PENOBSCOT RIVER MERCURY STUDY

Chapter 7

Field Investigations of Hydrodynamics and Particle Transport in Penobscot River and Bay

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1 SUMMARY

A set of field measurements were obtained in the Penobscot River estuary between Fort Point (near Searsport) and Bangor, Maine (ME), to characterize the hydrodynamics and sediment transport processes in the region of significant mercury (Hg) contamination. The measurements were conducted between April 1 and June 30, 2010 and March 16-Aug. 24, 2011. They included 90-day moored measurements of currents and water properties at 8 locations, shipboard profiles of water properties and currents at selected times during the mooring deployments, water samples for calibration of sensors for suspended sediment concentration, bottom grab samples for sediment grain size analysis, and side-scan sonar surveys for sediment texture.

Tidal motion, river outflow and estuarine forcing (flow driven by the density difference between fresh and salt water) all contributed significantly to the currents, which ranged from 0.8 to 1.8 m/s in the main channel of the Penobscot and from 0.3 to 0.7 m/s in the side embayments and near the mouth of the estuary. The influence of river outflow was most pronounced during freshet conditions at the Winterport mooring, causing maximum ebb currents of up to 2 m/s. The influence of estuarine forcing was most evident in the tidally averaged flow, which showed landward flow (generally northward except in the side embayments) near the bottom and seaward near the surface, with magnitudes of 0.05-0.4 m/s.

Salinity showed large variations both in time and in space, due to seasonal and tidal variations of the estuarine salinity structure. During high flow conditions and neap tides, the along-estuary salinity had a salt-wedge structure, with strong vertical gradients and a strong front at the landward limit of salt. During low-flow, spring-tide conditions, partially mixed salinity structure was evident, with moderate horizontal and vertical gradients. The advection of the salinity structure by the tides resulted in strong temporal variations of salinity, particularly in the main channel of the Penobscot in the vicinity of Mendall Marsh.

Suspended sediment concentrations reached peaks of more than 200 mg/l in the near-bottom waters during spring tides. Highest concentrations occurred in deep regions of the main channel of the Penobscot. Typical concentrations of 20-40 mg/l occurred in the channels of the side embayments. Sediment transport was generally seaward during the freshet period, but then it reversed to the landward direction during low flow conditions.

Bottom sediment samples indicate that the sedimentary characteristics of the estuary are highly variable, with areas of cobbles and gravel, sand, mud and wood chips. A notable finding of the bottom sampling is the presence of uniform layers of light colored, unconsolidated mud, sometimes 10 cm or greater in thickness. The color and texture of this sediment indicates that it was recently deposited. These deposits make up a “mobile pool” of sediment that is remobilized and redistributed by changes in the hydrodynamic forcing conditions through the year. Although the size of the mobile pool could not be determined directly from these measurements, the combination of geochemical chronology (i.e., estimating depositional timescales from isotopes) and relatively uniform mercury concentrations on the mobile sediment suggest that it has a

long residence time - likely more than 20 years, which suggests that the mass of the mobile pool of sediment is many times the annual sediment input to the system. A rough estimate of the size of the mobile pool, on the order of 500,000 tons, is largely consistent with the residency time estimates from core data.

2 BACKGROUND AND OBJECTIVES

This document describes the results of field observations in Penobscot River and Bay during the months of April-June, 2010 and March-August 2011, that quantify hydrodynamics and sediment transport processes in the region of significant mercury (Hg) contamination. The motivation for this study was the recognition of the essential roles of hydrodynamic and sediment transport processes on the transport, trapping, export and long-term fate of mercury in the environment due to releases from the HoltraChem Manufacturing Company (Fig 7a-1). These measurements provide essential information for understanding and quantifying the processes responsible for the present distribution of Hg, the rate of natural attenuation, and the efficacy of different remediation alternatives. The data are also required for assessment of numerical modeling of the hydrodynamics, sediment transport, and contaminant fate, transport and bio-accumulation.

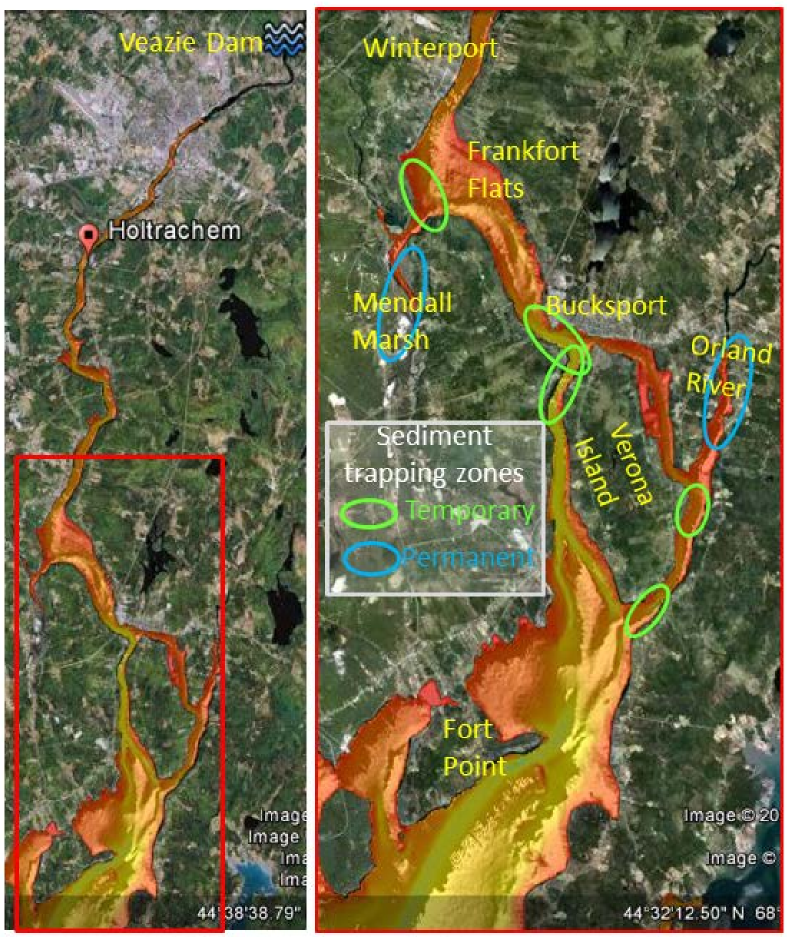


Figure 7-1. Aerial image of the Penobscot River study area. NOAA bathymetry is shown and the HoltraChem site, Veazie Dam, and other locations of interest are noted. On the right, regions of enhanced estuarine sediment trapping at temporary (seasonal) and longer time scales are indicated.

Specific objectives of this study include:

a) quantification of the tidal, estuarine and fluvial currents in the Study Area and their dependence on the forcing variables (e.g., tidal forcing, river flow, storm surge);

b) quantification of the sediment transport processes, including loading from the Penobscot River, resuspension, transport, trapping and export in the Study Area, and exchange between the Penobscot and the contaminated side-embayments;

c) characterization of the spatial variability of surficial sediment characteristics, in order to delineate sediment and contaminant trapping areas and to quantify the spatial variability of erodibility.

3 METHODS

3.1 Moored Measurements

Bottom tripods with upward-looking acoustic Doppler current profilers, conductivity-temperature-pressure and optical backscatter sensors were placed at 6 locations in the estuary in 2010 and 2 locations in 2011 (Figure 7-2, Figure 7-1). The water properties were measured 0.6 m above the bottom. The bottom-most velocity was measured approximately 1 m above bottom. Velocity was measured through the water column at 0.2-0.5 m increments, depending on the station depth. Acoustic backscatter was also recorded through the water column and converted to suspended sediment concentration, based on calibration with shipboard concentration measurements (see below). Surface moorings with temperature-salinity-optical backscatter sensors were co-located with the tripods. Optical backscatter was converted to concentration based on nearby water samples in which suspended sediment concentration was determined by gravimetric analysis (see below).

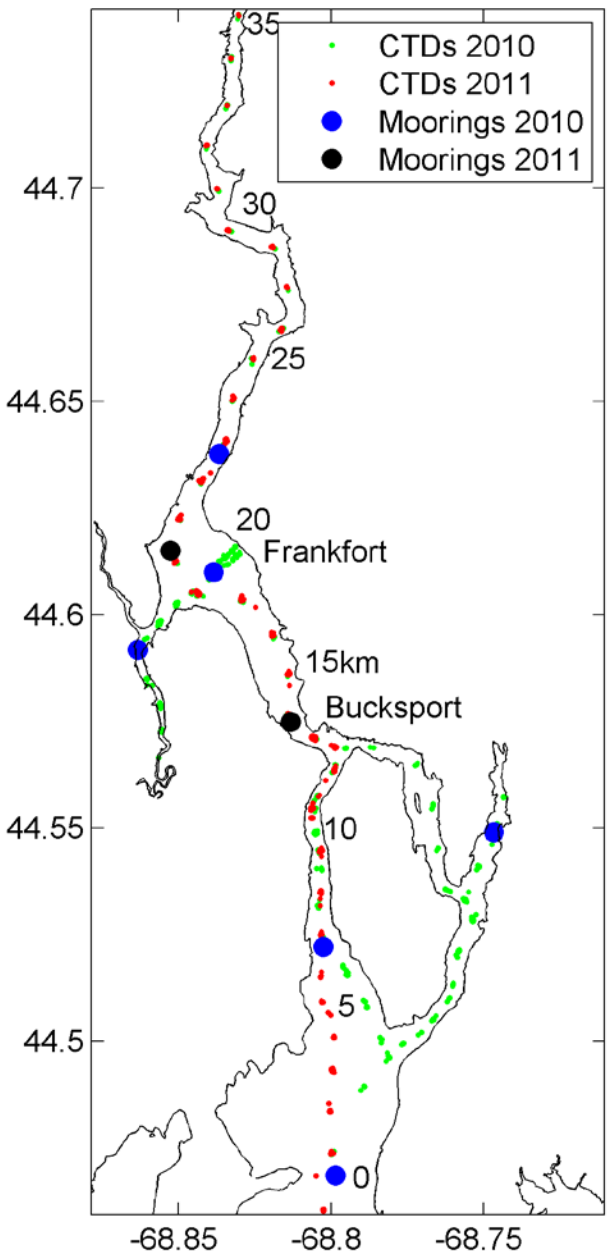


Figure 7-2. Map of moorings and conductivity-temperature-depth (CTD) survey stations in 2010 and 2011. Distance along-estuary is shown in km from Fort Point.

Figure 7-1: Mooring Locations					
Mooring Name	**Dates of Deployment**	**Type of Environment**	**Water Depth**	**Latitude**	**Longitude**
Winterport	Apr. 2-June 29, 2010	Penobscot main channel	10 m	44°38.26′	68°50.20′
Frankfort Flats	Apr. 2-June 29, 2010	Lateral shoal	5 m	44°36.60′	68°50.31′
Frankfort Channel	Mar. 16-June 24, 2011	Penobscot main channel	9 m	44° 36.90′	68° 51.16′
Mendall Marsh	Apr. 2-June 29, 2010	Side embayment	3 m	44°35.50′	68°51.81′
Bucksport	Mar. 16-Aug. 23, 2011*	Penobscot main channel	18 m	44°34.49′	68°48.80 ′
Verona	Apr. 2-June 29, 2010	Penobscot main channel	21 m	44°31.33′	68°48.15′
Orland River	Apr. 2-June 29, 2010	Side embayment	3 m	44°32.94′	68°44.79′
Fort Point	Apr. 2-June 29, 2010	Penobscot main channel	20 m	44°28.11′	68°47.91′
* Tripod was buried shortly after deployment. Limited data recovery.					

3.2 Water-Column Surveys

In 2010, surveys were conducted on three occasions, first during the freshet on April 1-5, 2010, second on May 10-14, and third on June 26-29 (Figure 7-2). During each interval, large-scale surveys were conducted over the entire estuary from Fort Point to Bangor (Figure 7-2) and tidal-cycle surveys were conducted over selected transects. During 2011, measurements were obtained during 4 periods, in March, April, May and June (Figure 7-2), with repeated along-estuary surveys conducted along the main channel of the Penobscot.

The vertical profiles were obtained with an RBR XRX-620 conductivity-temperature-depth recorder (CTD) with a Seapoint optical turbidity sensor (OBS). A 1.2 l Nisken bottle with a bottom-actuated trigger was used to obtain water samples for calibration of the suspended sediment at selected sites. A total of 68 water samples were obtained for calibration in the 2010 measurements, and 376 bottles were obtained in 2011. The bottles were refrigerated and stored in the dark until they were filtered at WHOI. All or part of the sample was filtered through a 0.45 μm Millipore mixed cellulose ester membrane filter, and the filter was dried at 60°C overnight before weighing.

A 1.2 MHz acoustic Doppler current profiler (ADCP) was mounted on the side of the research vessel (the 25’ *R/V Mytilus* from WHOI) during the tidal cycle surveys. The ADCP provides 0.25 m vertical resolution of the currents and acoustic backscatter. The acoustic backscatter was converted to profiles of estimated suspended sediment concentration based on calibration with the OBS and the bottle samples. Station spacing for the large-scale surveys was approximately 1 km. For the tidal-cycle surveys, continuous data were obtained by the ADCP, and vertical profiles were obtained at discrete stations separated by 0.75-1 km.

