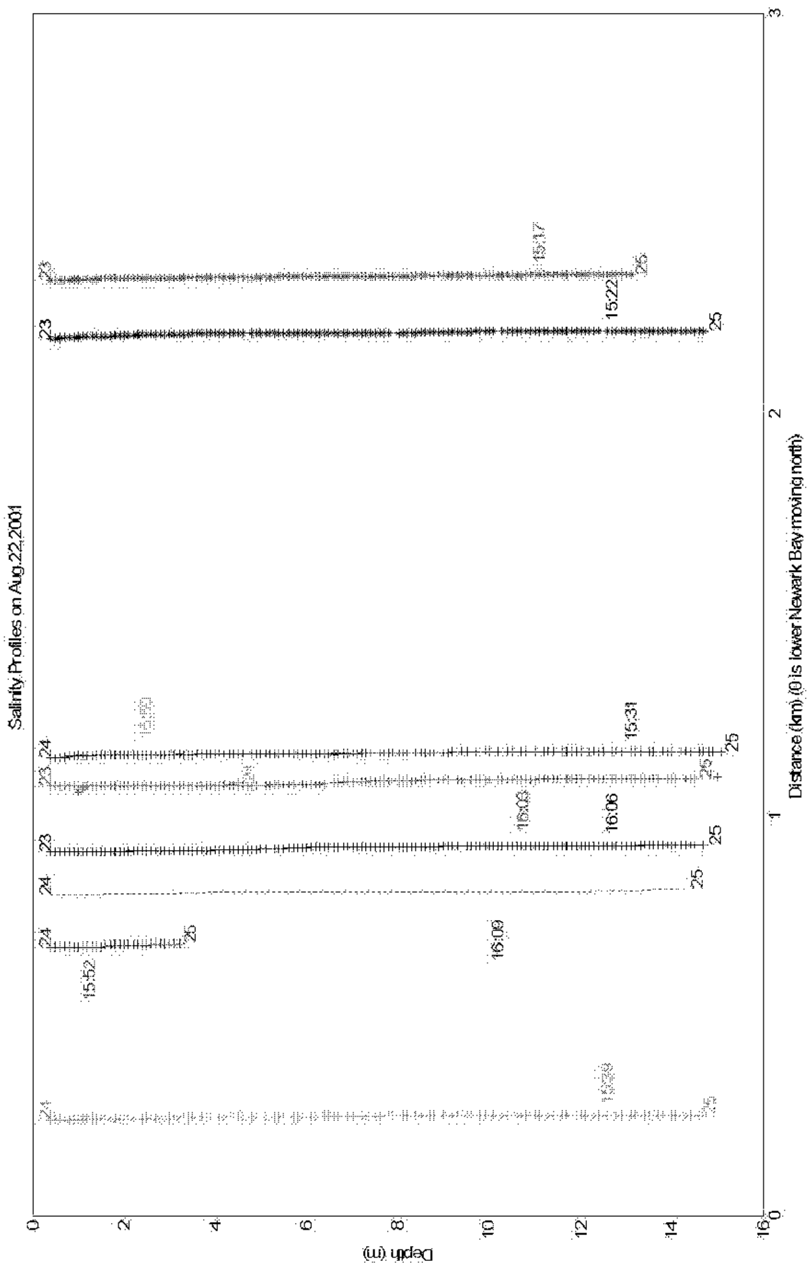


Transect 2 Note: Transects were split between 2 vessels on August 22, 2001. These transects were taken from the R/V Deep Explorer.

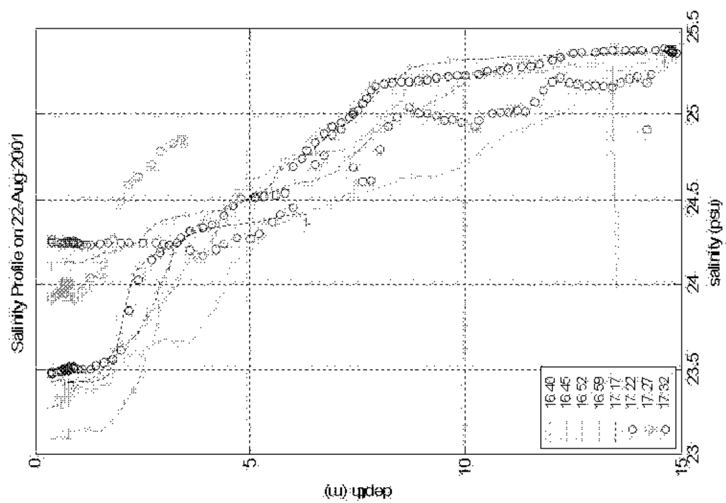


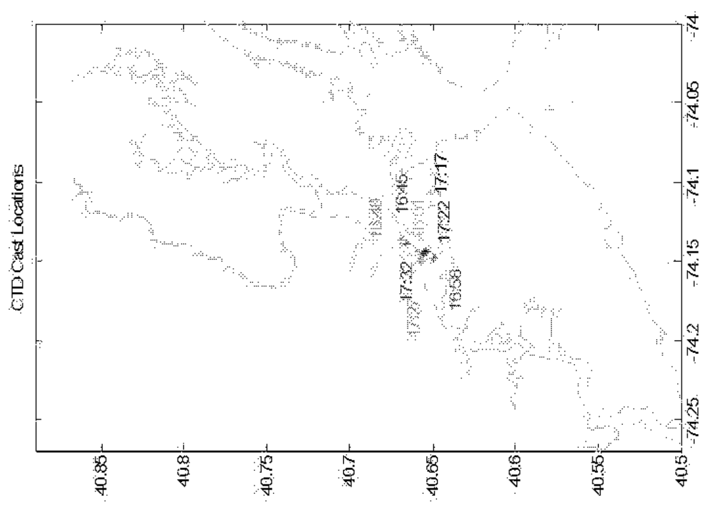


Transect 3 Note: Transects were split between 2 vessels on August 22, 2001. These transects were taken from the R/V Deep Explorer.

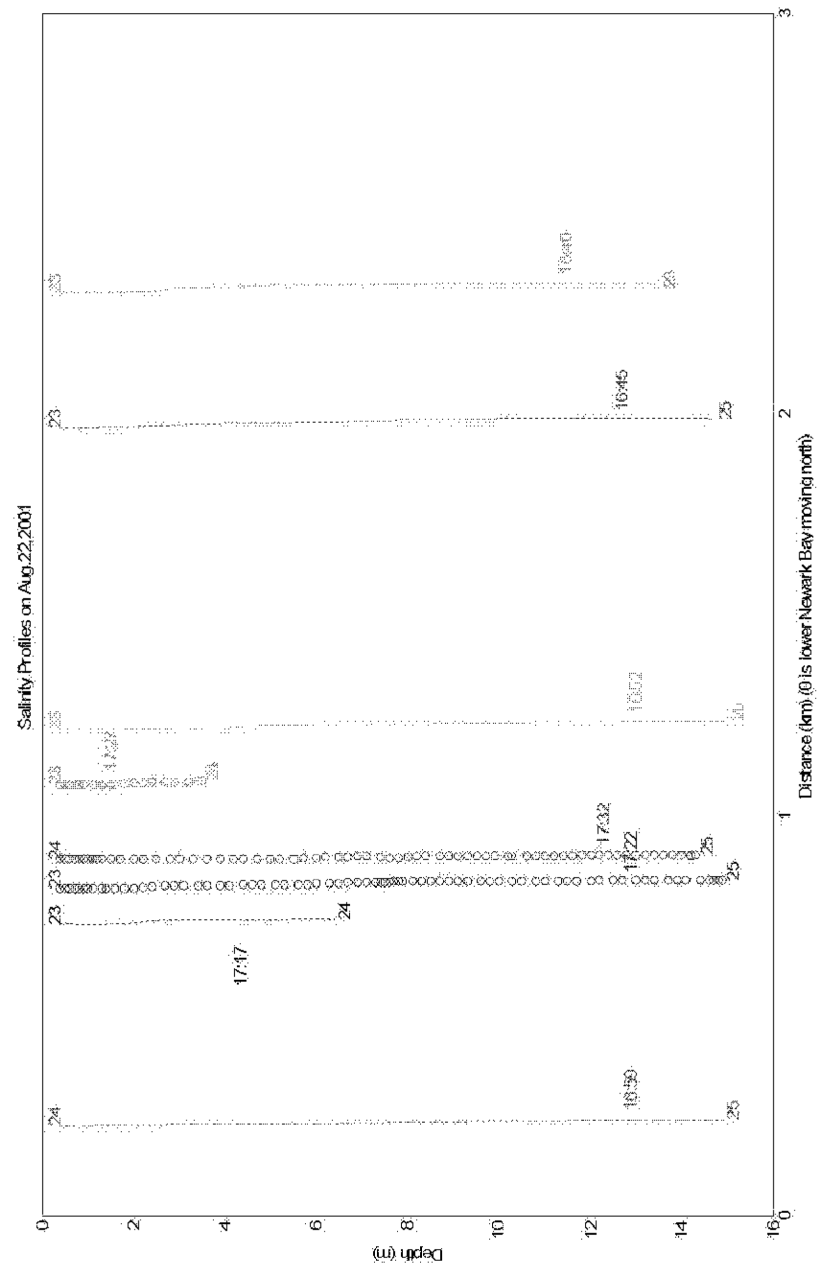


Transect 3 Note: Transects were split between 2 vessels on August 22, 2001. These transects were taken from the R/V Deep Explorer.

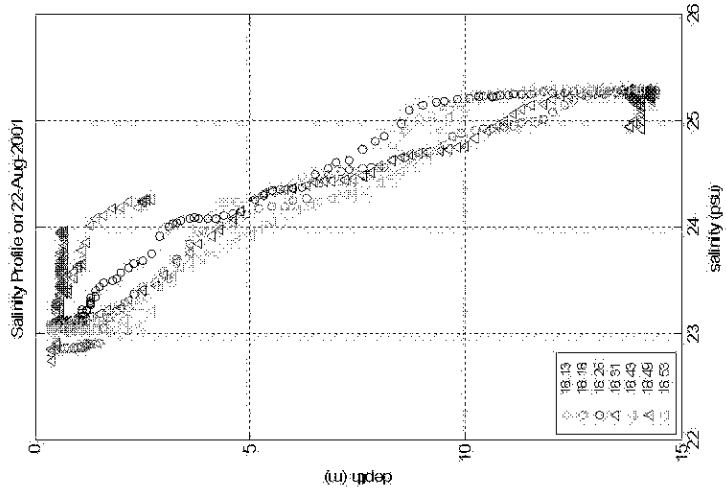


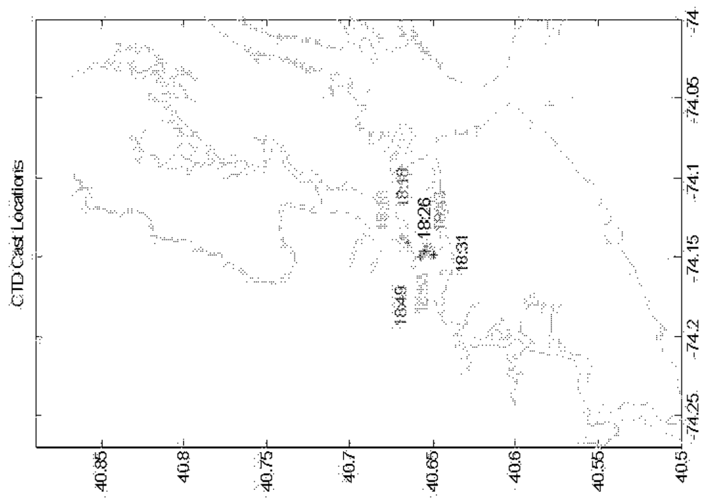


Transect 4 Note: Transects were split between 2 vessels on August 22, 2001. These transects were taken from the R/V Deep Explorer.

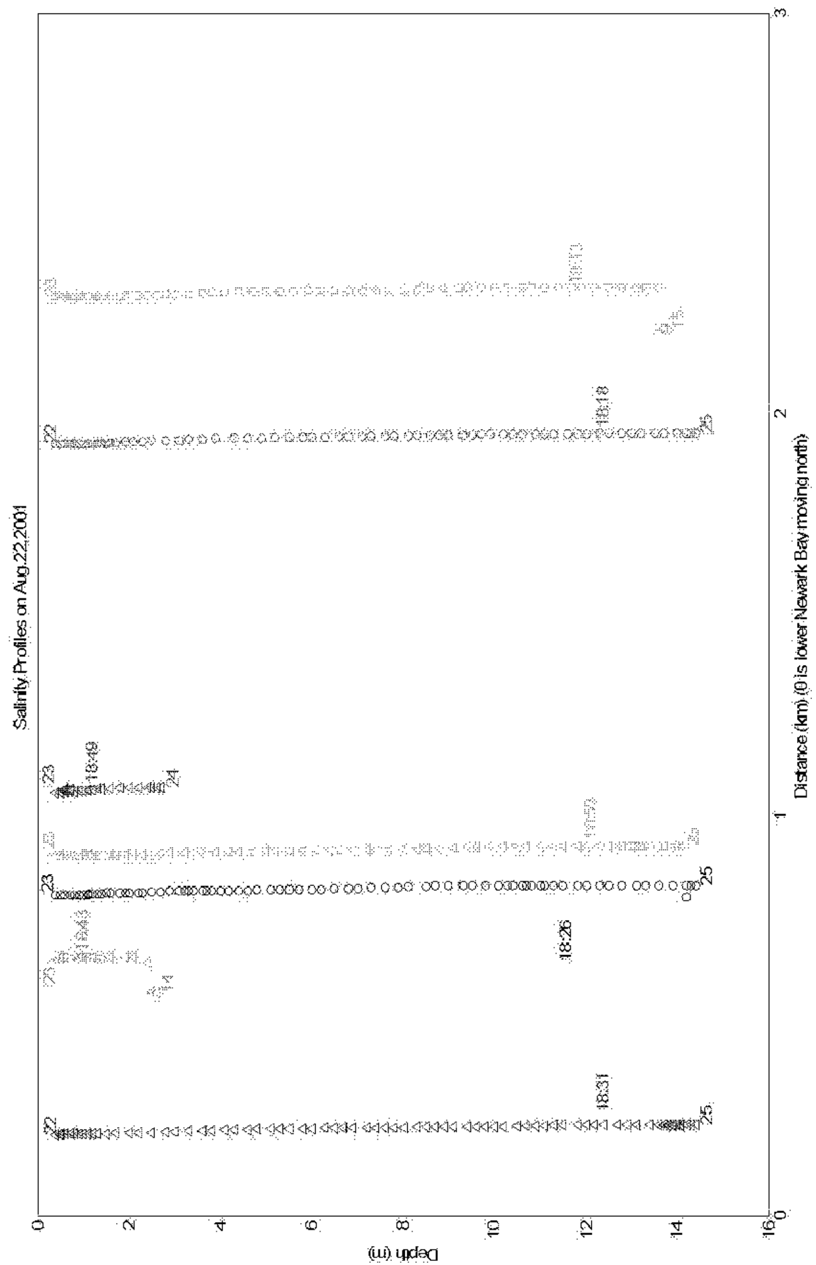


Transect 4 Note: Transects were split between 2 vessels on August 22, 2001. These transects were taken from the R/V Deep Explorer.

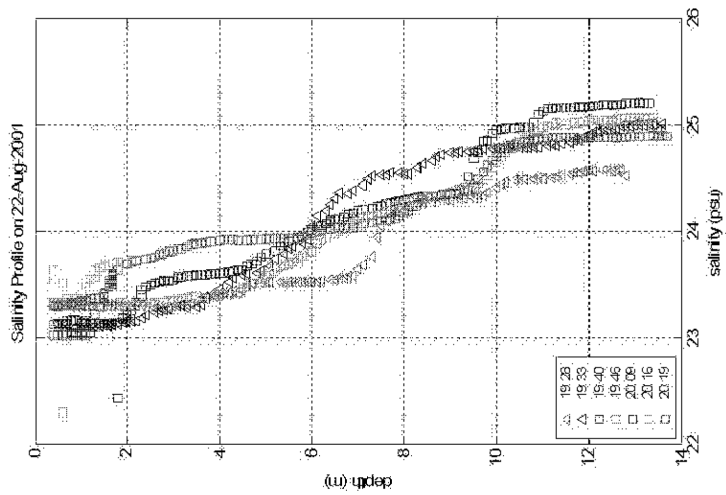


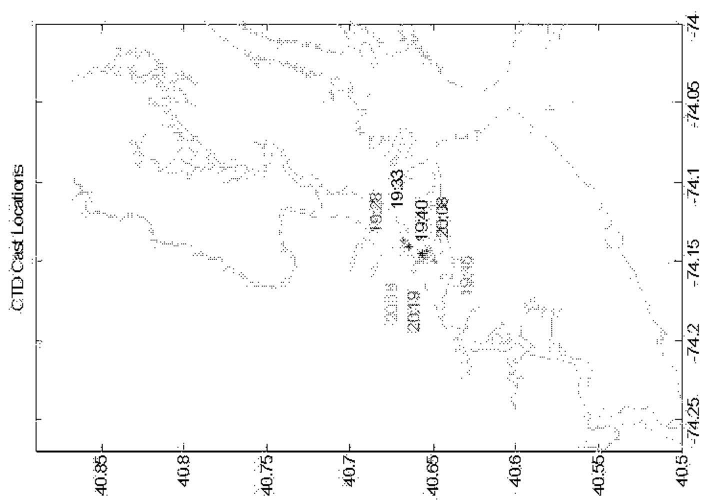


Transect 5 Note: Transects were split between 2 vessels on August 22, 2001. These transects were taken from the R/V Deep Explorer.

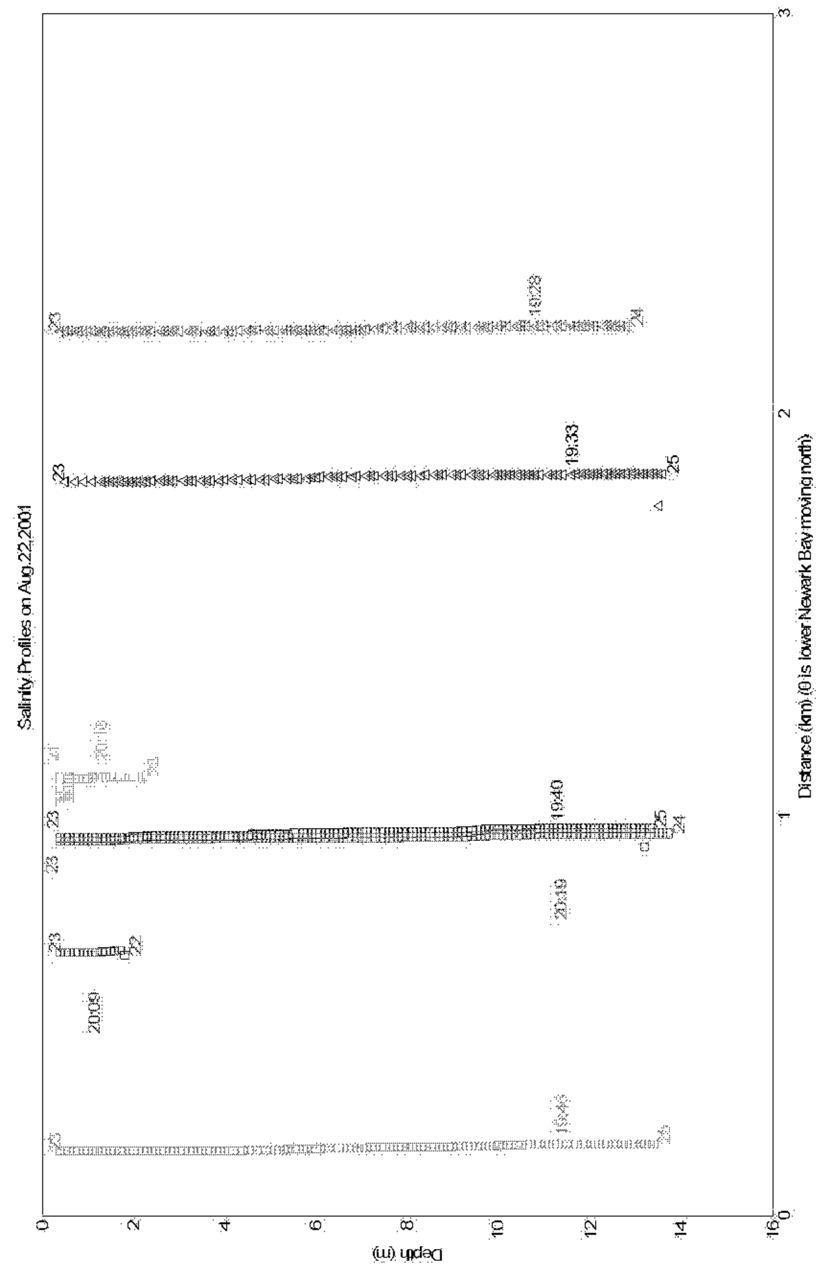


Transect 5 Note: Transects were split between 2 vessels on August 22, 2001. These transects were taken from the R/V Deep Explorer.

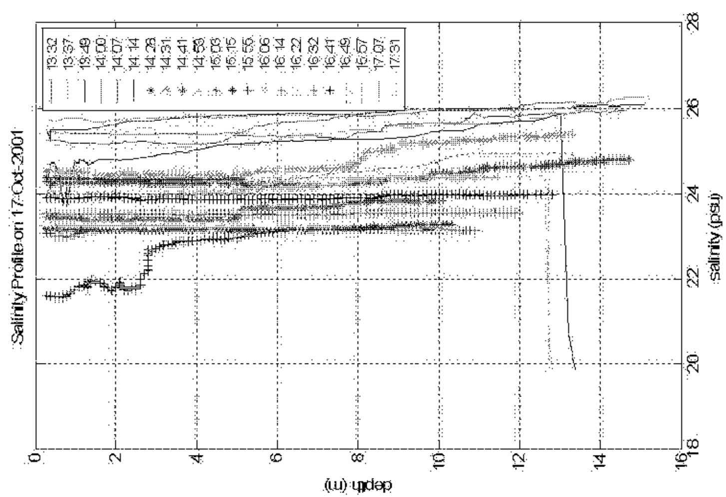


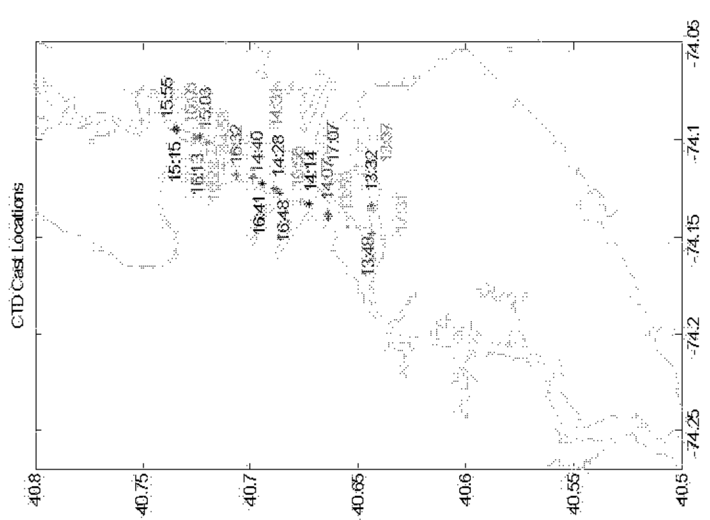


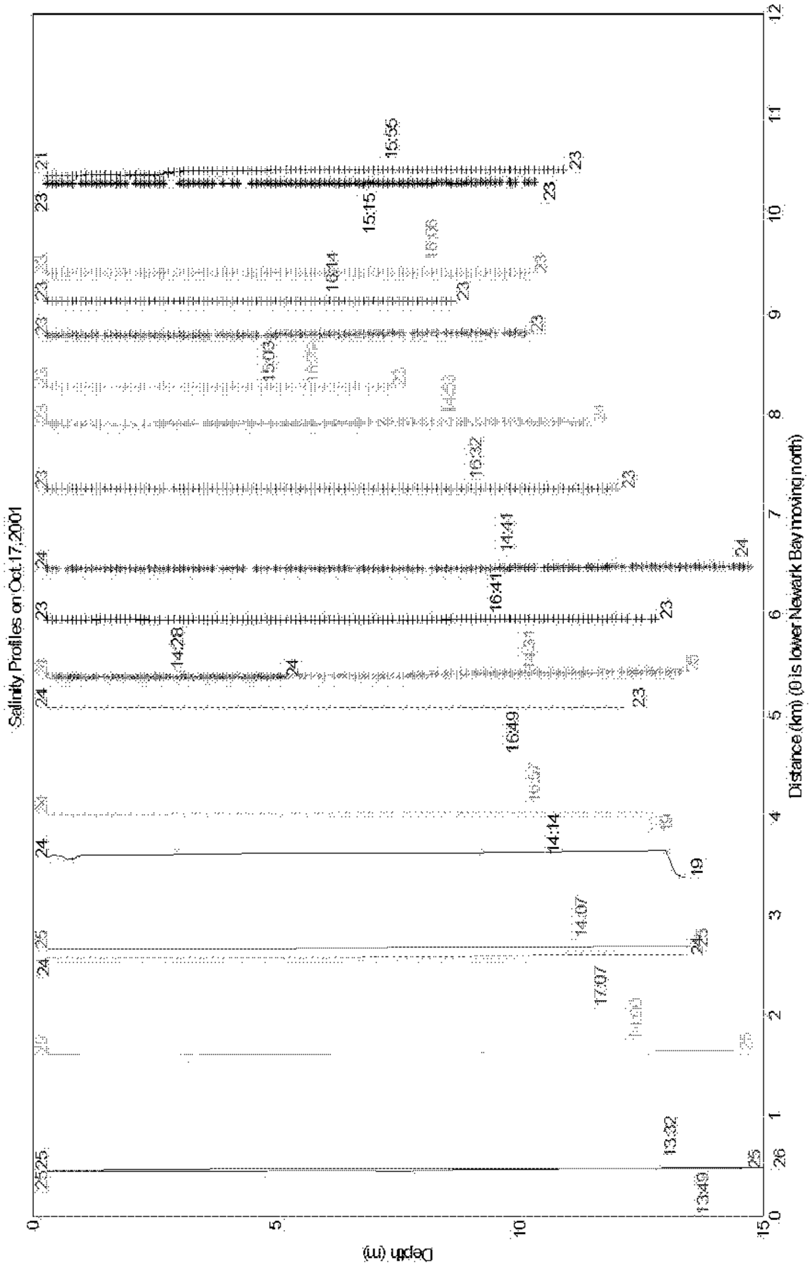
Transect 6 Note: Transects were split between 2 vessels on August 22, 2001. These transects were taken from the R/V Deep Explorer.

