FINAL REPORT

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Mechanisms of Sediment Trapping and Accumulation in Newark Bay, New Jersey: An Engineered Estuarine Basin (HRF 008/07A)

by

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ABSTRACT

A study sponsored by the Hudson River Foundation (HRF Project 008/07A) was conducted by University of Delaware and Rutgers University researchers to establish the fluxes of suspended matter to and from Newark Bay, and to identify mechanisms and patterns of seasonal sediment deposition and long-term accumulation. The project extended from 2007 to 2009 and was motivated by questions regarding the sources and sinks of fine-grained sediment in the bay, and also by uncertainties concerning changes in bay circulation brought about by recent deepening of the federal shipping channel. A two-component observational study was executed including 1) moored observations of hydrodynamic flow and sediment transport (Rutgers), and 2) a study of short-term (seasonal) sediment deposition and historical bathymetric change (U. Delaware). Specific tasks completed in support of the study included the following: 12 months of hydrodynamic and sediment-transport observations at six mooring locations; a single-beam bathymetric survey of the entire bay floor; grab sampling at 126 sites for analyses of sediment properties; quarterly seabed coring at ten sites for one year; vibracoring at seven locations; and an analysis of historical bathymetric data for 1934 and 2008.

The most definitive result of the sediment-flux study was a steady transport of sediment from the Kill Van Kull to Newark Bay estimated at ~140,000 metric tons/yr. This source dominated the seasonal influx of sediment to the bay during the observational period. By comparison, the Passaic and Hackensack rivers supplied ~17,000 and ~5,000 tons/year, respectively. Approximately 20,000 tons/year of sediment was exported from the bay via Arthur Kill. The total net influx of sediment was 162,000 tons/year, which is comparable to previous estimates. Sediment imported to the bay during the study period was observed to converge (deposit) within northern Newark Bay shipping channel, most conspicuously in conjunction with the December 2008 flood of the Passaic River.

The most unexpected result of the hydrodynamics study was evidence for a dramatic increase in the non-tidal exchange flow in the Kill Van Kull, presumably a consequence of the recent deepening of the shipping channel. The exchange flow (the mean flow from NY Harbor to Newark Bay) approximately doubled between 1997–1998 and 2008–2009, based on comparison of data obtained through past and the present work. Because circulation and sediment transport in Newark Bay is dominated by the Kill Van Kull, the increased exchange flow has potential to increase the supply of suspended sediment to the bay relative to the pre-deepening supply.

Repeat coring and seabed measurements of the short-lived radionuclide Be-7 ($t_{1/2}$=53.3 days) indicate that seasonal burial of fine-grained sediment occurs throughout the bay, but that deposition resulting from river discharge events is most intense in the northwestern bay between the mouth of the Passaic River and the marine terminals. Be-7 activity was detected in the surficial sediments (0–2 cm) at all of the coring stations reoccupied during the study, indicating that suspended particles rapidly cycle between the water column and seabed. Sediment inventories of Be-7 suggest that the mean residence time of Be-7 (and suspended particles) in the water column is ≤30 days. Based on the depth of detectable Be-7 activity in cores, deposition of new sediment between quarterly sampling visits ranged from 2 to 8 cm in the northwestern part of the bay, and <1 cm to 2 cm on the subtidal flats in the eastern and southwestern bay. Preserved sediment layering in cores from the northwestern bay suggests that new (Be-7 labeled) sediment was emplaced by current-controlled deposition. Deposition in this area of the bay appears to respond rapidly to Passaic River discharge events and associated convergences in suspended-sediment flux. In contrast, some combination of current-controlled deposition and biological mixing was responsible for burial of new sediment on the subtidal flats during the study period. Sediment deposition on the flats did not appear to respond to observed sediment-transport events; unlike the northwestern bay area, deposition on the flats did not appear to vary with changes in suspended-sediment flux recorded by the moored instrumentation. This spatial variation in short-term deposition most likely reflects the complex bathymetry of the bay and related differences in circulation and sediment-transport conditions specific to the channel and the shallower flats. Preferential entrapment and deposition of sediment within the channel may limit its ability to be subsequently remobilized and dispersed to the subtidal flats.

Results of the 1934–2008 bathymetric change analysis revealed that sediment accumulation on the subtidal flats is patchy and highest where the seabed has been modified by excavation and filling, or where tidal flow and sediment transport have been altered by construction of fixed structures. Net sediment accumulation averaged 1934–2008 ranged from ~0.5 to 5 m; net accumulation was greatest in the channel connecting the Passaic River and the marine terminals, and most laterally continuous on the subtidal flats across-bay of the terminals. The overall pattern of long-term sediment accumulation is broadly similar to the pattern of short-term deposition resolved during the 2008–2009 coring study. This indicates that short-term depositional zones in the bay, and the underlying hydrodynamic and sediment-transport conditions, are more-or-less stable on time scales of several decades. Ongoing work is considering the extent to which historical changes in the hydraulic geometry of the bay have impacted bay circulation and sediment accumulation at subtidal flat locations where the bottom has not been modified by human activities.

1. Research Objectives

This report describes results of Hudson River Foundation (HRF) Project 008/07A, conducted by the University of Delaware (C.K. Sommerfield) and Rutgers University (R.J. Chant) between 1 October 2007 and 30 September 2009. The project was motivated by a general need to fill knowledge gaps regarding pathways, fluxes, and depositional patterns of suspended sediment in the Newark Bay system. To this end the project had three specific objectives: 1) to elucidate processes that drive the circulation, stratification, and sediment transport in the bay on tidal, fortnightly, and seasonal time scales; 2) to quantify the relative importance of various sediment sources and sinks in the system based on sediment-flux measurements; and 3) to establish patterns and rates of sediment deposition and accumulation on seasonal and longer time scales. To meet these objectives, an observational program was undertaken including time-series measurements of hydrodynamic flow and sediment-transport throughout the bay, and a study of seasonal deposition and longer-term bathymetric change. Fieldwork and laboratory tasks completed during the course of work included the following:

- A 12-month study of hydrodynamics and sediment transport at six locations
- A single-beam bathymetric survey of the entire bay floor
- Grab sampling at 105 sites analyses of sediment physical properties
- Seasonal seabed coring at reoccupied sites for analysis of Be-7 activity
- Vibracoring at seven sites for sedimentological measurements
- An analysis of historical bathymetric change in the bay, 1934 to 2008

Synergistic activities accomplished during the 2007–2009 award period included regular communication and exchange of data with Elizabeth Butler, an EPA project manager involved in the Newark Bay RI/FS. To date we have provided Ms. Butler with grain size, bathymetric, and hydrodynamic data generated by our study and have agreed to provide additional data in the future. Additionally, in following the "engineered estuaries" theme of our project, we organized and chaired a special session on human-impacted estuaries at the 2009 Estuarine Research

Federation meeting in Portland, Oregon. This session, entitled " Natural and Anthropogenic Changes in Estuaries: A Historical Perspective", brought together a diverse group of researchers to present work on human impacts in estuaries, ranging from dredging impacts to eutrophication. Conference presentations stemming from our HRF project are listed below:

1. Chant, R., and Sommerfield, C.K., 2009. Direct evidence of the effect of channel depth on estuarine exchange flow. 2009 Gordon Research Conference, Colby-Sawyer College, New London, New Hampshire.

2. Chant, R., Sommerfield, C., Dove, G., 2009. The response of estuarine flows to channel deepening. Biannual Meeting of the Coastal and Estuarine Research Federation, Portland, Oregon, Abstracts of Technical Program.

3. Halonen, J.R. and Sommerfield, C.K., 2010. Effects of historical morphologic change on sediment accumulation in Newark Bay, New Jersey. 2010 Ocean Sciences Meeting, Portland, Oregon, Abstracts of Technical Program.

4. Guo, D., Sommerfield, C.K., Chant, R.J., 2010. The effects of channel deepening on tides, salinity and estuarine circulation in Newark Bay. 2010 Ocean Sciences Meeting, Portland, Oregon, Abstracts of Technical Program.

5. Talke, S., Sommerfield, C.K., Jay, D., and Chant, R.J, 2009. Introduction to natural and Anthropogenic Changes in Estuaries: A Historical Perspective. Biannual Meeting of the Coastal and Estuarine Research Federation, Portland, Oregon, Abstracts of Technical Program.

The major findings of HRF Project 008/07A are summarized in this report with emphasis placed on how the goals in our grant's Statement of Work were addressed.

2. Background

Understanding sediment transport dynamics as it relates to contaminant dispersal has become a ranking priority among environmental managers and regulatory officials in the New York-New Jersey Port region. For example, EPA is presently overseeing a study to determine the nature and extent of contaminants released by the Diamond Alkali Company on the lower Passaic River, and sedimentary processes figure prominently in this effort (EPA, 2008). While it is well-established that the bay is a depocenter for fine-grained sediments and contaminants derived from local and distal sources (Suszkowski, 1978; Bopp et al., 1991; Crawford et al., 1995; Gillis et al., 1995), questions surrounding the origin and long-term fate of this material have lingered for decades. Indeed, although a large amount of sediment observational and modeling work has been performed in the Hudson River estuary and NY-NJ Harbor region, relatively little attention has been given to questions of hydrodynamic flow and sediment transport in Newark Bay specifically. Prior to the present study, most of what was known about sedimentary processes in the bay was based on a short-term study of currents and suspended sediments by Suszkowski (1978), who demonstrated that Newark Bay imports fine-grained sediment from the Hudson River and Harbor system. Subsequent work by Chant (2005) revealed that the circulation of the Newark Bay-Kills complex is time dependant, and that the trajectory of net transport changes with variations in freshwater inflow and wind forcing. For this HRF project we endeavored to build upon prior work by identifying mechanisms of sediment mass transport (tidal versus non-tidal) to and from Newark Bay, and characterizing patterns and rates of fine-grained sediment deposition.

In addition to questions of sediment-transport pathways, our project was motivated by uncertainties over human impacts on circulation in Newark Bay, given that its hydraulic geometry has been modified during historical times by channel deepening. Between 1885 and 2000, the shipping channel connecting Newark Bay, the Kull Van Kull, and Arthur Kill was progressively deepened from a natural depth of ~12–20' to 35–40', and after 2004 it was deepened further to 50' as part of the U.S. Army Corps of Engineers (USACE) Harbor Improvement Project (*www.nan.usace.army.mil/harbor/deep.htm*). At the outset we hypothesized that the most recent deepening will modify tidal and non-tidal circulation in the channel, which influences sediment transport and depositional processes in the bay. Although the Environmental Impact Statement issued for the Harbor Improvement Project addressed the immediate impact of dredging on water and sediment quality (USACE, 2007), it did not explicitly consider how the deepened channel could potentially alter circulation and sediment transport on the long term. Our study squarely addressed this question, and the results (described in Section 3.1.5.) provide compelling evidence that channel deepening between 1998 and 2008 has modified tidal and non-tidal flow between NY Harbor and Newark Bay via Kill Van Kull.

3. Results and Interpretation

3.1. Hydrodynamics and sediment transport

Hydrodynamic measurements conducted for this study consisted of long-term moored observations throughout the bay. The mooring time series, which spanned 12 months at six locations, represents the most extensive mooring deployment to date in Newark Bay, greatly exceeding observations performed for the 2001–2002 Contaminant Reduction and Assessment Program (CARP) both in duration and number of moorings.

