

Division of Science, Research and Technology

Research Project Summary

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The New Jersey Toxics Reduction Workplan for New York - New Jersey Harbor: Study I-E – Hydrodynamic Studies in the Newark Bay Complex

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Abstract

The Newark Bay Complex, which is part of New York-New Jersey (NY-NJ) 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 has resulted in reduced water quality, fisheries restrictions/advisories, and general adverse impacts to the estuarine and coastal ecosystems. Study I-E of the New Jersey Toxics Reduction Workplan for NY-NJ Harbor is a comprehensive hydrodynamic study 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. In addition, a three-dimensional hydrodynamic model of the complex has been developed that replicates the available water elevation, salinity, and current velocity data. 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. This circulation pattern 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 east/west wind events can produce large “flow-through” flushing events in the Newark Bay Complex, with currents predominantly directed through the Kill Van Kull. 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.

Introduction

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

The New York-New Jersey Harbor Estuary Program Comprehensive Conservation and Management Plan (HEP CCMP; March 1996) has identified at least fifteen chemi-

cals of concern, including polychlorinated biphenyls (PCBs), dioxins/furans, chlorinated pesticides, polycyclic aromatic hydrocarbons (PAHs), and metals. The HEP CCMP includes a number of actions to achieve its goals and objectives related to the “Management of Toxic Contamination”:

- (1) reduce continuing discharges of the chemicals of concern to the estuary;
- (2) remediate selected contaminated sediments;
- (3) minimize human health risks due to the consumption of contaminated fish and shellfish; and
- (4) better understand the problem and take additional actions as more is learned.

The Joint Dredging Plan for the Port of New York and New Jersey (October 7, 1996) stresses the economic importance of the port, and the associated need to dredge navigation

channels and maintain port facilities. The Joint Dredging Plan has two major objectives:

- (1) to promote greater certainty and predictability in the dredging project review process and dredged material management; and to
- (2) facilitate effective long-term environmentally sound management strategies for addressing dredging and disposal needs for the region.

As part of the commitments included in the Joint Dredging Plan, the States of New Jersey and New York agreed to implement the HEP CCMP as it relates to a number of sediment and toxic contamination concerns. In response, the HEP Contaminant Assessment and Reduction Program (CARP) was developed and implemented. The New Jersey Toxics Reduction Workplan for NY-NJ Harbor (NJTRWP) is the New Jersey component of CARP.

The NJTRWP includes a series of studies designed to provide the NJ Department of Environmental Protection (NJDEP) 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 to begin to understand the effects of tidal, meteorological, and freshwater forces on circulation patterns in the system. In the Newark Bay Complex, tidal motion is dominated by semidiurnal (occurring twice a day) motion driven by the gravitational effects of the sun/earth/moon system. Subtidal motion refers to motion at periods longer than one day, and is driven by meteorological conditions (i.e., wind-forcing) in the estuary and ocean. 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. 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.

In addition, because the data collected were 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.

Methods and Data Analysis

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. During the years 2000-2002 a series of hydrodynamic measurements, including long-term (~30-day) mooring deployments and short-term profiling/transects, were implemented in the Newark Bay Complex in order to characterize aspects of the tidal and subtidal flow, salinity, and the suspended sediment load. Figure 1 shows the approximate times and durations of the various components of the NJTRWP hydrodynamic work.

Figure 2 shows the approximate locations of the mooring stations established as part of the study:

- ◆ Stations NB1 and NB3 are located in upper and lower Newark Bay, respectively;
- ◆ Station KVK1 is located in the western portion of the Kill Van Kull;
- ◆ Stations AK1 and PA1 are located in the upper and lower Arthur Kill, respectively.