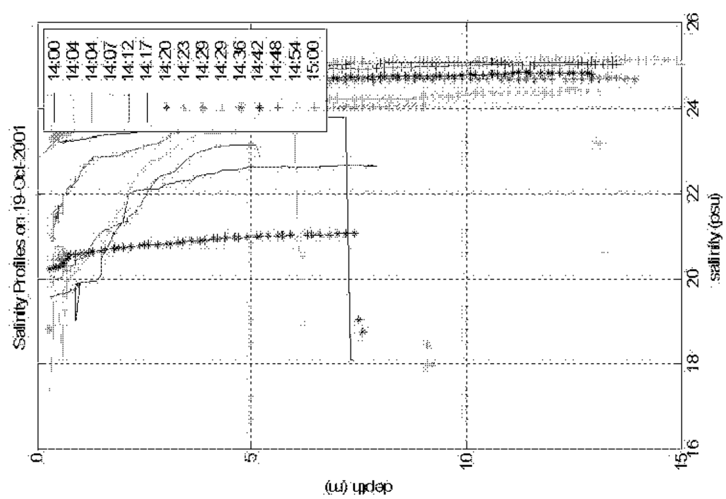


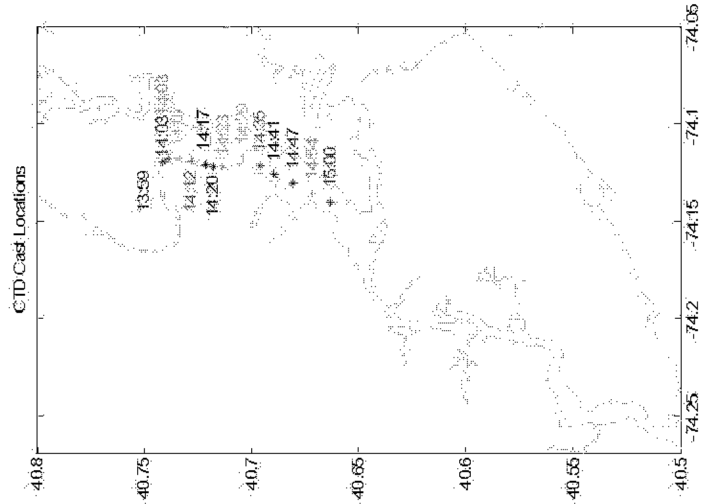
Transect 6 Note: Transects were split between 2 vessels on August 22, 2001. These transects were taken from the R/V Deep Explorer.

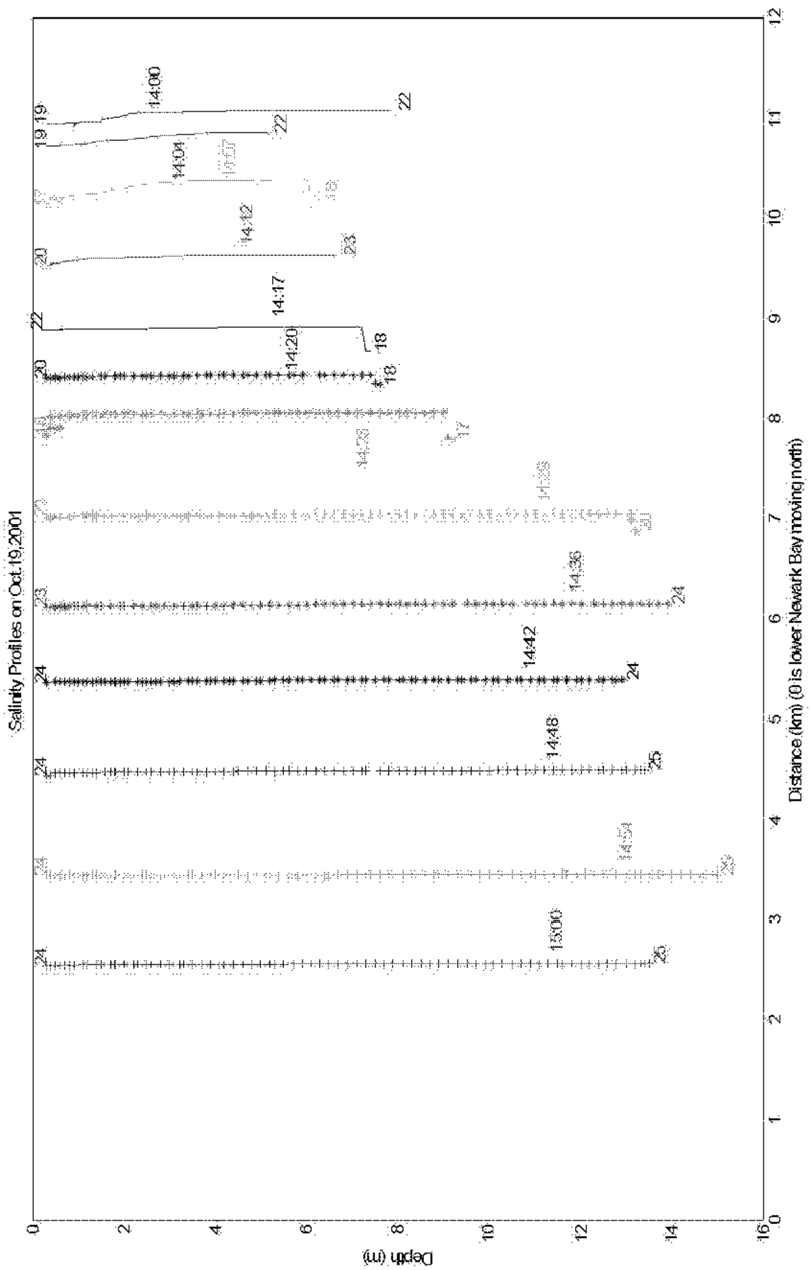

Salinity Profile on 17-Oct-2001
depth (m)
salinity (psu)

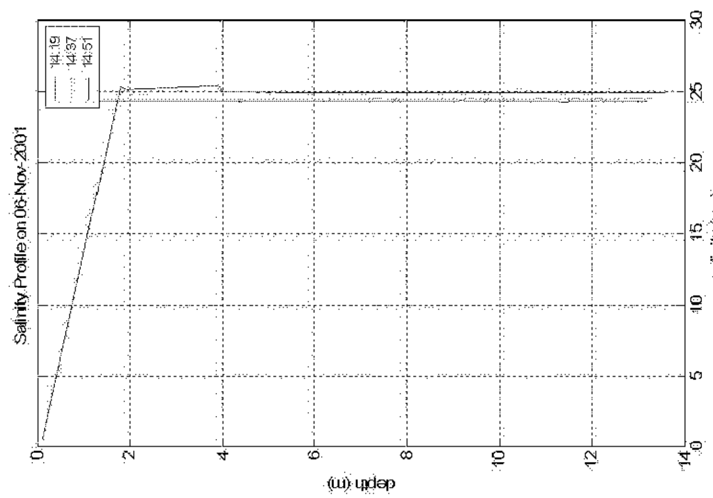

CTD Cast Locations

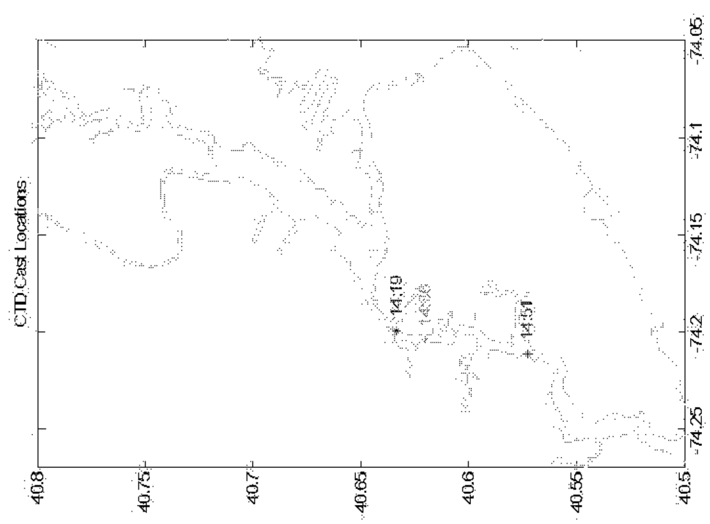

Salinity Profiles on Oct.17,2001
Depth (m)
Distance (km) (0 is lower Newark Bay moving north)


Salinity Profiles on 19-Oct-2001
salinity (psu)
depth (m)
14:00
14:04
14:04
14:07
14:12
14:17
14:20
14:23
14:29
14:29
14:36
14:42
14:48
14:54
15:00

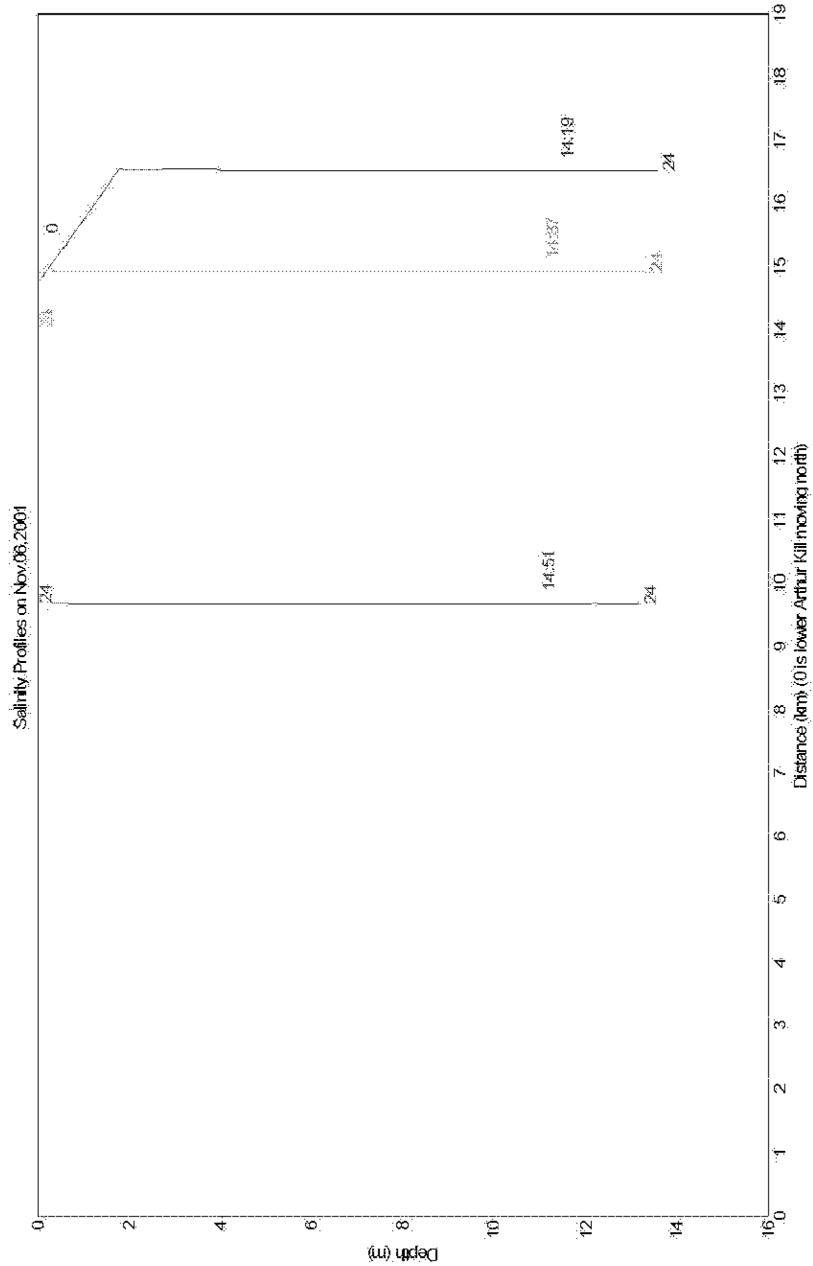

CTD Cast Locations
13:59
14:12
14:17
14:20
14:35
14:41
14:47
15:00

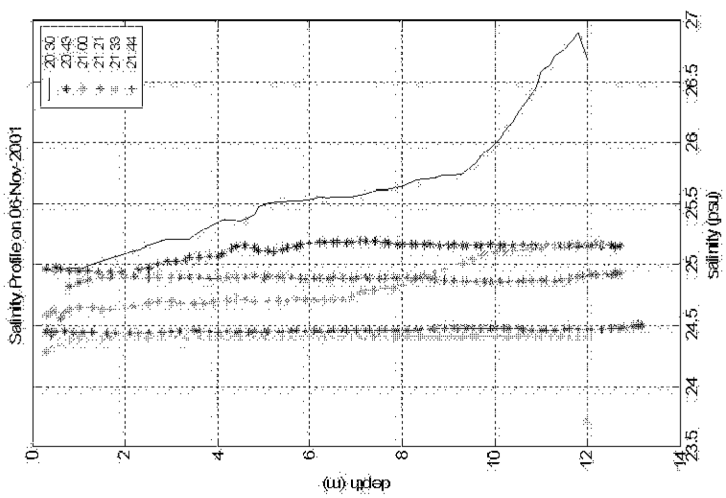

Salinity Profiles on Oct.19,2001
Distance (km) (0 is lower Newark Bay moving north)
Depth (m)

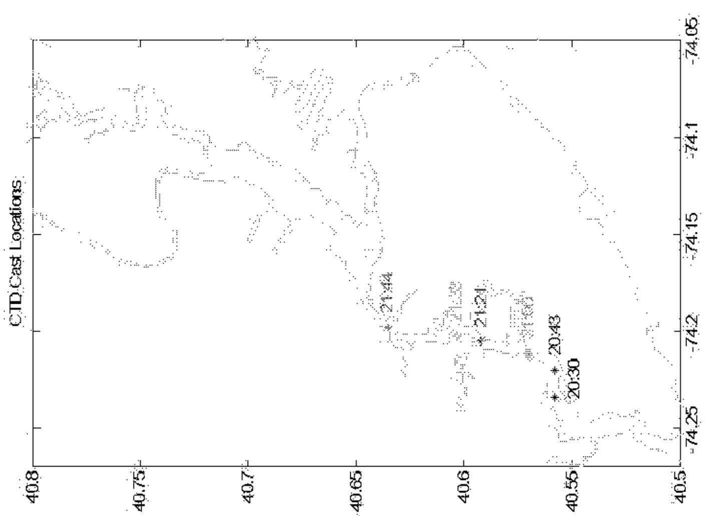




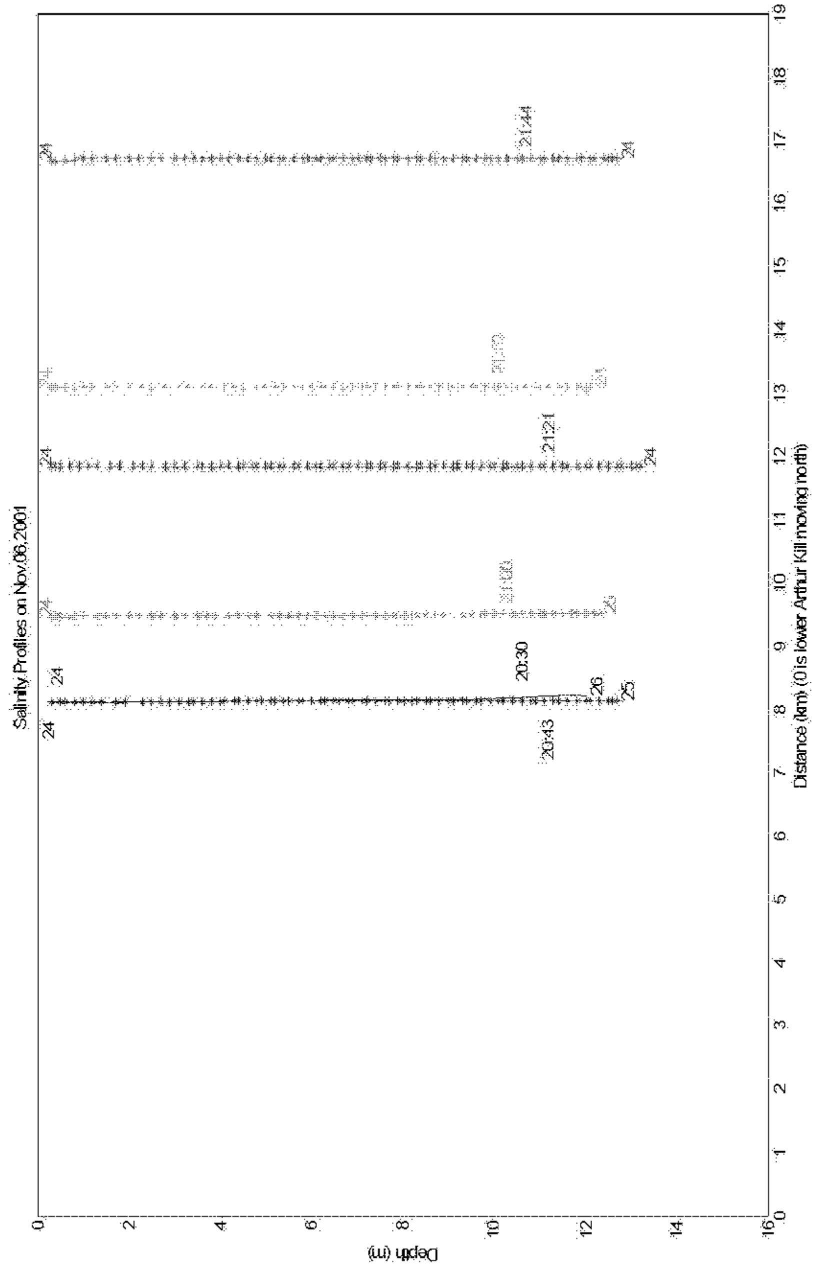
Note: Transects were split between 2 vessels on November 6, 2001. These transects were taken from the R/V Deep Explorer.


Salinity Profiles on Nov.06,2001
Distance (km) (0 is lower Arthur Kill moving north)
Depth (m)
14:51
14:19
24
0

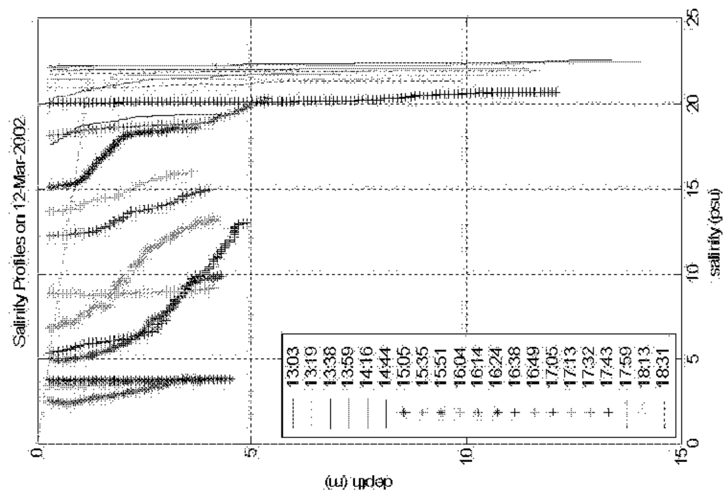


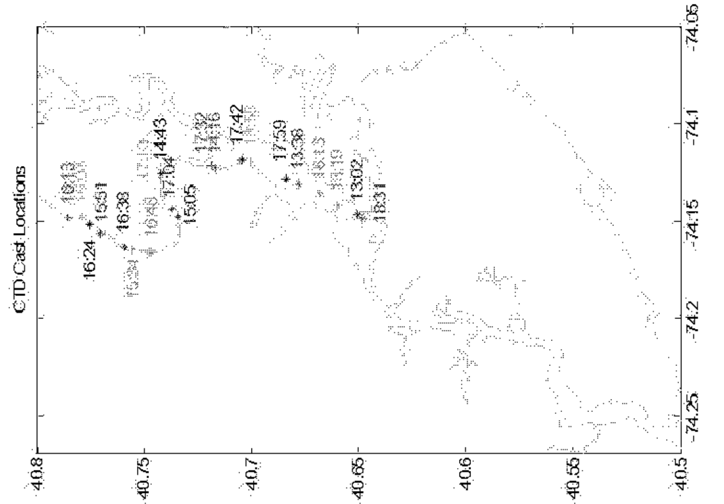


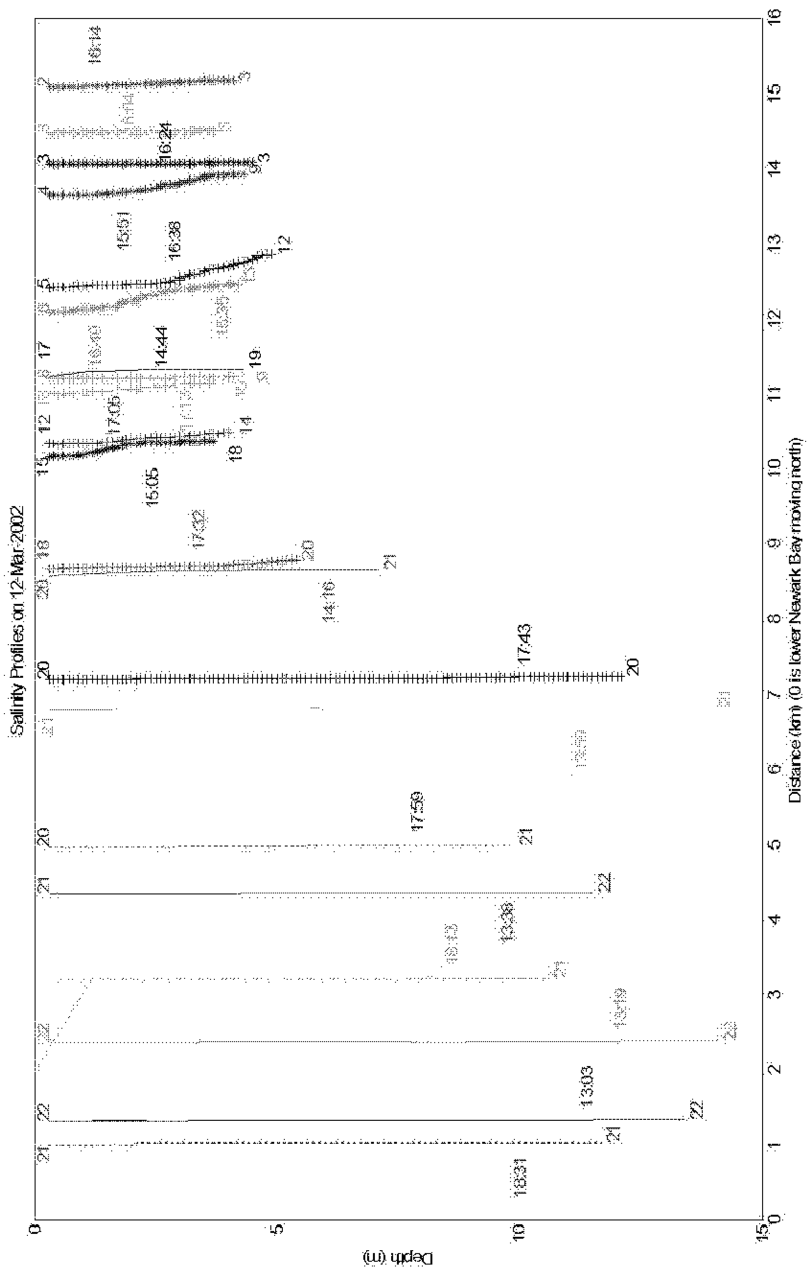
Note: Transects were split between 2 vessels on November 6, 2001. These transects were taken from the R/V Phoenix.

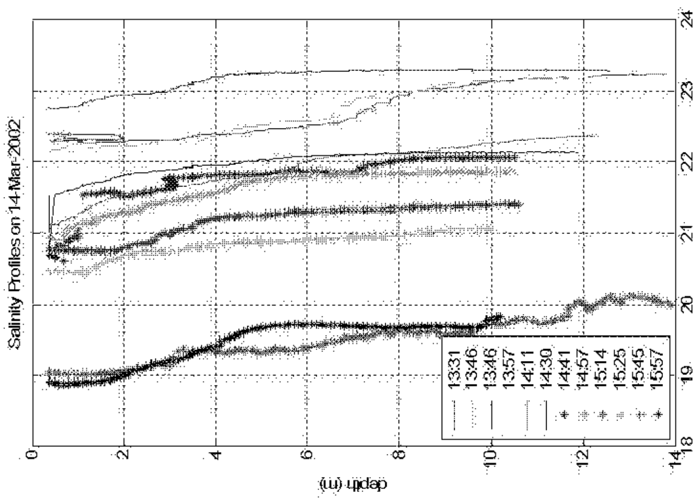


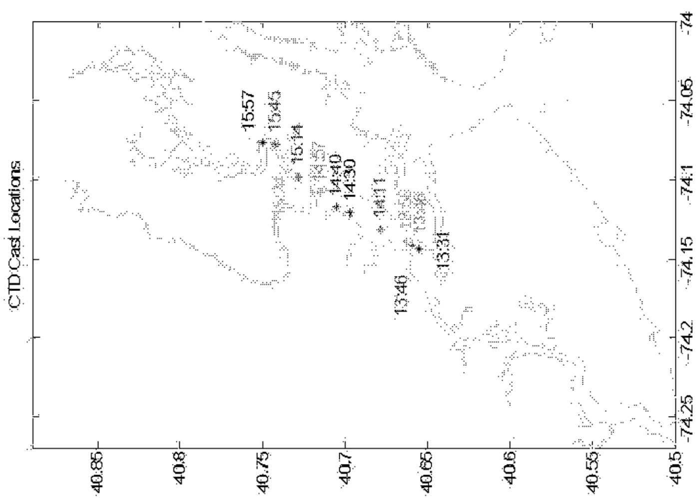
Salinity Profiles on Nov.06,2001
Distance (km) (0 is lower Arthur Kill moving north)
Depth (m)
20:30
20:43
21:21
21:44


Salinity Profiles on 12-Mar-2002
depth (m)
salinity (psu)
13:03
13:19
13:38
13:59
14:16
14:44
15:05
15:35
15:51
16:04
16:14
16:24
16:38
16:49
17:05
17:13
17:32
17:43
17:59
18:13
18:31

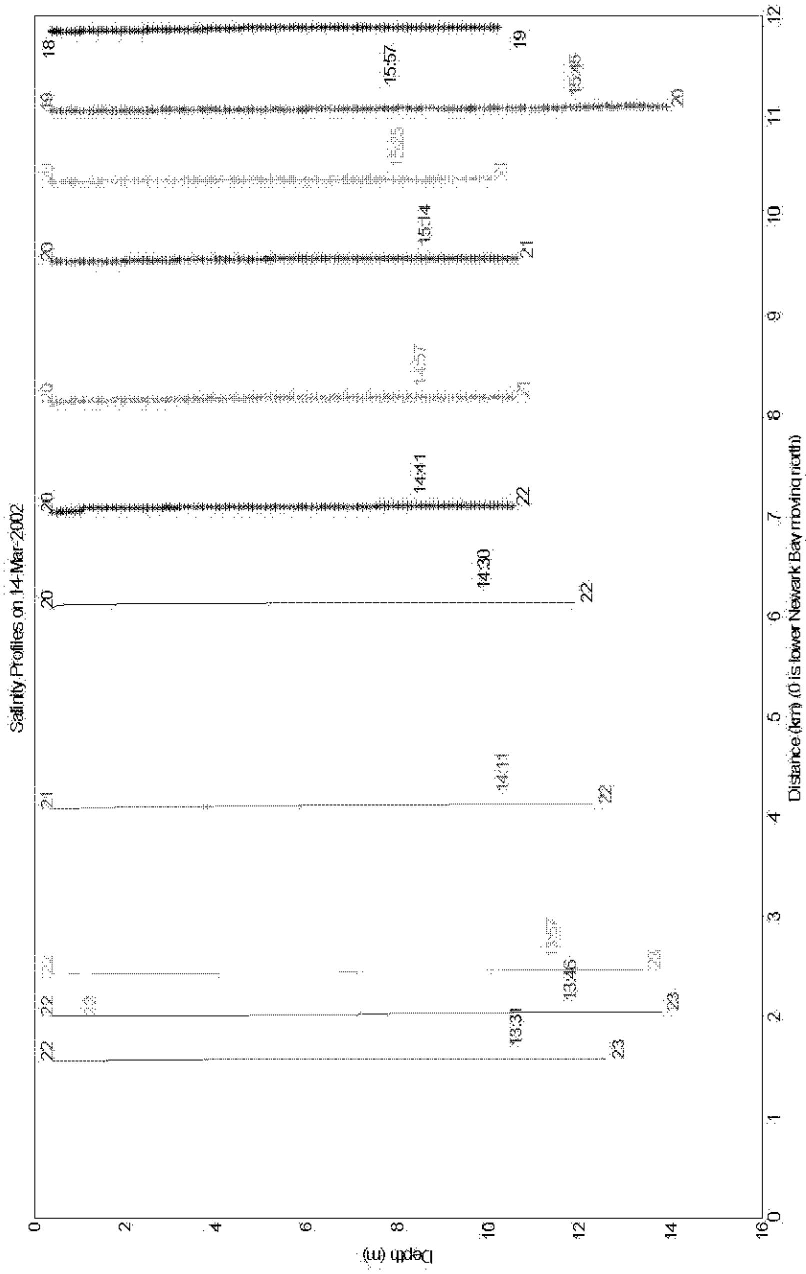

CTD Cast Locations


Salinity Profiles on 12-Mar-2002
Depth (m)
Distance (km) (0 is lower Newark Bay moving north)