The mooring program consisted of a six-element mooring array (Figure 1). Each mooring consisted of an acoustic Doppler current meter, surface and bottom conductivity and temperature (CT) sensors, and near-bottom optical backscatterance (OBS) sensors. The mooring array was designed with two objectives in mind. First and foremost it was necessary to determine the relative importance of various sediment transport mechanisms (i.e., tidal pumping vs. non-tidal transport) on the total sediment flux. The second objective was to obtain estimates of sediment fluxes and sediment convergences within the bay, and relate these estimates to patterns of seasonal sediment deposition resolved through the concurrent study of the seabed (see Section 3.2). Additionally, the time-series data were compared to similar measurements made by R. Chant in 1997–1998, prior to the recent deepening of the shipping channel, to determine the extent to which the system has been altered hydrodynamically. In particular, the analysis

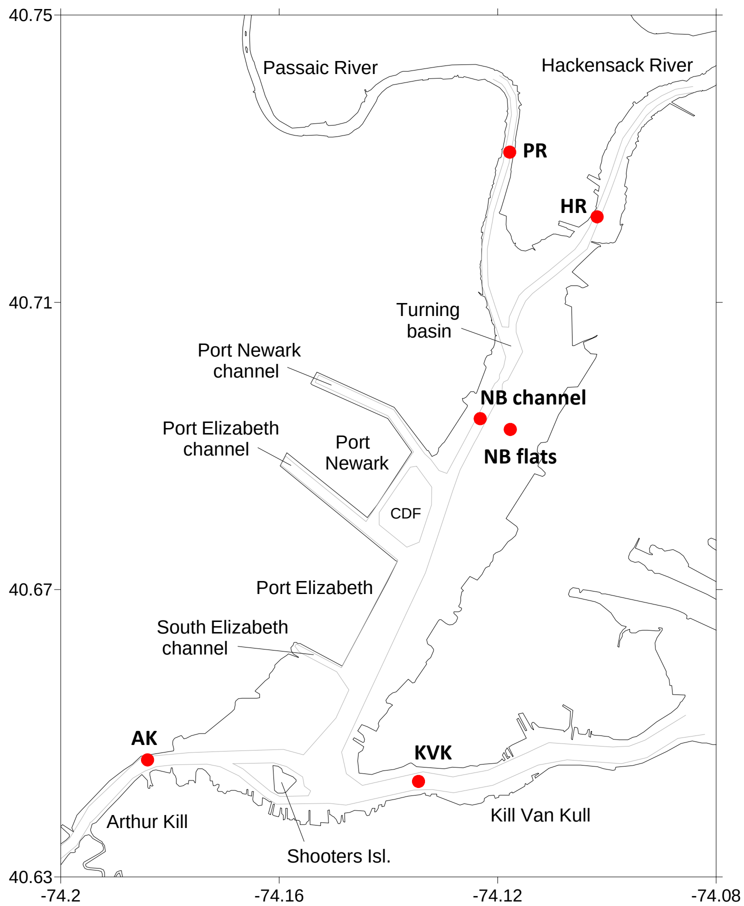

Figure 1. Locations of moorings deployed in Newark Bay (red circles). The NB flats mooring was removed after three months and is not discussed in this report. The confined disposal facility (CDF) is an area of shallow seabed adjacent to the shipping channel, the boundaries of which are shown by grey lines.

focused on changes in the vertical tides as well as on tidal and non-tidal mean flows in the Kill van Kull (KVK) associated with the 4-m increase in channel depth from 1997–1998 to 2008. The 1997–1998 hydrodynamic data were collected near Bergen Point by NOAA as part of the PORTS program, whereas the post-deepening data were obtained through the present study by Rutgers University at nearly the same location. The availability of pre-deepening hydrodynamic data for the KVK represented an unprecedented opportunity to evaluate changes in tidal and non-tidal circulation associated with channel deepening, because long-term hydrodynamic datasets are generally not available to assess human impacts in urbanized estuaries.

The moored dataset includes two separate deployments of instrumentation. The first array was deployed on 11 April 2008 and recovered on 15 August 2008, and the second was deployed on 16 September 2008 and recovered on 10 March 2009. Aside from the loss of surface CT sensors in the Kills, all other instruments were recovered and contained good data, with the exception of a fouled salinity sensor in the Passaic River. A timeline of the field work is shown in Figure 2 along with a record of Passaic River flow and near-bottom salinity in the bay. Passaic River discharge was moderate during the first half of the first deployment and decreased towards the end of the first deployment. Discharge was more variable during the second deployment, though it tended to be low through November and relatively high during the second half of the deployment. River discharge peaked at 159 m^3/s on 14 December 2008 and remained elevated for approximately one week thereafter. Averaged over the entire observational period, mean discharge of the river was 25 m^3/s.

The mooring deployment covered a range of tidal conditions and significant meteorological forcing during 2008–2009. In addition to river discharge, past work has shown that estuarine exchange flow, stratification, and sediment transport in the Newark Bay system respond to tidal amplitude and meteorological forcing. In general, variable meteorological forcing is apparent in the low frequency sea-level, which represents primarily remotely forced motion associated with wind-driven Ekman flows in the Mid-Atlantic Bight. Due to enhanced winds during the winter months, meteorological forcing is significantly stronger in winter than in summer.

3.1.1. Salinity observations. Forcing associated with tides, river discharge, and meteorology are apparent in both the low-passed (tide filtered) near-bottom salinity (Figure 2) and in the non-filtered raw data, which includes higher frequency tidal variability (Figure 3). For brevity, only three sites worth of salinity data are plotted in Figures 2 and 3 to resolve the along-

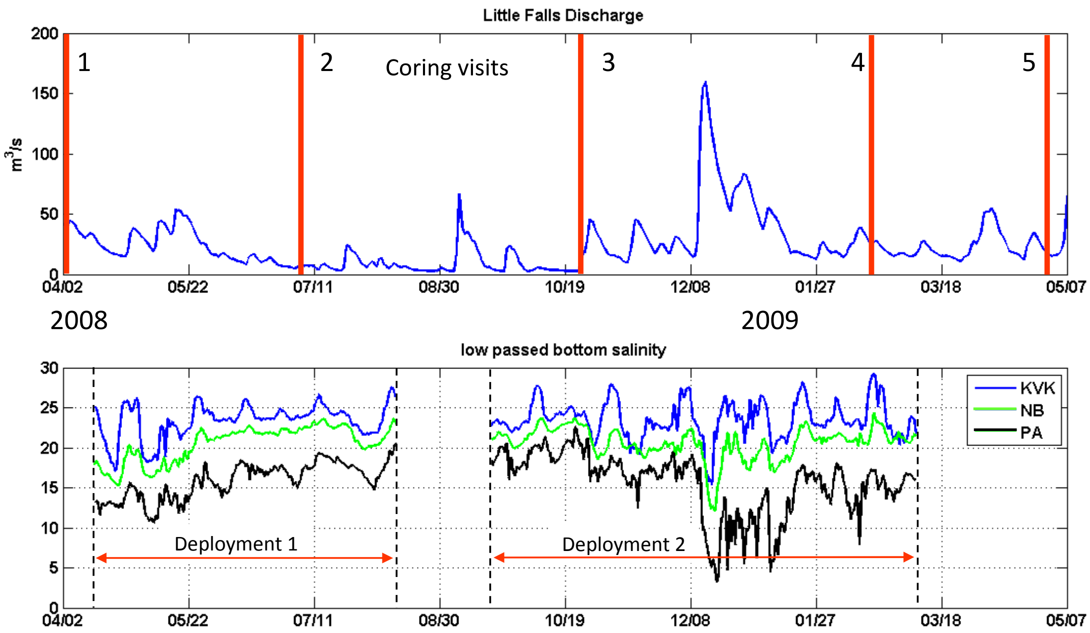

Figure 2. Timeline showing the times of coring (top) and mooring deployments (bottom). Passaic River discharge at Little Falls and salinity data in PSU are shown for reference. KBK=Kill Van Kull mooring, NB=Newark Bay channel mooring, PA=Passaic River mooring.

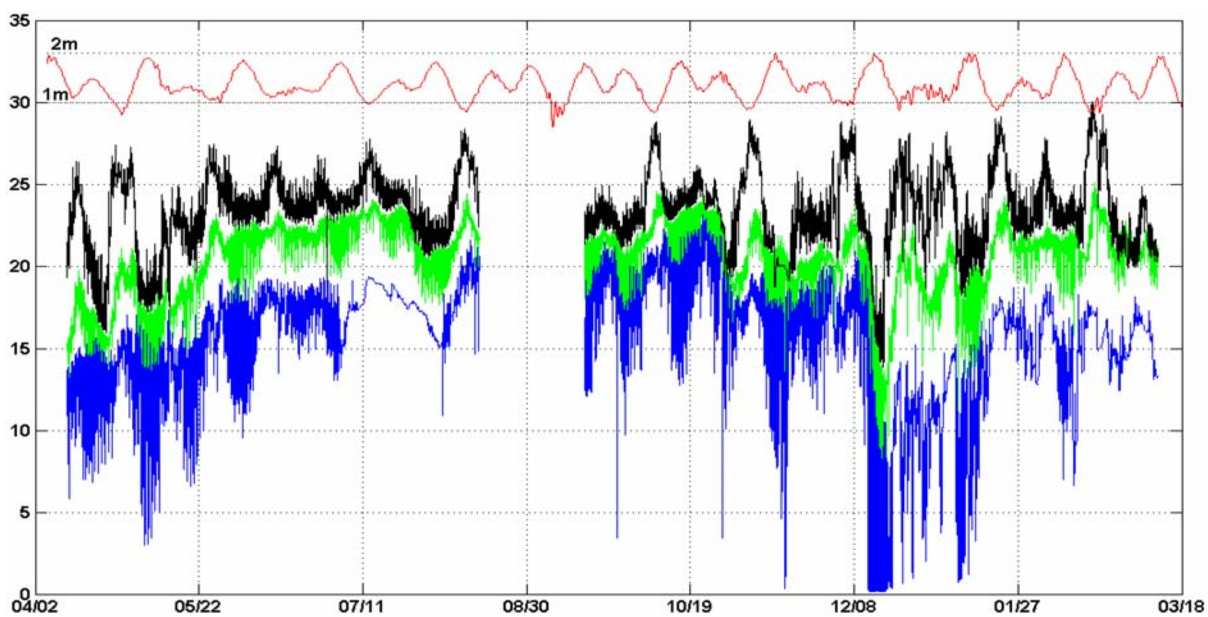

Figure 3. Unfiltered, near-bottom salinity records for the Passaic River mouth mooring (blue), the Newark Bay channel mooring (green), and the KVK mooring (black). Tidal range at the Battery is shown in red.

estuary salinity gradient from the mouth of the Passaic River to the KVK. At all locations a clear spring/neap cycle is apparent in near bottom salinity, though it is less apparent at the Newark

Bay mooring site than at the KVK or the Passaic River sites. Spring/neap variability in near-bottom salinity in the KVK is characterized by increased salinity during neap tides, whereas at the Passaic River mouth spring/neap variability is characterized by a dramatic increase in intra-tidal variability due to significant freshening during the ebb phase of spring tides. This tidal freshening occurs during spring-tide conditions, particularly during moderate to high discharge events, because the salt wedge in the Passaic River is transported to the mouth of the river. Thus, during neap tides, salinity gradients increase in the southern half of the bay, whereas during spring tides the salinity gradient is more pronounced in the upper bay.

3.1.2. Stratification. Surface and bottom salinity data recorded at the mooring sites allow for an assessment of stratification in the system. At the Newark Bay channel site, bottom salinity ranged from 10 PSU following the discharge event in December 2008 to >24 PSU during low-flow, neap-tide conditions (Figure 4). Surface salinity exhibited significantly more tidal period variability, which is evident by the wider swath of the red line relative to the blue line in Figure 4. This variability is related to freshwater from the Passaic River reaching the mooring location during ebb tides. Stratification (bottom minus surface salinity) is persistent in Newark Bay, even during times of low flow, and shows relatively weak spring/neap variability. During low-flow, spring-tide conditions, stratification was ~0.5 PSU during the flood tide but exceeded 5 PSU on the ebb. During low-flow, neap-tide conditions, stratification did not drop below a few PSU during the flood tide. During high-flow conditions in late 2008 and early 2009, stratification increased markedly and averaged ~10 PSU for several weeks. Following this period, stratification exhibited significantly more spring-neap variability primarily due to increases in near bottom salinity during neap tides.