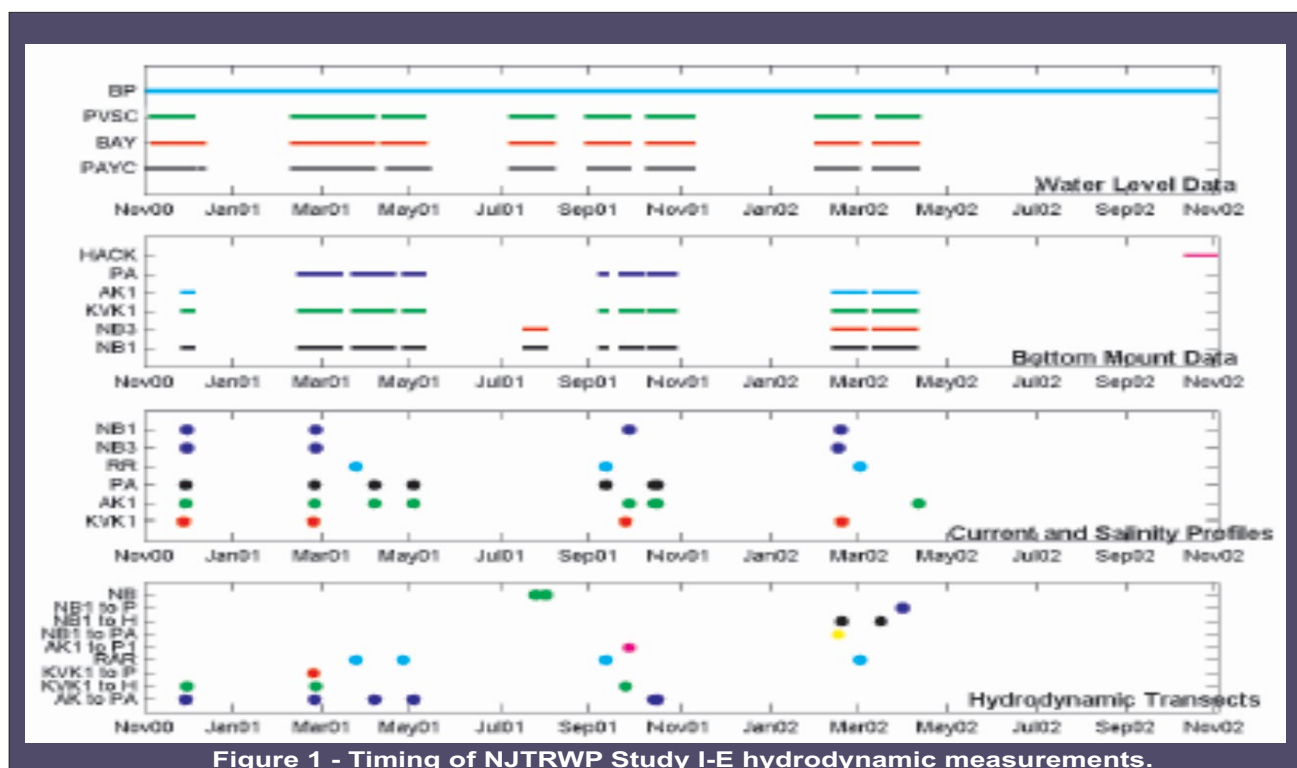


Figure 1 - Timing of NJTRWP Study I-E hydrodynamic measurements.