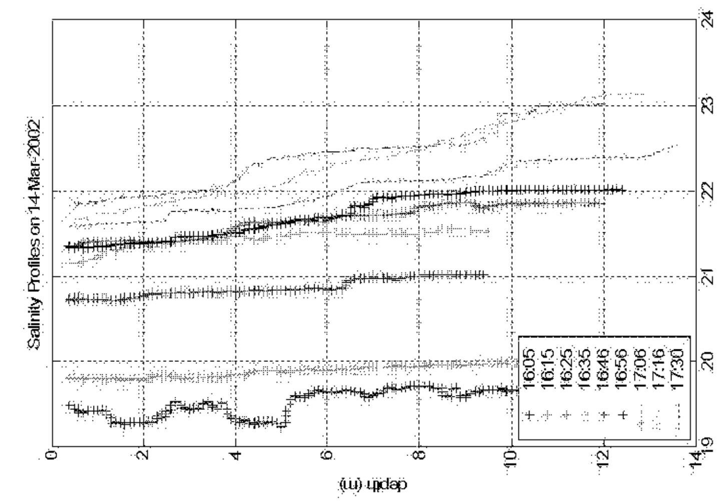

Salinity Profiles on 14-Mar-2002
depth (m)
salinity (psu)
13:31
13:46
13:46
13:57
14:11
14:30
14:41
14:57
15:14
15:25
15:45
15:57

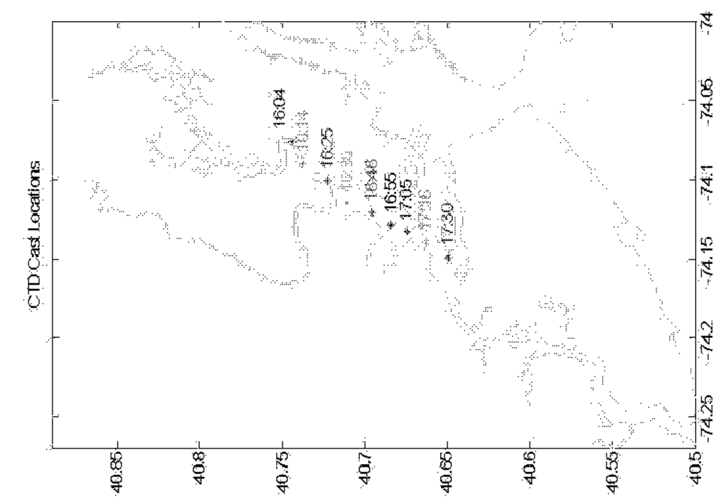

CTD Cast Locations
15:57
15:45
15:14
14:40
14:30
14:11
13:31
13:46

Transect 1

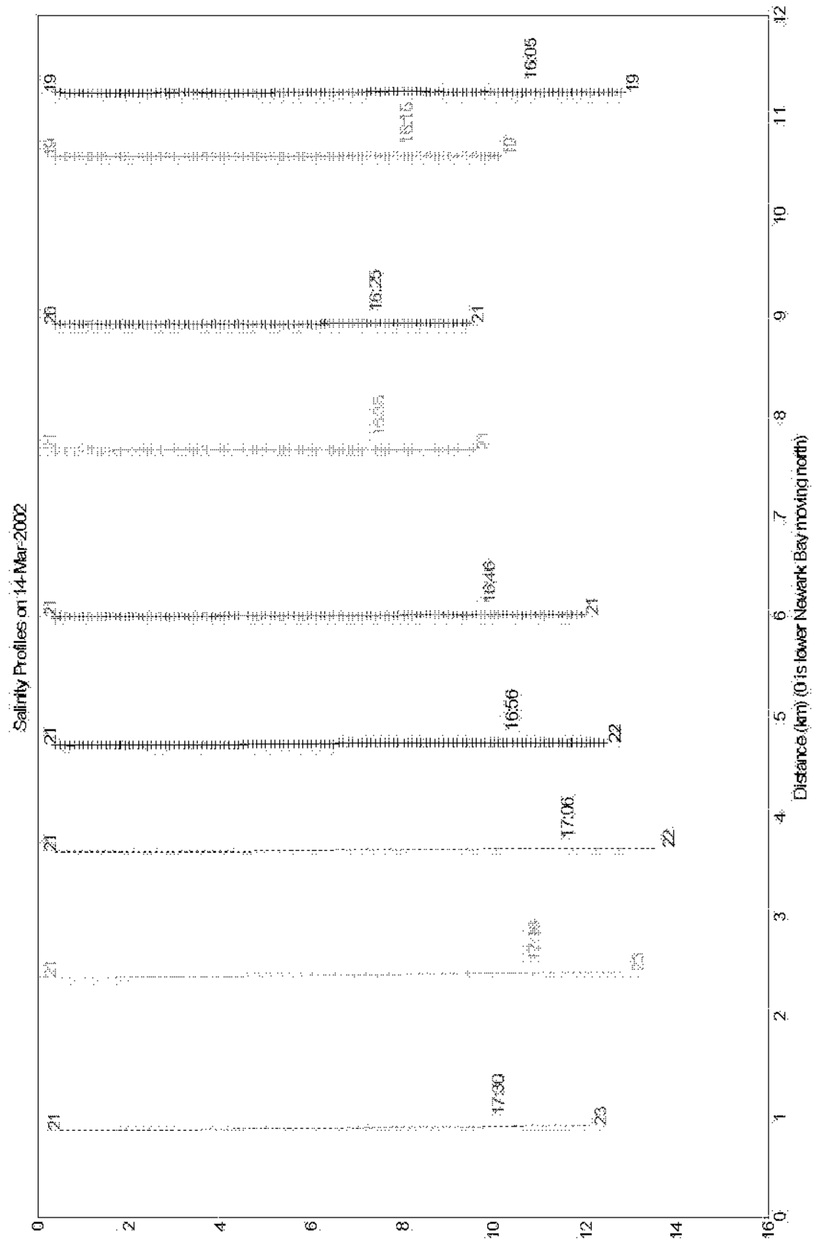

Salinity Profiles on 14-Mar-2002
Depth (m)
Distance (km) (0 is lower Newark Bay moving north)
13:31
13:46
13:57
14:11
14:30
14:41
14:57
15:14
15:25
15:45
15:57

Transect 1

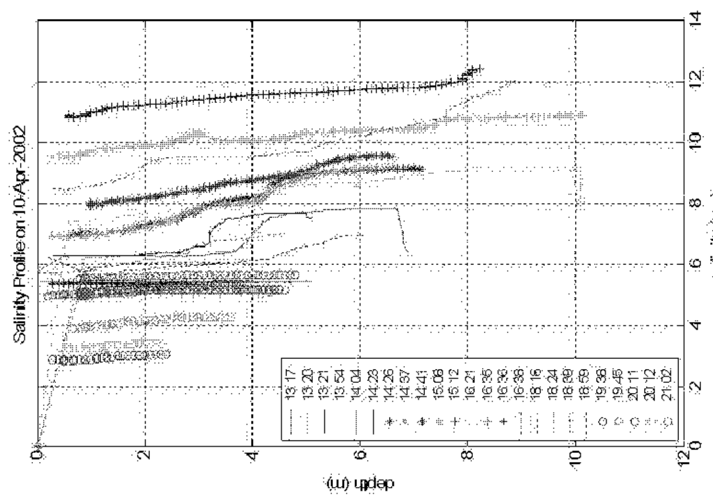

Salinity Profiles on 14-Mar-2002
depth (m)
salinity (psu)
16:05
16:15
16:25
16:35
16:46
16:56
17:06
17:16
17:30

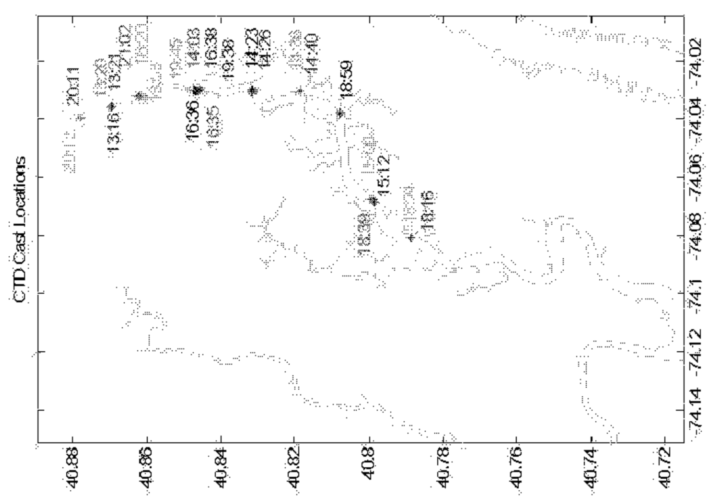

CTD Cast Locations
16:04
16:25
16:55
17:05
17:30

Transect 2

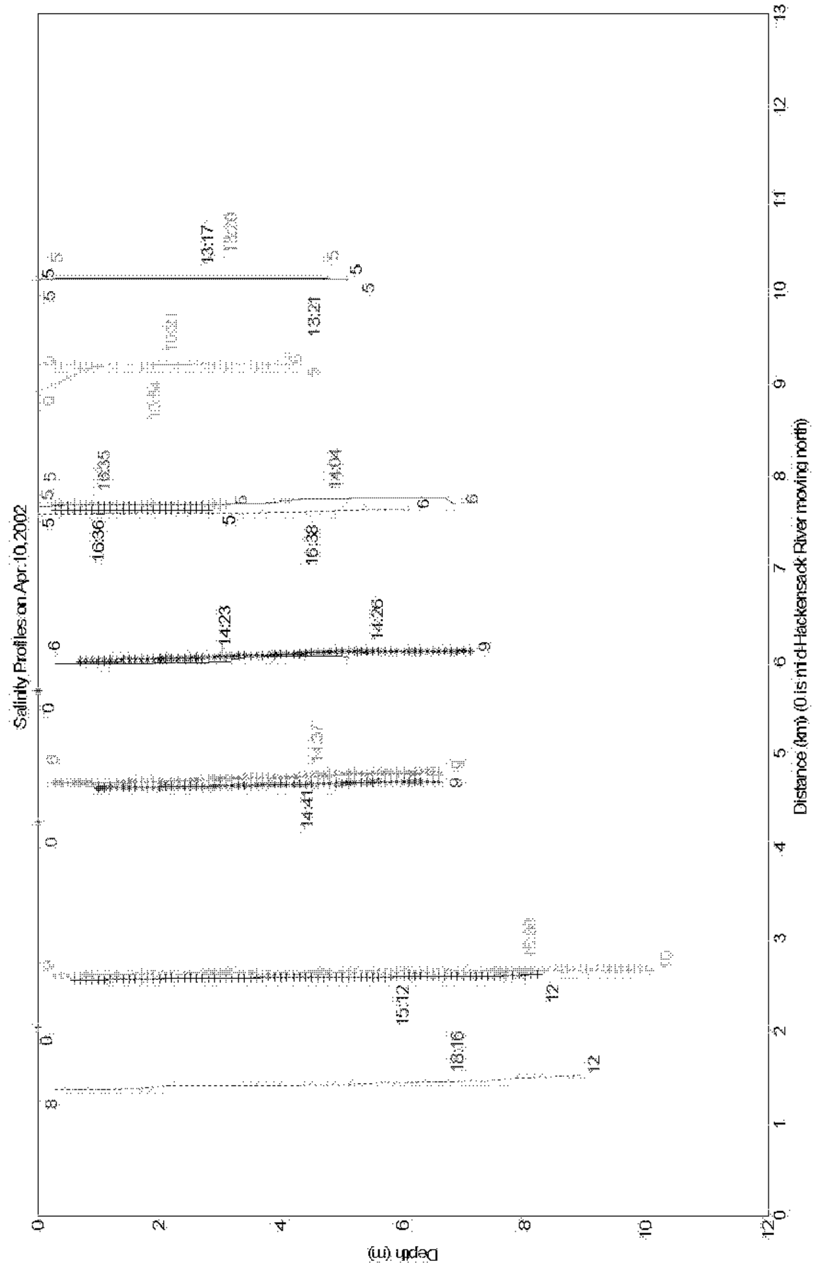

Salinity Profiles on 14-Mar-2002
Depth (m)
Distance (km) (0 is lower Newark Bay moving north)

Transect 2

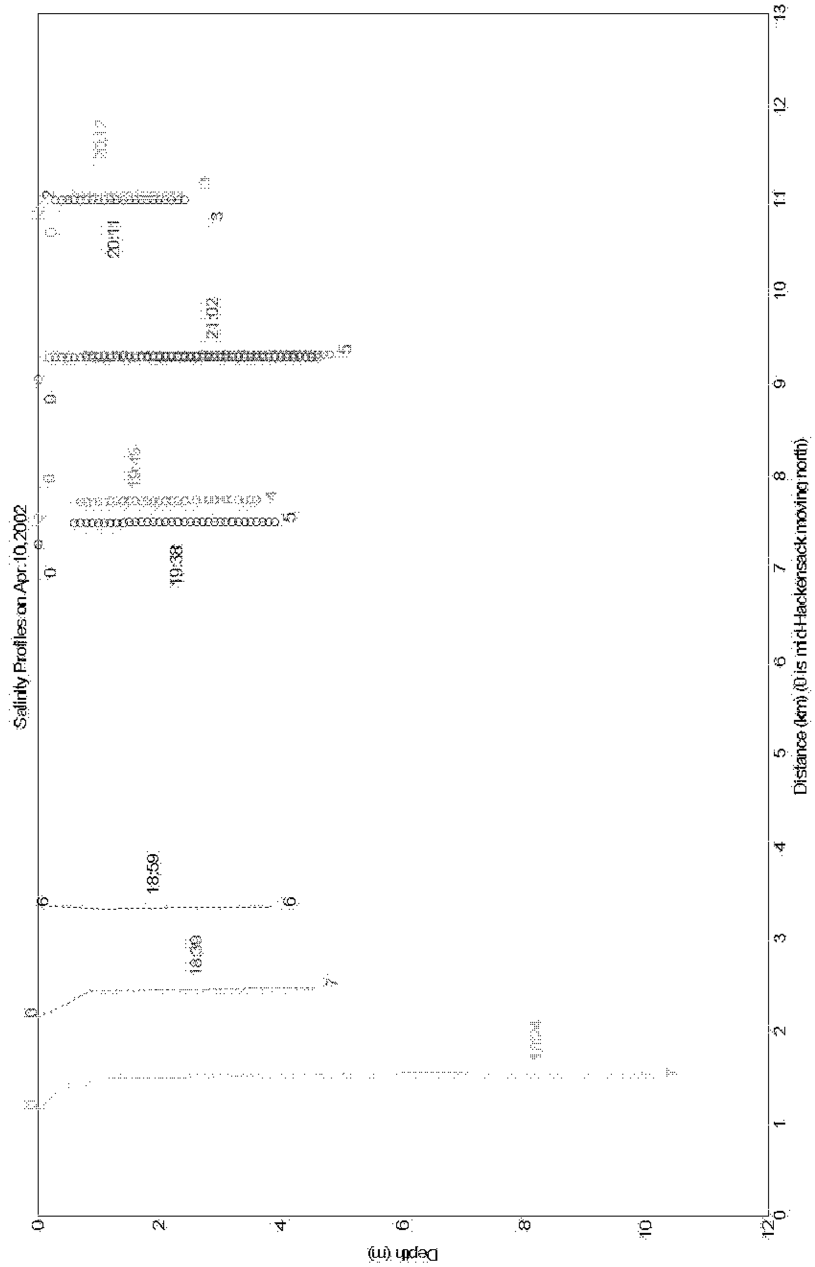




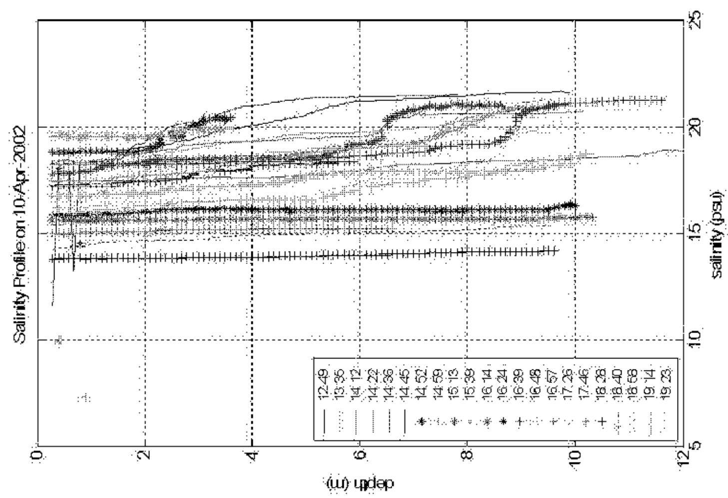
Note: Transects were split between 2 vessels on April 10, 2002. These transects were taken from the R/V Phoenix.

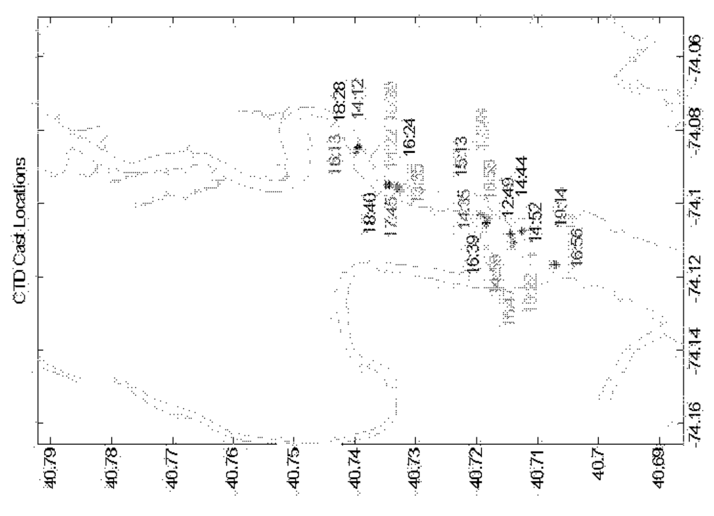


Transect 1 Note: Transects were split between 2 vessels on April 10, 2002. These transects were taken from the R/V Phoenix.

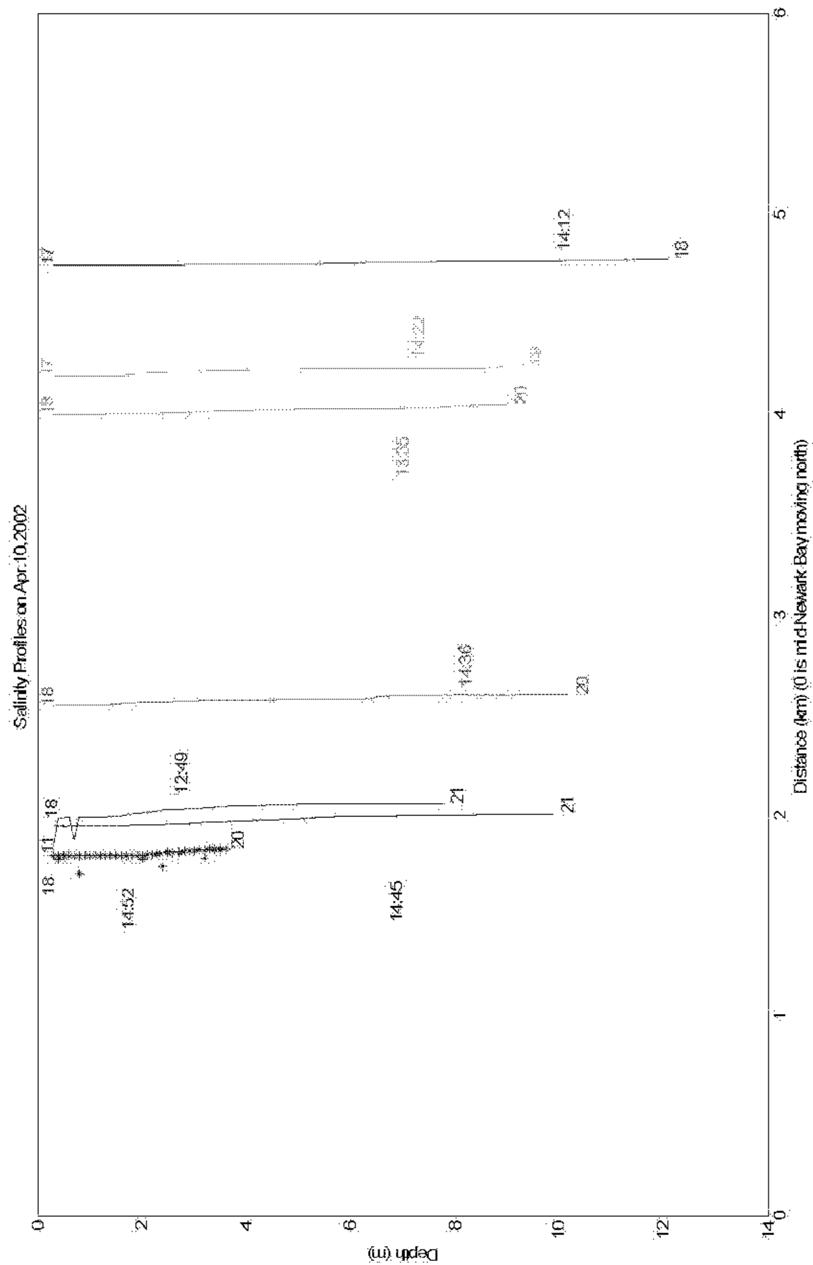


Transect 2 Note: Transects were split between 2 vessels on April 10, 2002. These transects were taken from the R/V Phoenix.

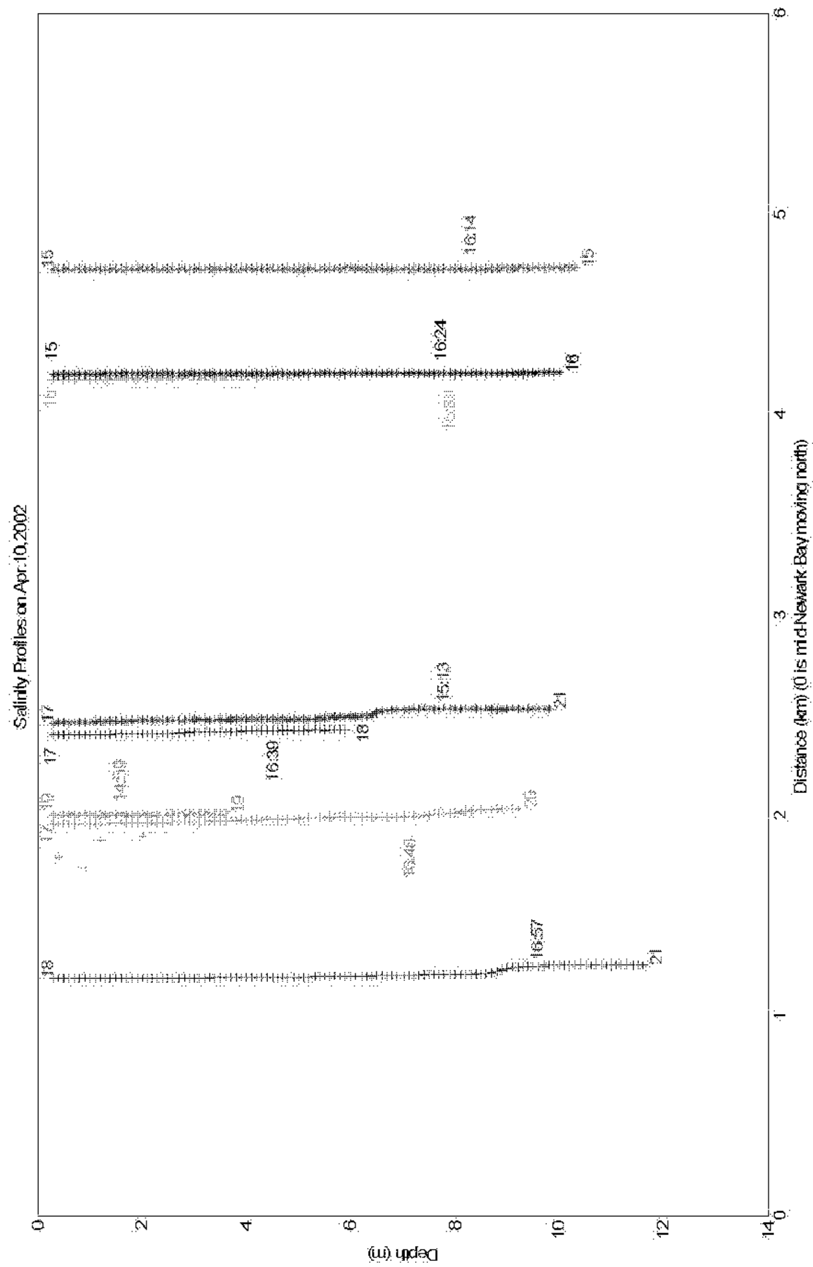




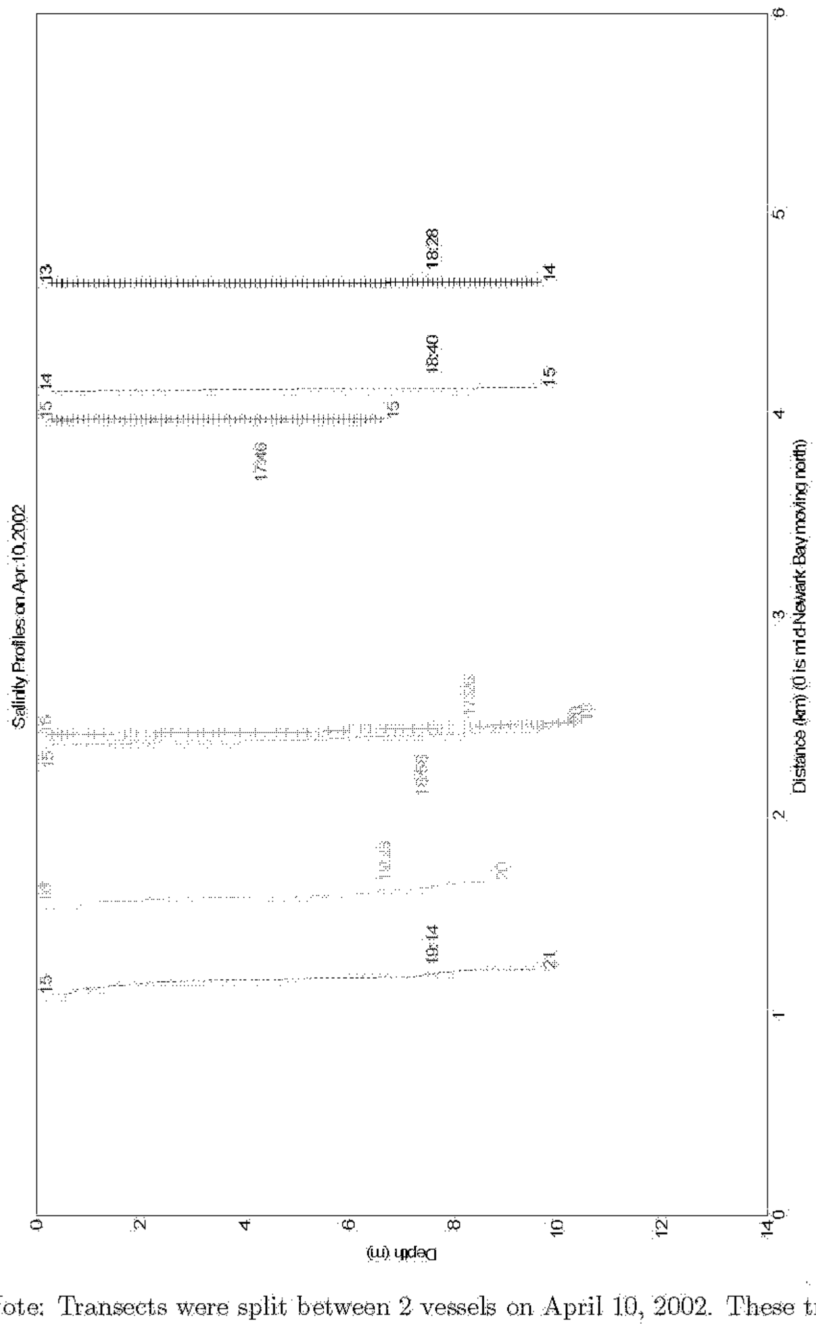
Note: Transects were split between 2 vessels on April 10, 2002. These transects were taken from the R/V Deep Explorer.