Figure 7-2: Shipboard Surveys, 2010 and 2011

Date	Survey Type	Location
April 1, 2010	Large-Scale	Penobscot River
April 2, 2010	12-hour tidal	Mendall-Frankfort
April 4, 2010	12-hour tidal	Orland River-Verona East
April 5, 2010	12-hour tidal	Verona-West
May 10, 2010	Large-Scale	Penobscot River
May 11, 2010	12-hour tidal	Mendall-Frankfort
May 12, 2010	12-hour tidal	Orland River-Verona East
May 12, 2010	12-hour tidal	Verona-West
June 26, 2010	12-hour tidal	Mendall-Frankfort
June 27, 2010	12-hour tidal	Orland River-Verona East
June 29, 2010	Large-Scale	Penobscot River
Mar. 17-18, 2011	Large-Scale	Penobscot River
Apr. 15-16, 2011	Large-Scale	Penobscot River
May 12, 2011	Large-Scale	Penobscot River
May 13, 2011	12-hour tidal	Penobscot River
June 22, 2011	Large-Scale	Penobscot River

3.3 Bottom Grab Sampling

A limited set of grab samples were obtained during the April, May, 2010 cruises, and more extensive data were obtained in June, 2010, June, 2011, and August, 2011 (Figure 7-3). A Van Veen grab sampler that provided a maximum penetration of 10 cm was used for all of the 2010 samples, and a smaller Ponar grab sampler with a maximum of 6 cm penetration was deployed off the *Mytilus* for sampling the shallower locations in 2011.

For each site, as many as three attempts were made to obtain a sample. If a sample could not be obtained, the site was designated as non-depositional. In muddy sediments, the sediment-water interface could be approximately identified, and the thickness of mud layers could be approximately estimated. For each core, the color, texture and other characteristics of the grabs were described, and the cores were photographed. Based on these descriptions and photographs, 10 classes of grab samples were identified:

1. unconsolidated mud;
2. consolidated mud;
3. mix of unconsolidated mud and anything else;
4. mixed mud, sand, shells, rocks, woodchips;
5. mussels with rocks, etc.;
6. sand with mud;
7. sand;
8. sand with rocks, shells, woodchips, mussels;
9. gravel or rocks; or scoured; and
10. woodchips.

Grain size analysis was performed on subsamples of the grab samples obtained from the top 3 cm (as best as it could be estimated). Wet sieving with a mesh size of 62.5 µm was used to distinguish “fine” and “coarse” fractions. The coarse fraction was subsequently dried and sieved to distinguish very fine sand (62.5-128 µm), fine sand (128-256 µm), medium (256-512 µm), coarse sand (512 µm to 1 mm) and gravel (>1 mm). Organic content was determined from loss on ignition of a sub-sample of the grab. The samples were dried for at least 24 hours at 60 degrees C and weighed, then heated to 550°C for 4 hours, to determine the loss on ignition.

Table 17a-3: Grab Sampling Surveys, 2010 and 2011

Date	Grab locations	Number of Grabs
April 2, 2010	Near Moorings, Fort Point to Winterport	7 grab samples
May 12, 2010	Near Moorings, Fort Point to Winterport	7 grab samples
June 25, 2010	Near Moorings and Near Frankfort Flats and Mendall Marsh entrance	25 grab samples
June 21-23, 2011	Central Estuary - Winterport to Fort Point	191 grab samples
Aug. 24, 2011	Upper estuary - Bangor to Winterport	57 grab samples

3.4 Side-Scan Survey

A side-scan sonar survey was conducted in the vicinity of Frankfort Flats to map the fine-scale texture of the bottom. Technical problems due to interference of the sonar with the hull of the ship limited the utility of the results.

4 RESULTS

4.1 Forcing Conditions

River discharge based on the gauge at West Enfield, ME (USGS station 01034500) reached a peak of 1900 m^3/s on April 1, 2010 and then declined through the course of the spring, with several small peaks due to precipitation following the freshet (Figure 7-3). The mean discharge of 492 m^3/s was in the 37th percentile (slightly drier than normal), and the peak of 1900 was in the 64th percentile (slightly above average). During 2011, the mean discharge of 754 m^3/s was in the 94th percentile (much wetter than average), but the peak discharge of 1,700 was in the 53rd percentile (average).

Tidal forcing conditions (based on NOAA observations in Portland) are approximately 2.2 m during weak neap tides and 3.8 m during strong spring tides. Winds and direct precipitation were not considered to be important forcing variables, and they were not considered in this report.

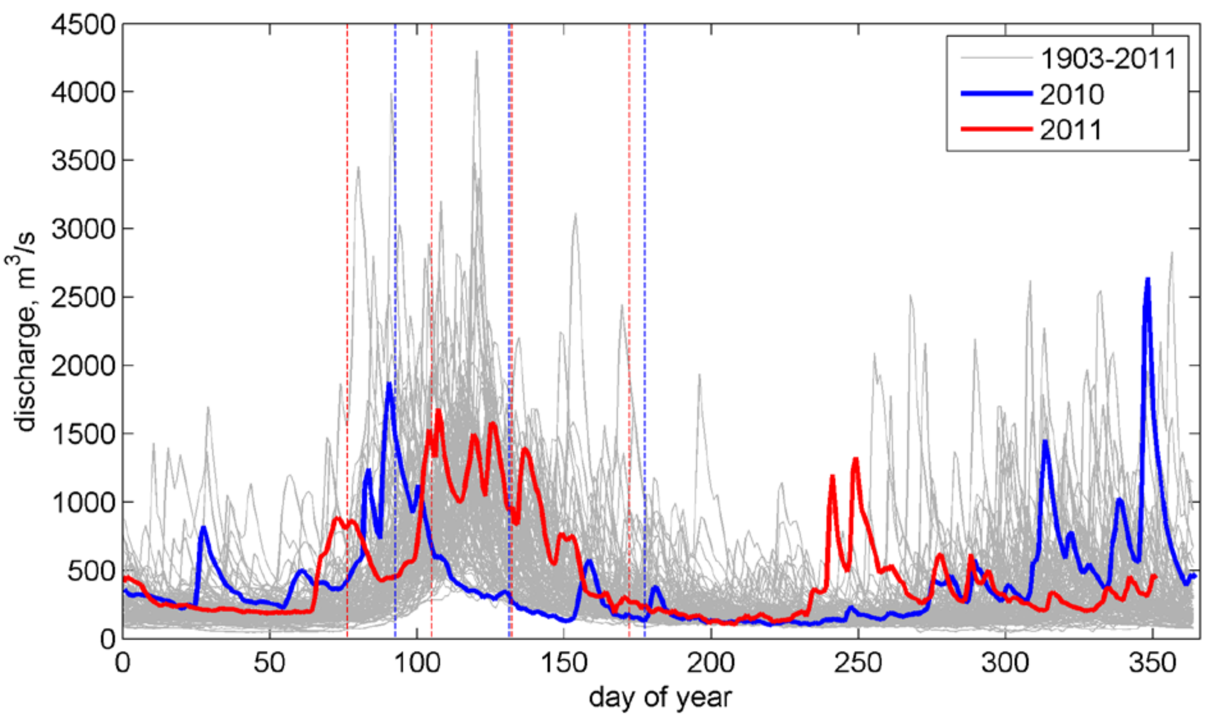


Figure 7-3. Annual cycle of Penobscot River discharge (1903-2011), highlighting 2010 and 2011 (vertical dashed line indicate observation periods each year).

4.2 Moored Measurements

4.2.1 Velocity

Tidal currents were strongest in the constricted parts of the Penobscot River, and weakest in the side embayments (Figures 7a-4 and 7a-5). The strongest spring tidal currents of almost 1.5 m/s occurred at the Bucksport site. At the Winterport and Frankfort Channel stations the tidal currents were around 1 m/s. The wider portions of the river had weaker tidal currents, on the order of 0.5-0.6 m/s. The side embayments of Mendall Marsh and Orland River had even weaker tidal currents, 0.5 and 0.3 m/s at spring tides, respectively.

The non-tidal, residual (or low-frequency) currents were determined by low-pass filtering the velocities with a 33-hour filter. A comparison of the instantaneous currents and the low-pass currents for the 2011 record at Frankfort Channel are shown in Figure 7-5 (lower panel). The residual near-surface currents were southward (negative) at speeds of up to 0.5 m/s - weaker than the tides but important for influencing the net movement of water. The near-bottom residual current varied in direction, with a typical strength of 0.2 m/s.

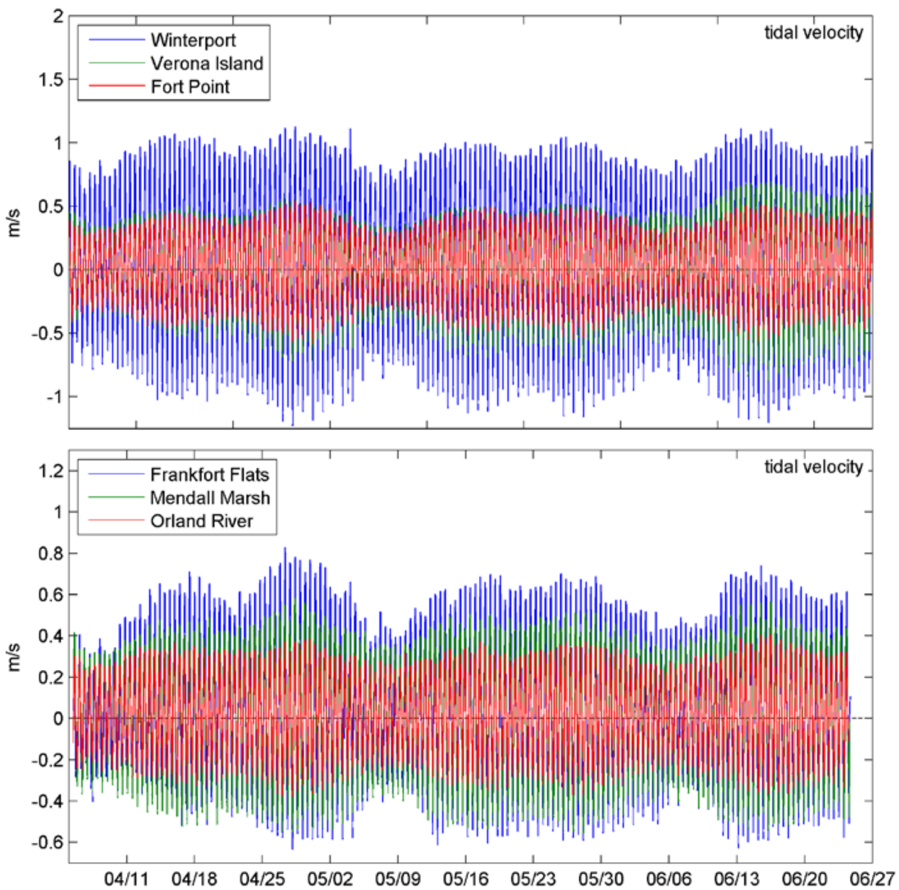


Figure 7-4. Tidal velocities at moorings in 2010. Top panel shows stations in the channel of the main stem of river, and bottom panel has stations in side embayments and on the lateral shoals of the main stem (Frankfort Flats). Positive values indicate flooding currents.

The near-surface and near-bottom residual velocities during the 2010 deployment are shown in Figure 7-6. The consistent pattern at all stations is for near-surface residual currents to be directed out-estuary, and for near-bottom currents to be directed in-estuary. The only significant exception is the near-bottom Winterport currents, which were directed outward at up to 0.4 m/s during the beginning of the record. This pattern of surface outflow and bottom inflow is the result of the forcing by the along-estuary density gradient is called the “estuarine circulation”. The reason the Winterport current reversed is that the river outflow was so strong at that time as to overwhelm the estuarine circulation. The shorter-timescale fluctuations, particularly notable in the surface currents, are presumably due to variations in wind forcing and low frequency sea-level variations.