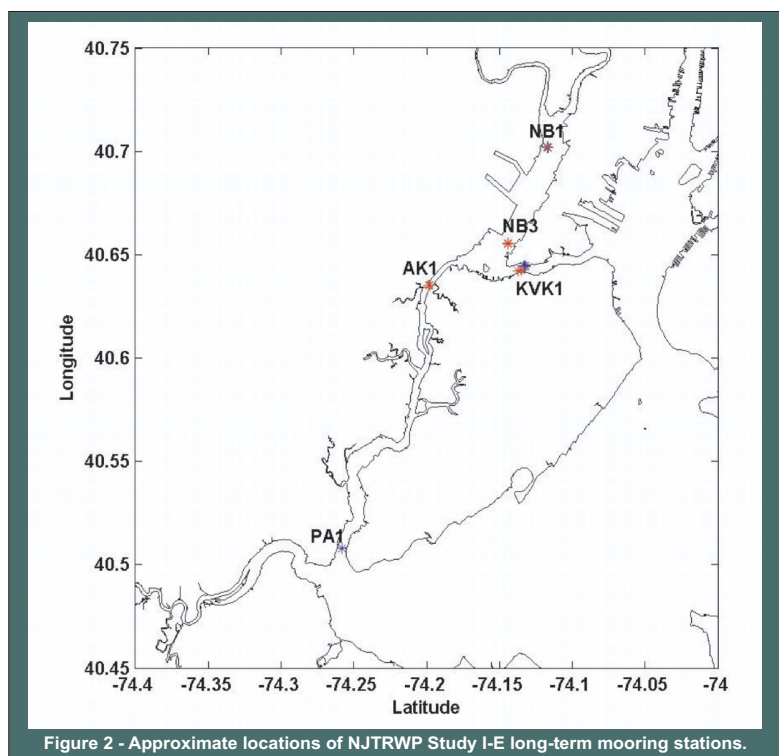


Figure 2 - Approximate locations of NJTRWP Study I-E long-term mooring stations.

Each bottom mount deployment involved at least three moorings, with two of the moorings located at Stations NB1 and KVK1, and the third deployed in the Arthur Kill either at Station AK1 or Station PA1. In addition, there were two deployments at Station NB3 in 2001/2002.

Each hydrodynamic equipment mooring contained strain gauge pressure sensors, a 1.5 kHz Sontek Acoustic Doppler Profiler (ADP), an optical backscatter sensor (model OBS3), a Seabird conductivity and temperature sensor (CT sensor SBE37si), and a Laser In-Situ Scattering and Transmissometry (LISST-100) instrument (see Figure 3). The ADP measures vertical profiles of currents by transmit-

ting and receiving acoustic pulses. The OBS also provides estimates of suspended sediment (SS) through the backscatter of an optical signal. Unlike the ADP, which provides vertical profiles of SS, the OBS only provides estimates at a point in the water column. The intensity of the acoustic/optical backscatter from these two instruments can be used as a proxy for the SS concentration, but this requires calibration with *in situ* SS samples. The CT sensor measures the temperature and electrical conductivity of the water, from which salinity and density are estimated. Finally, the LISST provides estimates of the particle size distribution of material suspended in the water column by measuring the forward scattering of a laser as it is transmitted through the water.

Raw data for the moored ADP, conductivity-temperature-depth (CTD), and OBS instruments were collected at 30-second intervals. The data was screened for obvious outliers (defined as current speeds exceeding 3 m/sec) and averaged into 30 minute intervals. Once averaged, the tidal frequency motion was separated from the lower frequency subtidal period motion by applying a low-passed filter to the data using a Lancos window (Emery, 1998). Both the tidal

period and subtidal period motion were characterized in terms of their depth-averaged and depth-dependent structure, and these were then characterized in terms of the tidal range, Passaic River flow, and meteorological forcing.

Water level data were obtained from tide gages located at Bergen Point (western Kill van Kull), the Passaic Valley Sewage Commission (northern end of Newark Bay), Constable Hook (Bayonne; eastern Kill van Kull), and the Perth Amboy Yacht Club (southern Arthur Kill). Water level data was collected as described in NOAA/NOS (2004).

In addition to the long-term mooring deployments, vessels were used to obtain short-term current and salinity profiles while moored at those same locations (and at a location in the lower Raritan River) and along transects in various sections of the Newark Bay Complex. These short-term profiles were collected during vessel transect sampling operations conducted in association with the NJTRWP Study I-D and I-E water quality sampling work (NJDEP, 2001). One of two vessels would anchor at the water quality sampling stations, while another vessel(s) would conduct transects within the harbor. Each vessel would perform casts over the side using a CTD (with an OBS attached) and a LISST to gather salinity, temperature, and SS data through the water column. In addition, the transecting vessel(s) would tow a bottom-tracking ADP to measure water currents through the time of sampling.