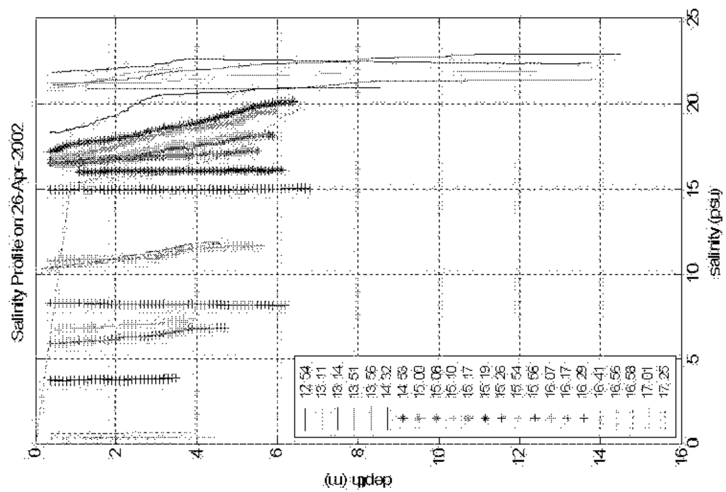
Transect 1 Note: Transects were split between 2 vessels on April 10, 2002. These transects were taken from the R/V Deep Explorer.

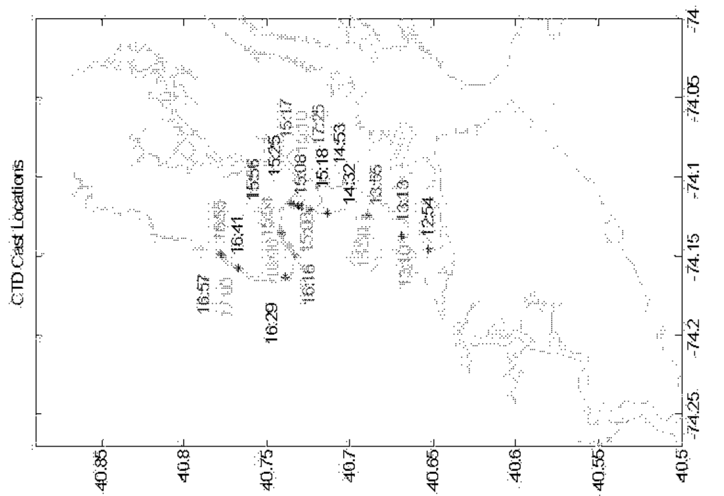


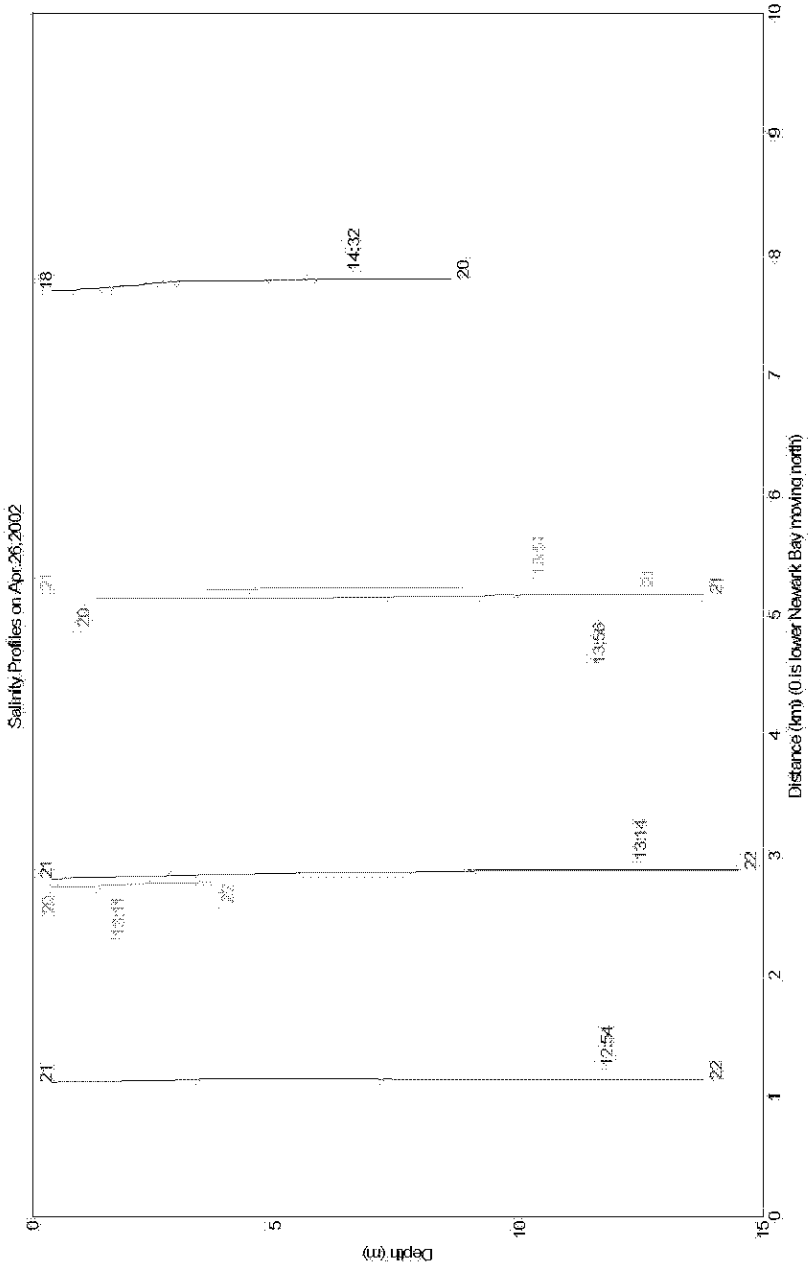
Transect 2 Note: Transects were split between 2 vessels on April 10, 2002. These transects were taken from the R/V Phoenix.



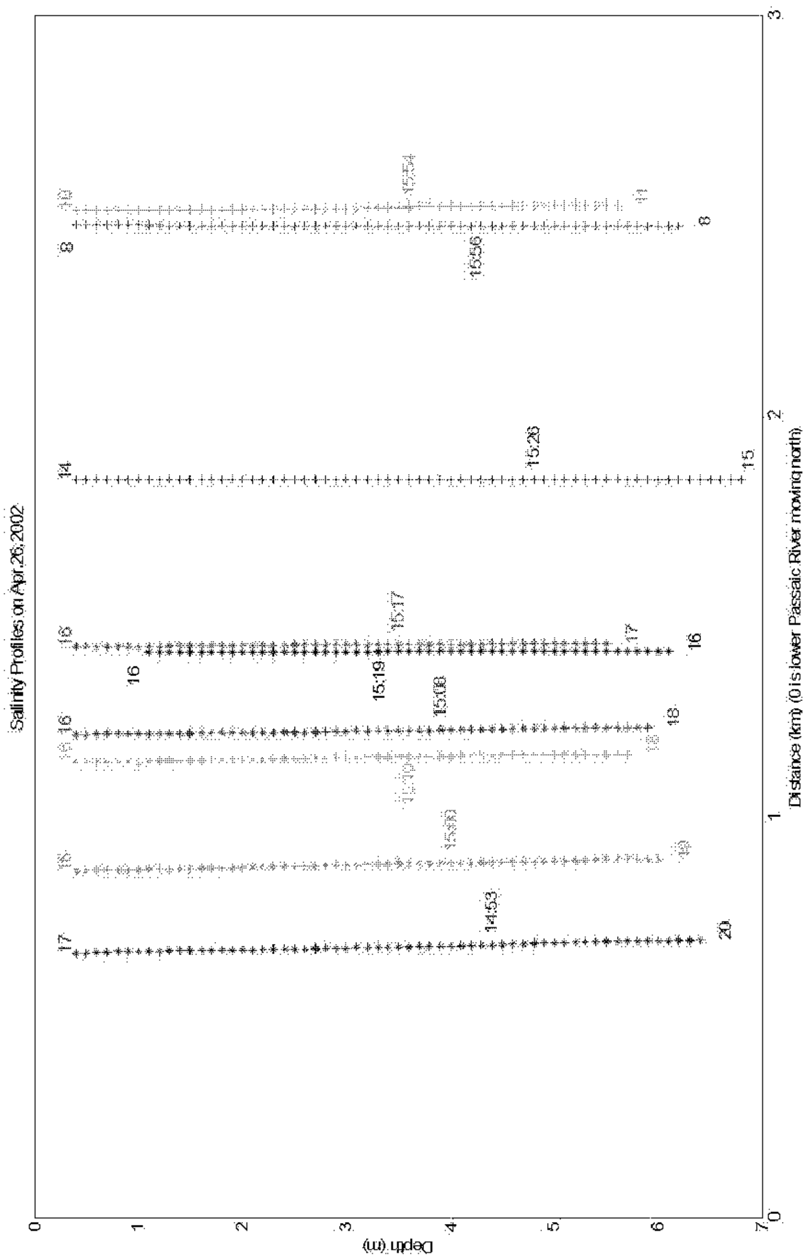
Transect 3 Note: Transects were split between 2 vessels on April 10, 2002. These transects were taken from the R/V Phoenix.


Salinity Profile on 26-Apr-2002
salinity (psu)
depth (m)
12:54
13:11
13:14
13:51
13:56
14:32
14:53
15:00
15:08
15:10
15:17
15:19
15:26
15:54
15:56
16:07
16:17
16:29
16:41
16:56
16:58
17:01
17:25

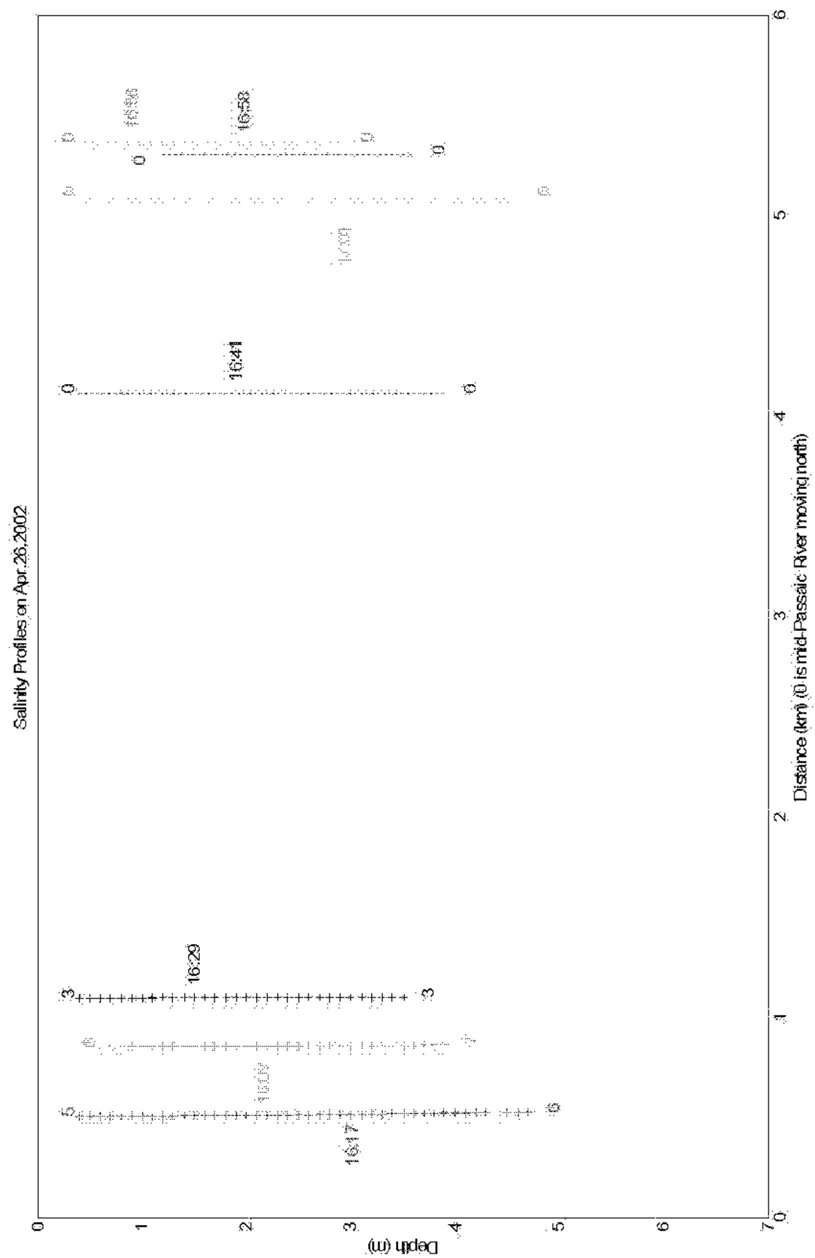

CTD Cast Locations



Newark Bay Section of Transect



Lower Passaic River Section of Transect



Middle Passaic River Section of Transect

Appendix E

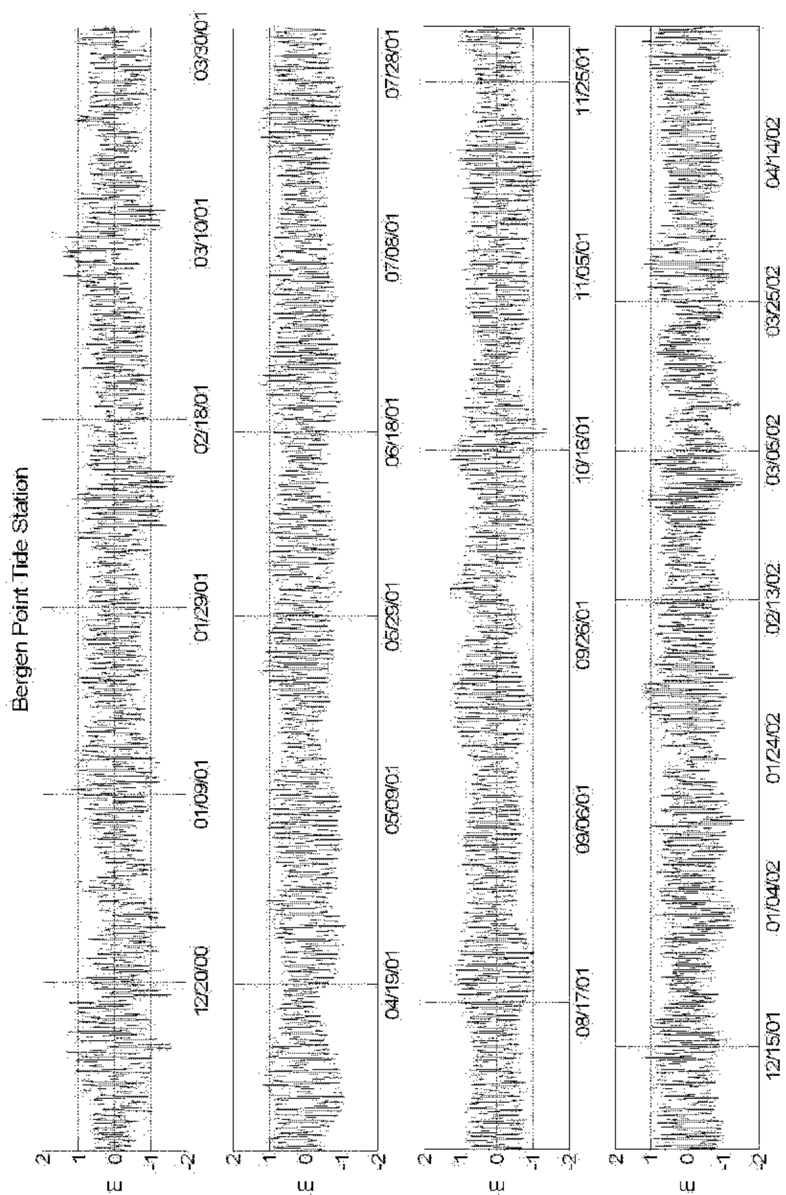
Model Data Comparison

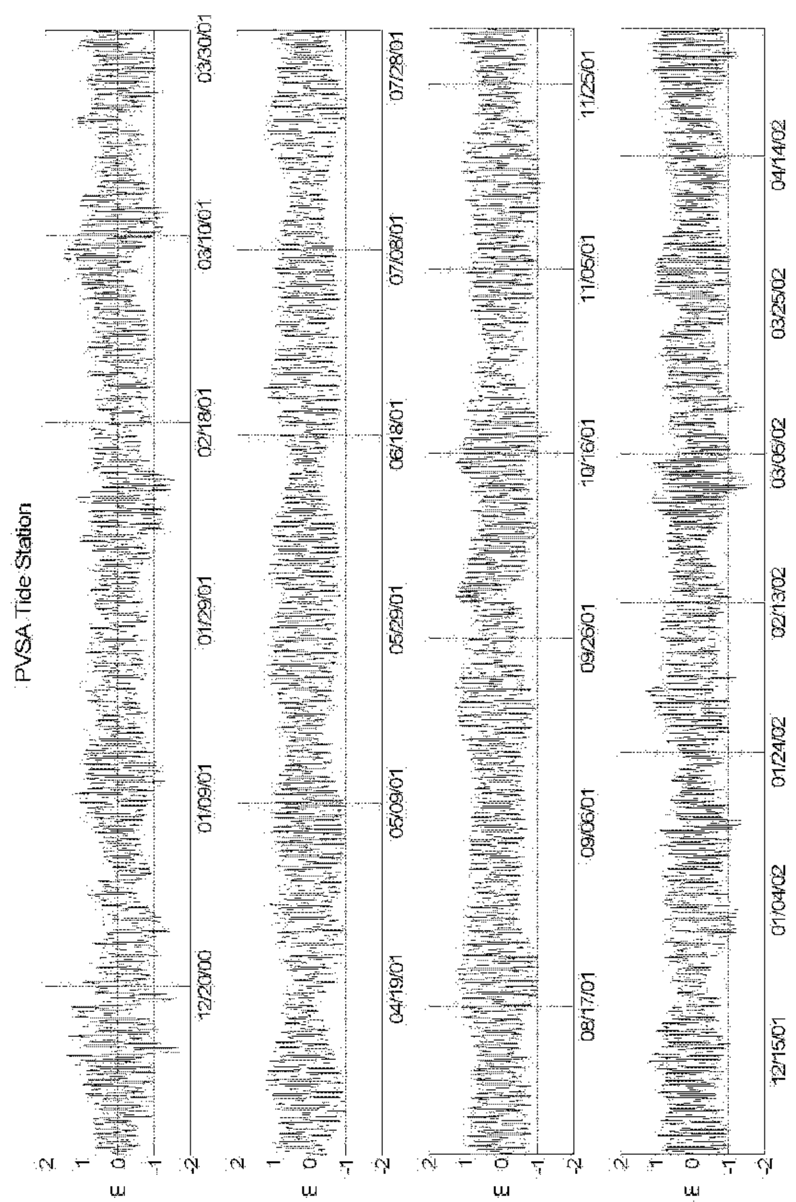
Appendix E Key

Bergen Point - BP (40° 38.4'N, 74° 8.8'W)
Passaic Valley Sewerage Commission -PVSC (40° 43'N, 74° 8'W)
Constable Hook in Bayonne - BAY (40° 40.2'N, 74° 4.2'W)
Perth Amboy Yacht Club PAYC (40° 30'N, 74° 15'W)
Hackensack River -HACK (N/A)
Perth Amboy - PA (40° 30.6'N, 74° 15.6'W)
North end of the Arthur Kill -AK1 (40° 37.8'N, 74° 12'W)
Western end of the Kill van Kull -KVK1 (40° 38.4'N, 74°7.5'W)
North end of Newark Bay -NB1(40° 42'N, 74° 7.2'W)
South end of Newark Bay -NB3 (40° 40'N, 74° 8.4'W)
Raritan River - RR (40° 24'N, 74° 18'W)

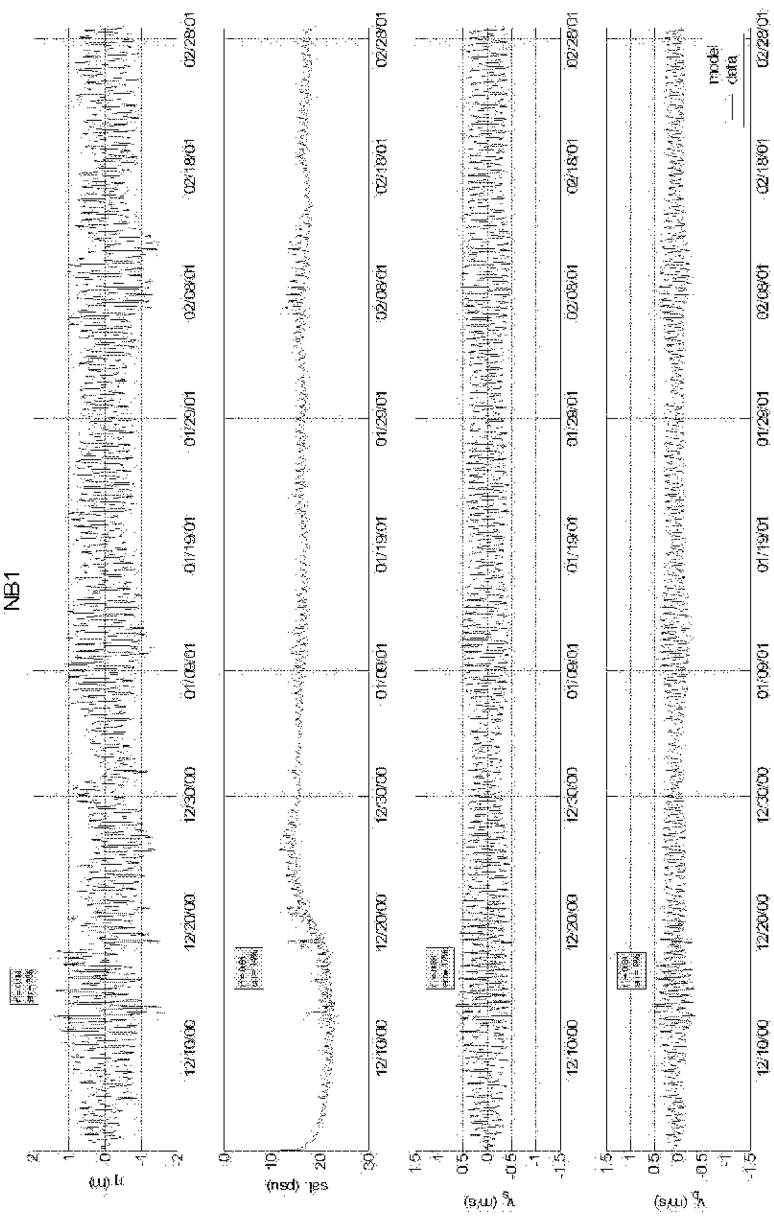
All times are GMT
Model output is in blue, data is in red
Surface (s) and bottom (b) velocities are shown
Velocity is positive into Newark Bay