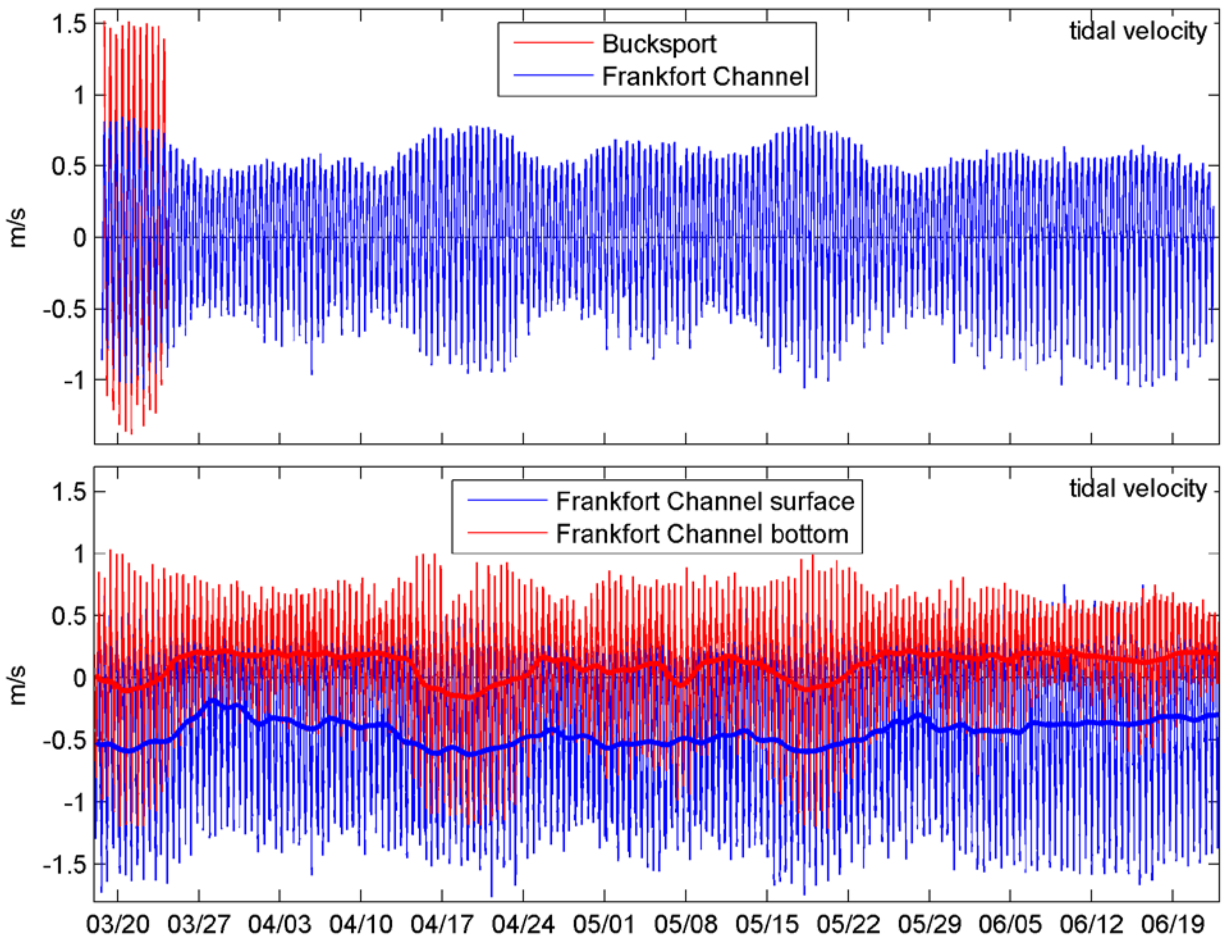


Figure 7-5. Tidal velocities at moorings in 2011. (top) Depth-averaged velocity; the Bucksport mooring was buried shortly after deployment. (bottom) Near-surface and near-bottom velocities at Franfort Channel, with tidally averaged velocity (thick).

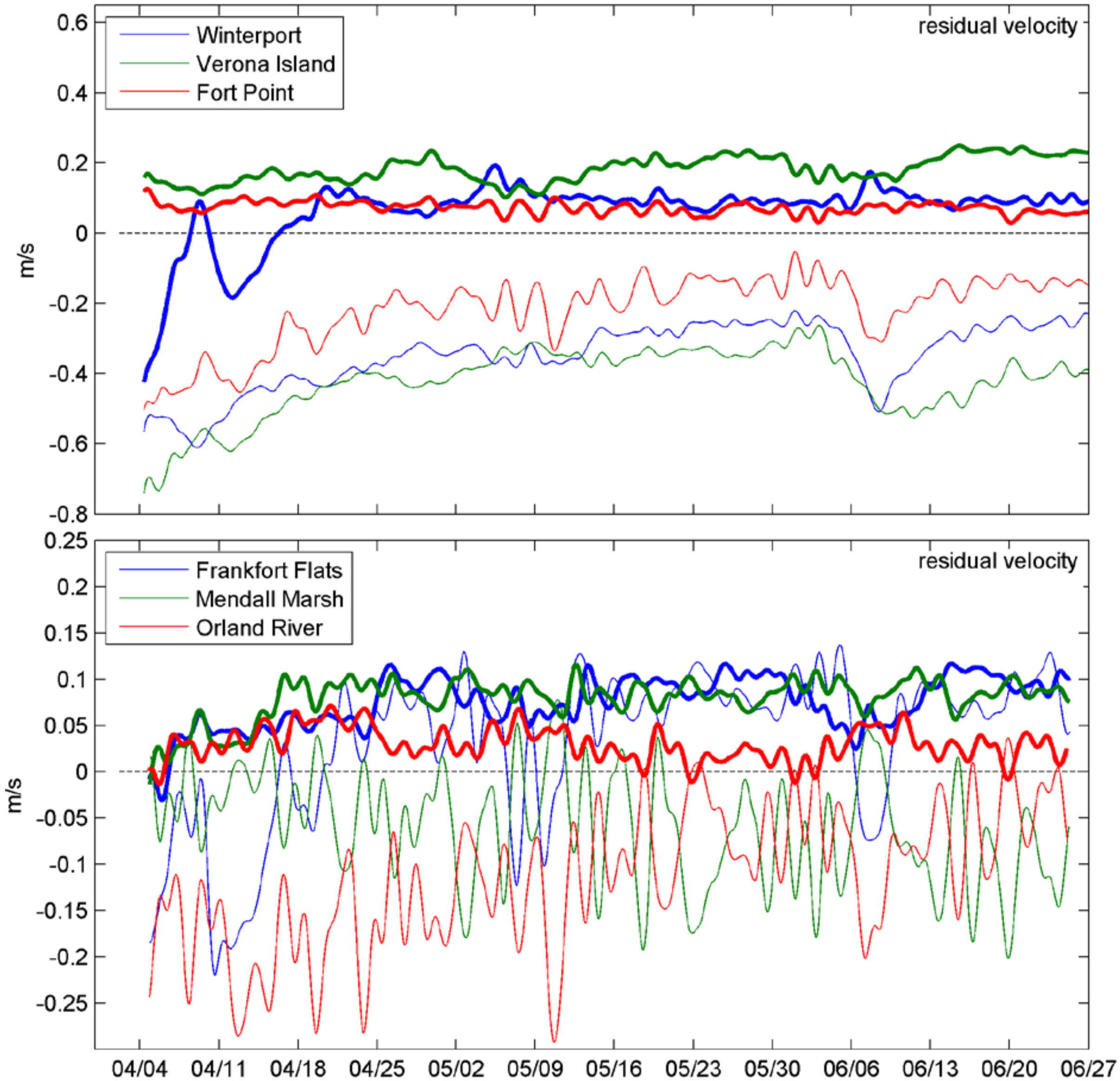


Figure 7-6. Tidally averaged velocities in 2010. Top panel is stations in the main stem of river, and bottom panel has stations in side embayments and on lateral shoals. Thick lines are near-bottom (generally in) and thin lines are near-surface (mostly out).

4.2.2 Salinity

One of the most notable characteristics of the Penobscot estuary is the variability of salinity, both in space and time. A dramatic illustration is the time series of salinity at Frankfort Channel during 2011 (Figure 7-7). At times during the record, the near-bottom salinity shows variations within a tidal cycle of almost 30 psu, indicating that the salinity front is being advected back and forth across this site. These strong variations occur following freshet pulses (blue curve on bottom panel). The near-surface salinity also shows large tidal fluctuations (indicating surface frontal conditions), but they occur during lower discharge conditions.

The low-pass filtered salinity also shows large variability, due to the combination of the variations in river discharge and tidal amplitude. Salinity decreases as river discharge increases (with a lag of a couple days), and stratification (the difference between near-bottom and near-surface salinity, as indicated by the distance between thin and thick lines of the same color in the middle panel), varies inversely with the tidal amplitude. In the absence of river flow variations, stratification would be lowest during spring tides and highest during neaps. This variation is observed, for example comparing 4/19/2011 with 4/26/2011, but the river flow variability also contributes.

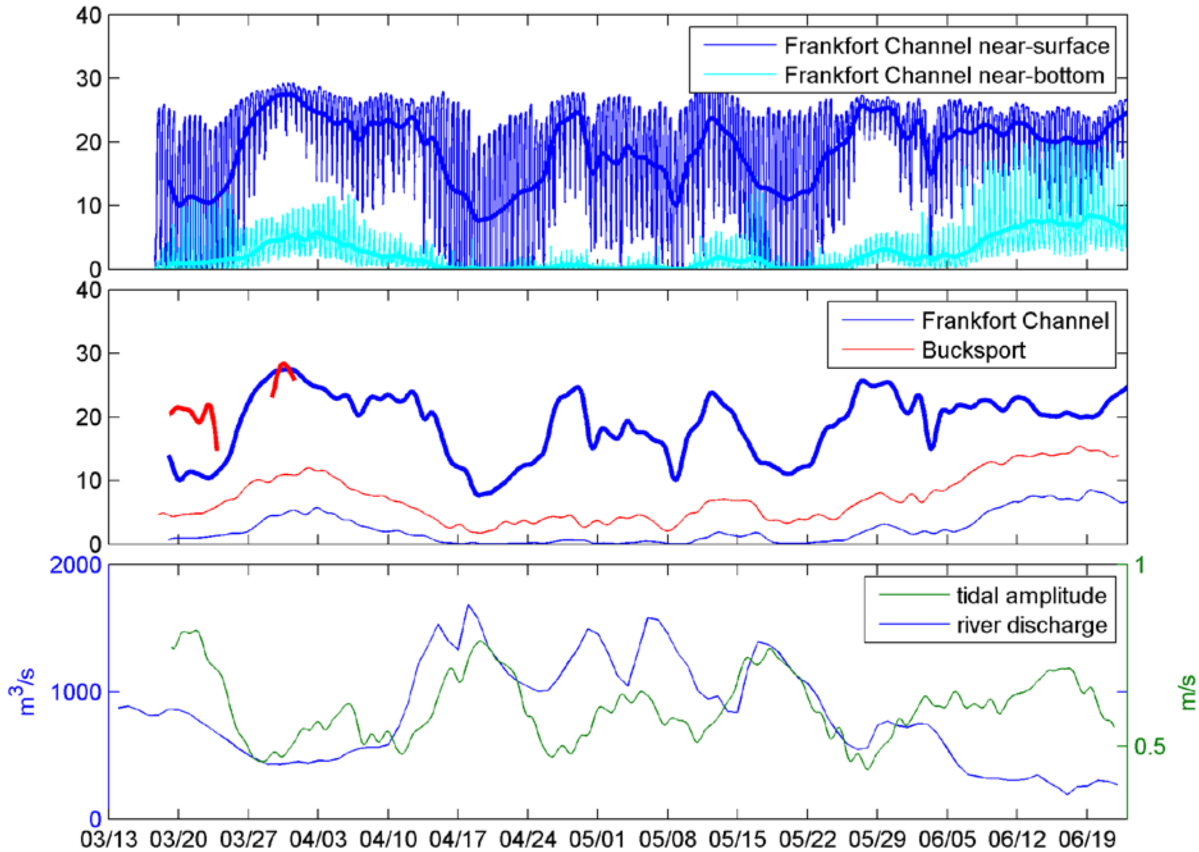


Figure 7-7. Salinity at moorings in 2011. (top panel) Tidal and residual near-bottom and near-surface salinity at Frankfort Channel. (middle) Residual (non-tidal) near-bottom (thick lines) and near-surface (thin lines) salinities; note the bottom sensor at Bucksport was buried by sediment shortly after deployment. (bottom) Tidal amplitude and river discharge during the observations.

The 2010 data (Figure 7-8) also show the combined influence of discharge variations and tidal amplitude variations. The overall increase in salinity was consistent with the decrease in river flow during the deployment period at all estuarine locations (except for the deep water at Fort Point and Verona, which appeared to be uninfluenced by the Penobscot discharge). The spring-neap variation in stratification was particularly evident at the Winterport location-its bottom salinity increased sharply each neap tide and decreased during the springs, while the near-surface salinity showed a weak response to the spring-neap cycle. This spring-neap variation in stratification is caused by increased tidal mixing during spring tides, which reduces the vertical density contrast. Weaker tides during neaps allow stratification to become stronger. All of the sites remained stratified throughout the deployment period except for Orland River, which became well mixed during spring tides from the middle of May onward.