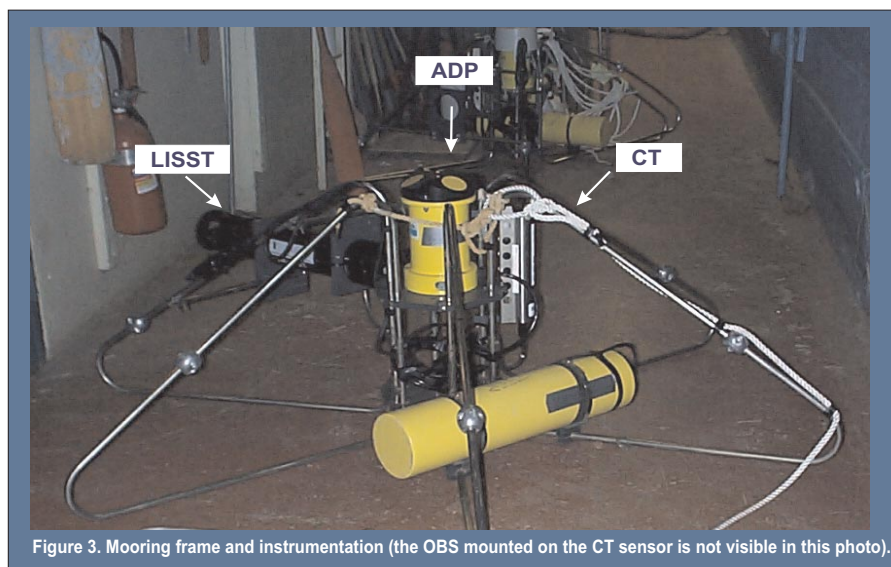
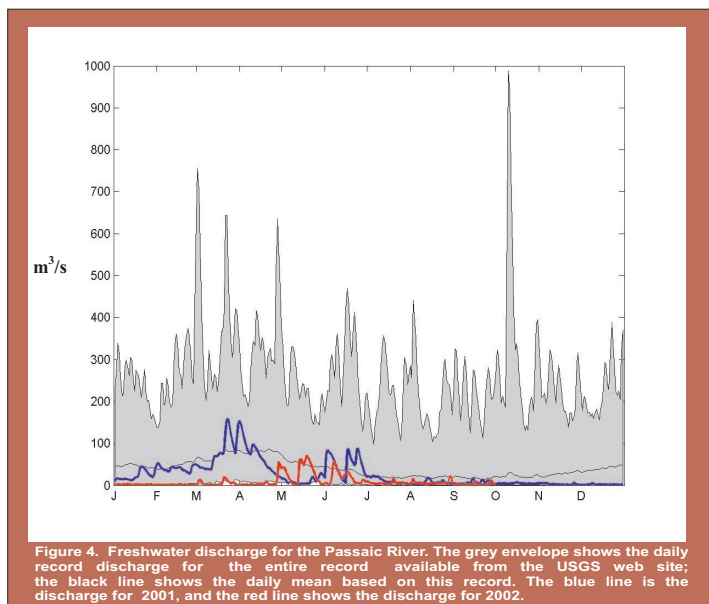