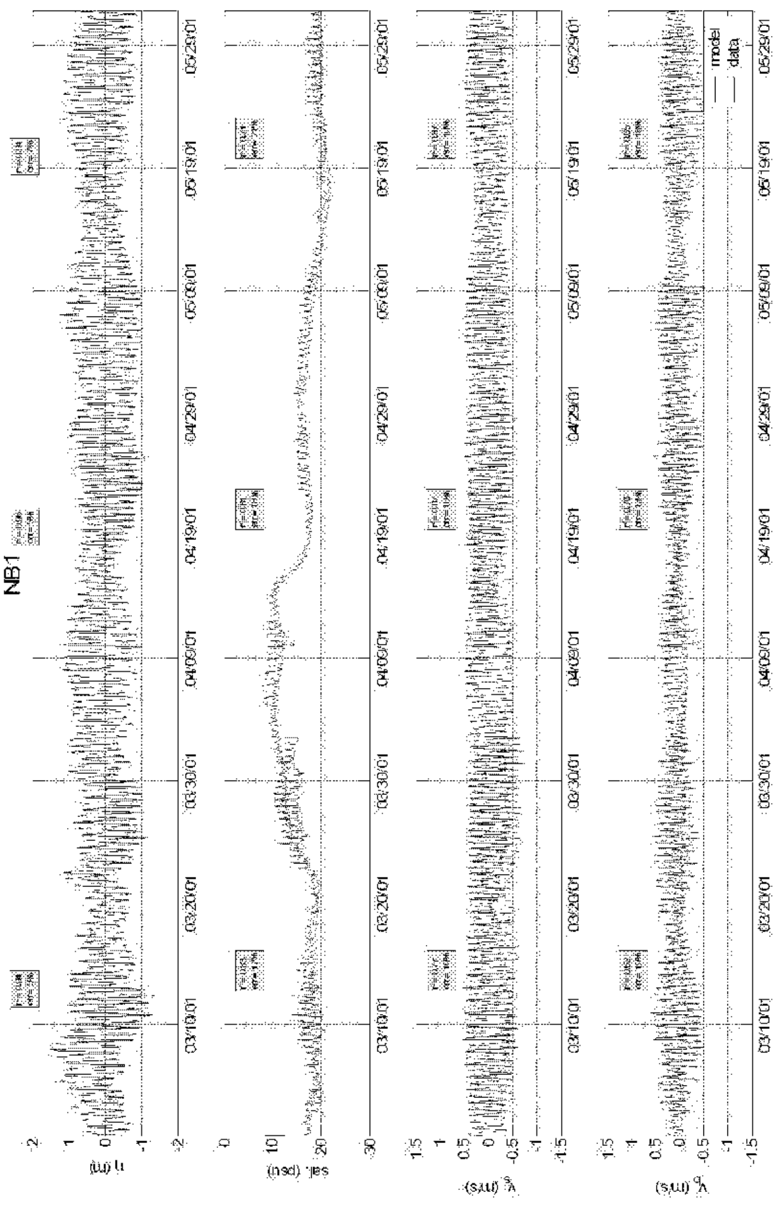
Water Elevation Comparisons

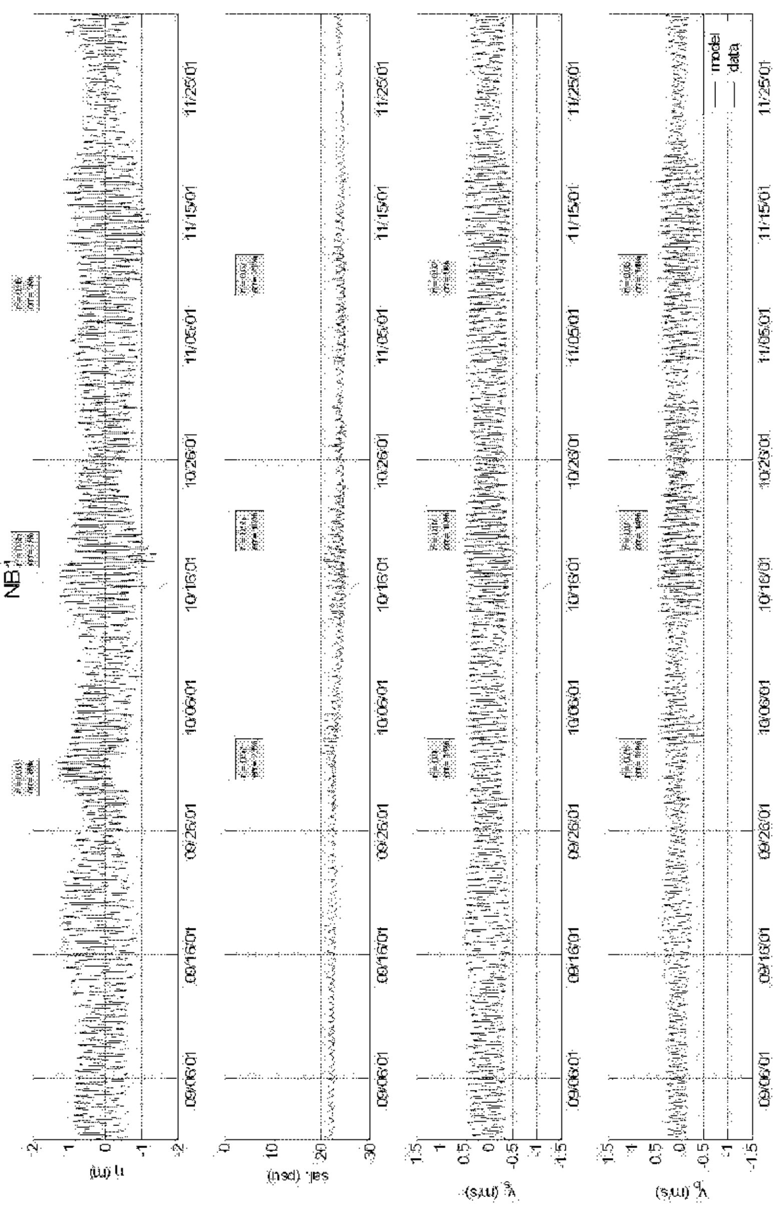


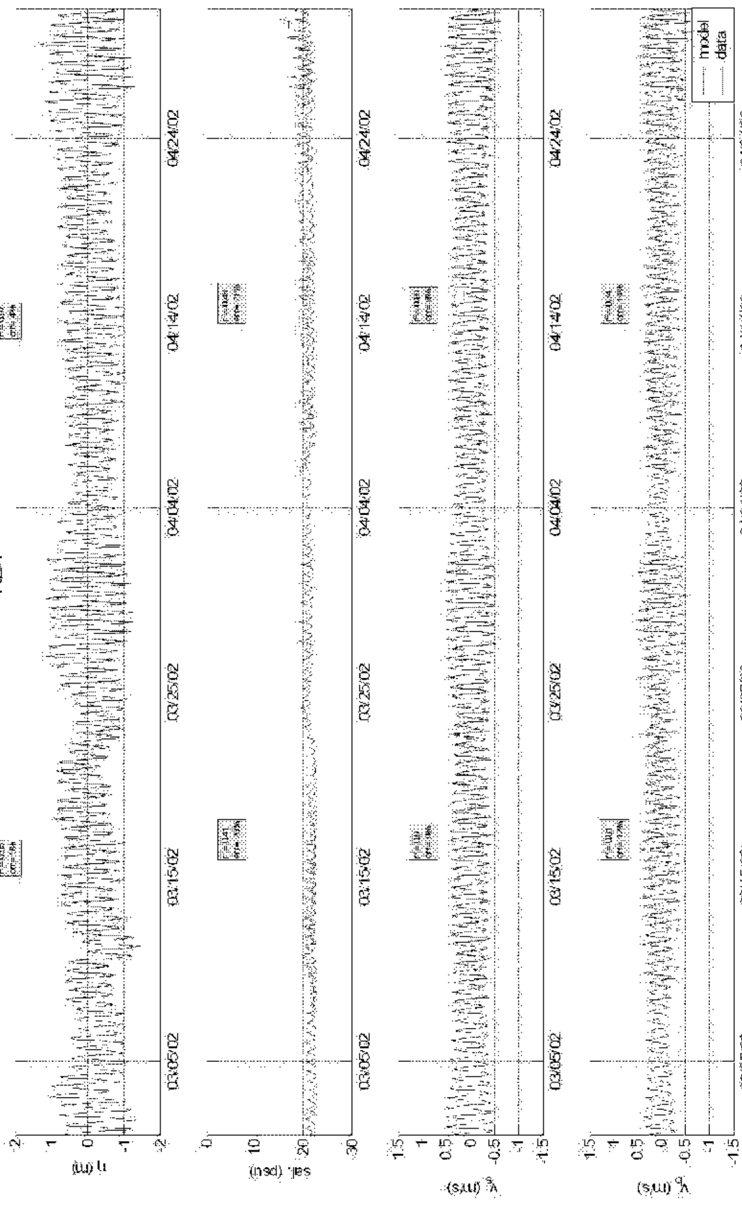

PVSA Tide Station
m
12/2/00
01/09/01
01/29/01
02/18/01
03/10/01
03/30/01
04/19/01
05/09/01
05/29/01
06/18/01
07/08/01
07/28/01
08/17/01
09/06/01
09/26/01
10/16/01
11/05/01
11/25/01
12/15/01
01/04/02
01/24/02
02/13/02
03/05/02
03/25/02
04/14/02

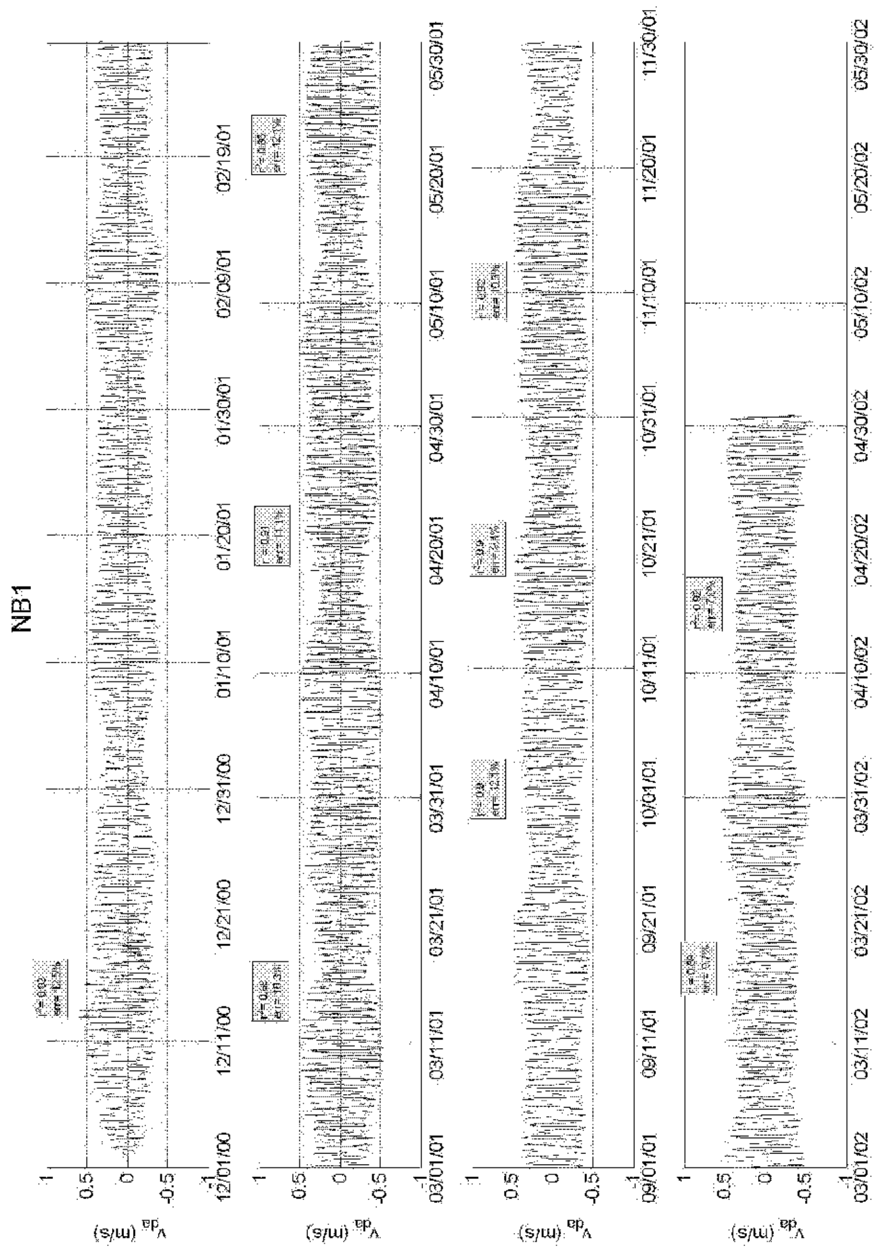
Hourly Comparison with Moored Data

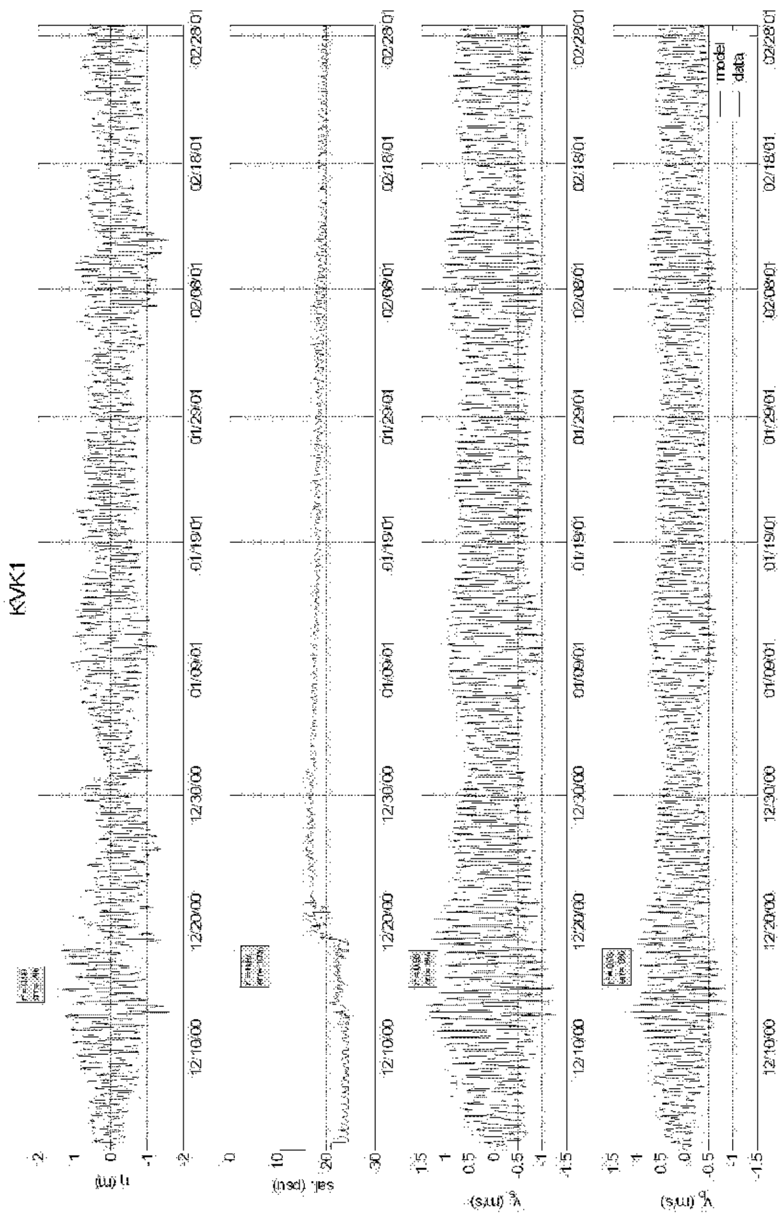


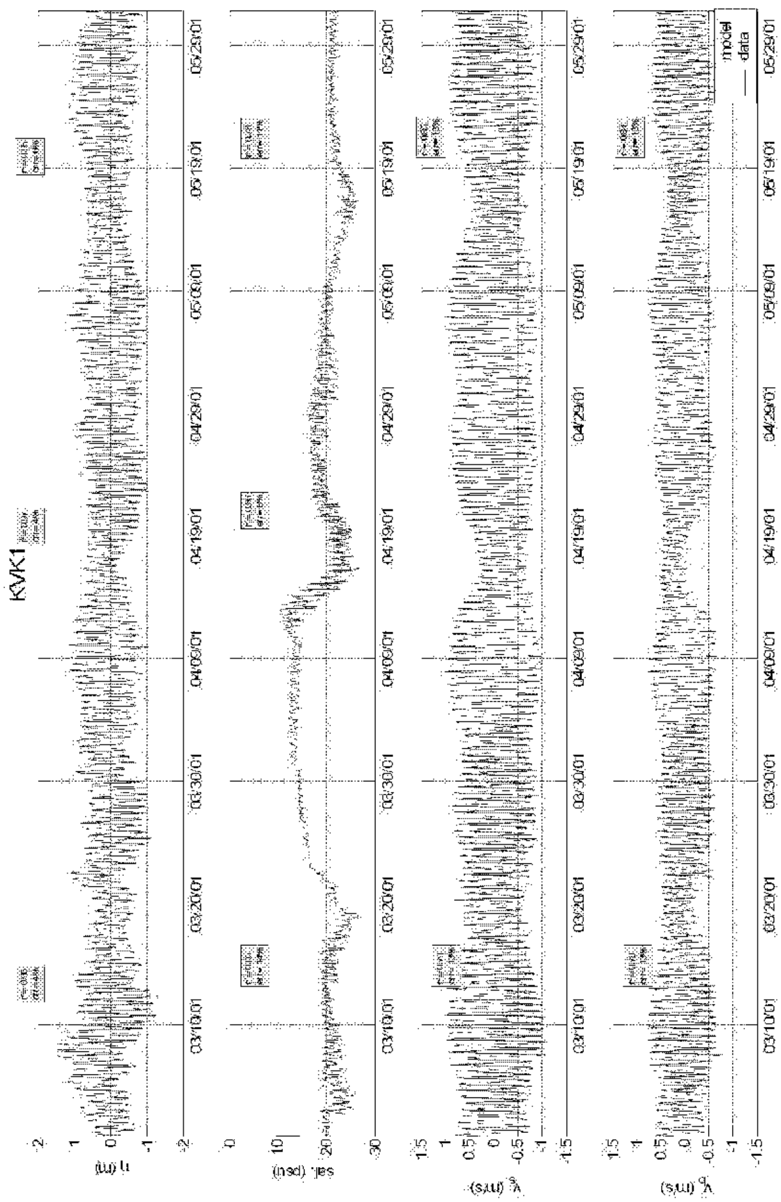

NB1
η (m)
sal. (psu)
model
data
03/10/01
03/20/01
03/30/01
04/09/01
04/19/01
04/29/01
05/09/01
05/19/01
05/29/01


NB1
η (m)
sal. (psu)
model
data
09/06/01
09/16/01
09/26/01
10/06/01
10/16/01
10/26/01
11/05/01
11/15/01
11/25/01

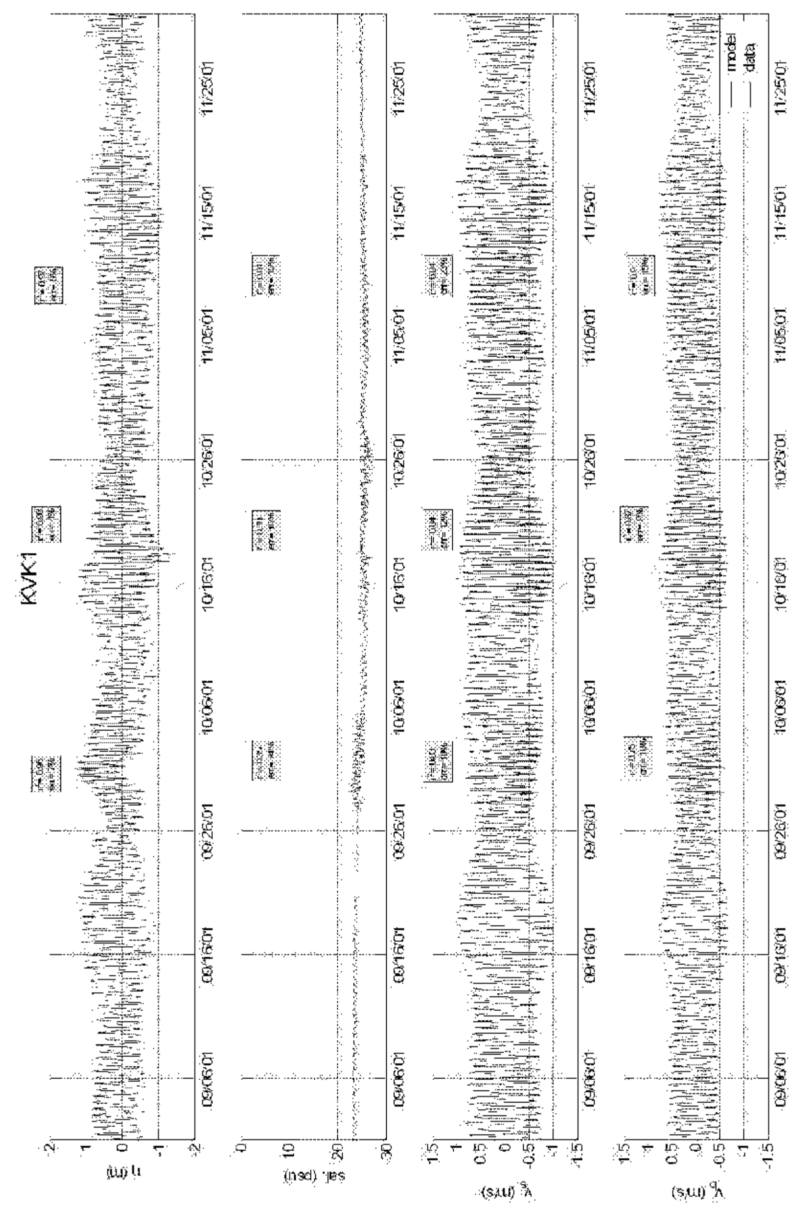

NB1
η (m)
sal. (psu)
03/05/02
03/15/02
03/25/02
04/04/02
04/14/02
04/24/02
model
data

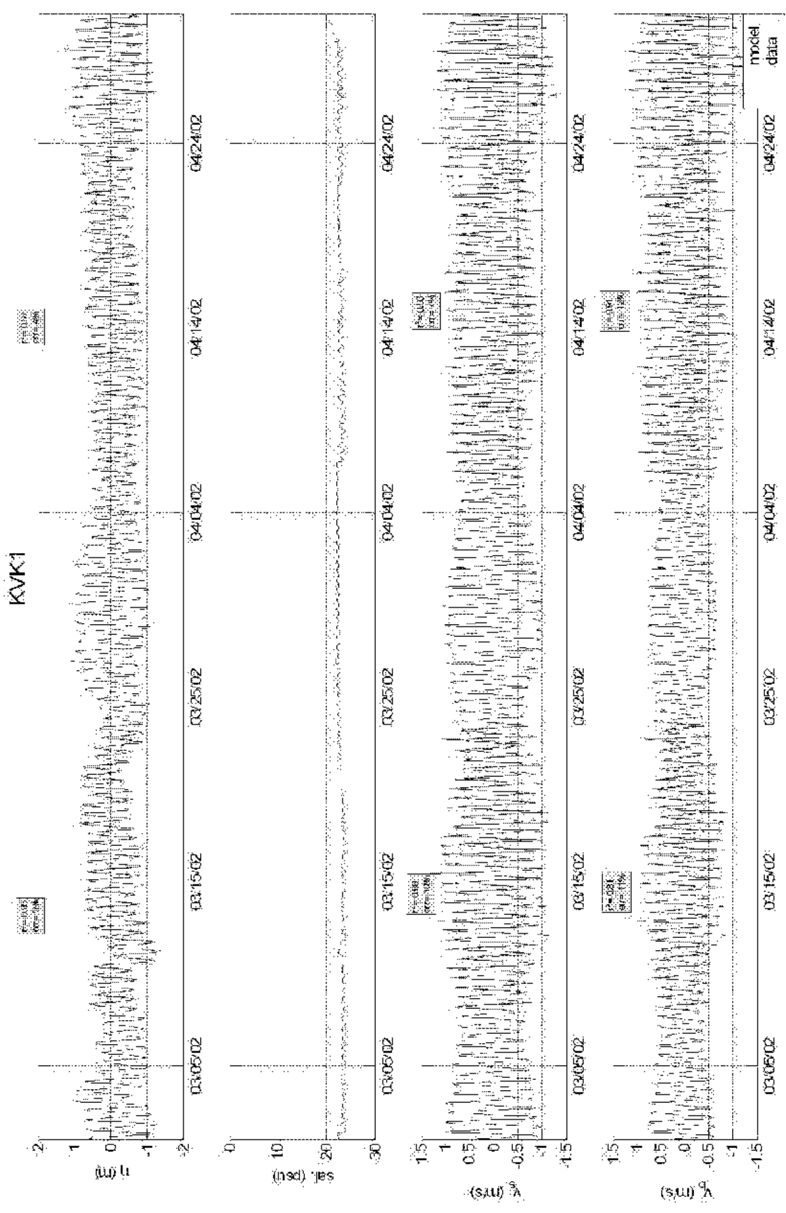

NB1
v_{da} (m/s)

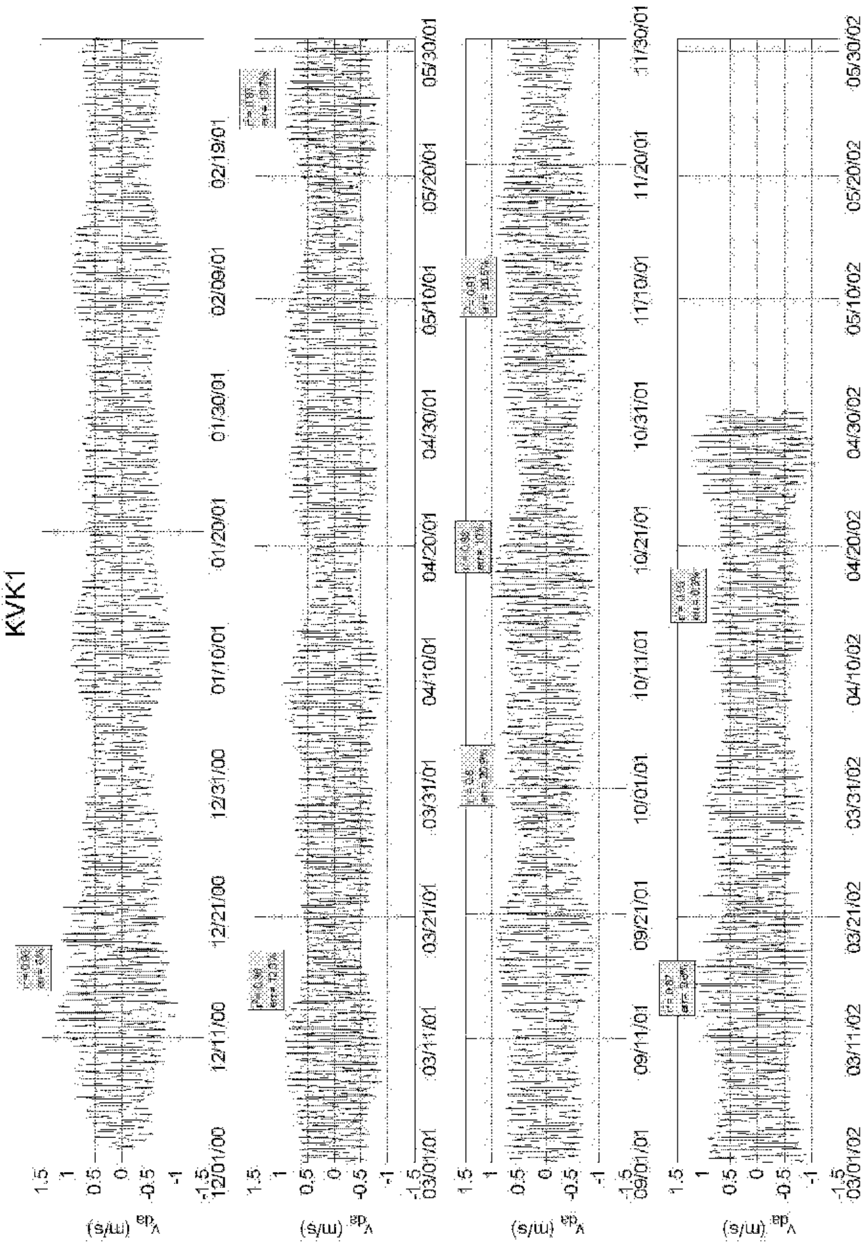

KVK1
η (m)
sal. (psu)
model
data
12/10/00
12/20/00
12/30/00
01/09/01
01/19/01
01/29/01
02/08/01
02/18/01
02/28/01