In Newark Bay the persistence of stratification and its tendency to increase during ebb tides, even during conditions of extremely low freshwater inflow, has important implications for

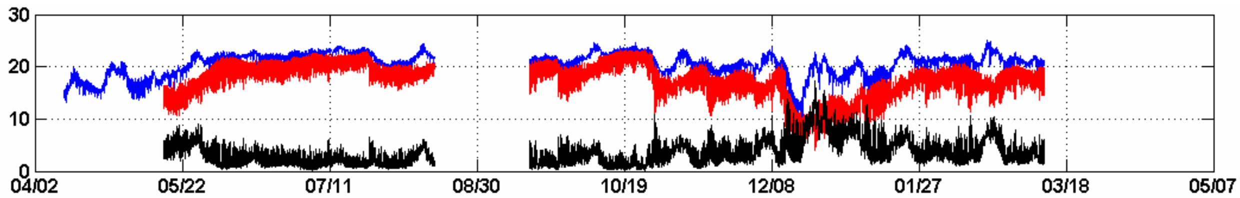

Figure 4. Records of surface (red) and bottom (blue) salinity and stratification (black line) for the Newark Bay channel mooring site during 2008–2010. The salinity units are PSU.

sediment transport. Specifically, during the flood tide, sediment resuspension into the upper water column is enhanced by the weakly stratified water column. In contrast, during the ebb tide, stratification is intensified and significantly reduces resuspension and the amount of sediment carried by the current. Persistent stratification in the bay is likely to entrap sediment, particularly in the deeper shipping channel, by decreasing sediment transport during ebbing tides and during periods of high outflow of the Passaic River.

3.1.3. Depth-averaged mean flows in the KVK. Depth-averaged currents and stress averaged over the entire deployment period are shown for each mooring site in Figure 5. Persistent mean flows were observed at all sites. A mean counterclockwise circulation is evident around Staten Island, characterized by an inflow from New York Harbor to the KVK and an outflow through the Arthur Kill. The corresponding time series of the current, which was developed by assuming that the flow is uniform across the channel, shows that transport through the Kills, while persistent, is strongly modulated by low-frequency variability associated with meteorological forcing and tidal range. A simple linear model correlating this transport with wind stress (directed along 150 degrees) and tidal range explains 66% of the variance of the flow. The linear model represents the flow as follows:

$$U = 0.0567A - 3.129\tau - 0.0258 \quad (1)$$

where A is the tidal range in meters, τ is the wind stress in Pa directed along 70 degrees, and U is

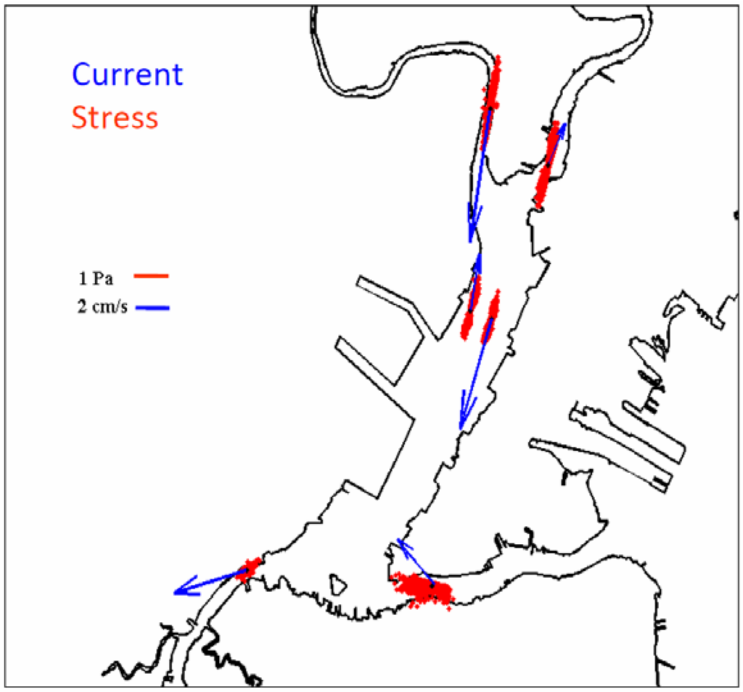

Figure 5. Mean, depth-averaged current velocity (blue arrows) and near-bottom stress (red scatter plots) averaged over the entire mooring deployment.

the along channel current (m/s) with positive flow to the east in the KVK. A comparison between this simple model and the data is shown in Figure 6. Averaged over the deployment period the mean transport through the Kills was ~120 m^3/s.

3.1.4. Exchange flows. Strong and persistent non-tidal exchange flows are evident at all sites. Most notable, however, is a dramatic increase in the exchange flow in the KVK associated with channel deepening. This increase is clear upon comparing our 2008–2009 mooring data and data from a 1-year mooring deployment by NOAA in 1997–1998, when the channel depth was 14 meters (in contrast to today's 18-m deep channel). The exchange flow — the maximum inflowing velocity minus the maximum outflowing velocity — for both records is shown in Figure 7. The exchange flow has approximately doubled in intensity between 1997–1998 and 2008–2009, consistent with classical theory suggesting that exchange flow is proportional to channel depth to the third power (Hansen and Rattray, 1966). In the KVK, the exchange flow

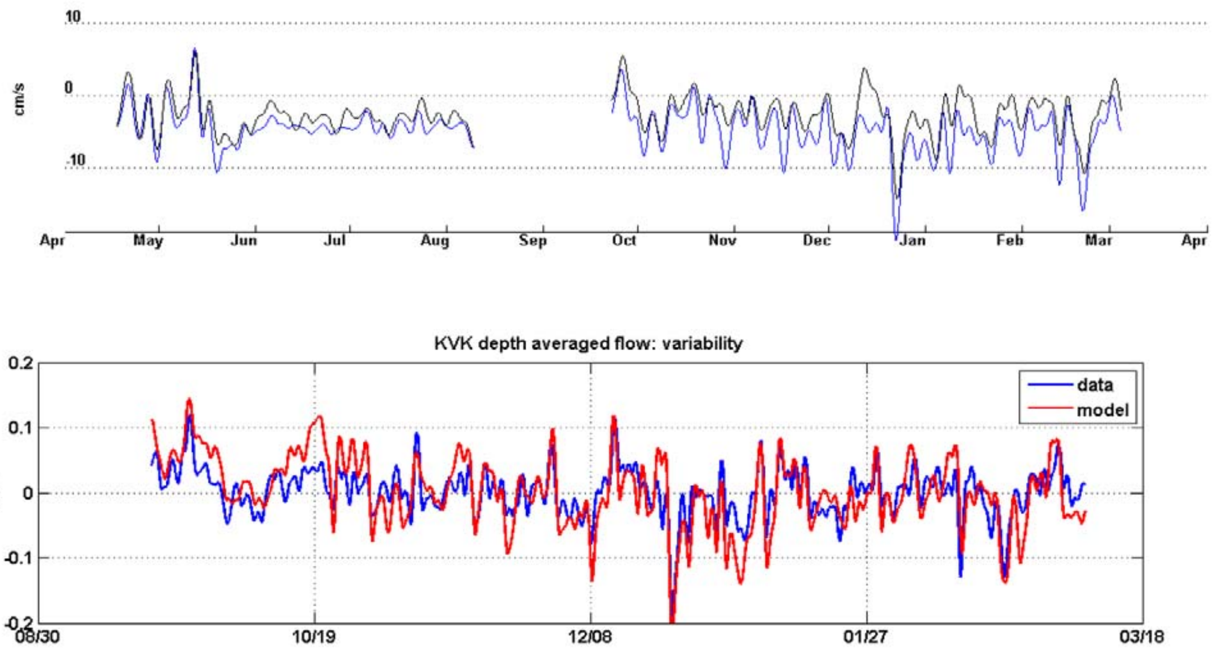

Figure 6. Upper panel: depth-averaged along-channel flows in KVK (blue) and Arthur Kill (black). Lower panel: depth-average flow in KVK (blue) and KVK flow predicted by the linear model discussed in the text.

increased by a factor or 1.8, from 7.8 cm/s to 14.1 cm/s, comparable to the increase predicted by theory, i.e., $(18/14.5)^3 = 1.9$. The vertical structure of the mean flow for the 1997–1998 and 2008–2009 observations emphasizes the dramatic increase in mean shear post-deepening (Figure 8). It is important to note that this scaling assumes a constant horizontal salinity gradient. However, both theoretical (MacCready and Geyer, 2010) modeling studies (Hetland and Geyer, 2004) predict that for steady-state solutions the salt intrusion length scales with $H^{8/3}$, suggesting that the sensitivity of the exchange flow should only vary with $H^{1/3}$. Moreover, changes in mixing due to variations in tidal current speed associated with the deepening, and potentially the height of the bottom boundary layer (Ralston et al., 2008), would tend to reduce the effect of channel depth on exchange flow even further. Nevertheless, these observations indicate a cubic increase in the exchange flow with depth, suggesting that horizontal salinity gradients have not decreased as per theoretical predictions. In contrast, as will be shown later, near bottom salinity

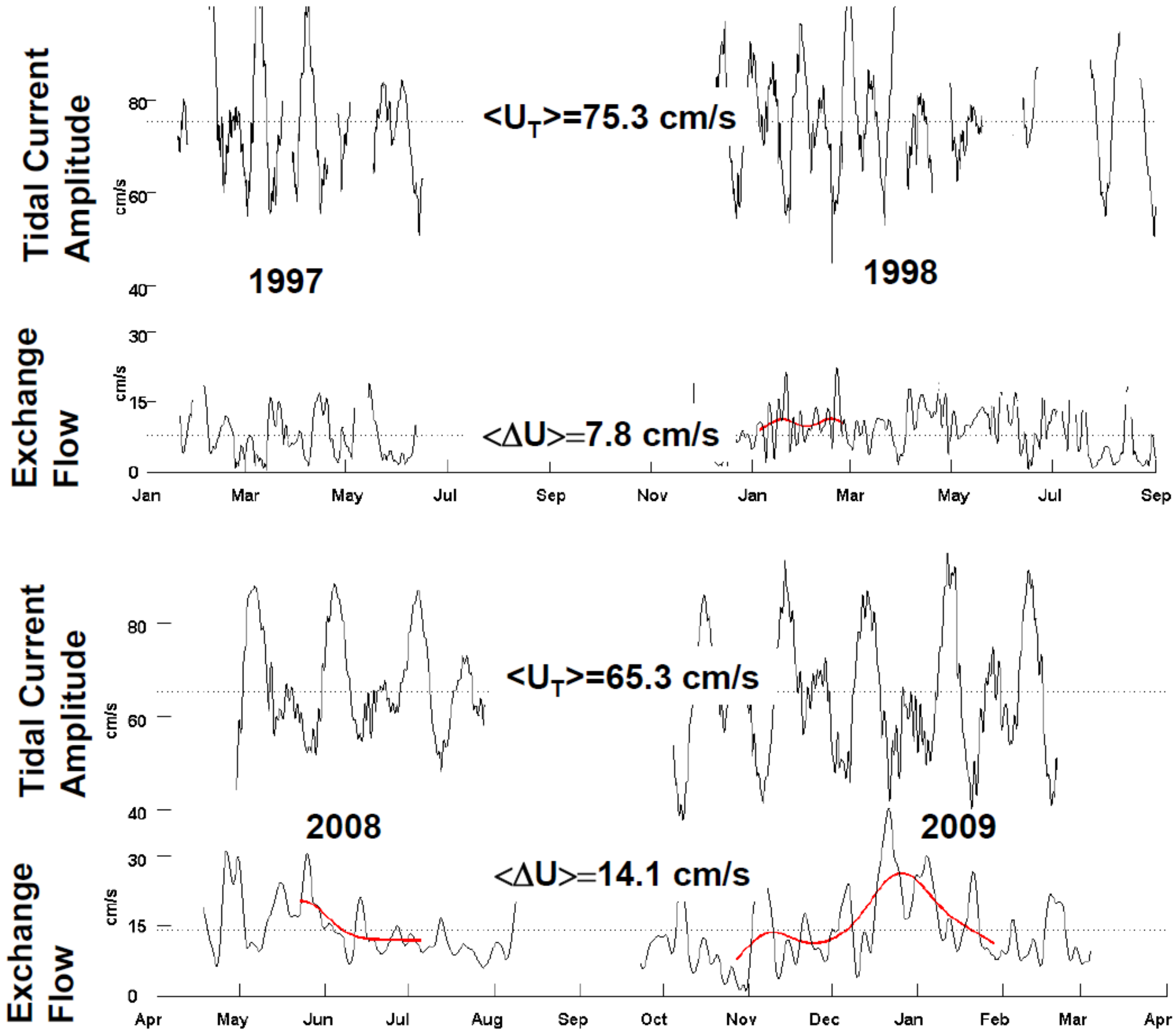

Figure 7. Tidal current amplitude and exchange flow intensity computed for the 1997–1997 NOAA deployment in KVK and the 2008–2009 deployment conducted for this study.