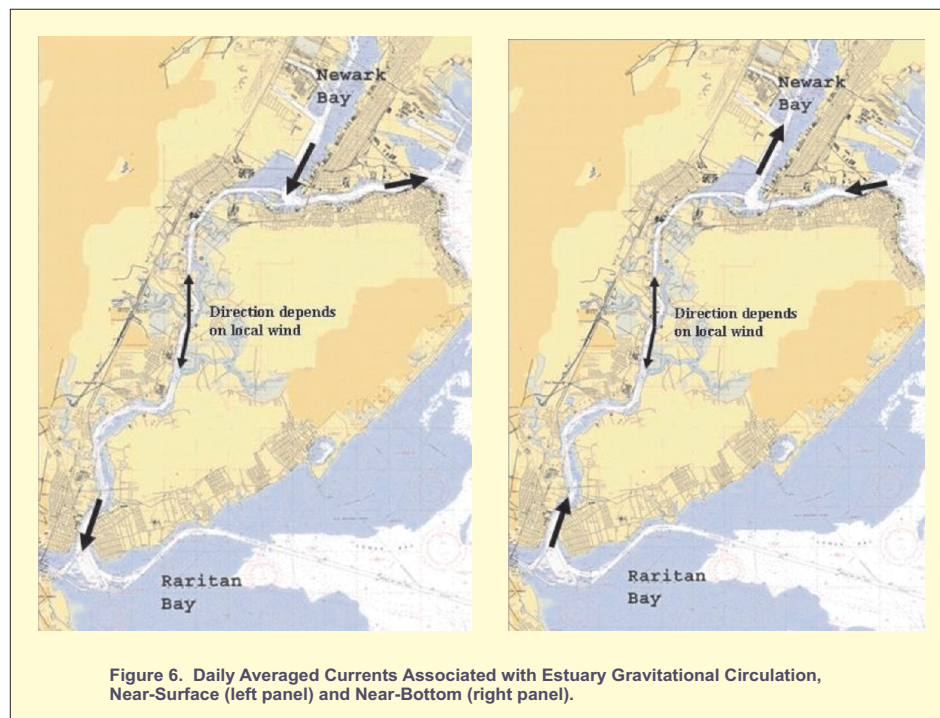
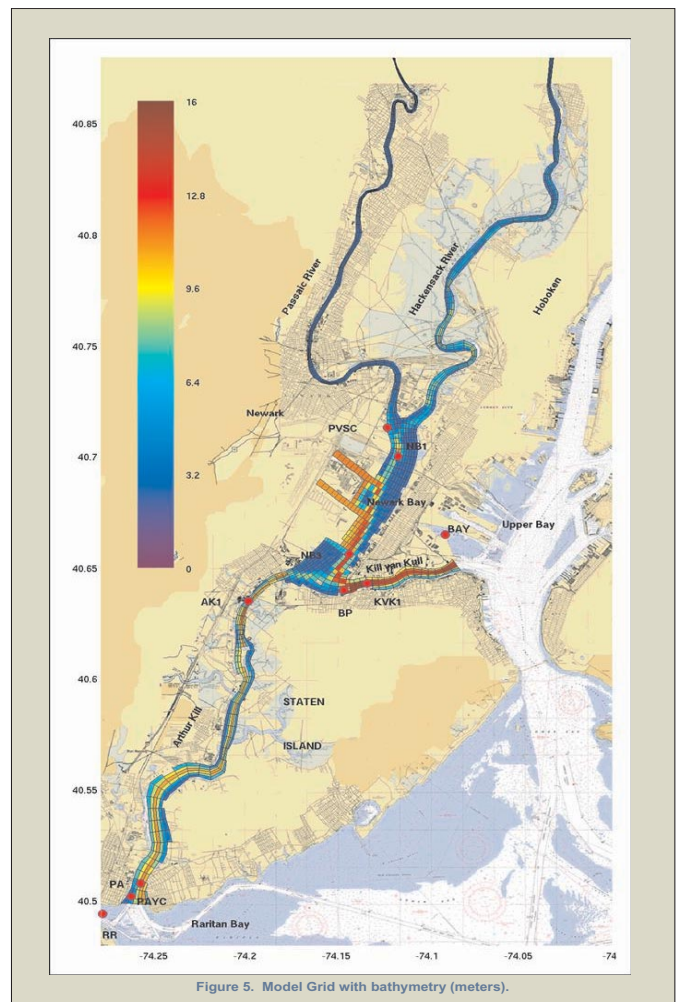
Figure 3. Mooring frame and instrumentation (the OBS mounted on the CT sensor is not visible in this photo).



Some aspects of the suspended sediment load, primarily based on the acoustic backscatter data from the ADP, were also investigated. Estimates of the suspended sediment load were based primarily on a calibration made in October 2003, when nearly 100 1-Liter pumped SS samples were taken while at anchor over a mooring at Station NB1 and profiling with the CTD/OBS and LISST instrument package.