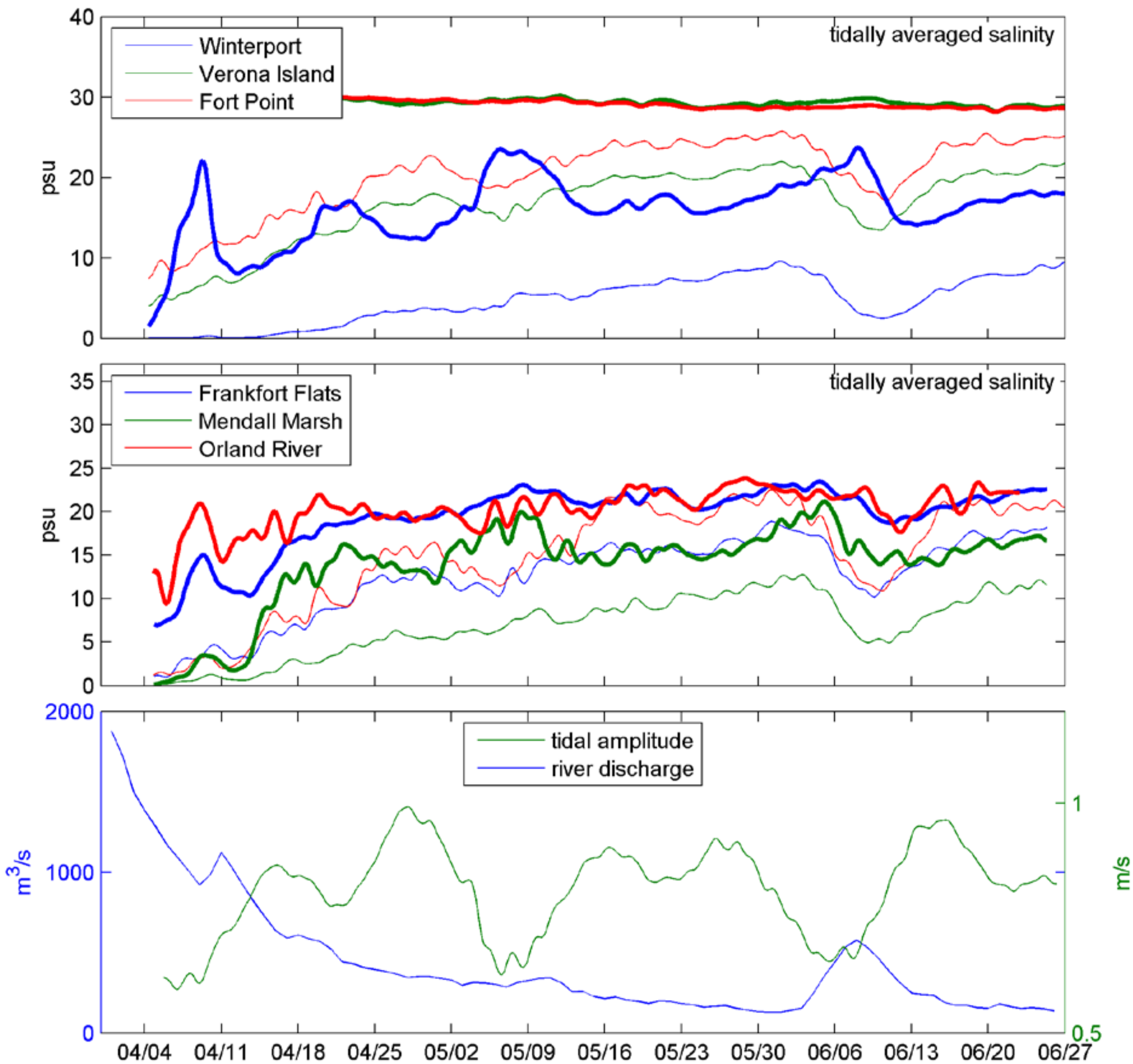


Figure 7-8. Salinity at moorings in 2010. (top panel) Tidally averaged near-bottom (thick lines) and near-surface (thin lines) salinities in the main stem; (middle) same, in the side embayments and lateral shoals; (bottom) Tidal amplitude and river discharge during the observations.

4.2.3 Suspended Sediment

The suspended sediment concentrations for 2011 show very large tidal, spring-neap and vertical variability (Figure 7-9). The near-bottom data at the Frankfort Channel site show large peaks corresponding to each spring tide as well as individual peaks within each tidal cycle. These provide clear evidence of the importance of tidal resuspension. Peak concentrations reach as high as 3,000 mg/l during the spring tide in early March, and subsequent peaks are about 2,000 mg/l. Although these numbers are remarkably high, they are consistent in magnitude with the peak observed gravimetric analysis from water samples (see Appendix). The near-surface concentration at Frankfort Channel was an order of magnitude lower, indicating a significant settling rate relative to the turbulent resuspension rate. The surface data also indicate a strong spring-neap signal. This is due both to the influence of resuspension and the weakening of stratification during spring tides, which allows greater vertical exchange between the lower and upper water column. There appears to be a seasonal signal in the concentration variations as well, with higher concentrations during the March spring tides, and diminished concentrations later in the deployment.

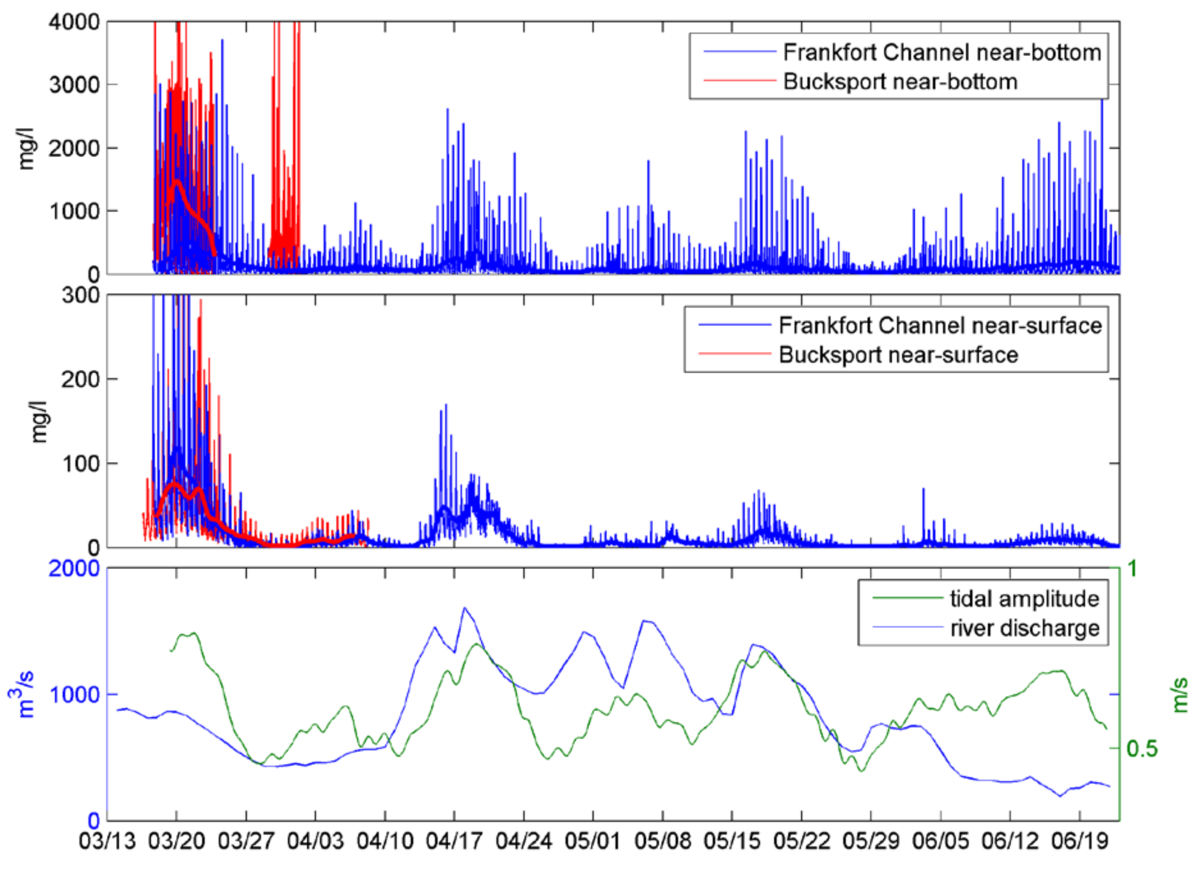


Figure 7-9. Suspended sediment concentrations at the moorings in 2011, based on optical backscatter sensors. (top) Near-bottom sediment concentrations. (middle) Near-surface sediment concentrations. (bottom) Tidal amplitude and river discharge during the observations.

The data at the Bucksport site were limited in duration, due to burial of the bottom tripod and fouling of the surface instrument. During the first spring tide, the concentrations were similar at Bucksport to Frankfort, but the concentrations were much higher around 4/1/2011, after which the sensor abruptly stopped working, when the tripod was buried. The high concentrations just before burial are indicative of the intense sediment trapping conditions that led to the burial of the tripod.

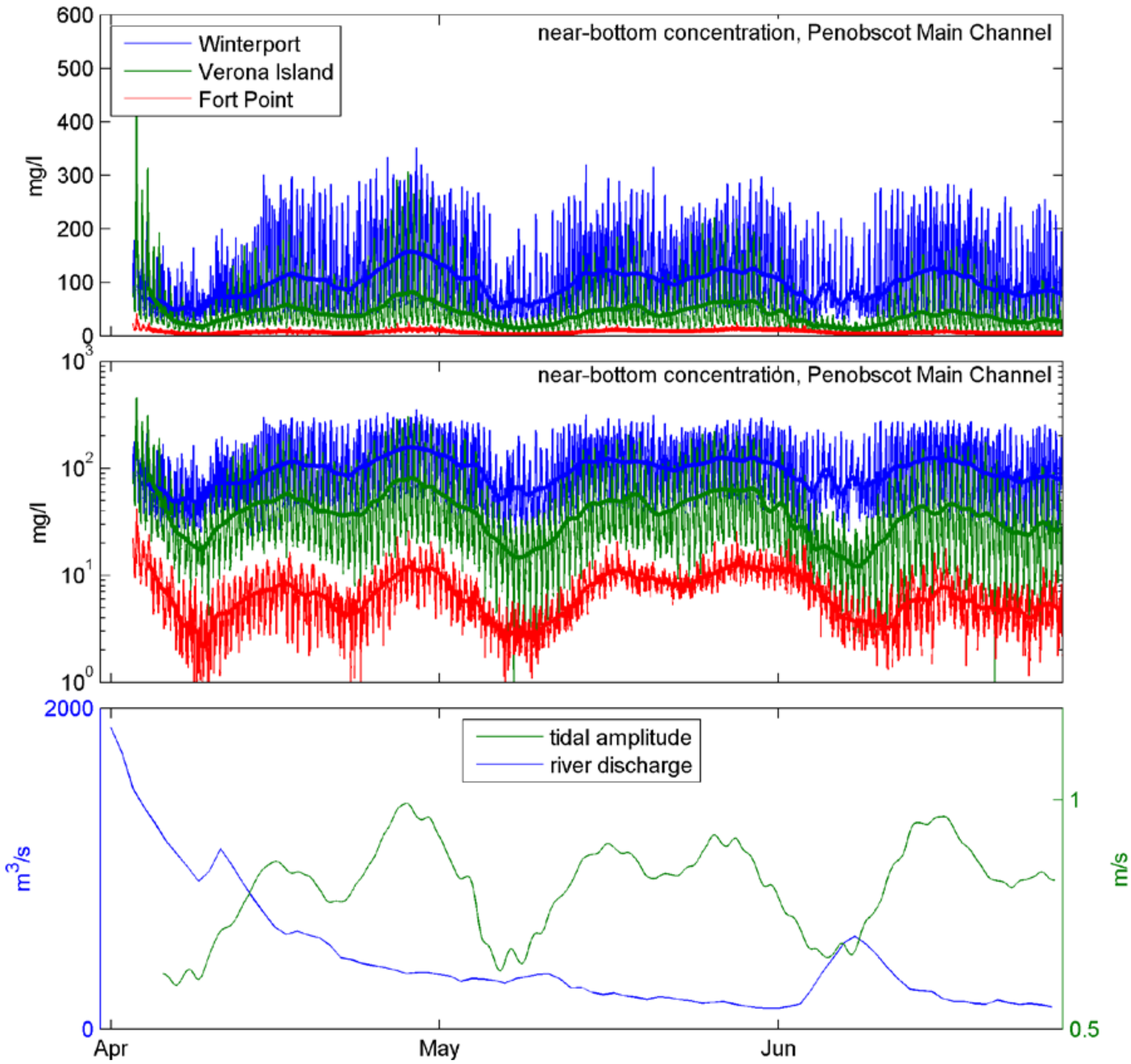


Figure 7-10. Near-bottom suspended sediment concentrations in the main stem of the river in 2010. (top) Tidal (thin lines) and residual (thick lines) concentrations. (middle) Same, but on logarithmic scale. (bottom) Tidal amplitude and river discharge during the observations.

The optical sensors during the 2010 deployment were problematical, due to instrument malfunctions, fouling and operator error. The acoustic backscatter from the ADCPs was used as an alternative means of quantifying the suspended sediment concentrations. The nonlinear calibration of the acoustics makes these measurements less reliable than the 2011 optical measurements, and there were fewer calibration samples during 2010, so the concentration data have to be treated with caution for 2010. However the general characteristics of the temporal and spatial variability are robust.