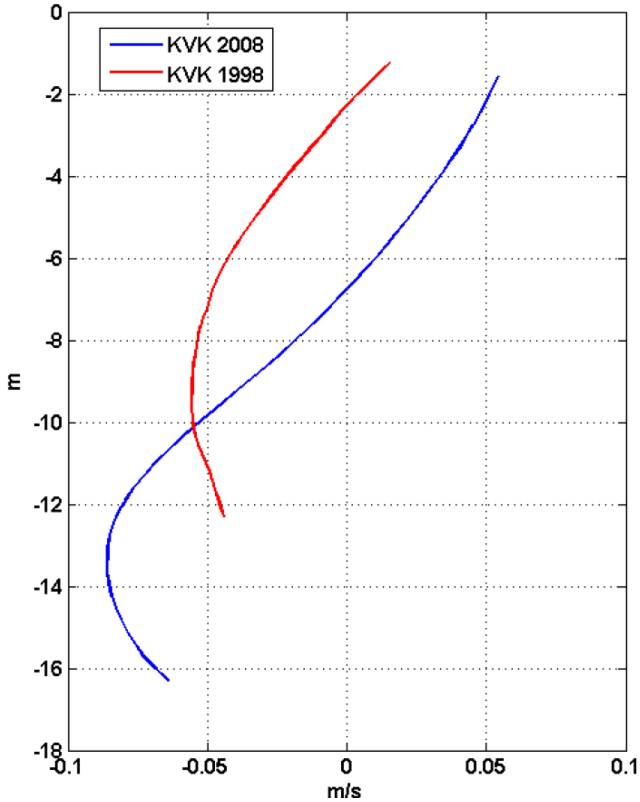

Figure 8. Depth-dependant mean flow in the KVK averaged over the 1997-1998 NOAA deployment (red) and the 2008–2009 deployment conducted for this study.

data indicates that the along-channel salinity gradient has actually increased, which we feel is consistent with the combined effect of deepening of Newark Bay and long-term shoaling in the lower Passaic River (Chant, 2005).

It is important to note that the comparison above is complicated by variations in river discharge. Specifically, Passaic River discharge during the NOAA deployment was 39 m^3/s whereas it averaged 25 m^3/s during the present study. Theory predicts that the exchange flow varies with river discharge to the 1/3 power, thus variable river discharge should modify our comparison of 1997–1998 and 2008–2009 exchange flows by no more than 10%.

Vertical mixing is also expected to be modified by a change in tidal current speeds associated with channel deepening. Tidal variability in Newark Bay is largely a standing wave with only a 10-minute phase shift across the entire system. Tidal current speed in a standing wave system would be inversely proportional to depth, so an increase in channel depth from 14 to 18 meters would correspond to a 20% decrease in tidal currents. Comparison of depth-averaged tidal current data obtained for the 1997–1998 NOAA study and that for the present study do in fact show a 15% decrease in the tidal current speed (Figure 7). Complicating this comparison, however, is the 18.6-year modulation in the lunar tidal constituent. Taking the 18.6-year cycle into account, we conclude that tidal current speeds in the KVK have decreased since 1997–1998 by ~10% in association with channel deepening and by an additional 5% due to the 18.6-year cycle. Hence, the apparent reduction in tidal current speeds is only half of what we would predict. It would appear that tidal transports in the KVK have increased even though the tidal range in Newark Bay has remained relatively constant, violating continuity. One possible explanation for this discrepancy is that tidal currents elsewhere in the system have changed in compensation for enhanced tidal transport in the KVK, a topic of on-going research. Specifically, we are developing an analytical two-channel model that incorporates momentum and continuity to assess the impact of channel deepening on Newark Bay tides.

3.1.5. Suspended-sediment transport. Developing time series of suspended-sediment flux at the mooring sites involved calibrating the acoustic backscatter signal from the ADCPs against suspended-sediment concentrations (SSC), measured at the same sites through periodic water sampling and filtration in the laboratory. The resulting time series of SSC were then rendered with velocity data to derive continuous records of total sediment flux, which was decomposed into three components: 1) one associated with correlated tidal period variability in SSC and along-channel current; 2) a second associated with low frequency vertical structure in velocity and SSC; and 3) a third associated with depth-averaged low-frequency currents and SCC. The first term is often referred to as tidal pumping, the second the estuarine flux associated with density-driven gravitational flow, and the third is associated with river discharge (Lerczak et al., 2006).

Records of the total, depth-averaged sediment flux for the mooring sites are shown in Figure 9. The most definitive finding is a steady transport of sediment transport through the KVK into Newark Bay, which we estimate at ~140,000 metric tons per year. Decomposition of this flux indicates that it is *opposed* to the eastward mean flux associated with river discharge. Just over half of the total sediment flux through the KVK results from tidal pumping, which we estimate supplies approximately 75,000 metric tons/year of sediment to the bay. By comparison, the mean flow generated by the Passaic River provides approximately 37,000 metric tons/year, whereas the exchange flow within the KVK supplies an additional 25,000 metric tons/year.

The mean sediment transport from the Passaic River was directed toward Newark Bay throughout the observational period, but it is important to point out that the cumulative sediment flux was dominated by a single high-flow event in mid-December 2008. During this flow event the salt wedge was completely flushed out of the river for many consecutive ebb tides (Figure 12). Consequently, large loads of suspended sediment were released into Newark Bay, and at one point the tidally averaged load peaked at nearly 10 kg/s (Figure 10). Over 8,000 metric tons of sediment was transported to Newark Bay by the Passaic River during this event, nearly half of its estimated annual load of 17,000 tons/year. These observations make clear that river discharge events dominate sediment fluxes from the Passaic River to Newark Bay, and for this reason there are likely to be large inter-annual variations in sediment delivery from the river.

Averaged over the two deployment periods, the net sediment flux at the Newark Bay channel site was up-bay, suggesting that there is a localized convergence of flux (deposition) between the channel mooring site and the Passaic River. However, around the time of the Passaic River discharge event in December 2008 the sediment flux from the river increased significantly and the direction of sediment transport in Newark Bay channel reversed from up-

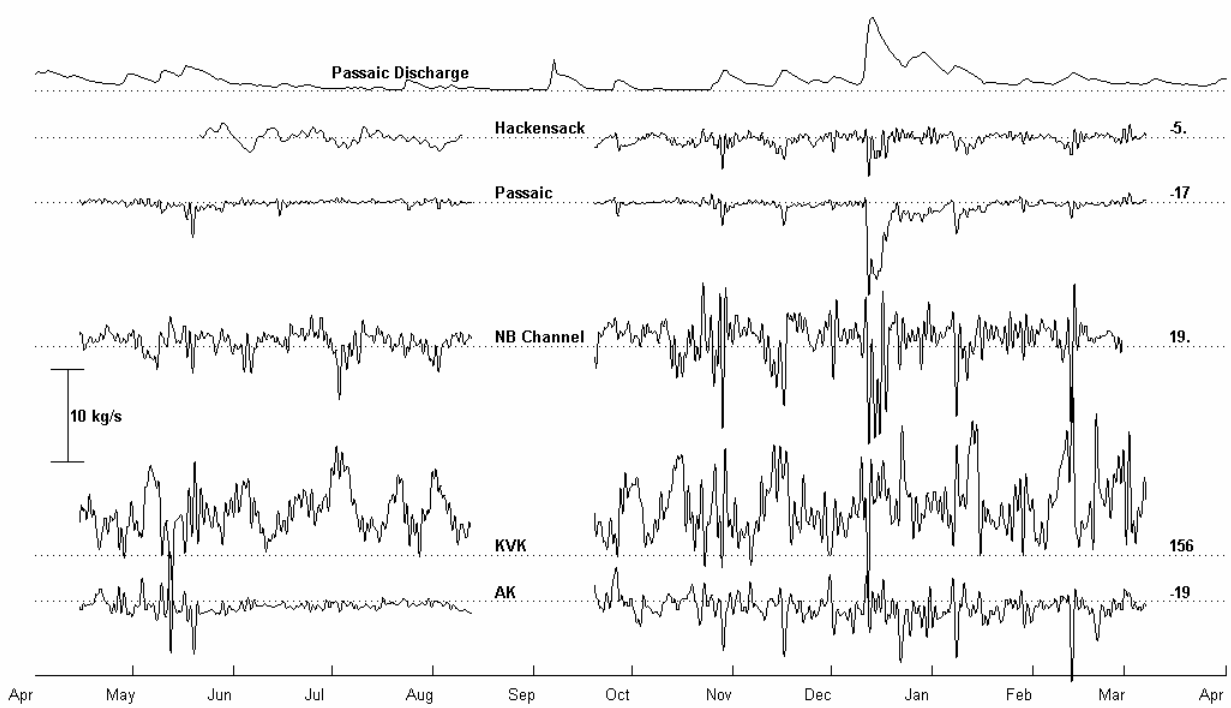

Figure 9. Time series of tidally averaged, along-channel sediment flux (kg/s) at the mooring sites during 2008–2009. Note the scale bar and the sign of transport about the zero crossing (dotted line). Positive and negative fluxes denote respective northward and southward transport at all sites except KVK, where positive and negative fluxes are westward (bayward) and eastward, respectively. The net, deployment-integrated sediment mass transported at each site is indicated in metric tons. These values were normalized to annual averages and are reported in metric tons/year in the text.

bay to down-bay (Figure 10). Interestingly, the flux of sediment from KVK remained westward during the discharge event, suggesting that greater Newark Bay was a convergence zone during this period. Our estimate of net sediment transport at the Newark Bay channel site is 22,000 metric tons/year, suggesting that most of the KVK sediment flux is not carried to the northern bay. There was a relatively small net export of flux of sediment from the bay through the Arthur Kill of approximately 20,000 metric tons/year, and the net flux of sediment at the Hackensack mooring site was 5,000 metric tons/year into the Bay. Hence, sediment mass balance implies that the convergence of sediment flux in Newark Bay is mostly a consequence of sediment derived from the Passaic River and the Hudson River–NY Harbor area, transported bayward through the KVK. As a caveat, at none of the mooring sites was lateral variability in flow and