Details of the data collection and analysis procedures (and various presentations of the data) are provided in Chant (2006) and Pence *et al.* (2006). The NJTRWP Study I-E hydrodynamics data has been archived at the Stevens Institute of Technology; please contact Dr. Michael Bruno at mbruno@stevens.edu for further information.

The primary source of freshwater affecting the Newark Bay is the Passaic River. Figure 4 shows the freshwater discharge for the Passaic River during 2001 and 2002, as well as longer term data. The study period largely coincided with a period of uncharacteristically low flow in the river. Thus, the results from NJTRWP Study I-E are essentially a characterization of the hydrodynamics in the Newark Bay Complex during low flow conditions.



SIT Model Development

The hydrodynamics data collected as part of NJTRWP Study I-E were not continuous in time and space (see Figure 1). Therefore, a high resolution three-dimensional model of the Newark Bay Complex, based on the Estuarine, Coastal and Ocean Model (ECOM) of Blumberg and Mellor (1987), was developed by SIT as a tool to further interpret the hydrodynamics of the Newark Bay Complex. The model grid includes ten vertical sigma layers, and is shown in Figure 5. The model was run for the 17 month period of December 2000-April 2002, and was calibrated and validated by comparison to the NJTRWP hydrodynamics data collected over this same time period. The model replicates the available water elevation, salinity, and current velocity data. *Pence et al.* (2006) provides a detailed description of the model development, calibration, and validation.

Results

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.