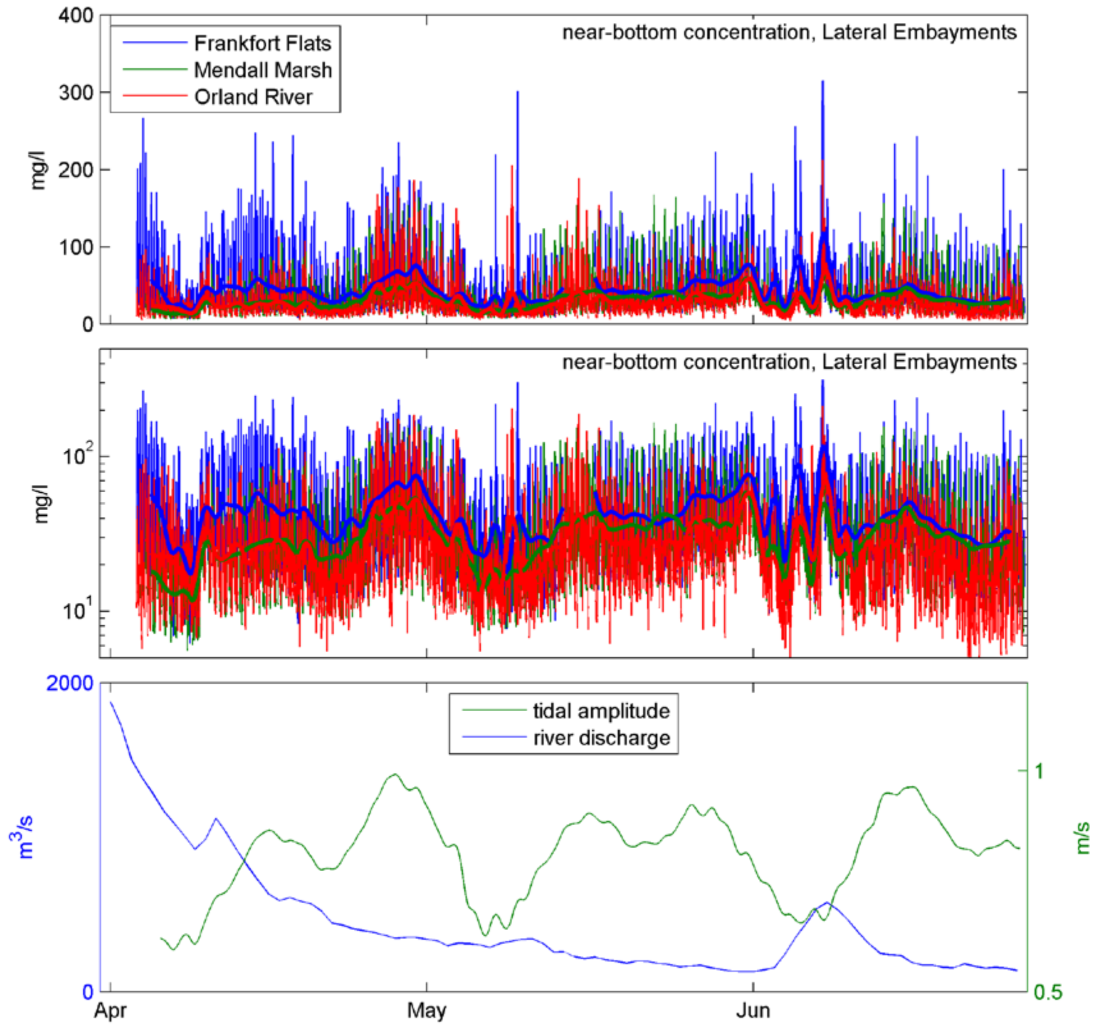


Figure 7-11. Near-bottom suspended sediment concentrations in side embayments and on lateral shoals in 2010. (top) Tidal (thin lines) and residual (thick lines) concentrations. (middle) Same, but on logarithmic scale. (bottom) Tidal amplitude and river discharge during the observations. All x-axes are the same.

The near-bottom concentrations in the main channel (Figure 7-10) show similar patterns of temporal variation as the 2011 data, although the peak concentrations are much lower. This may be partially an artifact of the acoustic method, but these stations were not located in the zones of intense sediment trapping (more discussion to follow), so the difference may reflect the spatial variability within the system. The concentrations were highest at Winterport, which is less than a tidal excursion away from the Frankfort Channel station. Intermediate concentrations were found at Verona Island, and very low concentrations (usually less than 10 mg/l) were found at the Fort Point location. The low concentrations at Fort Point indicate that in spite of the intense resuspension that occurs in the central estuary, little sediment remains in suspension at the mouth.

Concentrations at the side embayments (Figure 7-11) were lower than the Winterport site but significantly higher than Fort Point. Tidally averaged concentrations (thick lines on Figure 7-11) were typically 10-50 mg/l, and the peak tidal values reached 200 mg/l or more. Most of the variability was due to the spring-neap cycle, although it appeared that the run-off event in early June resulted in an elevation in concentration.

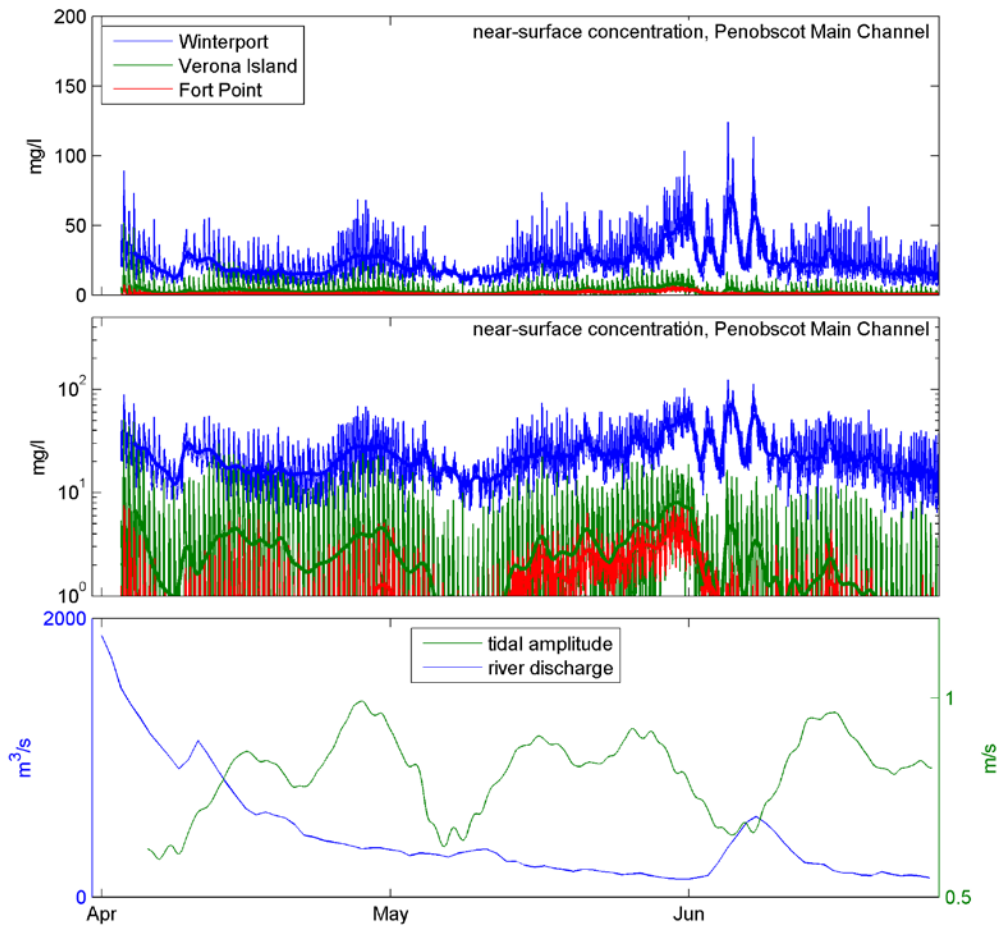


Figure 7-12. Near-surface suspended sediment concentrations in the main stem of the river in 2010. (top) Tidal (thin lines) and residual (thick lines) concentrations. (middle) Same, but on logarithmic scale. (bottom) Tidal amplitude and river discharge during the observations. All x-axes are the same.

Near-surface concentrations were difficult to estimate in 2010, due to interference of the acoustic signal by bubbles. An approximate estimate of near-surface concentrations was achieved by using the minimum acoustic backscatter within the water column, which was generally within 25% of the water depth from the surface. The results of this estimation process are shown in Figure 7-12. These concentrations were much lower than the near-bottom concentrations, as expected, and they show both spring-neap and river-flow-induced variability. The largest peak in near-surface concentration at Winterport occurred during the run-off event in early June. The side embayments showed less spring-neap variability of surface concentration and again the June run-off event resulted in a significant increases in concentration at all of the sites (Figure 7-13).

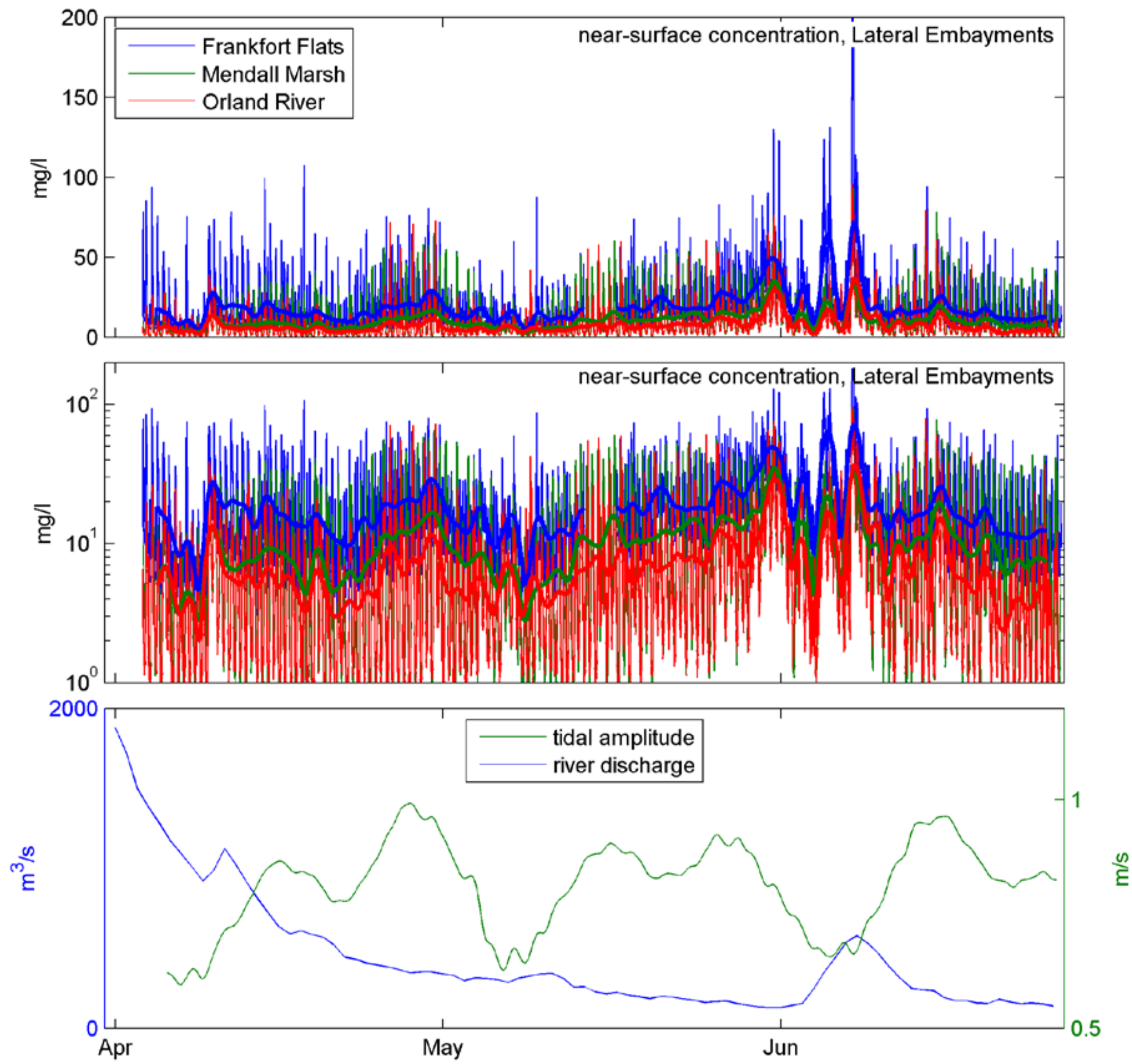


Figure 7-13. Near-surface suspended sediment concentrations in side embayments and on lateral shoals in 2010. (top) Tidal (thin lines) and residual (thick lines) concentrations. (middle) Same, but on logarithmic scale. (bottom) Tidal amplitude and river discharge during the observations. All x-axes are the same.

4.3 Survey Measurements

The 2011 survey data concentrated on the main channel of the Penobscot, whereas the 2010 survey data concentrated on more localized sub-regions of the system. In order to provide a large-scale perspective, this discussion will begin with the 2011 data.

4.3.1 2011 Survey Results

The times of the four surveys in 2011 are shown in Figure 7-14. The March and April surveys occurred during discharge peaks and nearly spring-tide conditions. The May survey occurred during high but not peak discharge and intermediate tides. The June survey occurred during low discharge and close to neap tides. The locations of the stations in 2011 followed the thalweg (deepest channel) of the Penobscot, with roughly 1 km spacing (Figure 7-2).

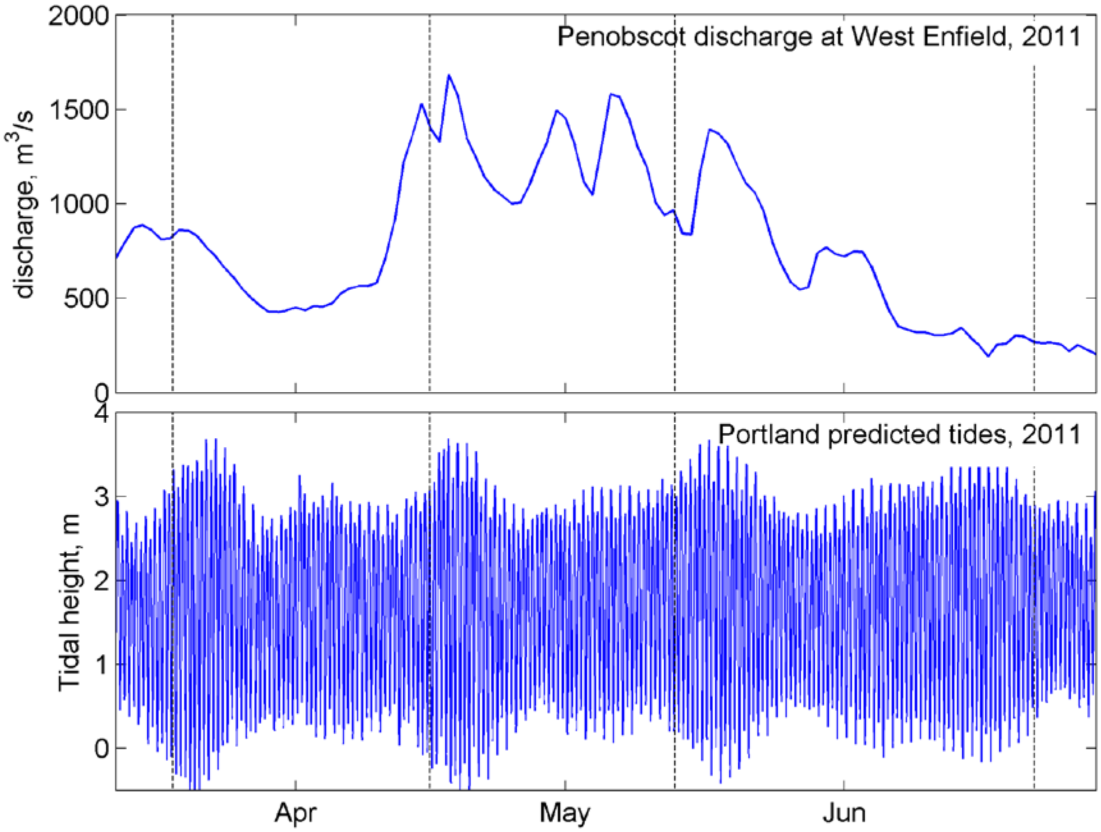


Figure 7-14. Discharge and tidal amplitude at the times of surveys in 2011 (noted with vertical dashed lines).