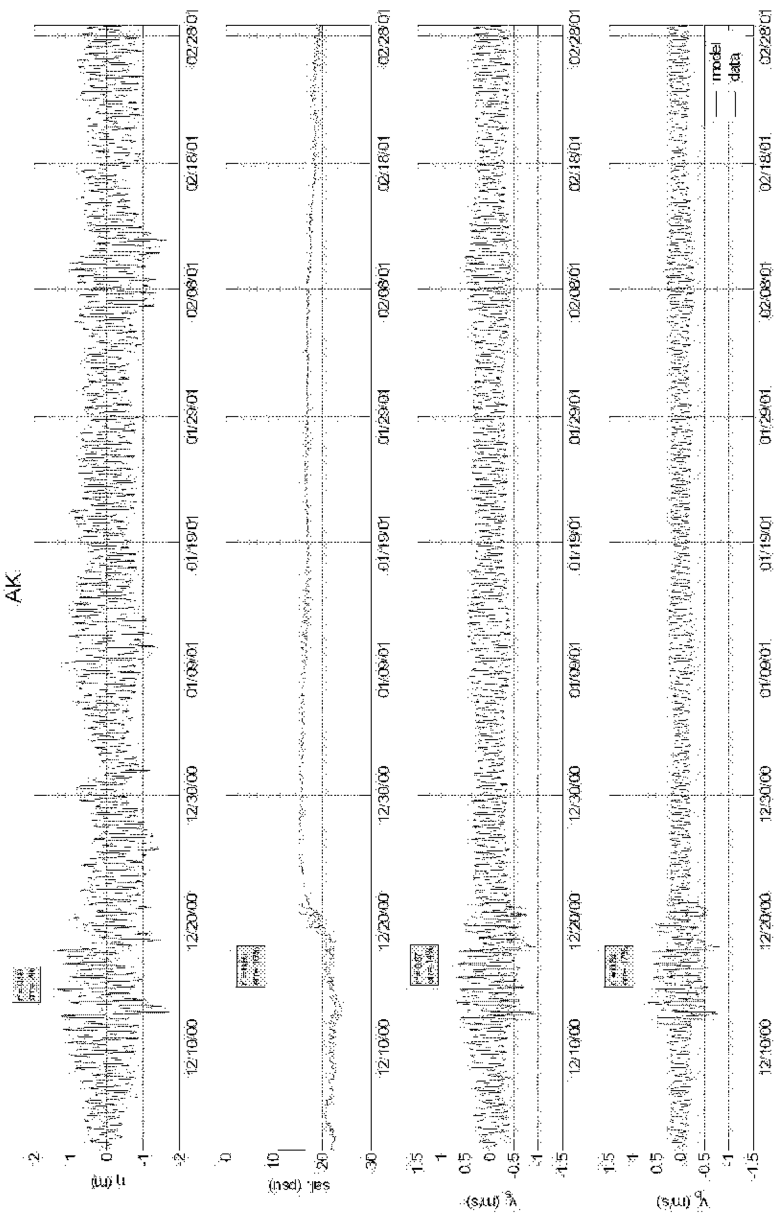


NJDEP00016078

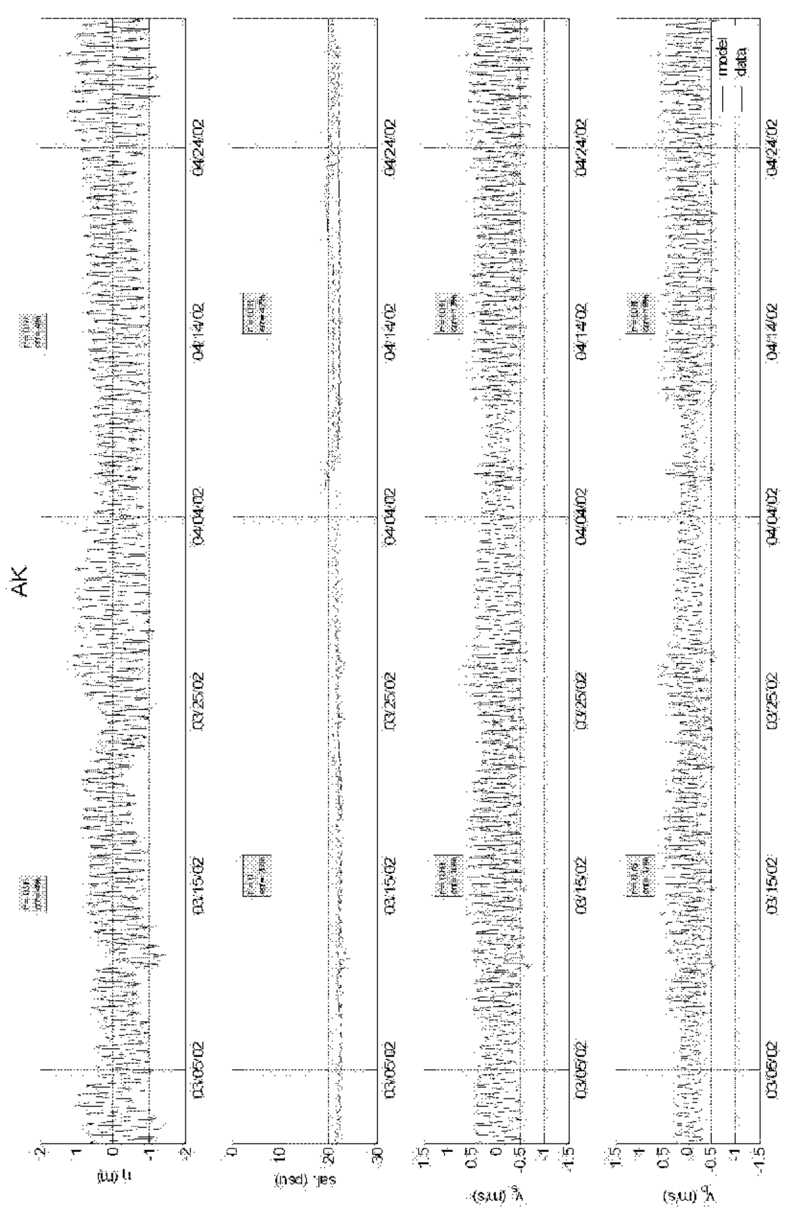

KVK1
sal. (psu)
09/06/01
09/16/01
09/26/01
10/06/01
10/16/01
10/26/01
11/05/01
11/15/01
11/25/01
model
data

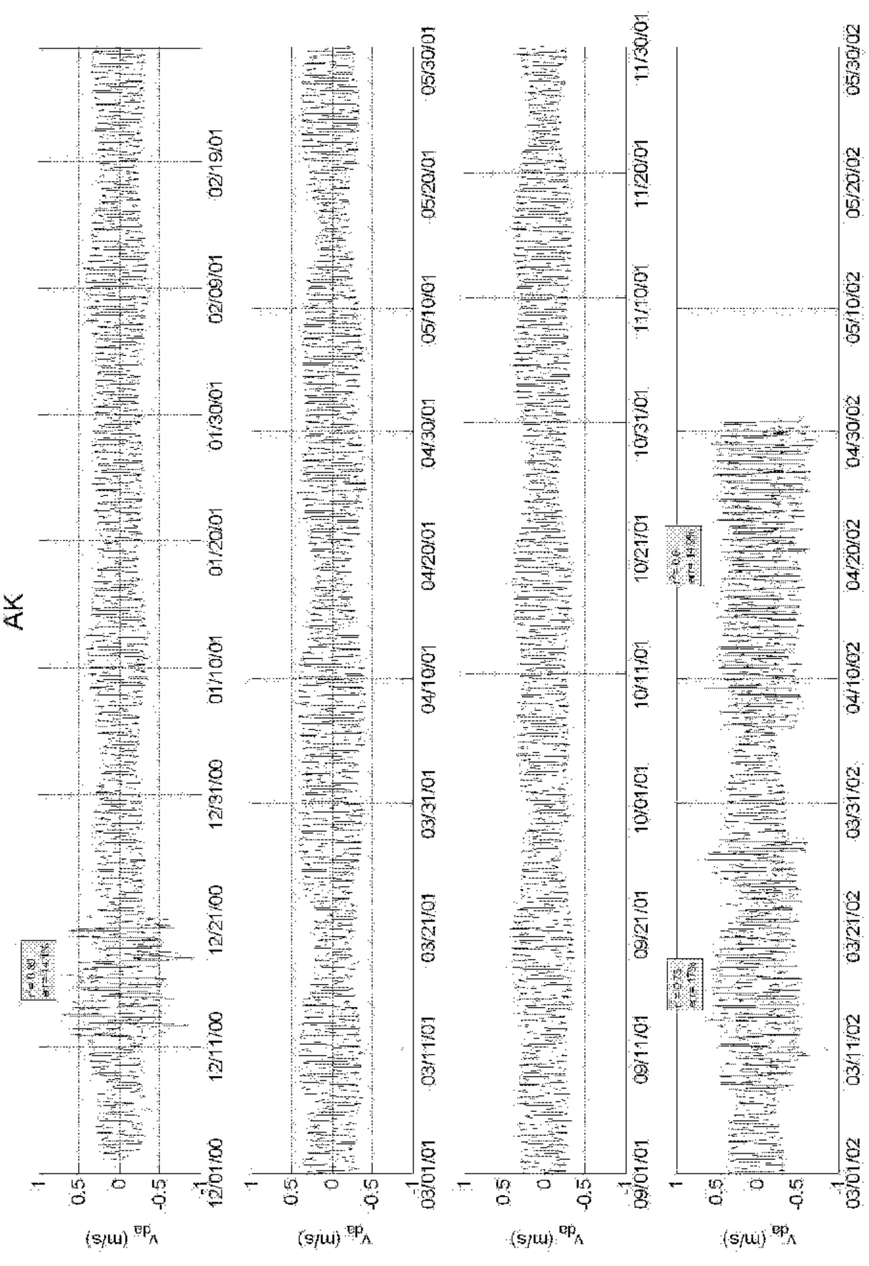

KVK1
model
data


KVK1

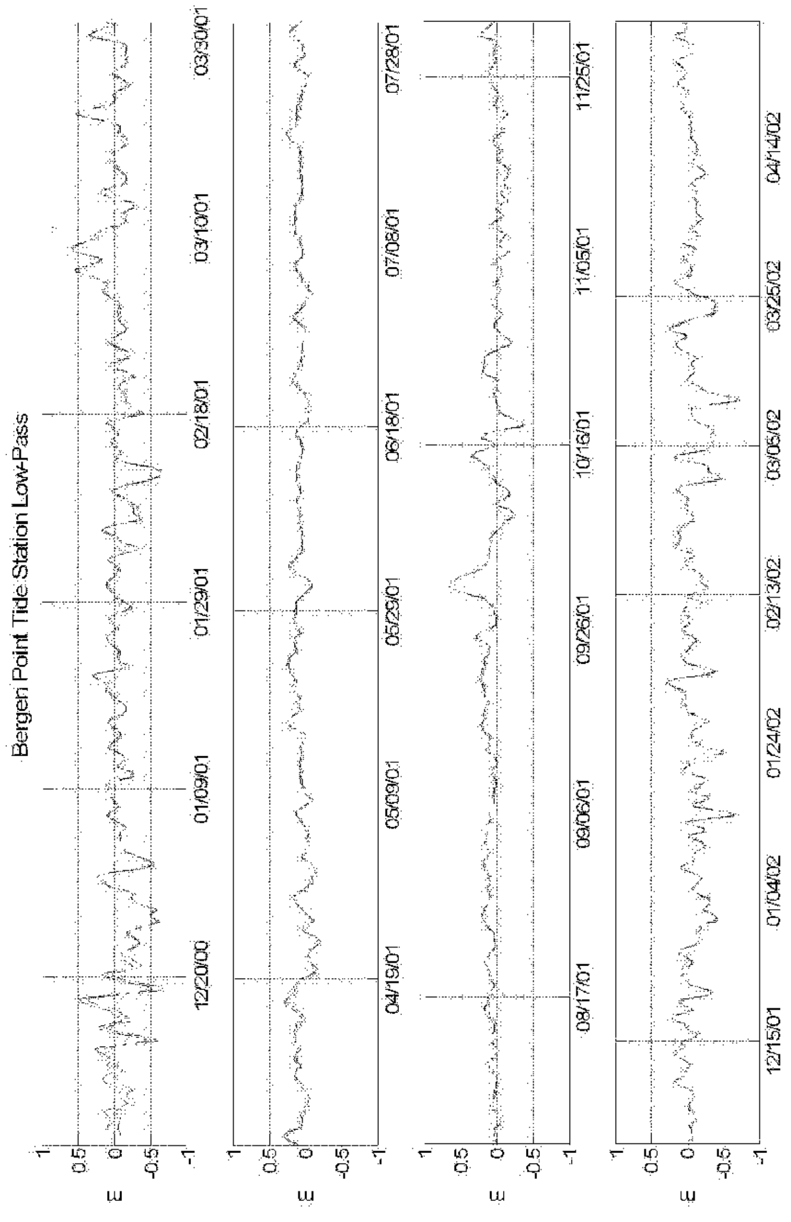


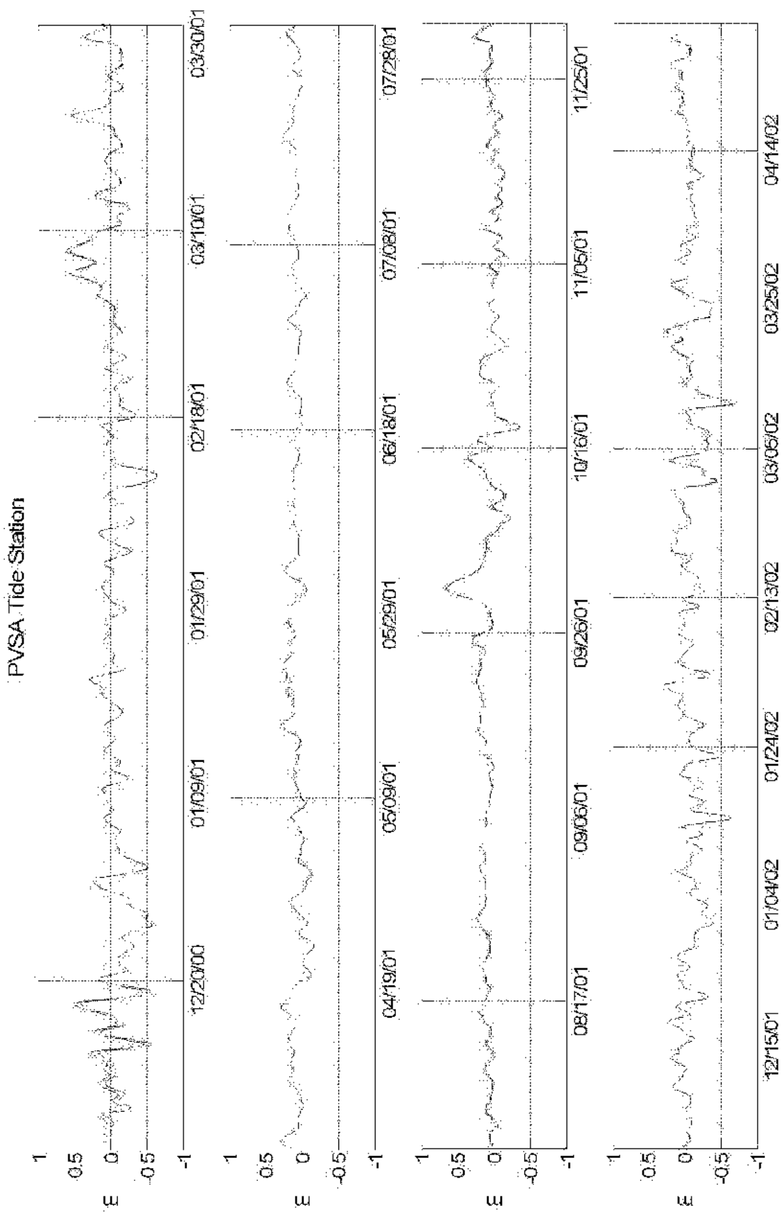
NJDEP00016082


AK
η (m)
sal. (psu)
model
data
03/05/02
03/15/02
03/25/02
04/04/02
04/14/02
04/24/02


AK
v_{da} (m/s)
1
0.5
0
-0.5
-1
12/01/00
12/11/00
12/21/00
12/31/00
01/10/01
01/20/01
01/30/01
02/09/01
02/19/01
03/01/01
03/11/01
03/21/01
03/31/01
04/10/01
04/20/01
04/30/01
05/10/01
05/20/01
05/30/01
09/01/01
09/11/01
09/21/01
10/01/01
10/11/01
10/21/01
10/31/01
11/10/01
11/20/01
11/30/01
03/01/02
03/11/02
03/21/02
03/31/02
04/10/02
04/20/02
04/30/02
05/10/02
05/20/02
05/30/02

Low-passed Comparisons with Moored Data




PVSA Tide Station
m
1
0.5
0
-0.5
-1
12/20/00
01/09/01
01/29/01
02/18/01
03/10/01
03/30/01
04/19/01
05/09/01
05/29/01
06/18/01
07/08/01
07/28/01
08/17/01
09/06/01
09/26/01
10/16/01
11/05/01
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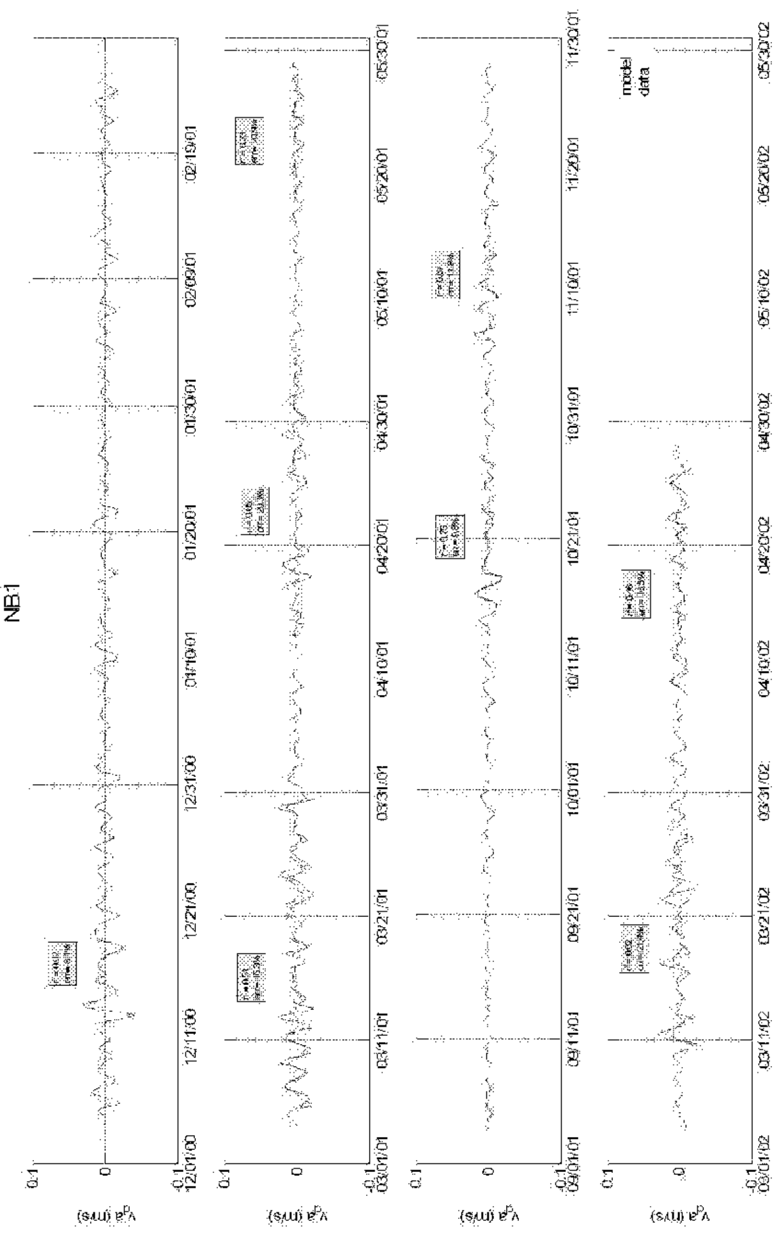
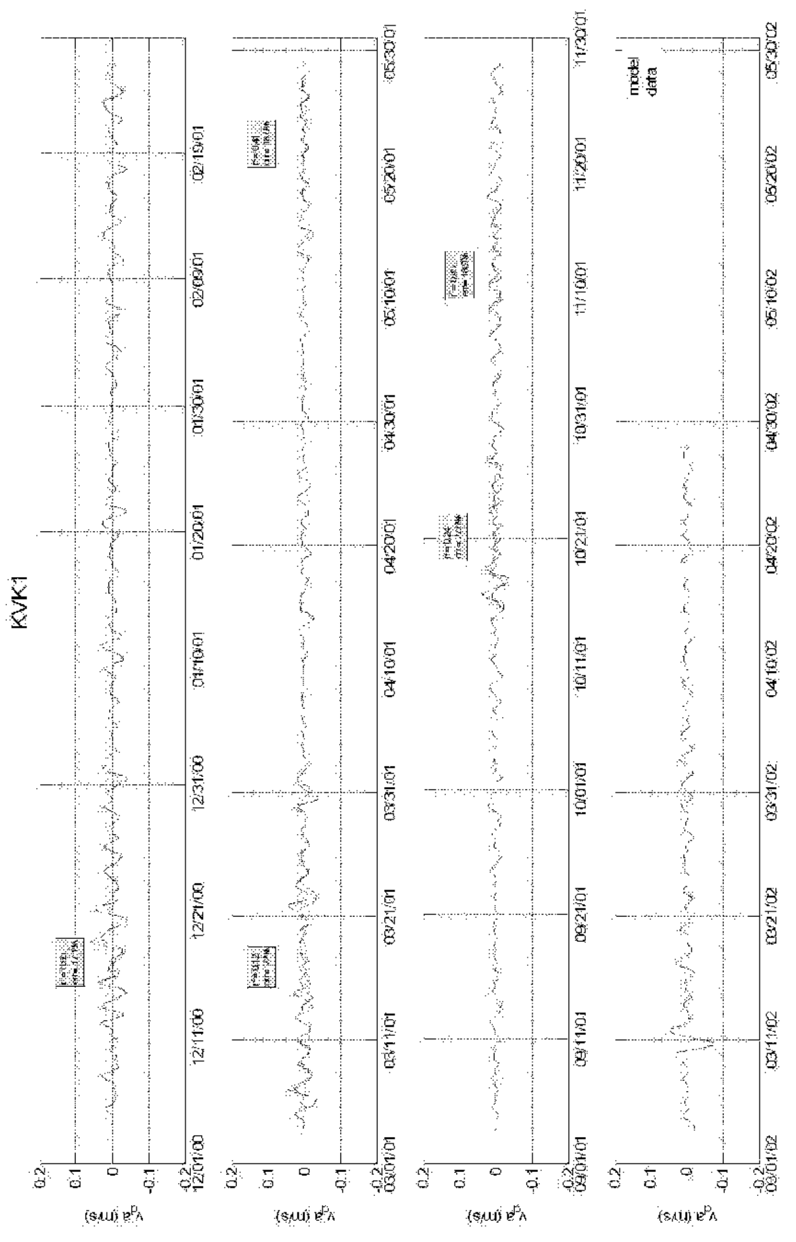
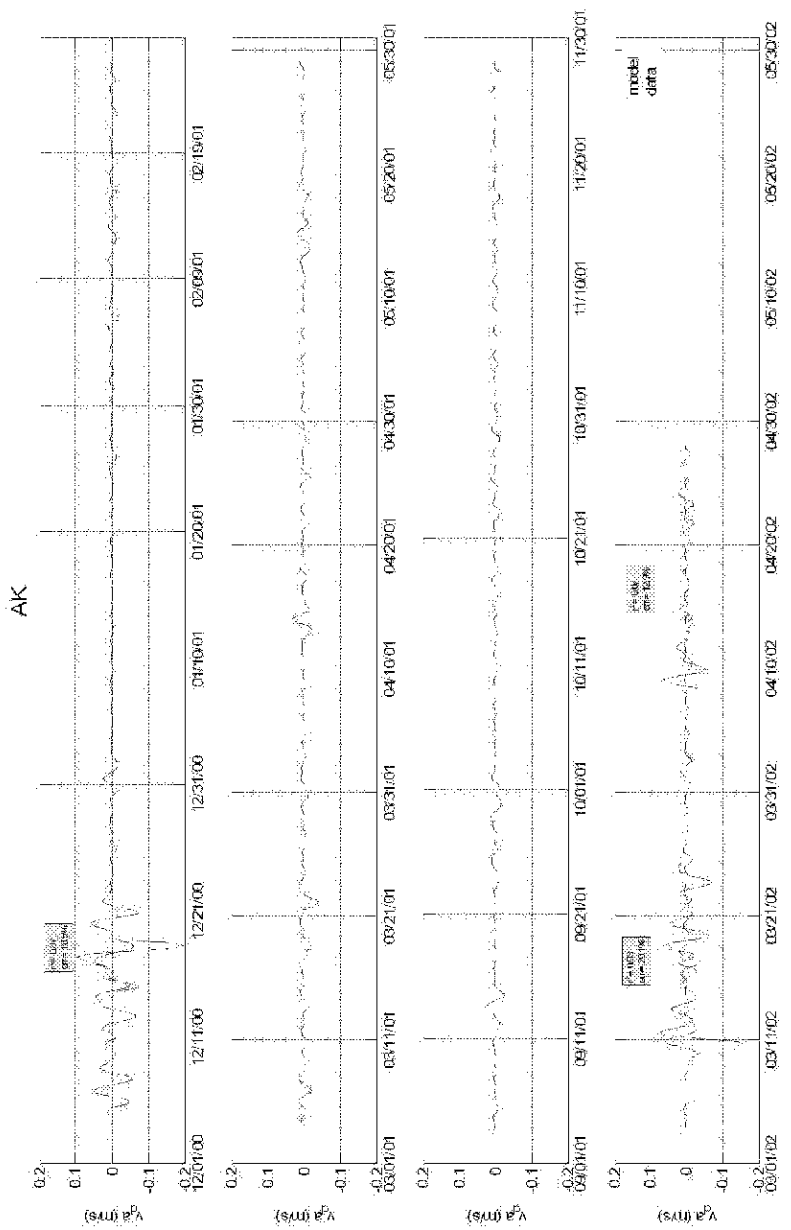
12/15/01
01/04/02
01/24/02
02/13/02
03/05/02
03/25/02
04/14/02