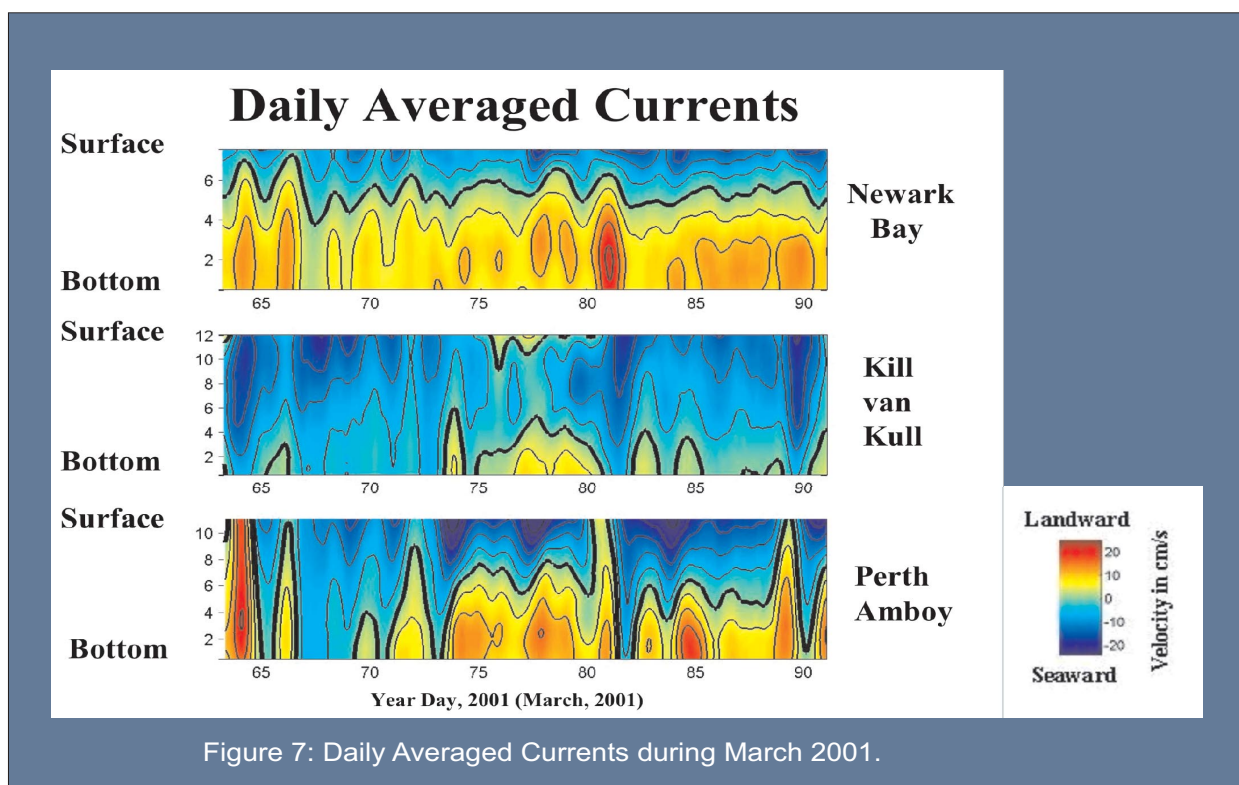
Gravitational Circulation

Within the navigation channel of Newark Bay, classic estuarine gravitational circulation occurs, with daily averaged cur-

rents (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 6 illustrates this classic estuarine circulation pattern in NY-NJ Harbor. 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.

The 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 7, 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 consider-



Crosses show locations of CTD casts taken during ebbing tides on March 14, 2001.

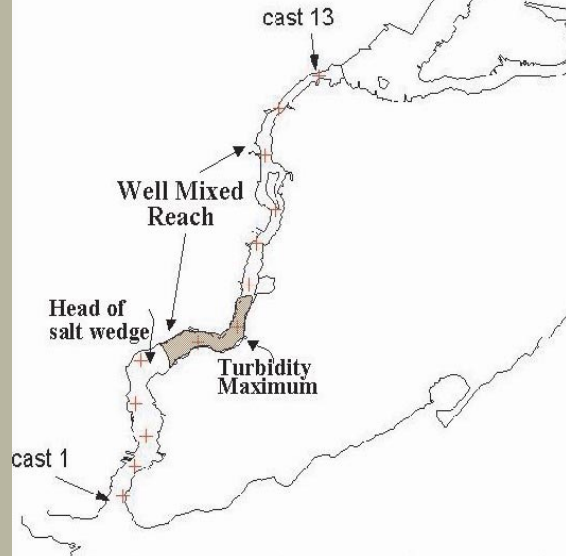


Figure 8: Location of the turbidity maximum in the Arthur Kill.

able 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.

In addition, the following observations concerning the tidal motion and salinity in the Newark Bay Complex have been made:

- ◆ the tidal wave can be characterized as a standing wave in Newark Bay and the Kill van Kull, but in the Arthur Kill it is not clearly a standing or a progressive wave;
- ◆ tidal currents are greater at the surface and exhibit strong vertical structure;
- ◆ tidal currents are strongest in the Kill van Kull (>70 cm/sec), somewhat weaker in the Arthur Kill (55-60 cm/sec), and weakest in Newark Bay (< 50 cm/sec).
- ◆ vertical structure in tidal currents is strongest where salinity stratification is strongest (upper Newark Bay and lower Arthur Kill);
- ◆ salinity responds rapidly to changes in the Passaic River discharge and to the spring/neap tidal cycle;
- ◆ shipboard conductivity-temperature-depth (CTD) sections/transects taken along the length of the Arthur Kill show a salt front that penetrates from Perth Amboy into the Arthur Kill, but only up to the channel bends in the vicinity of the Fresh Kills Landfill (see Figure 8).



Figure 9: Tidal Residual Currents during Strong, Large-Scale Winds from the West (left panel) and the East (right panel).

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, and in some extreme cases can disrupt the expected pattern of estuarine circulation. There is a tendency for these meteorologically-induced flows to be characterized as "through-flow" with circulation around Staten Island: inflow to (outflow from) the Kill van Kull is accompanied by a weaker outflow (inflow) through the Arthur Kill. This is in contrast to a pumping mode of circulation whereby Newark Bay would be filled (emptied) by a simultaneous inflow (outflow) in both the Kill van Kull and Arthur Kill. These flushing events have an important role in determining the fate and transport of sediment and contaminants in the estuary.