The along-estuary salinity sections for the March 2011 surveys are shown in Figure 7-15. During mid-ebb (top panel), the 1 psu contour was pushed south of Frankfort, and the main part of the salinity gradient (10-25 psu) formed a near-bottom frontal zone at km 10 (adjacent to Verona Island - see Figure 7-2 for locations). During the late flood the next morning (2nd panel), the salt front had advected roughly 10 km northward to Frankfort.

Figure 7-4: Conditions during 2011 surveys.			
Dates	**River Discharge, m^3/s**	**Tidal Range, m**	**Tidal Mixing Factor***
Mar. 17-18, 2011	830	3.14	1.26
Apr. 15-16, 2011	1420	3.13	1.24
May 12-13, 2011	960	2.89	0.98
Jun. 22, 2011	270	2.40	0.56
*The tidal mixing factor is based on the cube of the tidal range, normalized by its average for the 2010 and 2011 surveys.			

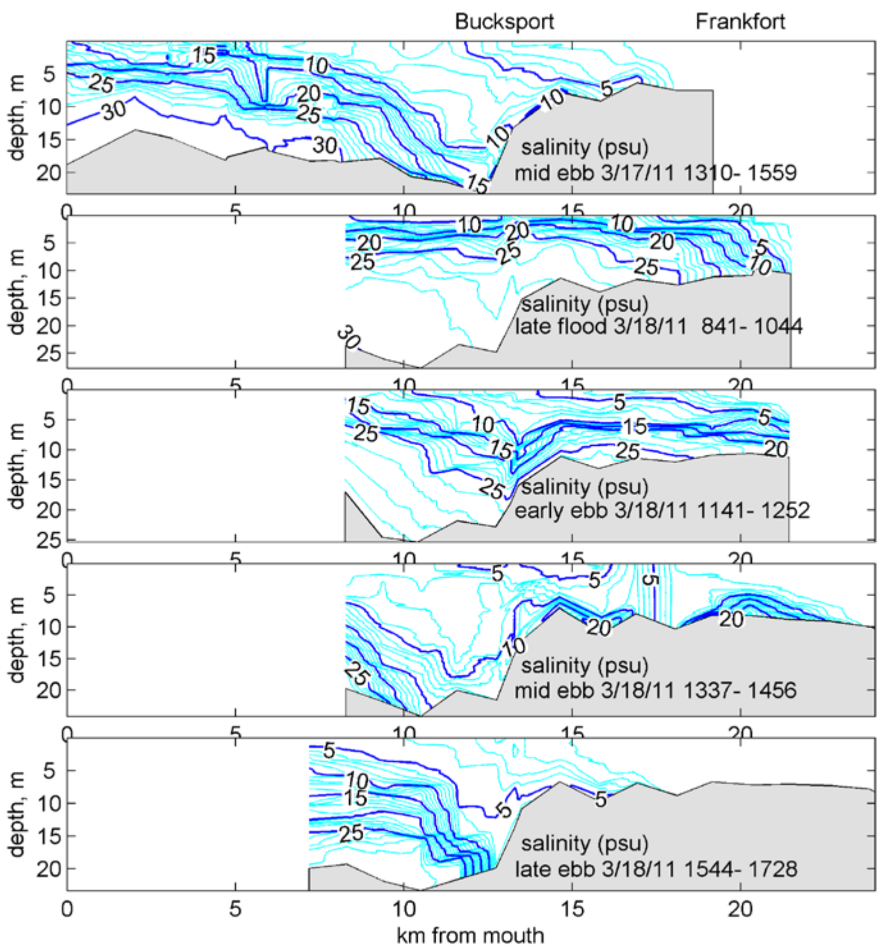


Figure 7-15. Salinity contours from along-channel surveys in March 2011. The mouth is defined here to be Fort Point at km 0.

During the ebb, the salt intrusion collapsed vertically, and by the end of the ebb, almost all of the salt water was expelled from the upper estuary, and the front reformed at 12 km.

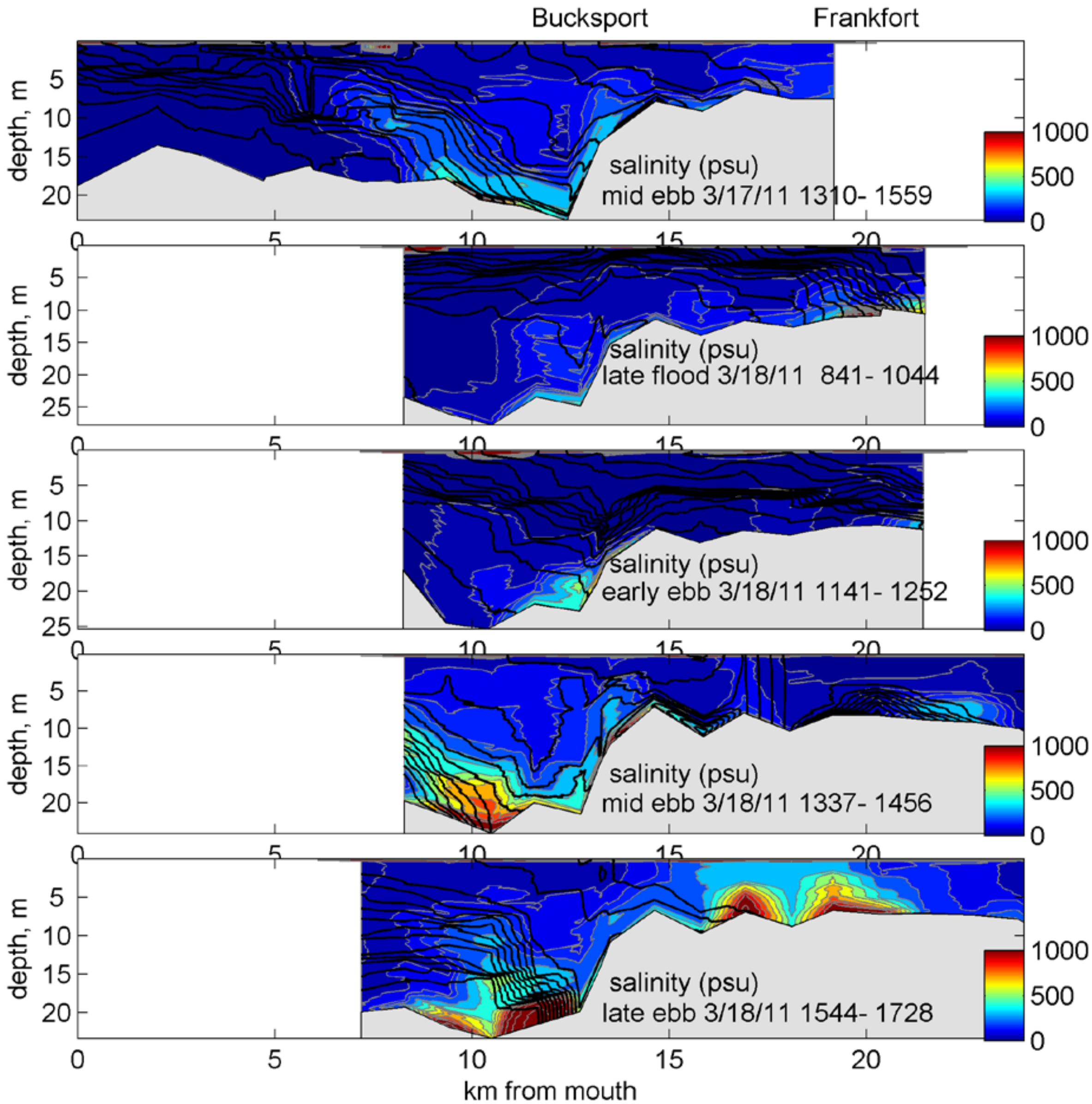


Figure 7-16. Suspended sediment from along-channel surveys in March 2011 (color contours, mg/l);salinity contours are overlaid in black.

The salinity fronts strongly influence the distribution of suspended sediment, as indicated in the combined salinity and suspended sediment plot for the March surveys (Figure 7-16). The highest suspended sediment concentrations were observed at the Bucksport frontal zone between km 8 and 12, most notably during the late ebb (lowest two panels), when the salinity front was located there. High suspended sediment concentrations were also observed at the northern frontal location, but the position of the high concentration was more variable and the concentrations were not as high. These observations are consistent with intense trapping during the ebb tide at the southern front, followed by advection of sediment with the front during the flood, which produces a secondary turbidity-maximum zone at the northern location, one tidal excursion from the main trapping zone. The high concentrations at km 20 during the last transect (bottom panel) indicate the resuspension of sediment that had been deposited within the front during the previous high tide (note that the front in the 3rd panel is just upstream of km 20).

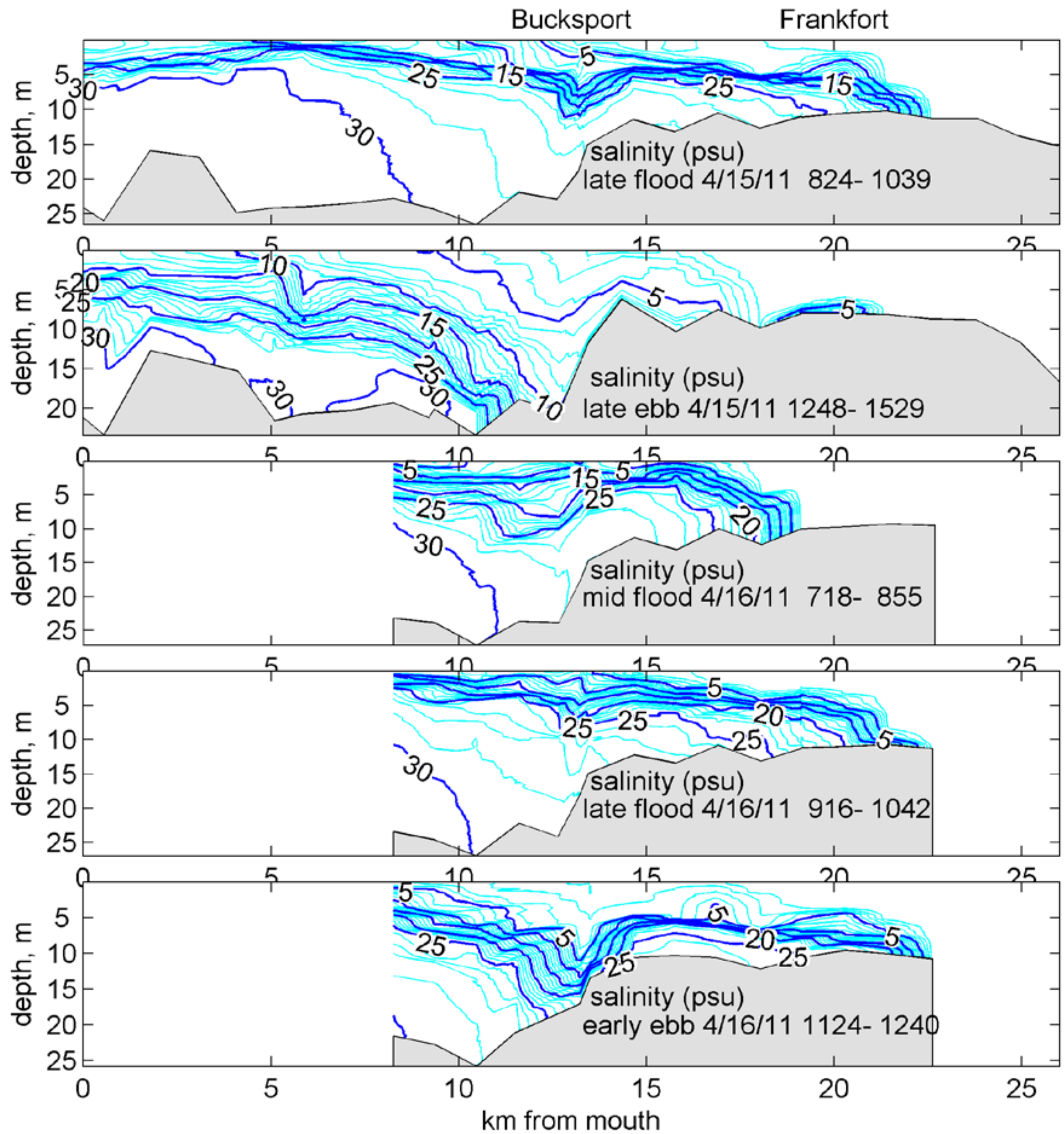


Figure 7-17. Salinity contours from along-channel surveys in April 2011.