NB1
model
data


KVK1
model
data


AK
model
data

Appendix F

Meteorological Events

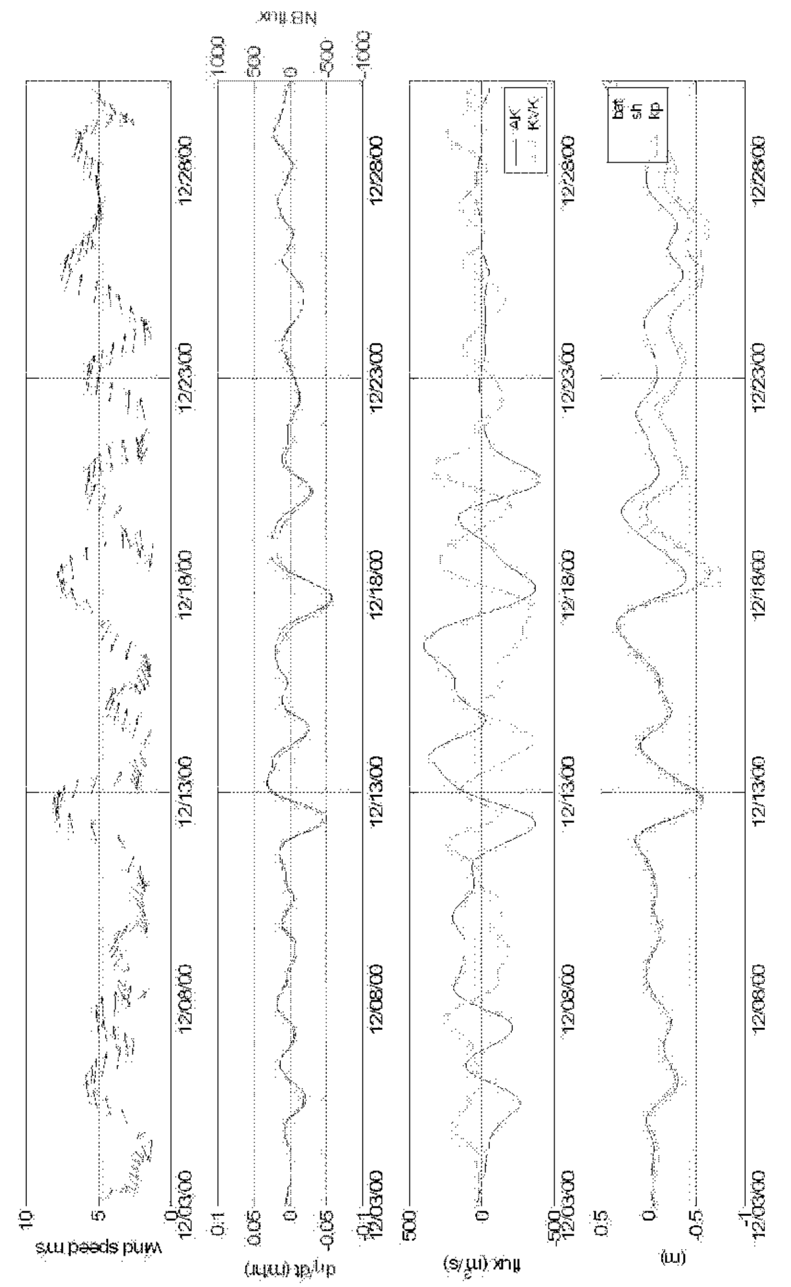
Appendix F Key

Bergen Point - BP (40° 38.4'N, 74° 8.8'W)
Passaic Valley Sewerage Commission -PVSC (40° 43'N, 74° 8'W)
Constable Hook in Bayonne - BAY (40° 40.2'N, 74° 4.2'W)
Perth Amboy Yacht Club PAYC (40° 30'N, 74° 15'W)
Hackensack River -HACK (N/A)
Perth Amboy - PA (40° 30.6'N, 74° 15.6'W)
North end of the Arthur Kill -AK1 (40° 37.8'N, 74° 12'W)
Western end of the Kill van Kull -KVK1 (40° 38.4'N, 74°7.5'W)
North end of Newark Bay -NB1(40° 42'N, 74° 7.2'W)
South end of Newark Bay -NB3 (40° 40'N, 74° 8.4'W)
Raritan River - RR (40° 24'N, 74° 18'W)

All times are GMT

Arrows on wind plots indicate direction wind is from
(north is along the positive vertical axis)

Fluxes are positive into Newark Bay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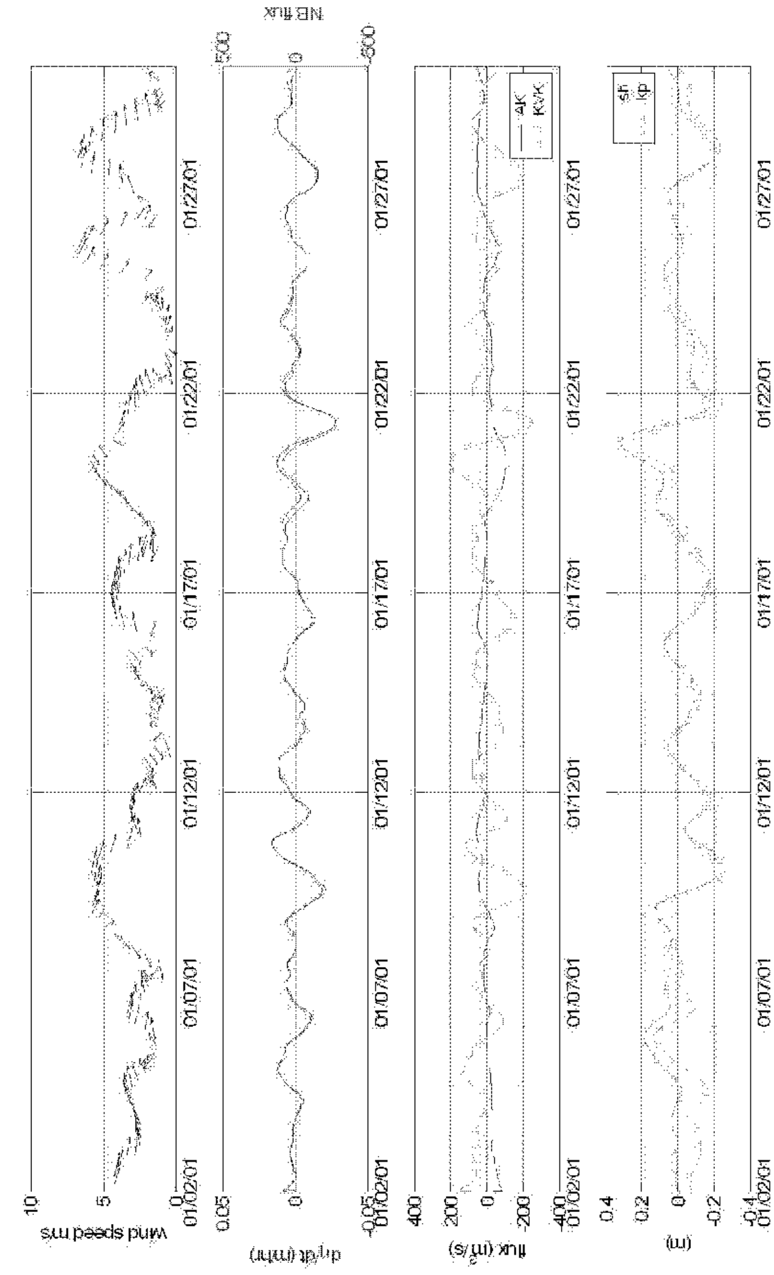
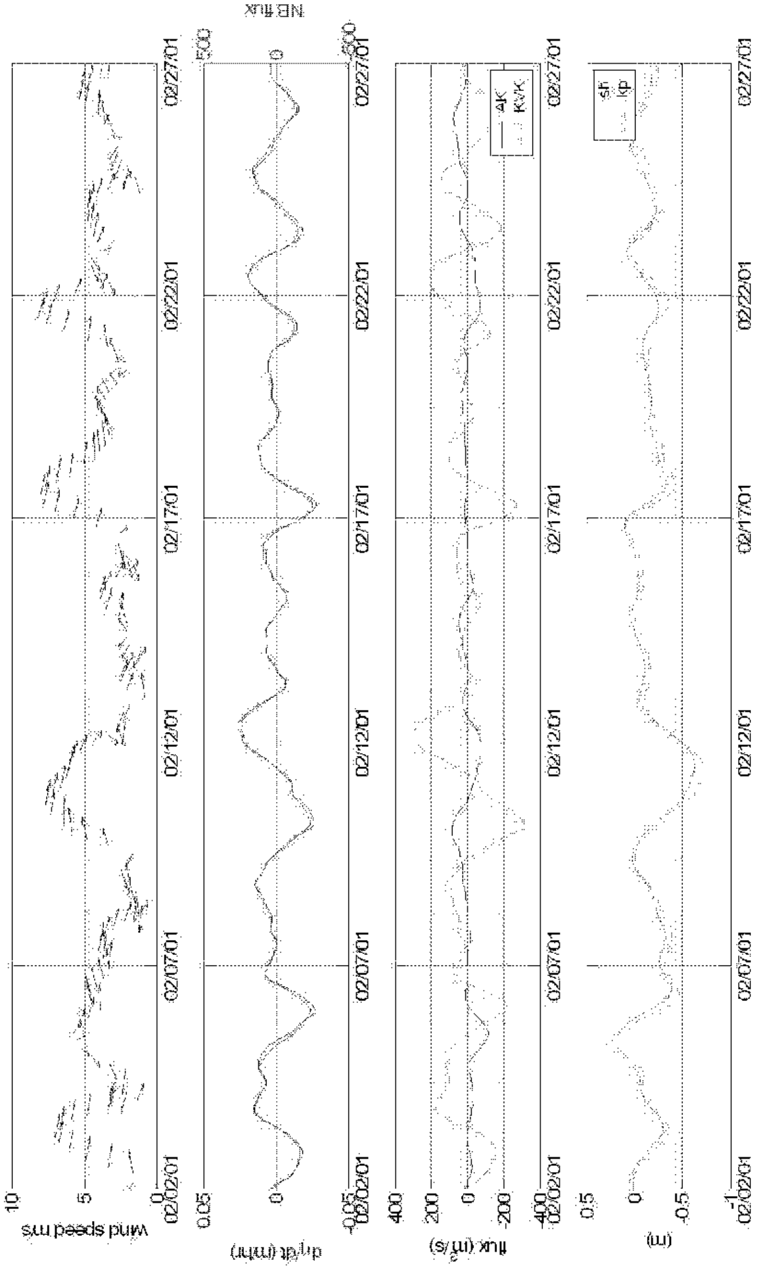
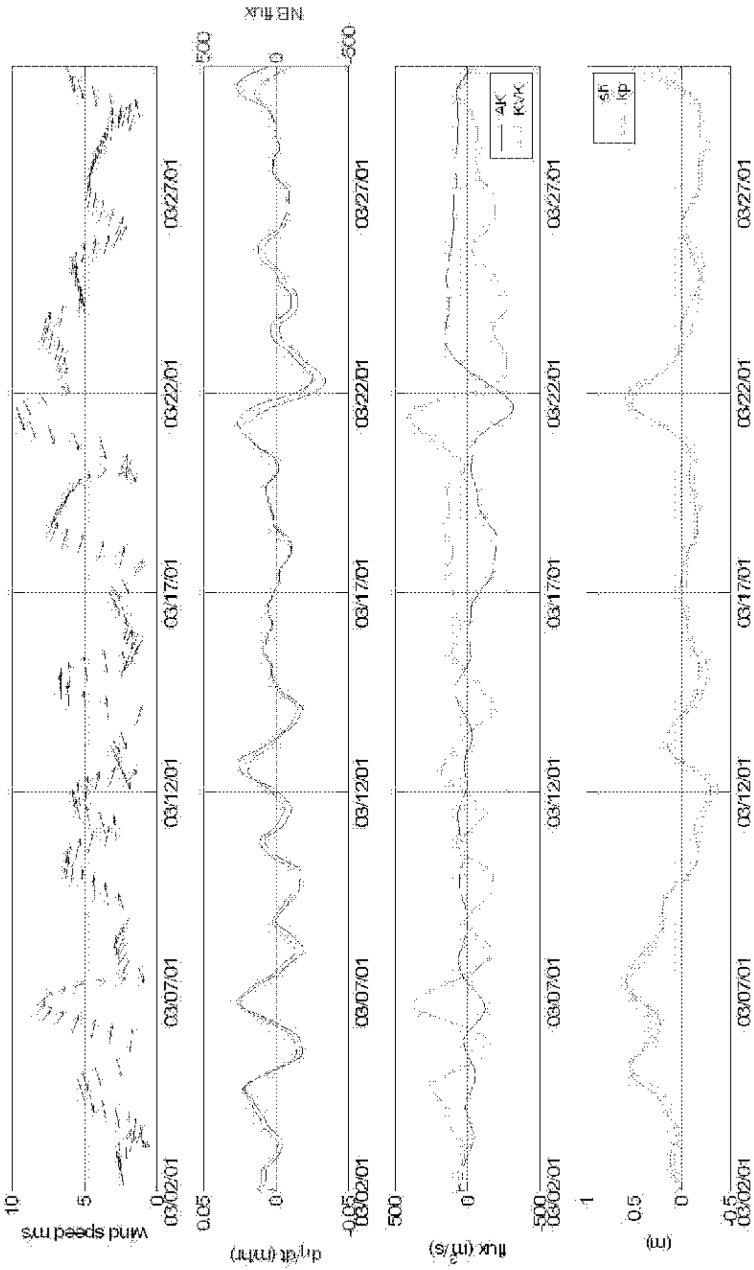
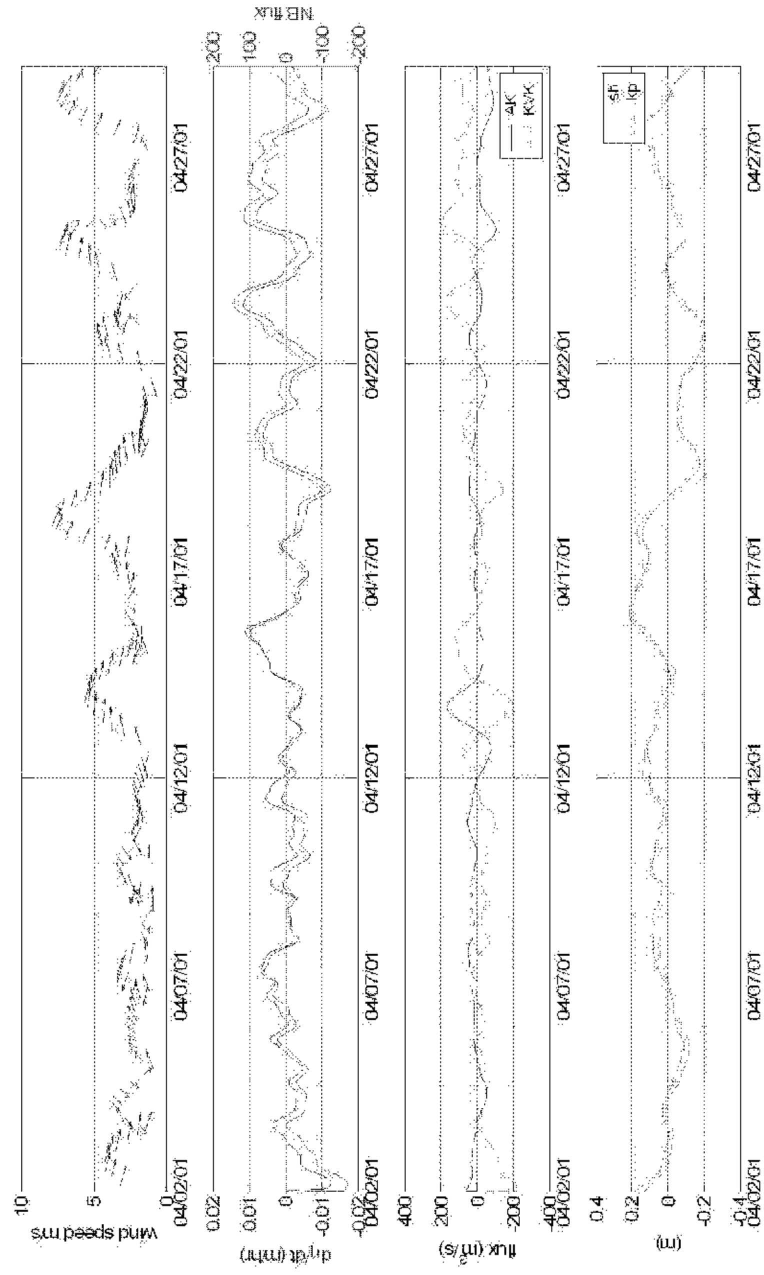
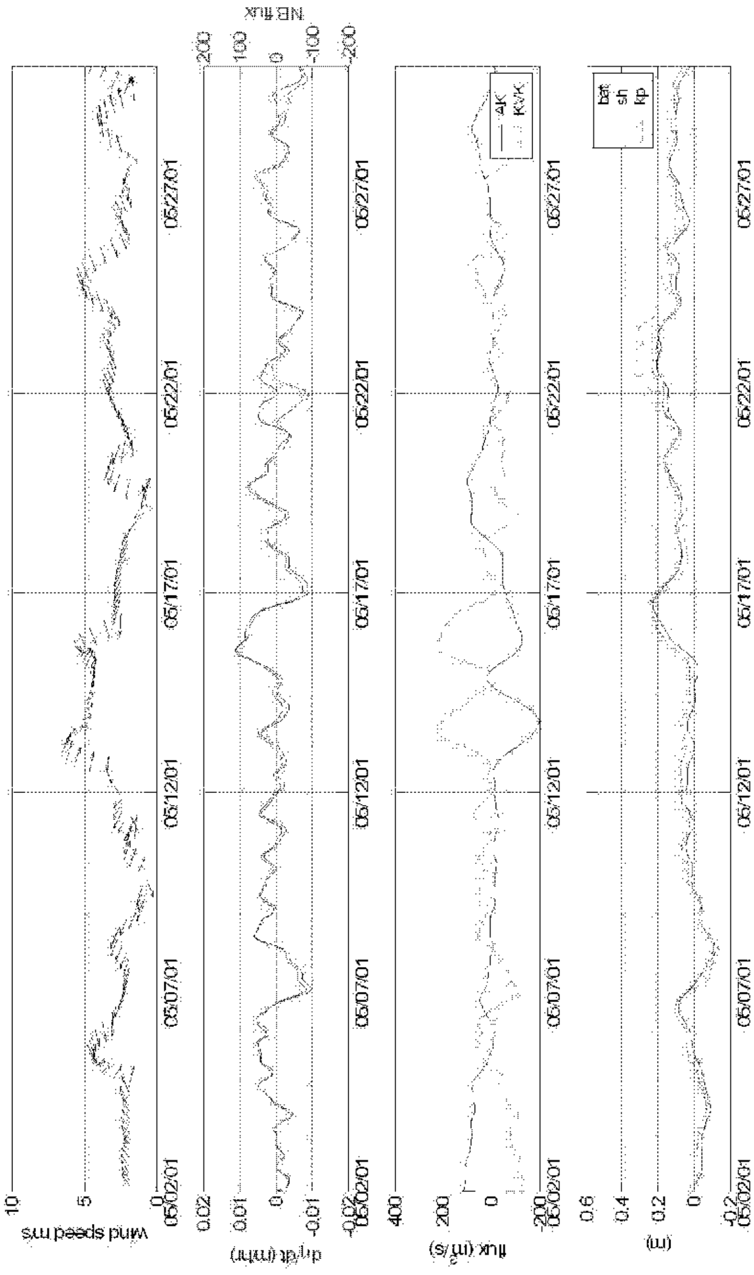
NB flux
flux (m^3/s)
(m)
12/03/00
12/08/00
12/13/00
12/18/00
12/23/00
12/28/00
4K
KVK
bat
sh
kp


wind speed m/s
dη/dt (m/hr)
NB flux
flux (m³/s)
(m)
4K
KVK
sh
kp
01/02/01
01/07/01
01/12/01
01/17/01
01/22/01
01/27/01


wind speed m/s
dη/dt (m/hr)
NB flux
flux (m³/s)
(m)
AK
KVK
sh
kp
02/02/01
02/07/01
02/12/01
02/17/01
02/22/01
02/27/01


wind speed m/s
NE flux
flux (m³/s)
(m)
4K
KVK
sh
kp
03/02/01
03/07/01
03/12/01
03/17/01
03/22/01
03/27/01


wind speed m/s
NB flux
flux (m²/s)
(m)
04/02/01
04/07/01
04/12/01
04/17/01
04/22/01
04/27/01



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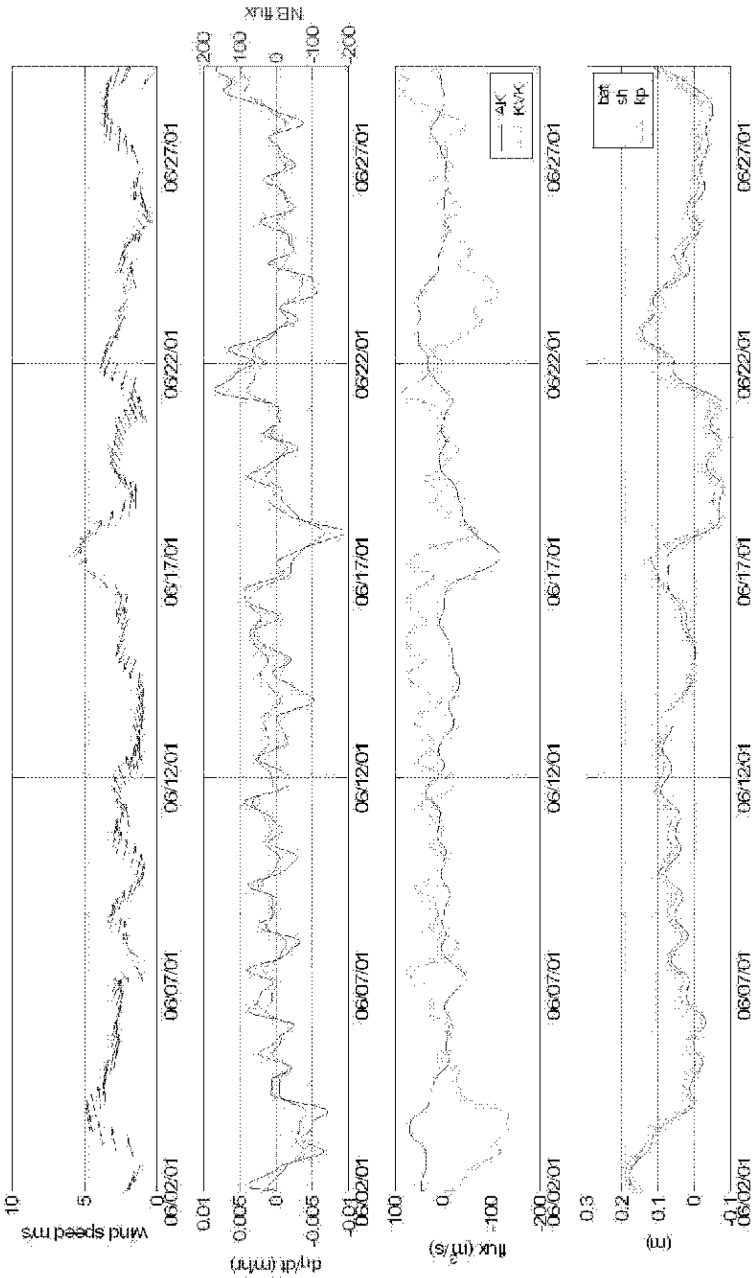
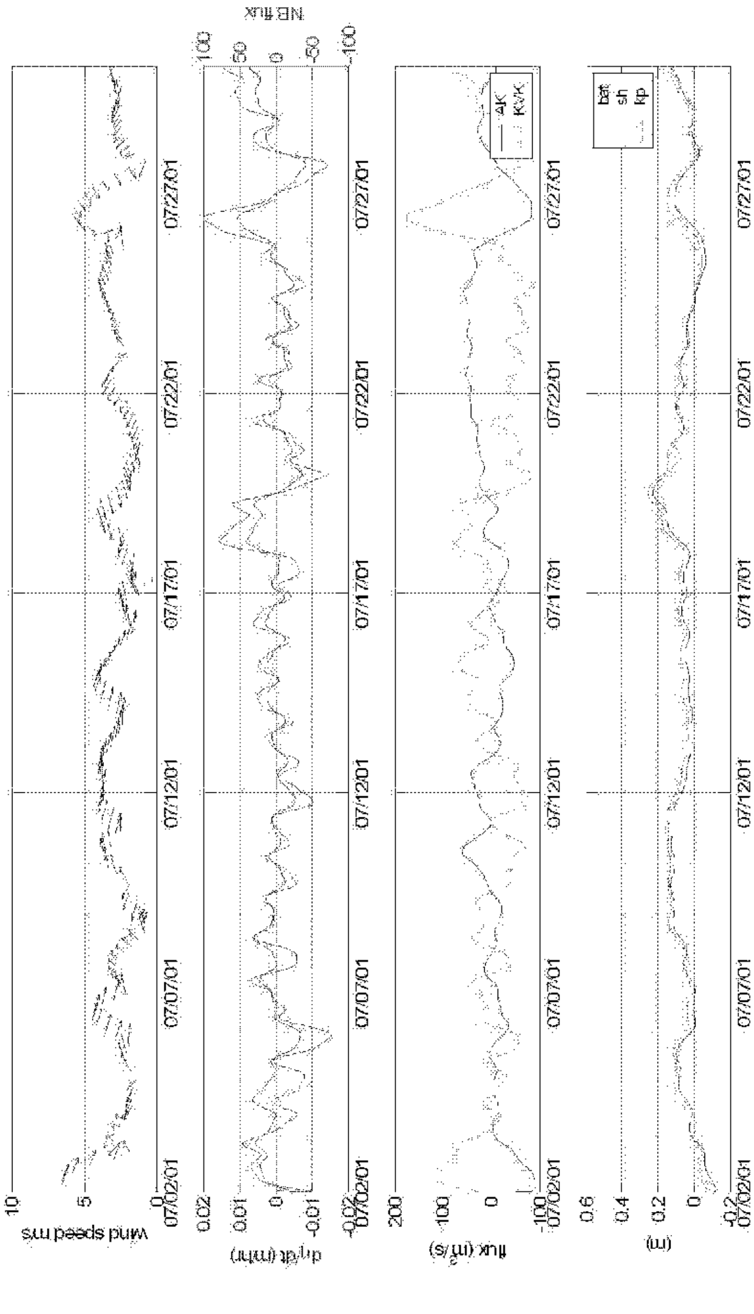

wind speed m/s
NB flux
flux (m²/s)
(m)
4K
Kv/K
bat
sh
kp
06/02/01
06/07/01
06/12/01
06/17/01
06/22/01
06/27/01