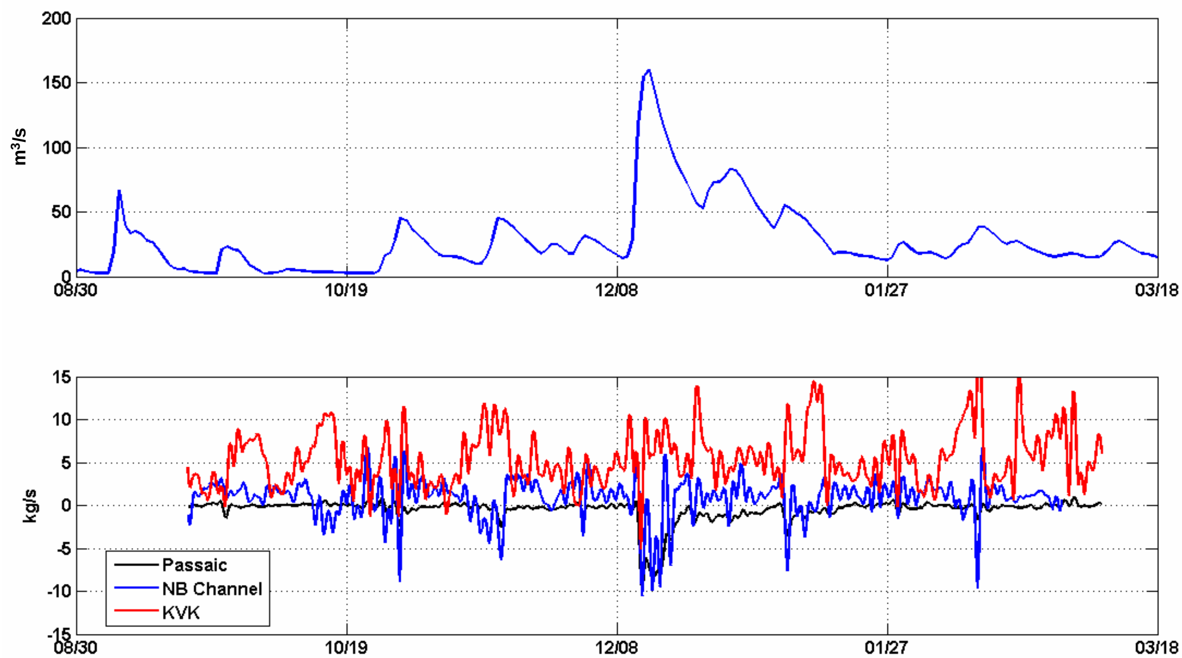

Figure. 10 Time series of Passaic River discharge (top) and sediment flux (bottom). Positive and negative sediment fluxes are respectively northward and southward at the Passaic River and Newark Bay channel mooring sites, and westward (bayward) and eastward at the KVK site. Convergences in sediment flux occur during spring tides and in association with Passaic River peakflows. Note the strong flux convergence around the time of the December 2008 discharge event.

sediment flux fully resolved — there are likely to be differences between our estimates and the actual fluxes.

To summarize, the total influx of sediment measured during the observational period was 162,000 metric tons/yr, collectively supplied by the KVK, Passaic River, and Hackensack River. Approximately 20,000 metric tons/yr was *exported* from the bay through Arthur Kill. The net influx of 142,000 tons/yr is comparable to the influx of 117,000 tons/yr reported by Suszkowski (1978). In contrast to our findings, Suszkowski observed that Arthur Kill supplies sediment to the bay while the Hackensack River imports sediment from the bay. Some of the difference between the results of Suszkowski's study and the present work may be related to methodology. For example, sediment fluxes reported by Suszkowski were computed from periodic measurements of surface and bottom currents and sediment concentration, perhaps aliasing some component of transport, whereas continuous flux measurements throughout the water column were made in the present study. Additionally, the difference could simply reflect temporal variations in flow and sediment-transport conditions during the respective years of study. The most significant difference between results of past and the present work is the role of Arthur Kill, which our observations suggest is a pathway for sediment export from Newark Bay. Prior to the present study the potential for sediment export from the bay was unresolved issue.

3.2 Seabed sedimentology and sedimentary processes

The purpose of the seabed component of the project was to identify stationary zones of mud accumulation in the bay, and to characterize the underlying processes of sediment deposition. Based on a reconnaissance grab-sampling survey of the bottom, ten stations located in muddy depositional areas were selected for repeat coring observations for a period of one year. Measurements of the radionuclide Be-7 ($t_{1/2}$=53.3 days) were used to constrain the amount and timing of new sediment deposited from April 2008 to April 2009. Be-7 is produced in the atmosphere by cosmic ray spallation of nitrogen and oxygen, and is delivered to Earth's surface through precipitation and dry deposition. In turbid river and estuarine environments, dissolved Be-7 rapidly associates with suspended particles and is sequestered in bed sediments when rates of particle uptake and settling are rapid relative to loss by lateral transport and radioactive decay in the water column (Olsen et al., 1986). When present at detectible levels, the sediment-depth profile and inventory of Be-7 can be used to quantify short-term deposition rates (Sommerfield et al., 1999) or biological mixing intensity (Krishnaswami et al., 1980). Previous work in the Hudson River estuary and NY-NJ Harbor region has proven Be-7 to be a useful tracer of short-term sediment deposition (Bopp et al., 1991; Feng et al., 1998; Woodruff et al., 2001).

3.2.1. Grab sampling and bed sedimentology. A grab sampling survey was conducted in 2008 to characterize the seabed sedimentology of Newark Bay. Sampling locations are shown in Figure 11. A total of 126 samples were collected using a Smith-McIntyre grab and later analyzed at the University of Delaware for grain size and loss-on-ignition (LOI) following the methods of Coakley and Syvitski (1991) and Heiri et al. (2001), respectively. The grain-size data provided information on locations of mud depositional zones in the bay, whereas the LOI measurements provided a measure of the organic matter content. Radionuclide adsorption on suspended particles is a strong function of particle size, surface area, and organic carbon content, thus the grain-size and LOI data provided information relevant to the Be-7 measurements.

Maps showing the weight percentages of sand, silt, clay, and LOI in bed sediments are presented in Figure 12. At 19 of the 126 stations the bottom consisted of bedrock, and either no sample was recovered or the material was too large for analysis (for these stations no grain-size data are shown in Figure 12). Fresh rock bottom was encountered within the newly deepened shipping channel in the KVK, Arthur Kill, and lower Newark Bay. Based on weight percentages of sand, silt, and clay, and following the classification scheme of Shepard (1954), the dominant sediment types in the bay are clayey silt, sandy silt, silty sand, and sand (Figure 13). Sand-sized grains were present in all samples at concentrations ranging from 4.9 to 94.6 %. Overall, the grain-size distribution resolved in the present study was qualitatively similar to that determined through a grab sampling survey in the 1970s by Suszkowski (1978).

The highest concentrations of sand were found in bed sediments the northern bay near the mouth of Hackensack River, on the subtidal flats across from Port Newark, and on the flats south of Port Elizabeth. The sand content of bottom samples generally increased with proximity to the shipping channel, where turbulence is sufficient to suspend sand-sized grains for lateral transport and deposition on the adjacent flats. Sand content was lowest in bed sediments from the subtidal

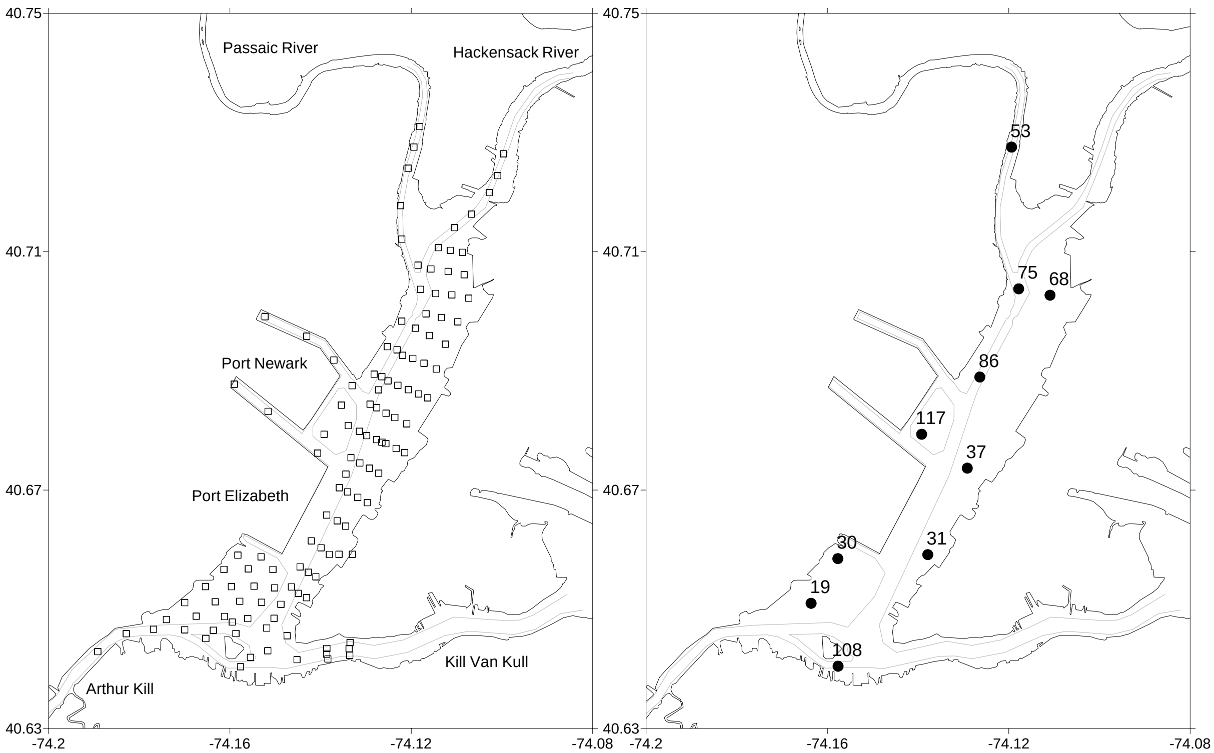

Figure 11. (Left) Locations of grab sampling stations in Newark Bay. (Right) The ten stations reoccupied during 2008–2009 for quarterly core-sampling and Be-7 measurements.

flat area across from Port Elizabeth, where the silt + clay (mud) content was highest among stations. As is typical for estuarine sediments, the sand content in all samples correlated inversely with the concentration of mud. Compositionally, the sand fraction consisted of a mixture of mineral grains (quartz), shell fragments, and vascular plant debris, but a detailed analysis of this material was not performed. The silt and clay content of bed sediments ranged from 1.6 to 59.2% and 2.4 to 51.6%, respectively. The mud concentration was high on the middle section of subtidal flats throughout the bay, in the marine terminals, at the mouth of the Passaic River, and in the vicinity of Shooters Island. LOI values ranged from 0.5 to 18.9 % and varied inversely with the concentration of sand. LOI varied directly with mud content and was more strongly correlated with the fine silt (<10 microns) and clay than with the coarse silt fraction (10–63 microns). This suggests that the LOI data as a whole reflect combustible organic