An important feature of the suspended sediment distribution is the plume of sediment that lifts off the bottom to the south of the Bucksport frontal zone. The 1st panel shows that the sediment roughly follows the salinity contours upward, but it weakens as it advects southward, and the concentration drops to background by km 5.

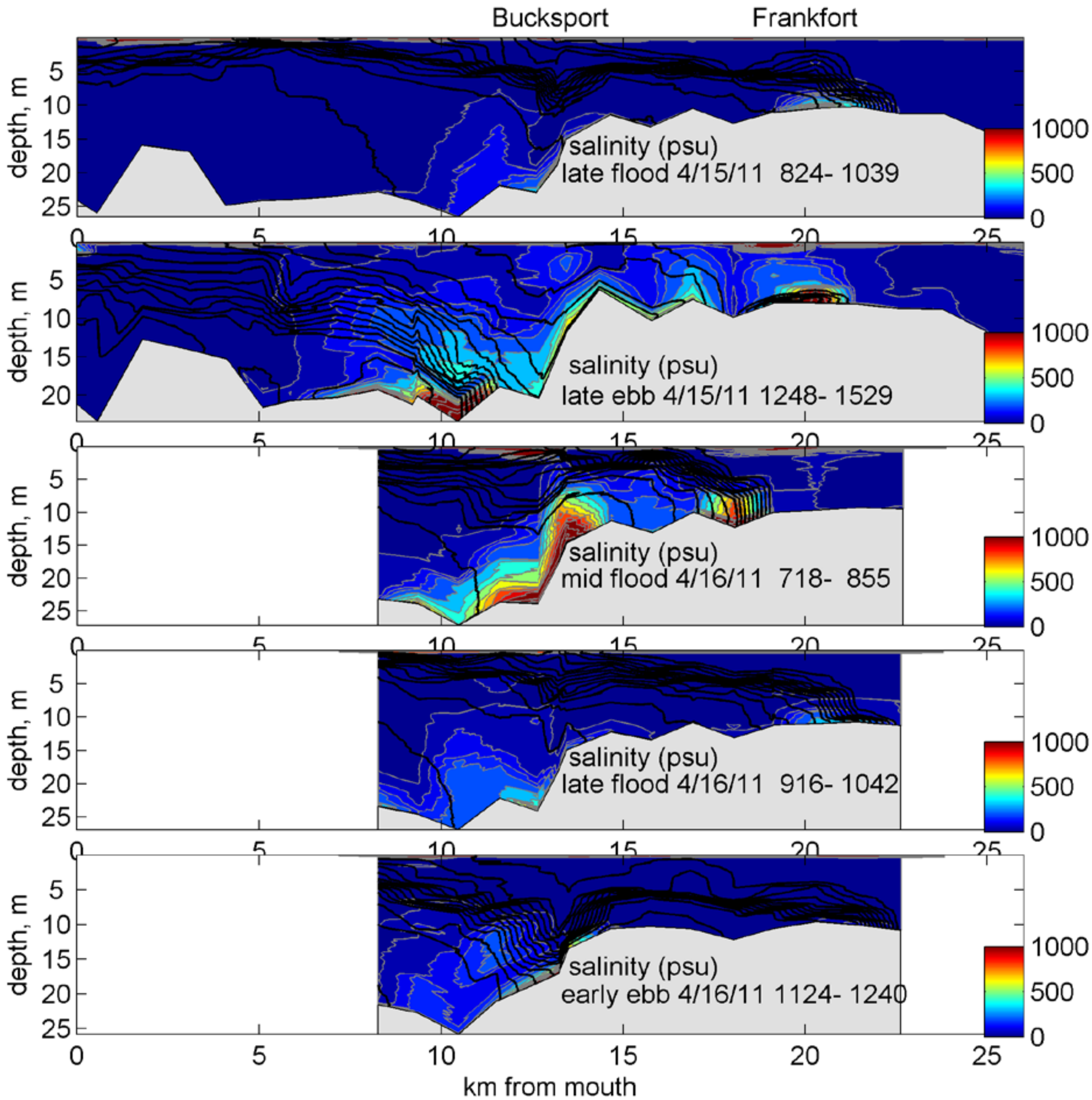


Figure 7-18. Suspended sediment from along-channel surveys in April 2011 (color contours, mg/l); salinity contours are overlaid in black.

The salinity data for April 2011 (Figure 7-17) show similar conditions to March. The frontal position varies between km 22 at high tide (1st panel) and km 12 at low tide (2nd panel). Unlike the March observations, the conditions during mid-flood (3rd panel) were observed in April, during which the salt front was rapidly advancing.

The suspended sediment data (Figure 7-18) again show the two zones of high suspended sediment. During the flood, the sediment from the Bucksport Frontal zone is remobilized, resulting in high concentrations between 12 and 14 km, even though the front has advanced to 17 km. Another zone of high concentration is located within the frontal zone.

During the May 2011 survey, the salinity was more persistently stratified than the March and April surveys, and the salt front extended farther up the estuary, to km 27 (Figure 7-19). This may be explained by the reduction in tidal amplitude, which results in a 25% reduction in the tidal mixing factor (Figure 7-4). River discharge variations do not explain the difference, as the discharge was stronger in May than in March. Concentrations were slightly lower during May (Figure 7-20), also reflecting the change in tidal energy.

During the June 2011 survey (Figure 7-21), the combination of low river flow and weak tides (Figure 7-4) allowed the salt intrusion to extend well up the estuary, past km 33. Strong stratification conditions persisted through the tidal cycle, due to the weak tides.

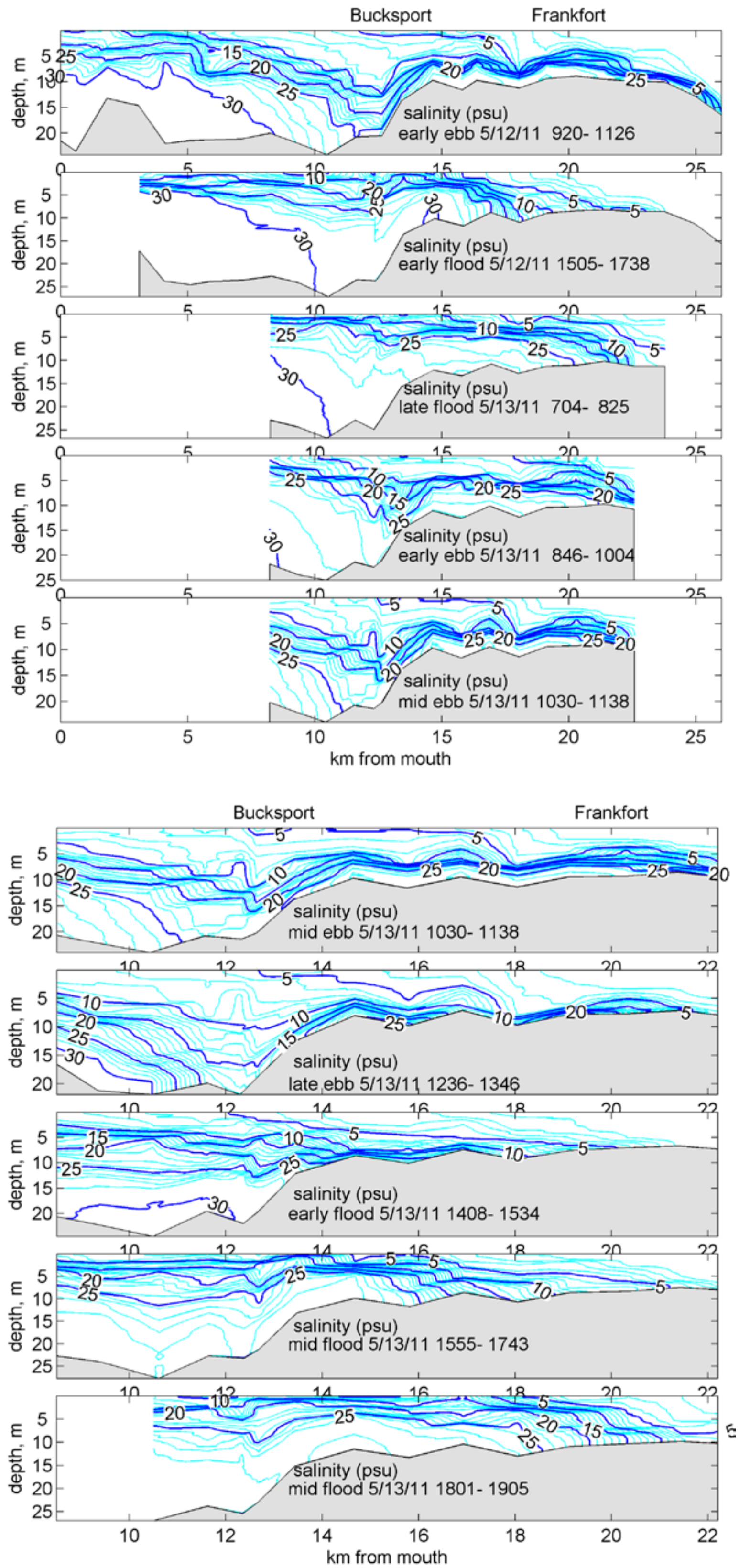


Figure 7-19. Salinity contours from along-channel surveys in May 2011.

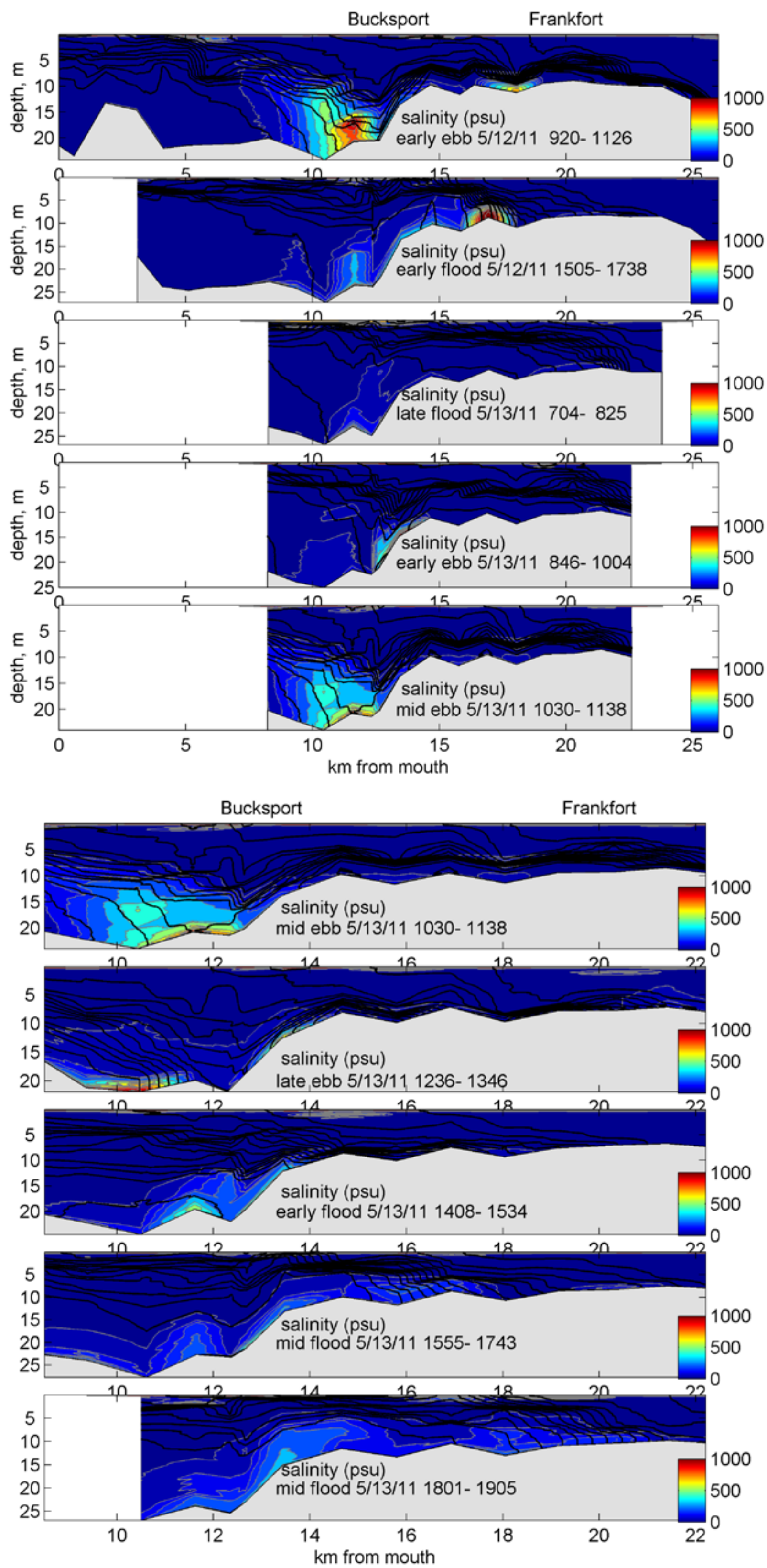


Figure 7-20. Suspended sediment from along-channel surveys in May 2011 (color contours, mg/l); salinity contours are overlaid in black.