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 9.

The results from an empirical orthogonal function (EOF) analysis 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. Thus, it is necessary to have knowledge of both to predict and understand the circulation in this complex system.

Fate of Passaic River Sediment - SIT Model of the Newark Bay Complex

The transport/fate of suspended sediment originating in the Passaic River is important to the estuary because it is contaminated with high levels of various toxic pollutants. At the beginning of each month of the model run, a suspended sediment (SS) concentration of 1 mg/L was specified in each model grid cell in the Passaic River. The fate of this sediment varied at the end of each month (see Table 1), but overall, the Hackensack River appears to be acting as a sink for a significant percentage of the SS from the Passaic River. Sediment losses from the system were highest during those months with the highest Passaic River flows (December 2000, March and April 2001). These higher flows bring the sediment further into Newark Bay and keep it in suspension, so it has a better chance of moving into the Arthur Kill and Kill van Kull. Most of the sediment that is transported into the Kill van Kull and Arthur Kill is subsequently flushed from the system. During months with moderate flows in the Passaic River (May, September, and October 2001), the suspended sediment is transported into Newark Bay, where it can settle and/or move up into the Hackensack River. When flows are lower in the Passaic River (September, October, and November 2001), the suspended sediment also tended to remain in the Passaic River.

Under most conditions, largely due to gravitational circulation, a significant amount of the suspended sediment from the Passaic River is transported into the Hackensack River. In order for the gravitational circulation to move the sediment, it must first be transported into Newark Bay by freshwater flows from the Passaic River. Increasing Passaic River flows increase the amount of sediment transported into the Hackensack River because (1) more sediment is initially transported into Newark Bay, and (2) more freshwater flow seaward along the surface of the estuary results in a greater salinity intrusion and sediment transport along the bottom of the estuary.

Month	Mean Passaic River Flow (m ³ /sec)	Final Concentration (%)					Total Loss from the Complex (%)
		Passaic	Hackensack	Newark Bay	Kill Van Kull	Arthur Kill	
Dec 2000	27	0.3	22.6	19.5	0.8	7.2	49.5
March 2001	61	0.1	16.8	14.6	0.9	0.3	67.2
April 2001	56	0.3	15.4	6.3	0.3	0.2	77.5
May 2001	9	2.8	42.4	17.3	0.7	1.4	35.4
Sept 2001	5	34.1	32.6	11.6	0.0	0.7	21.0
Oct 2001	3	35.9	26.9	10.1	0.0	0.2	26.9
Nov 2001	2	51.9	21.4	6.0	0.0	0.1	20.6

Table 1. Sediment distribution at the end of selected months of the SIT model run.

Based on the NJTRWP Study I-E observations and the results from the 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 Bay.

Tidal currents in the Kill van Kull drive a significant exchange of water and sediment between Newark Bay and Upper New York Bay. Although sediments are transported in both directions through the Kill van Kull, there is a net transport of sediment into the Newark Bay Complex from Upper New York Bay. 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. It has been concluded that the Kill van Kull represents the major pathway of sediment transport into Newark Bay. 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.

SIT Model of the Newark Bay Complex - 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.

Recommendations and Conclusions

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 col-

umn 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. These meteorological events disrupt the expected patterns of tidal circulation, and have a major role in the transport and fate of sediment and its associated contaminants.

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.

Future studies should attempt to develop more detailed estimates of the fluxes of suspended sediment and associated contaminants in the Kill van Kull, Newark Bay, and the Arthur Kill. High temporal resolution suspended sediment and water column chemistry samples should be taken to develop relationships between the character of the suspended matter and the contaminant load.

A shortcoming of NJTRWP Study I-E was that it occurred largely during drought conditions. In order to fully characterize the hydrodynamics of the Newark Bay Complex, addi-

tional work is needed during high flow Passaic River discharge conditions.

Acknowledgements

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