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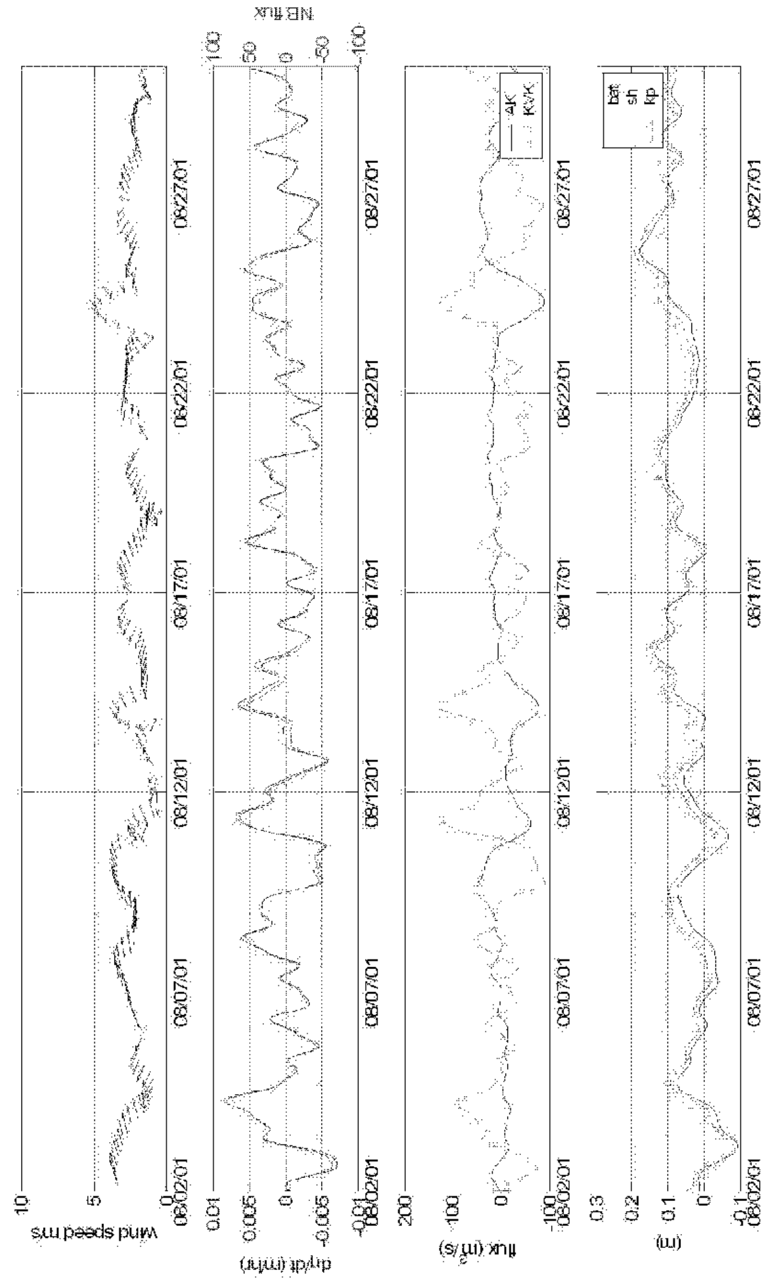
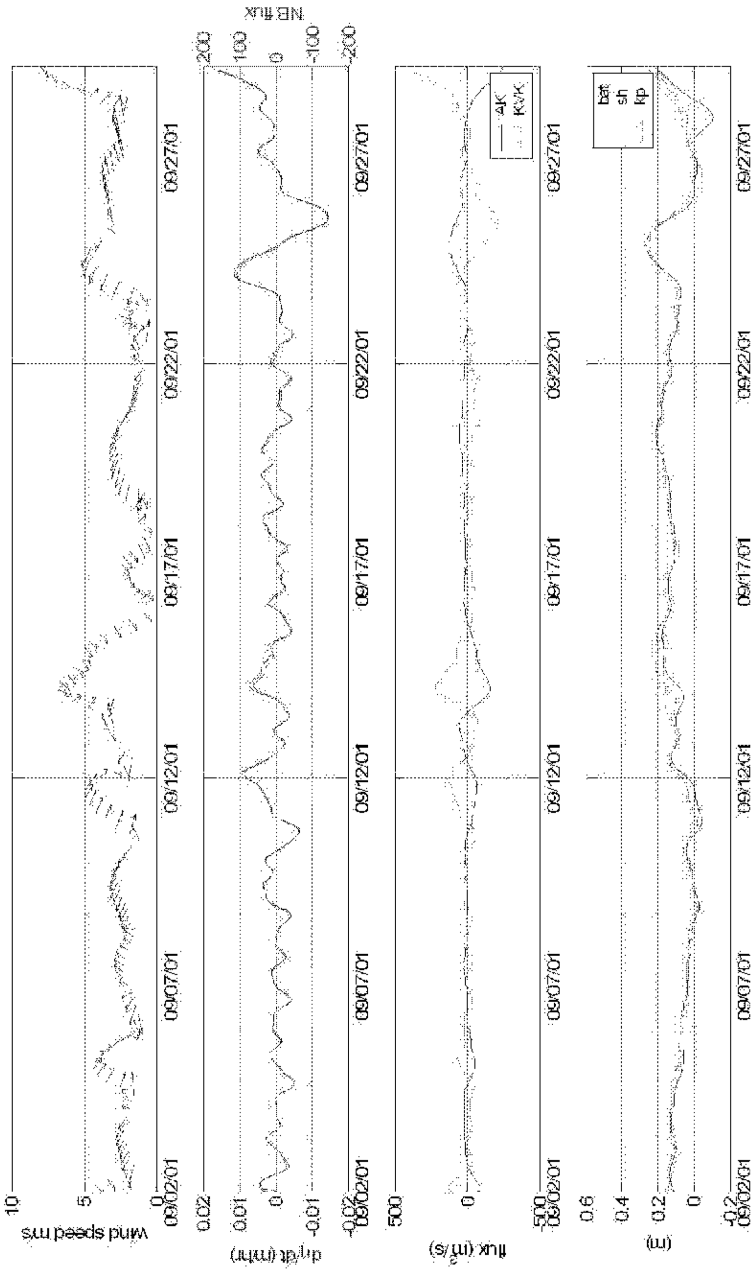
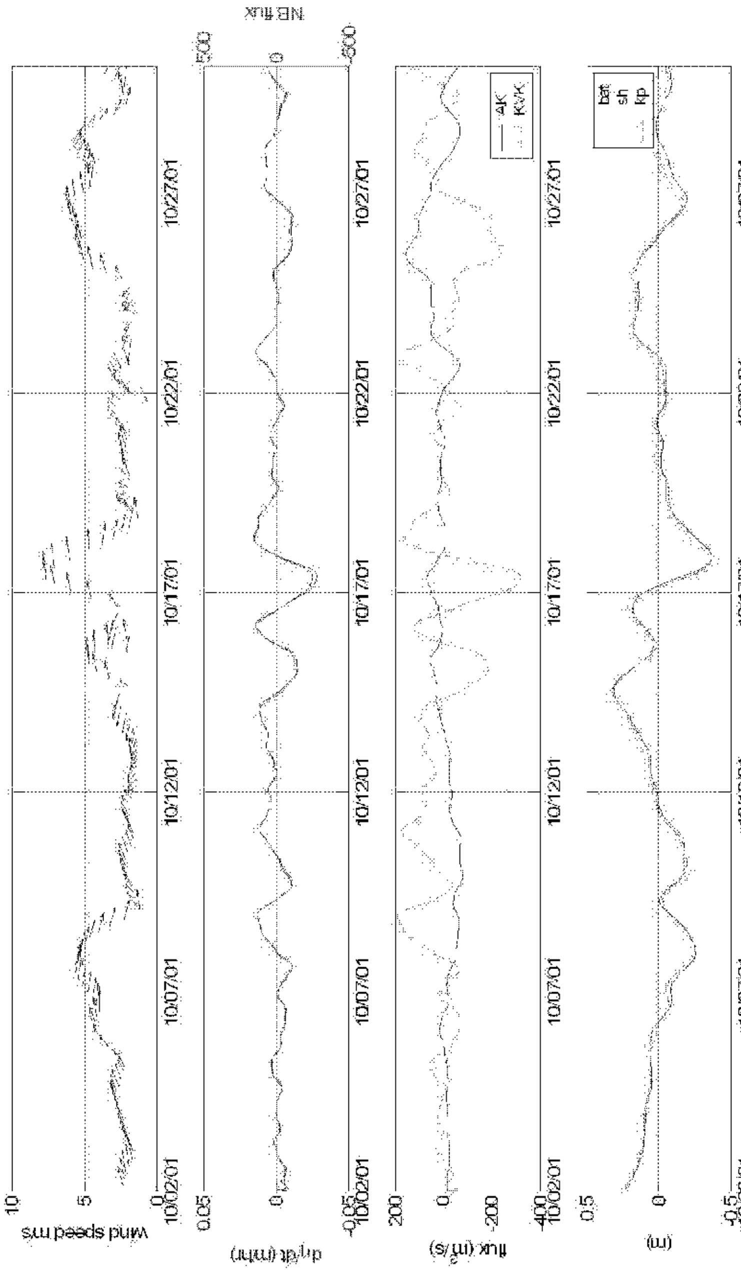

wind speed m/s
NB flux
08/02/01
08/07/01
08/12/01
08/17/01
08/22/01
08/27/01
bat
sh
kp


wind speed m/s
dη/dt (m/hr)
NB flux
flux (m²/s)
(m)
4K
KVK
bat
sh
kp
09/02/01
09/07/01
09/12/01
09/17/01
09/22/01
09/27/01



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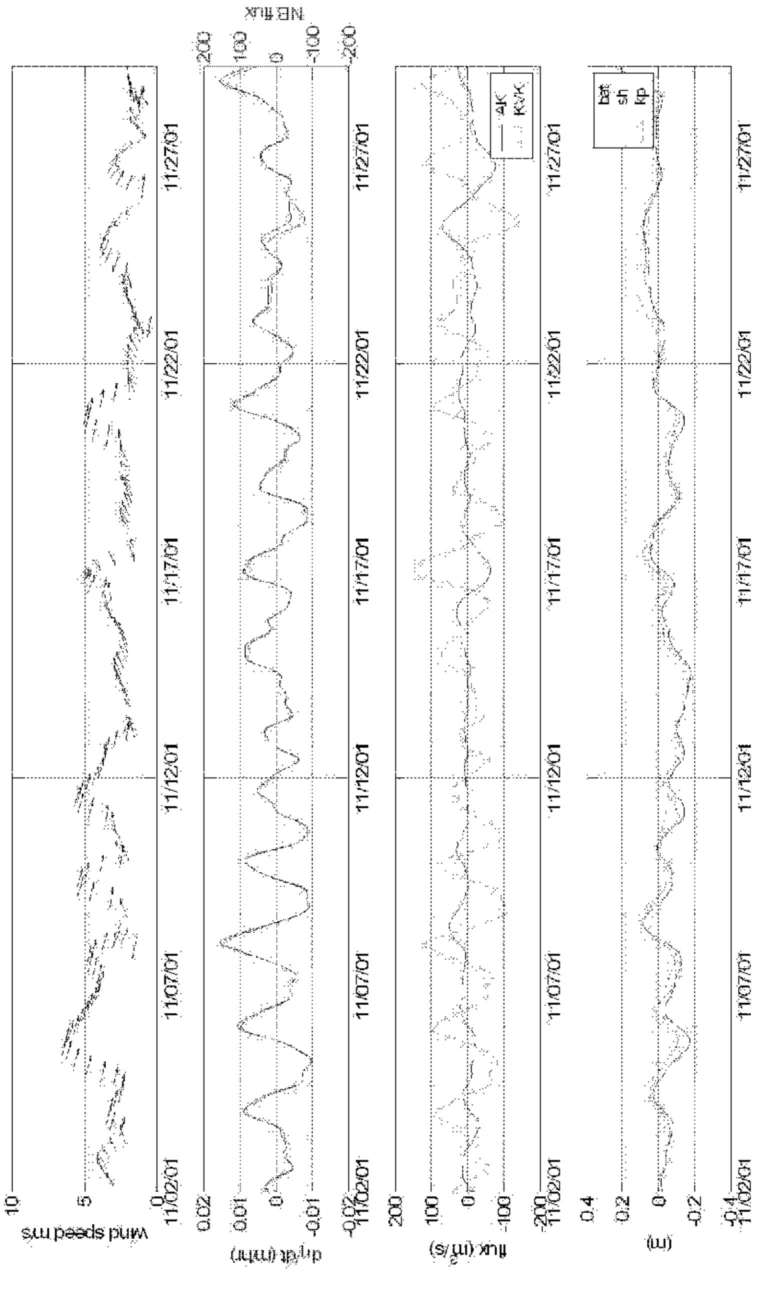
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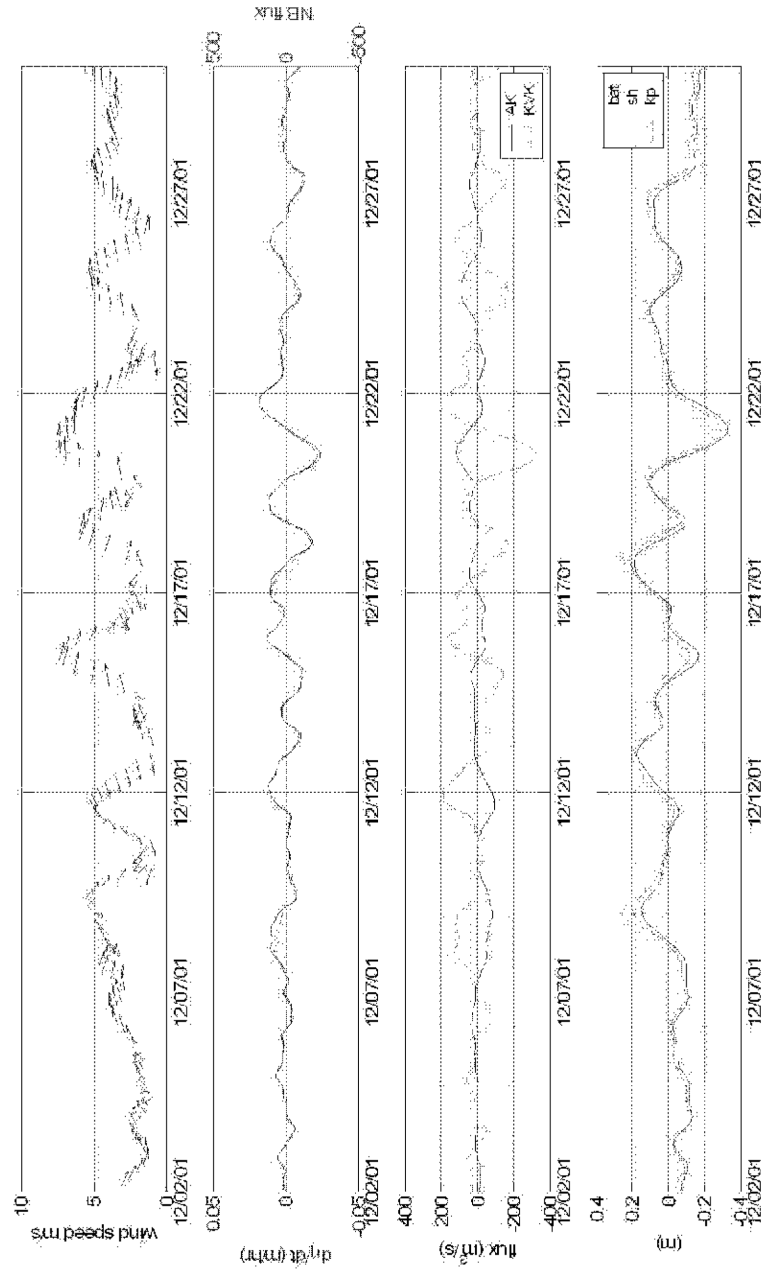
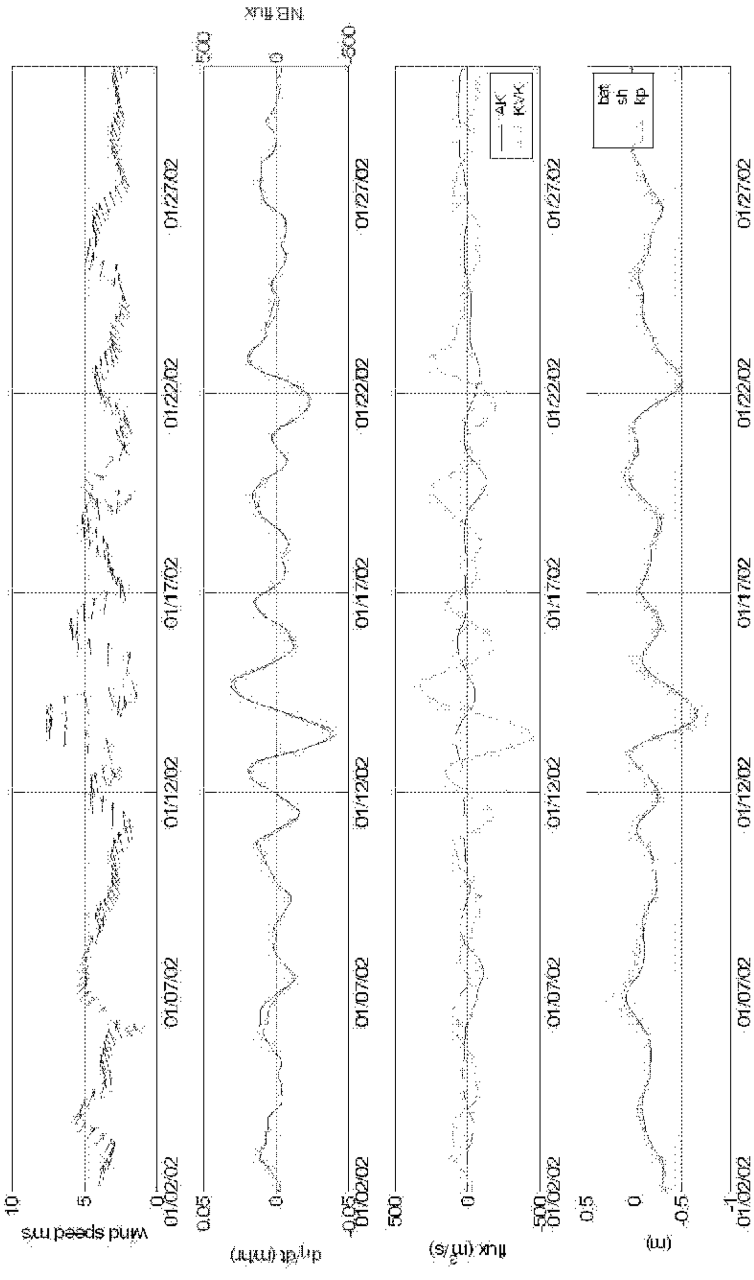
NB flux
bat
sh
kp
11/02/01
11/07/01
11/12/01
11/17/01
11/22/01
11/27/01


wind speed m/s
NB flux
flux (m³/s)
(m)
4K
KVK
bat
sh
kp
12/02/01
12/07/01
12/12/01
12/17/01
12/22/01
12/27/01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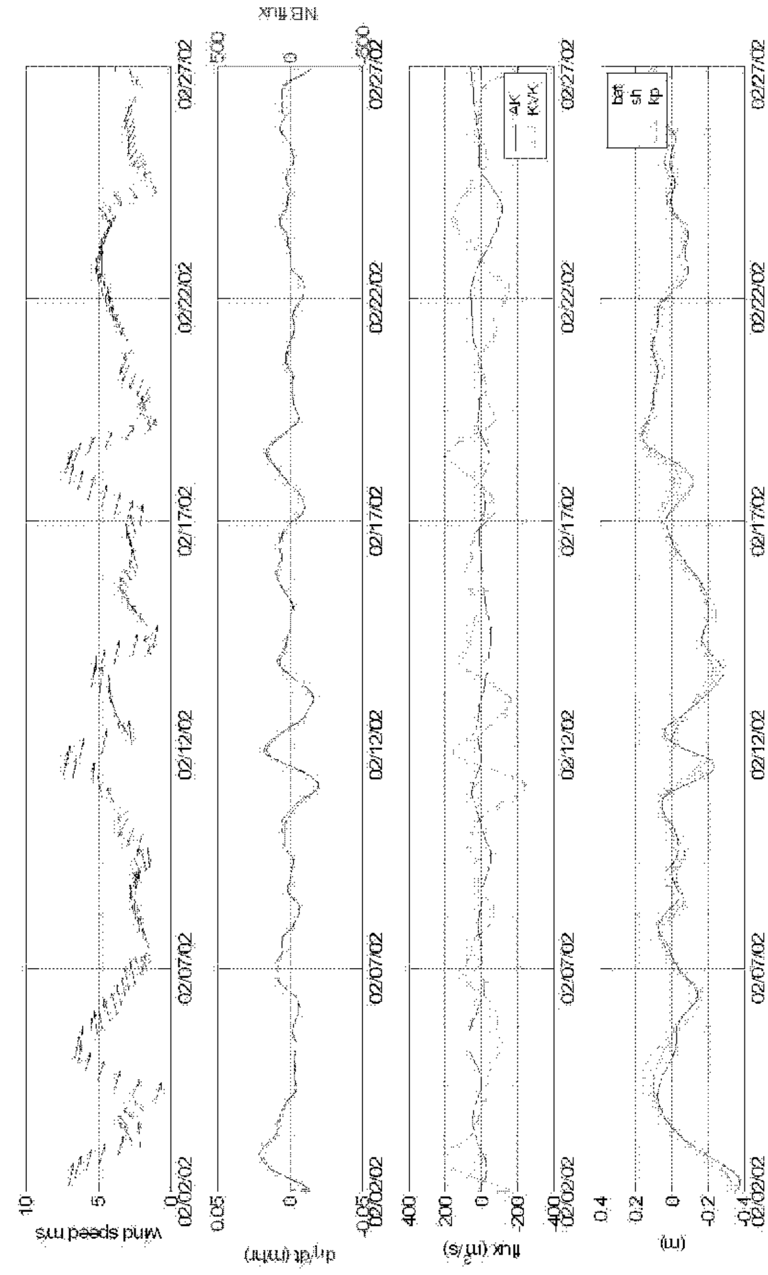
NE flux
dη/dt (m/hr)
flux (m²/s)
(m)
4K
KVK
bat
sh
kp
01/02/02
01/07/02
01/12/02
01/17/02
01/22/02
01/27/02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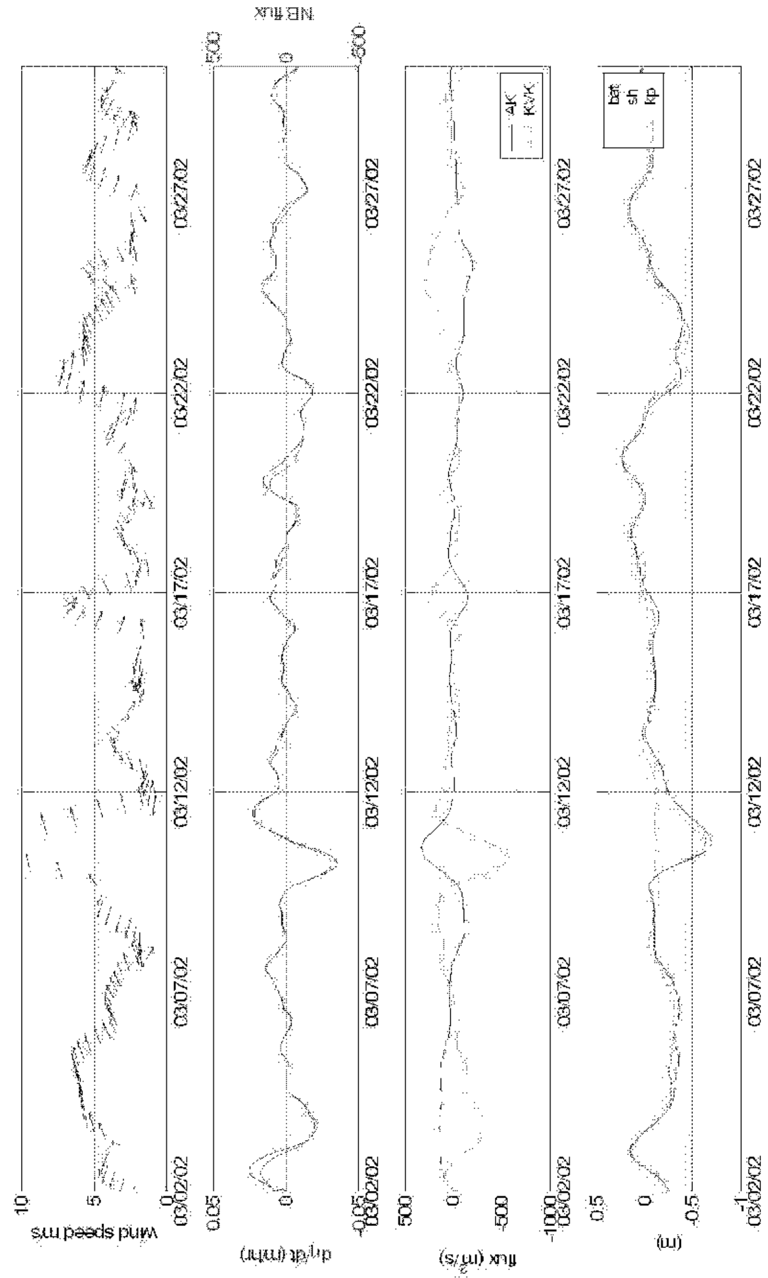
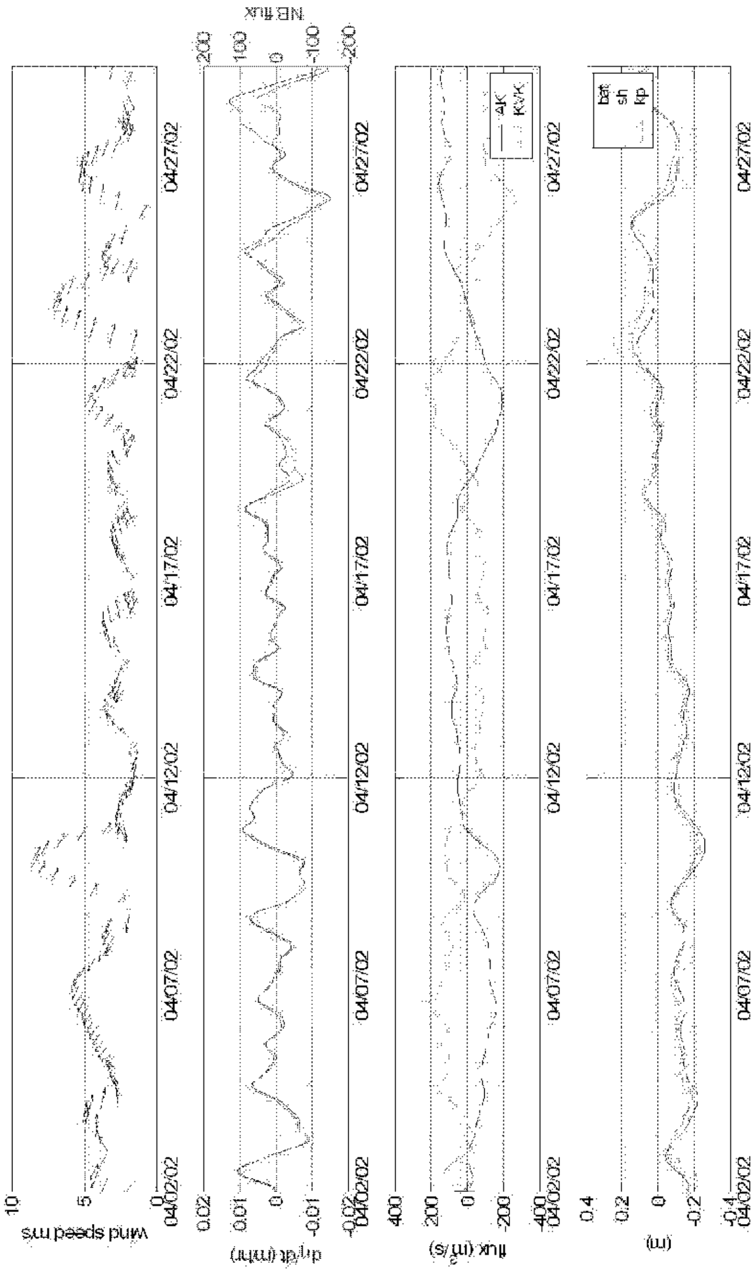
NE flux
flux (m²/s)
(m)
bat
sh
kp
02/02/02
02/07/02
02/12/02
02/17/02
02/22/02
02/27/02


wind speed m/s
dη/dt (m/hr)
flux (m²/s)
(m)
NB flux
4K
KVK
bat
sh
kp
03/02/02
03/07/02
03/12/02
03/17/02
03/22/02
03/27/02


wind speed m/s
dη/dt (m/hr)
NB flux
flux (m³/s)
(m)
4K
KVK
bat
sh
kp
04/02/02
04/07/02
04/12/02
04/17/02
04/22/02
04/27/02