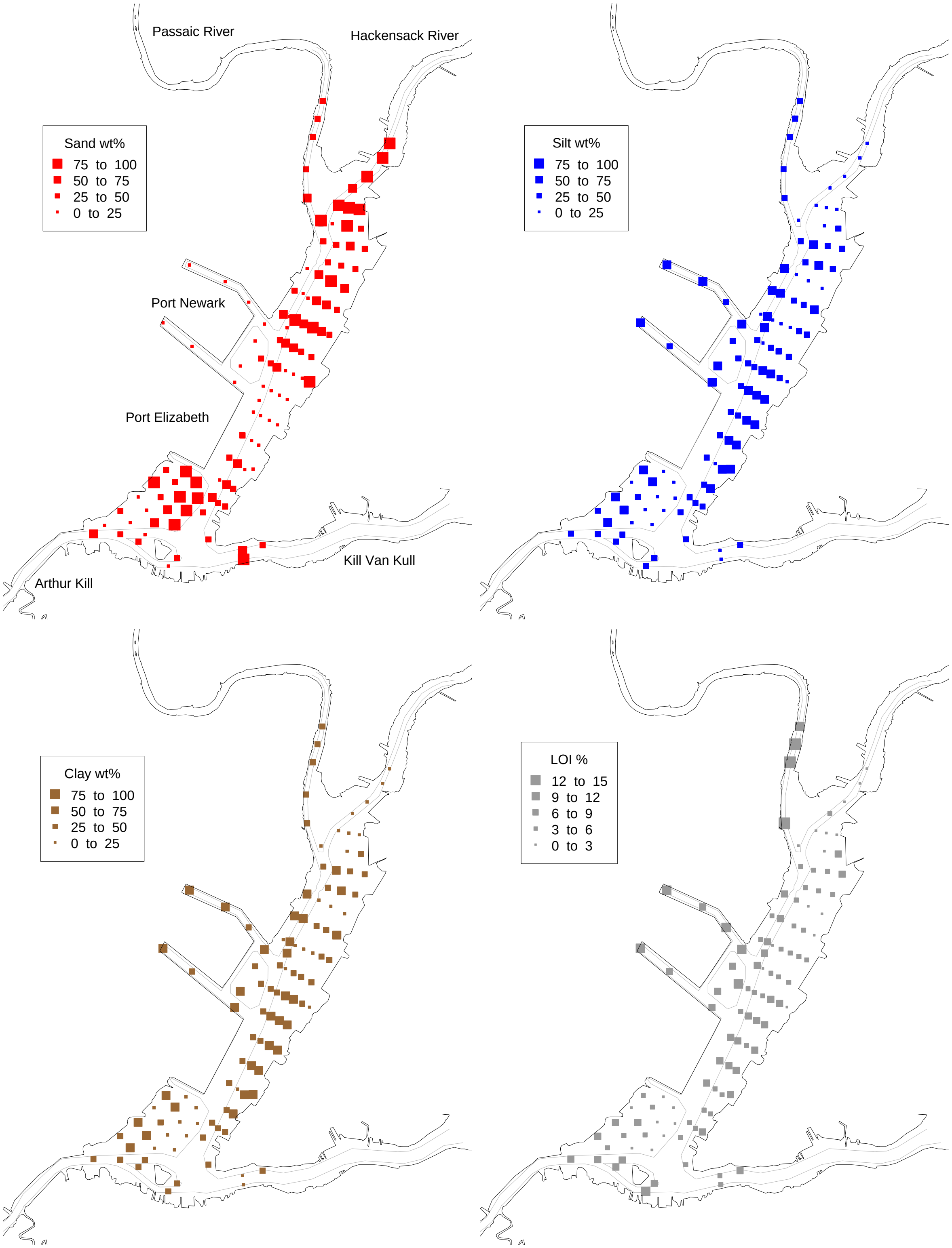

Figure 12. Grain-size and LOI distributions for bed sediments in Newark Bay.

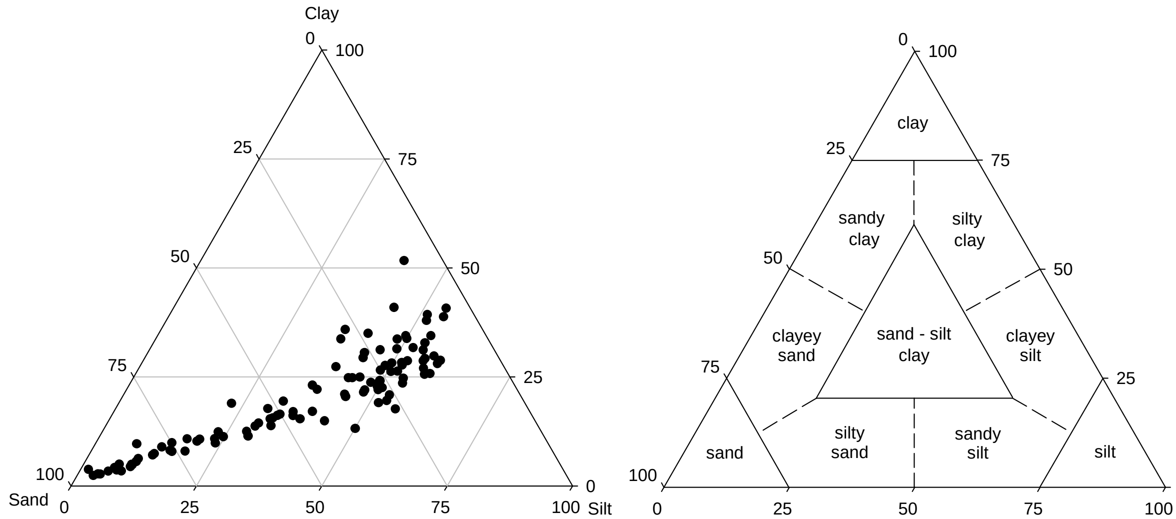

Figure 13. (Left) Ternary plot of the weight percentages of sand, silt, and clay in grab samples shown in Figure 12. (Right) Grain-size classification of Shepard (1954).

matter associated with particle aggregates, such as mudflocs. This is consistent with the general observation that estuarine particles less than ~10 microns in diameter are frequently transported in aggregate form. An exception to this trend is indicated for bed sediments at the mouth of Passaic River, where four samples with high LOI values (15–19%) had only moderate concentrations of fine silt and clay. At these sites a large quantity of sand-sized plant material was present and thus the LOI data reflect mostly detrital carbonaceous material.

3.2.2. Radionuclide measurements. Based on the results of the grab sampling survey, ten stations at muddy depositional sites were selected for repeat coring and radionuclide measurements during 2008–2009. A total of five coring trips were conducted: 1) 2 April 2008; 2) 8–9 July 2008; 3) 21 October 2008; 4) 23 February 2009; and 5) 27 April 2009; these dates correspond to coring visits designated 1–5 in Figure 15. A HAPS corer manufactured by KC-Denmark was used to collect undisturbed sediment cores ~30 cm in length. The HAPS corer is a lightweight seabed sampler that preserves the sediment-water interface. Interface preservation was critical to capture Be-7 activity, which in most estuarine environments usually does not extend below the uppermost 10 cm of the sediment column. The cores were vertically extruded in the field and sectioned in 1–2 cm intervals using stainless-steel spatulas. Sediment in contact with core barrel was trimmed and discarded to avoid material potentially pushed downward during the coring process. The spatulas were cleaned after each slice to prevent cross-contamination, and the sectioned mud was placed in plastic bags and sealed for later analysis.

In the laboratory, the sediment was weighed wet and again after drying to determine the water content and dry-bulk density. Activities of Be-7 were measured non-destructively via gamma spectroscopy of the 477 keV photopeak (Larsen and Cutshall, 1981). Approximately 25–50 g of dry sediment was ground to a powder, placed in a 60 ml plastic screw-lid jar, and counted for 24 hours in Canberra Instruments Model 2020 low-energy Germanium detectors (LEGe). Detector efficiencies were computed based on measured versus registered activities of NISST Standard Reference Material 4357B. The minimum detectable activity of Be-7 was ~0.2 dpm/g; measured activities at or below this level were considered non-detectable. Other radionuclides including ^{234}Th, ^{210}Pb, and ^{137}Cs were measured from the gamma spectrum of the samples, but the results are not discussed in this report.

The sediment inventory of Be-7 (i.e., the depth-integrated activity) was computed as:

$$I = \Sigma \rho_s X_i (1 - \phi_i) A_i \qquad (2)$$

where I is the radioisotope inventory (dpm/cm^2), ρ_s the mineral density (2.65 g/cm^3), X is the thickness of the sediment interval i (cm), ϕ is the porosity, and A is the specific activity at interval i (dpm/g).

During the period of observations, Be-7 was usually detectible to 2–6 cm sediment depths at all ten coring sites. Specific activities of the surface-most sample in cores (0–2 cm depth) ranged from 0.25 to 6.8 dpm/g and at a given station did not vary significantly between coring visits. This suggests that the resident inventory of Be-7 in the water column, as well as the partitioning of Be-7 between dissolved and particulate phases, did not change appreciably during the study period. Cores from the northwestern part of the bay, between the Passaic River mouth and the turning basin (Sites 53, 75, 86 and 117), and in the channel behind Shooters Island (Site 108) exhibited a 2–6 cm thick zone of olive-brown, iron-oxide (hydrous ferric oxide) rich sediment with detectable Be-7 activity. Cores from the eastern bay subtidal flats (Sites 31, 37, 68) and southern flats (Sites 19 and 30) had a thinner (<2 cm) zone of ferric-oxide colored sediment and Be-7 activity (Figure 14).

The association of ferric-oxide rich sediment and Be-7 activity, which has been observed previously in coastal-marine and estuarine sediments (Canuel and Martens, 1990; Sommerfield et al., 1999; Woodruff et al., 2001), reflects the similar time scales of iron diagenesis and Be-7 radioactive decay. In the northwestern bay, the relatively thick, Be-7 enriched ferric-oxide layer is mostly likely maintained by continual physical resuspension and redeposition of bottom sediments under strong tidal currents and perhaps ship scour. Resuspension exposes particles to dissolved oxygen and dissolved-phase Be-7 in the water column, promoting oxidation of iron coatings and scavenging of radionuclide, and rapid deposition produces a sediment bed enriched in ferrous oxide and Be-7. Left undisturbed, ferrous oxide reduces to ferrous sulfide (black- and gray-colored sediment) and Be-7 decays to extinction. This physically mediated mechanism of Be-7 burial is less obvious on the subtidal flats where bed disturbance is less intense and relatively infrequent. There, the thinner zone of ferrous oxide and Be-7 enriched sediment is more likely produced by a combination of tidal resuspension-deposition and biological mixing.

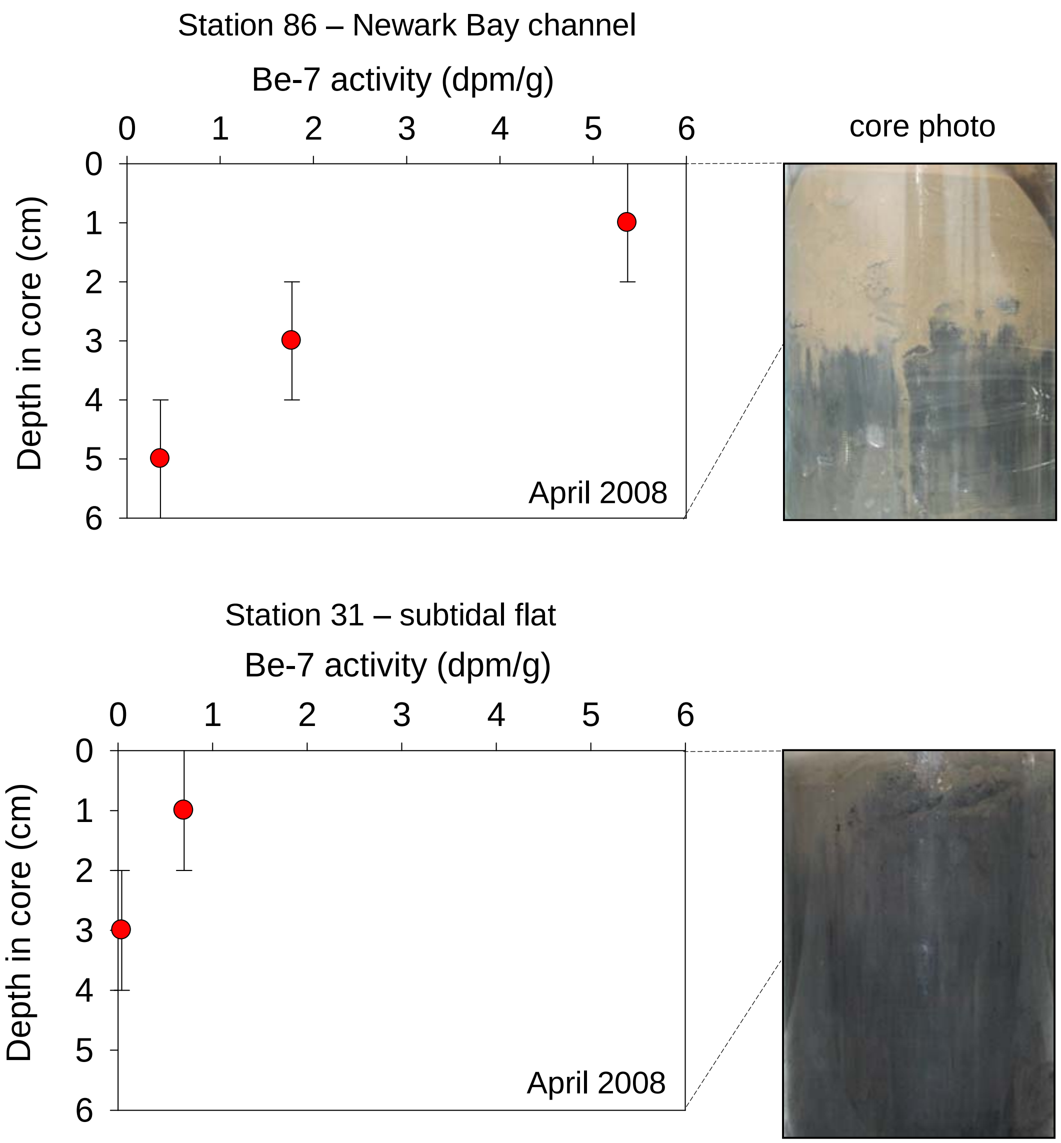

Figure 14. Example depth profiles of Be-7 activity with corresponding core photographs. The depth of detectable Be-7 in cores was generally coincident with the base of the ferric-oxide rich zone. Among stations the oxide-rich zone was thickest, and penetration of Be-7 deepest, in northwestern bay (Station 86) where physical disturbance of the bottom is frequent compared to subtidal flats elsewhere in the bay (e.g., Station 31). The lower data point in core 31 is just above the minimum detectable activity for Be-7.

Biological mixing introduces dissolved oxygen and Be-7 activity to bed sediments through the feeding and burrowing activities of benthic organisms. X-radiographs of sediment cores revealed well-preserved layering at the northwestern coring sites, suggesting that biological mixing is minimal to non-existent where the bottom is frequently disturbed. In contrast, on the subtidal flats, polychaete and bivalve burrow traces were present in X-radiographs. Following observations in other estuaries (e.g., Krishnaswami et al., 1980), it is very likely that biological mixing introduces some Be-7 to sites in the bay where the short-term deposition rate is low, such as on the subtidal flats. The influence of physical deposition and biological mixing on radionuclide burial in Newark Bay is a topic of ongoing research.

Sediment inventories of Be-7 ranged from 0.44 to 14.8 dpm/cm^2 during the study period (Figure 15). On the northwestern side of the bay (Sites 53, 75, 86 and 117), inventories were generally higher and more temporally variable compared to the subtidal flat sites in the eastern (Sites 31, 37, 68) and southwestern bay (Sites 19 and 30), where inventories varied only by about a factor of two during the study. This spatial variation in inventory reflects the different ways in which Be-7 is emplaced in the seabed, i.e., physically dominated deposition in the northwestern bay versus a combination of physically and biologically mediated burial on the subtidal flats. At sites 53, 86, and 117, a large increase in Be-7 inventory occurred in conjunction with the December 2008 flood of the Passaic River as described in Section 3.1.5. As shown in Figure 15, at these sites the Be-7 inventory increased by over a factor of five from the October 2008 coring visit to February 2009. In February 2009, about 4–8 cm of new (Be-7 labeled) mud was present at these sites, material most likely transported and deposited in association with the river flood and the sediment-flux resolved by the moored instrumentation (see Figure 10). Interestingly, none of the subtidal flat sites in the bay displayed a trend in Be-7 inventory that could be related to deposition triggered by the December flood. Hence, the magnitude and variability of Be-7 inventories reveal marked differences in depositional processes between the northwestern bay (between the Passaic River mouth and the marine terminals) and the subtidal flats. Seasonal deposition and bed reworking appears to be relatively intense in the northwestern

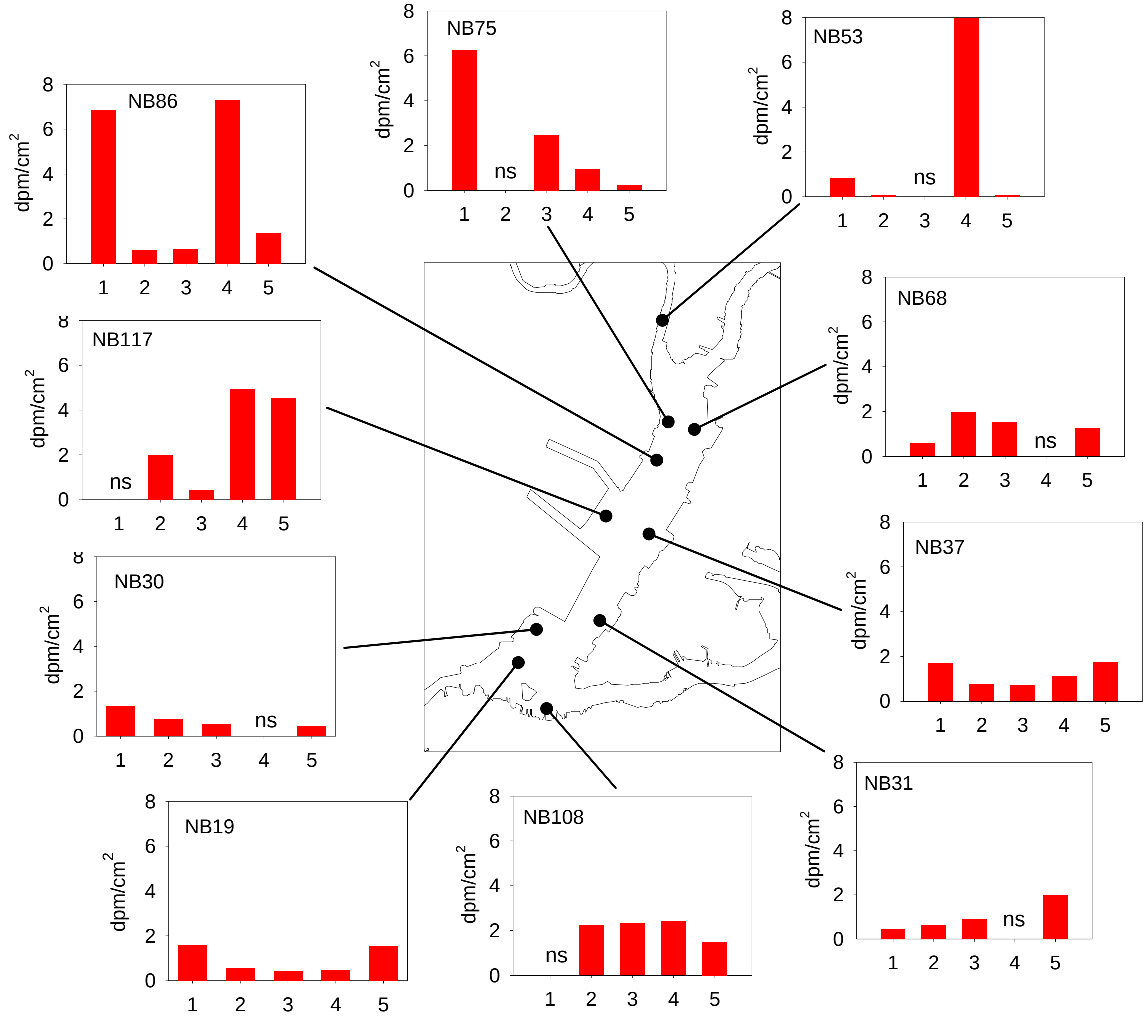

Figure 15. Records of Be-7 inventory measured at the coring stations during 2008–2009 study period. See the text for dates corresponding to coring events 1-5. ns=no sample collected.

bay where tidal currents are strong and the amount of sediment transported in suspension is large compared to the shallower subtidal flats.

The ubiquity of Be-7 activity in bed sediments of the bay makes clear that this radionuclide rapidly cycles from the atmosphere to the bottom. Removal of dissolved-phase Be-7 from the water column is enhanced by the shallow depth of the bay coupled with an abundance of fine-grained particles available to transfer Be-7 to the bottom through adsorption and deposition. The time scale of cycling can be estimated by comparing the local atmospheric flux of Be-7 with the measured sediment inventories. Although the atmospheric flux of Be-7 was not determined in this study, Krishnaswami et al. (1980) and Olsen et al. (1985) report mean atmospheric fluxes of 0.06–0.07 dpm/cm^2/day for the Mid-Atlantic region. For the purpose of discussion, these fluxes are assumed to be representative for the study area during the period of observations. Averaged over the 77-day mean life of Be-7, a steady-state atmospheric flux of 0.065 dpm/cm^2/day supports a theoretical sediment inventory of 5 dpm/cm^2. In other words, if the Be-7 atmospherically deposited over surface waters were quantitatively removed to bed sediments without loss through lateral transport and radioactive decay in the water column, the resulting inventory would be ~5 dpm/cm^2. By comparison, the mean Be-7 sediment inventory determined for this study was 2.0±2.3 dpm/cm^2 (1σ, n=61), less than half of the theoretical value. If the difference between the atmospheric flux of Be-7 and the measured sediment inventory is due to radioactive decay in the water column, the average residence time of Be-7 in Newark Bay waters is ~30 days. This is comparable to residence times of several days to a few weeks reported by Olsen et al. (1986) for Mid-Atlantic estuarine waters. At some sites (i.e., 53, 75, 86, and 117) the sediment inventory of Be-7 exceeded the 5 dpm/cm^2 reference inventory, suggesting that Be-7 activity is preferentially focused to some sites over others by lateral transport and deposition. For this reason the actual residence time of Be-7 in Newark Bay water is likely to vary within in the bay, and could be much less than 30 days in areas of rapid sediment deposition. A more refined understanding of Be-7 systematics in the bay would require coordinated measurements of seabed inventory and local atmospheric flux, which was beyond the scope of this study. Nonetheless, the available Be-7 data demonstrate that particle-reactive substances introduced to Newark Bay waters have potential to become sequestered in bed sediments on time scales well within one month.

3.2.3. Bathymetry and bathymetric change. Depth soundings were collected throughout the bay in 2008 to develop a bathymetric model of seabed for use in a study of historical bathymetric change since 1934, when the bay was last surveyed in its entirety by the Office of Coast Survey, the predecessor of the National Ocean Service. The purpose of this analysis was to identify areas of long-term sediment accumulation in the bay for comparison to the seasonal depositional pattern identified through the 2008–2009 coring study and Be-7 measurements. A Knudsen B/P 320 single-beam echosounder data was used obtain soundings at a trackline spacing of 50–100 m, and the resulting soundings were later processed using Caris HIPS/SIPS™ software. The survey tracklines are shown in Figure 16. The accuracy of the survey was evaluated using the cross-line check method described in the USACE Hydrographic Surveying Manual (*http://140.194.76.129/publications/eng-manuals/em1110-2-1003/toc.htm*). One hundred line-crossing points were obtained using Caris HIPS/SIPS™ subset editor. The cross-check point differences and statistics indicate that the precision of individual depth soundings was ±0.54 m with a bias of 0.401 m. As specified by USACE guidelines, this level of bias falls below the maximum allowable limit of 0.061 m, thus the bathymetric survey met generally accepted criteria for precision. To construct a continuous digital bathymetric model of the seafloor from interpolated trackline soundings, NAD83 was used as the controlling horizontal datum, and Mean Sea Level (MSL) for Bergen Point West Reach (National Ocean Service Station 8519483, National Tidal Epoch 1983–2001) was used as the vertical control datum.

To create a 1934 bathymetric surface for Newark Bay, digital soundings available from the National Geophysical Data Center hydrographic survey database were used (National Ocean Service, 2001). These soundings are referenced to the horizontal and vertical datums NAD83 and Mean Low Water (MLW), respectively. In order to compare the 2008 and 1934 bathymetric surfaces quantitatively, the 2008 and 1934 soundings were referenced to the same vertical datum.

To determine the offset in the MSL datum between 2008 and 1934, the mean sea-level trend of 2.77 mm/yr reported for Battery Park, New York (National Ocean Service Station 8518750), was used to compute a corresponding increase in MSL (0.208 m), which was added to each of the 1934 soundings. The 1934 soundings were originally referenced to mean low water (MLW), so an additional offset relating MLW to MSL (0.78, reported by NOS for Bergen Point) was applied. To define the shoreline for the 1934 bathymetric surface, two National Geodetic Survey Vector Shorelines (NJ1934A, EC123K01) were obtained by NOAA Shoreline Data Explorer and combined. The composite shoreline was referenced to the NAD83 datum.

3.2.4. Bathymetric models. To create the 1934 and 2008 bathymetric models, the digital soundings and shorelines were exported to Golden Software's Surfer 9^{TM}. The data were gridded using kriging method with a linear variogram. The two bathymetric models were gridded over the same area for the bathymetric change analysis. The 1934 bathymetric model does not extend to the southern shoreline or into Port Newark due to a lack of soundings available for these areas. The final 1934 and 2008 bathymetric models are shown in Figure 16.

3.2.5. Bathymetric change analysis. To produce map of net bathymetric change between 1934 and 2008, the bathymetric models were differenced in Surfer 9^{TM} and the residuals plotted (Figure 16). Positive residuals represent areas of natural accretion or subaqueous bed disposal (such as within the confined disposal facility shown in Figure 1), whereas negative residuals denote areas of erosion or deepening through dredging or excavation. Because the position of the shoreline changed after 1934 with construction of the marine terminals, the bathymetric change analysis centered on areas that have been water-covered during the period of interest.

As shown in Figure 16, there have been extensive changes in the bathymetry of the bay since 1934. The overall mean depth of the bay has increased (through channel deepening), whereas the mean width has decreased (due to shoreline engineering works and construction).

Most of the depth increase is associated with the deepened federal navigational channel, which now is ~25–30' deeper than it was in 1934. The overall pattern of bathymetric change is qualitatively similar to that reported by the USACE in a 2008 study of bay geomorphology (USACE, 2008); areas of significant accumulation (> 1 m change) from 1934 to 2008 include the shipping channel just south of the mouth of Passaic River, the confined disposal facility between the marine terminals, and areas adjacent to the Newark Bay Bridge. Accumulation has been particularly intense (≥5 m since 1934) within the channel linking the Passaic River and the marine terminals. By comparison, net sediment accumulation is less intense on the subtidal flats (≤1 m) but more laterally continuous. This pattern of long-term sediment accumulation — high rates in the northwestern bay channel and lower rates on the subtidal flats — is broadly consistent with the seasonal pattern of deposition resolved by the 2008–2009 coring study.

A more detailed analysis of historical morphologic change is ongoing by a graduate student at the University of Delaware. Preliminary results of this work were presented at the 2010 Ocean Sciences (Halonen et al., 2010). Specifically, this study is considering how morphological change in the bay associated with shoreline stabilization and channel deepening are reflected in the sedimentary record of the subtidal flats along the eastern bay, where the bottom has not been directly modified through dredging or engineering works. The study involves analysis of vibracores collected at sites where the bathymetric change study indicated net deposition between 1934 and 2008. The down-core sedimentology of these cores has potential to provide a record of changes in the near-bottom flow and sediment-transport environment in association with changes in the hydraulic geometry of the bay.

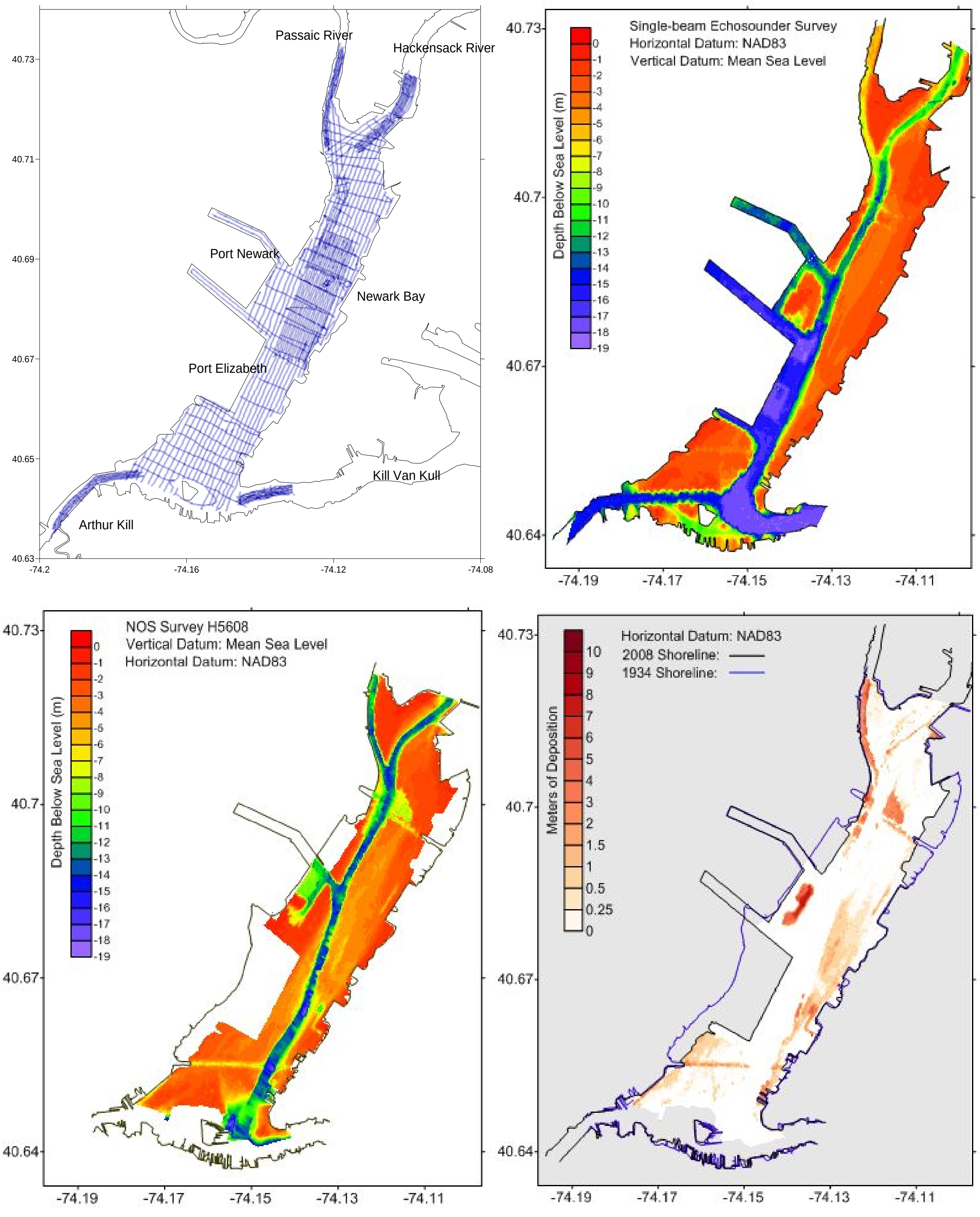

Figure 16. (Upper left) Trackline map of the bathymetric survey conducted in 2008. (Upper right) Bathymetric surface map created using the 2008 survey data. (Lower left) Bathymetric surface created using 1934 soundings archived by the National Ocean Service. (Lower right) Residual bathymetry created by differencing the 2008 and 1934 surfaces. See text for details.

CONCLUSIONS

The major findings of this study are provided below:

1) The most definitive result of the sediment-flux study was a steady transport of sediment from the Kill Van Kull to Newark Bay that we estimate at ~140,000 metric tons/yr. This source dominates the seasonal influx of sediment to the bay. By comparison, the Passaic and Hackensack rivers supplied ~17,000 and ~5,000 tons/year, respectively, and approximately 20,000 tons/year of sediment was *exported* from the bay via Arthur Kill. The total influx of sediment is 162,000 tons/year, which is comparable to previous estimates. Sediment imported to the bay was observed to converge (deposit) within northern Newark Bay shipping channel, most conspicuously in conjunction with the December 2008 flood of the Passaic River. Intense short-term deposition in this area of the bay was confirmed by core-sampling and Be-7 measurements during 2008–2009.
2) The most significant result of the hydrodynamics study was evidence for a dramatic increase in the non-tidal exchange flow from NY Harbor to Newark Bay via the Kill Van Kull, presumably in response to deepening of the shipping channel after 1998. The exchange flow (the mean flow from NY Harbor to Newark Bay) approximately doubled from 1997–1998 to 2008–2009 based on comparison of data obtained though past and the present work. Because circulation and sediment transport in the bay is driven partly by the Kill Van Kull, the increased exchange flow has potential to increase the supply of suspended sediment to the bay relative to the pre-deepening supply.
3) Repeat coring and Be-7 measurements indicate that seasonal and event-driven deposition of fine-grained sediment occurs throughout the bay but that deposition is most intense in the northwestern bay between the mouth of the Passaic River and the marine terminals. Be-7 activity was detected in the surficial sediments (0–2 cm) at all of the coring stations

reoccupied during the study, indicating that particle cycling between the water column and seabed is rapid; sediment inventories of Be-7 suggest that the mean residence of Be-7 in the water column is ≤30 days. Based on the depth of detectable Be-7 activity in cores, new deposition between quarterly sampling visits ranged from 2 to 8 cm in the northwestern part of the bay, and <1 cm to 2 cm on subtidal flats in the eastern and southwestern bay. Preserved sediment layering in cores from the northwestern bay suggested that new sediment was emplaced by current-controlled deposition. In this area, deposition appears to respond rapidly to Passaic River discharge events and associated convergences in sediment flux between the river mouth and the marine terminals. In contrast, some combination of current-controlled deposition and biological mixing was responsible for burial of new sediment on the subtidal flats during the study period. Sediment deposition on the flats was relatively unresponsive to observed sediment-transport events that elicited sediment-flux convergences in the northwestern bay channel.

4) Results of the 1934–2008 bathymetric change analysis revealed that sediment accumulation on the subtidal flats is patchy and highest where the seabed has been modified through excavation or where tidal flow and sediment transport have been altered by engineering works. This finding is broadly consistent with results of previous work (USACE, 2006). Net sediment accumulation averaged over the period of interest ranged from ~0.5 to 5 m and was most laterally continuous on the subtidal flats across-bay of the marine terminals. Significantly, long-term sediment accumulation occurs at locations where the 2008–2009 coring study resolved new deposition on seasonal time scales. This correspondence indicates that the short-term depositional zones resolved through Be-7 measurements, and the underlying hydrodynamic and sedimentary conditions, are more-or-less stationary on time scales of several decades.

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