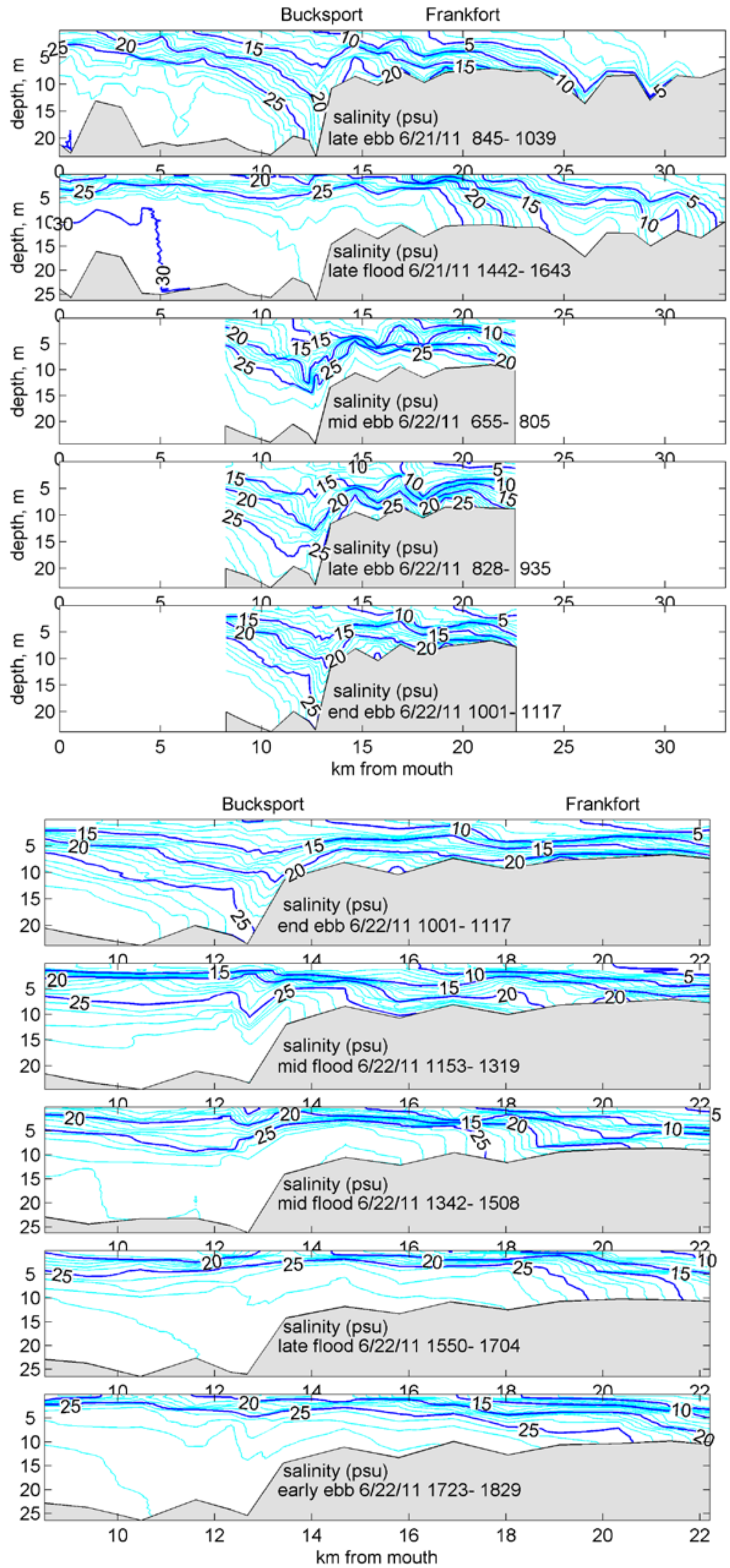
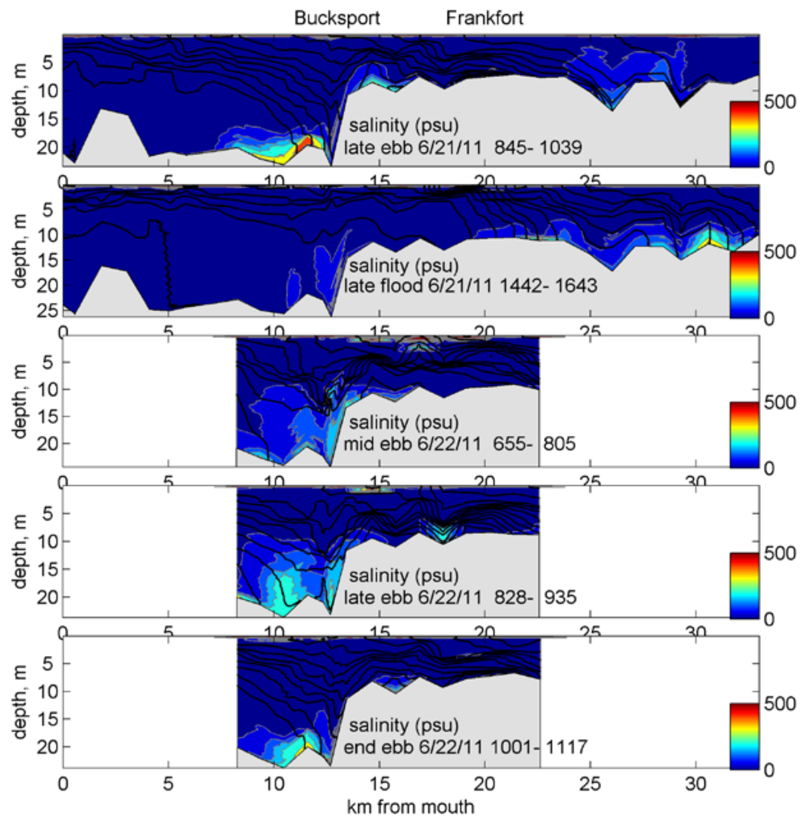


Figure 7-21. Salinity contours from along-channel surveys in June 2011.



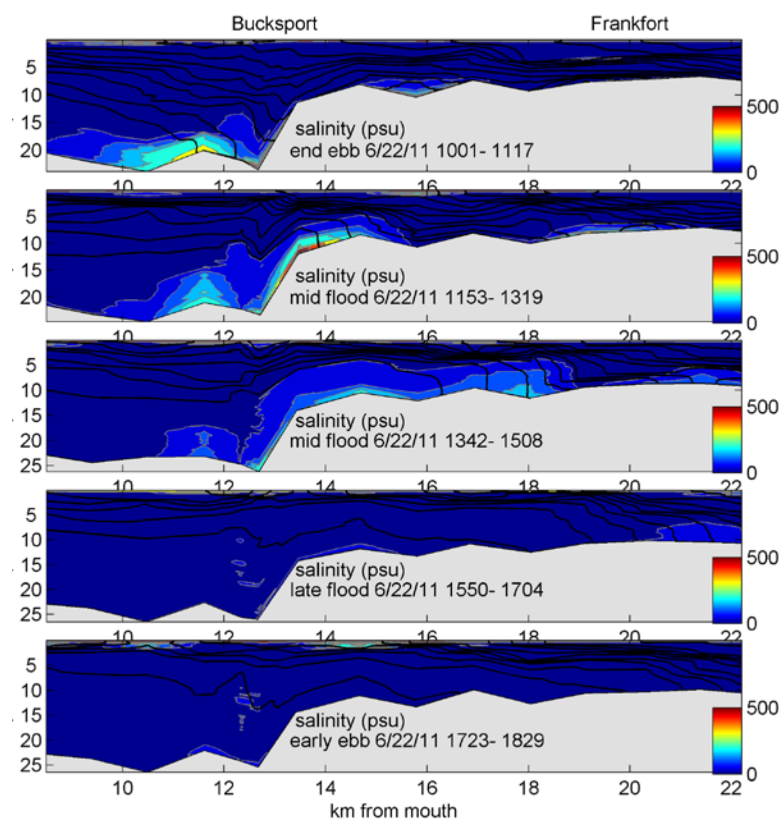


Figure 7-22. Suspended sediment from along-channel surveys in June 2011 (color contours, mg/l); salinity contours are overlaid in black.

The suspended sediment distribution (Figure 7-22) had significantly lower concentrations than other surveys, so the color scale was reduced by a factor of two. This reduction is due mainly to the drop in tidal energy, but there may also be a seasonal reduction in concentration due to the elapsed time since the freshet. The Bucksport trapping zone is still evident in the concentration data, but the Frankfort trapping zone has little resuspension. However, relatively high concentrations are evident well to the north, at km 32, during the late flood (2nd panel). This provides key evidence that as the discharge decreases and the salt intrusion moves northward, it carries suspended sediment with it.

4.3.2 2010 Survey Results

The times of the four surveys in 2010 are shown in Figure 7-23 relative to river flow and tidal conditions. The April survey occurred during high discharge, but the discharge rapidly decreased, and the May and June surveys occurred during low flow. Tidal conditions were strongest during the April survey, weakest in May, and intermediate in June. Most of the surveys in 2010 were localized to sub-regions of the estuary, so they do not provide the large-scale distributions. They do show important connections between the main stem and the sub-estuaries.

Figure 7-5: Conditions during 2010 Surveys.

Dates	River Discharge, m^3/s	Tidal Range, m	Tidal Mixing Factor*
April 1-5, 2010	1440	3.08	1.19
May 11-12, 2010	290	2.68	0.78
June 27-29, 2010	140	2.90	0.99

*The tidal mixing factor is based on the cube of the tidal range, normalized by its average for the 2010 and 2011 surveys.

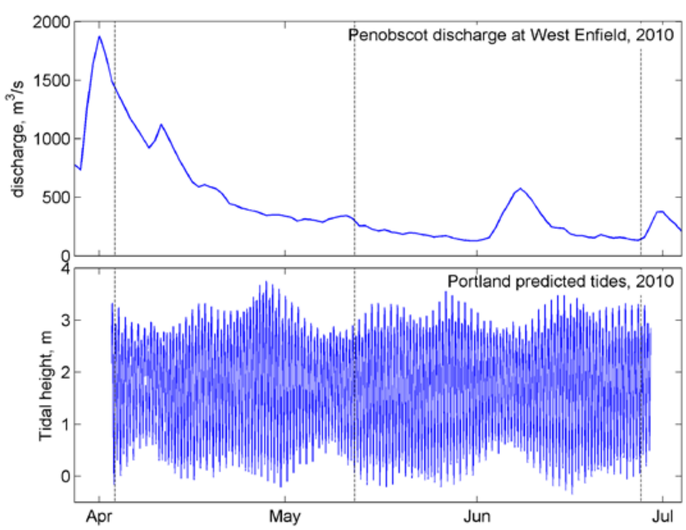


Figure 7-23. Discharge and tidal amplitude during 2010 of surveys.

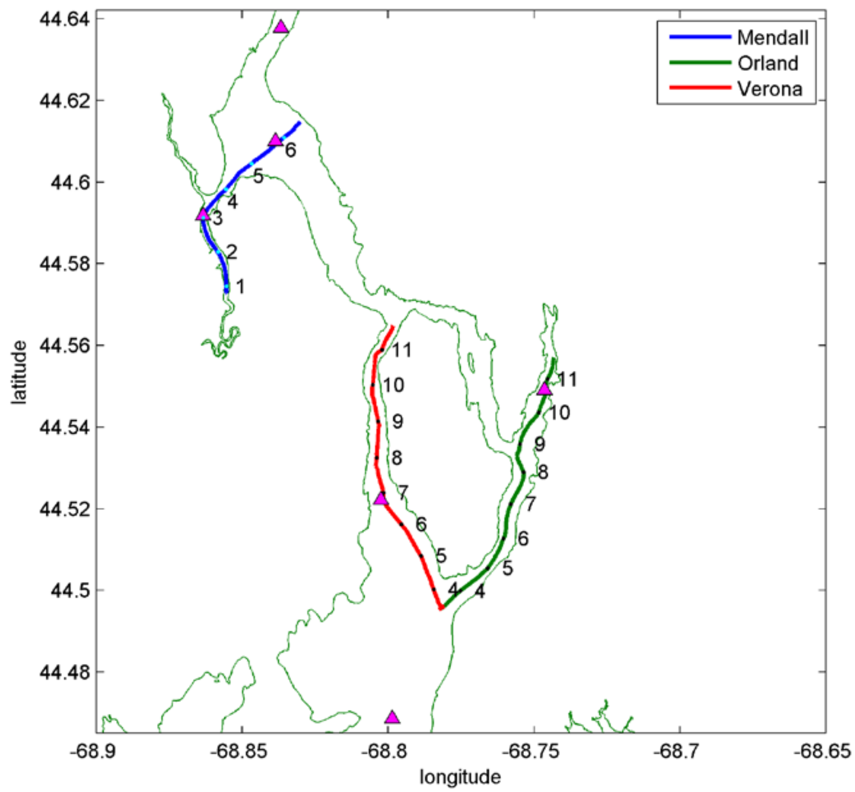


Figure 7-24. Map of 2010 transects**.**

Three survey lines were occupied in 2010, one that extended from the south end of Mendall Marsh to its mouth, and then across the Penobscot at Frankfort, the second that extended along the west side of Verona Island, and the third that extended along the south side of Verona Island and into the Orland River (Figure 7-24).

4.3.3 Mendall Marsh Line

The conditions in Mendall Marsh during the April, 2010 survey are illustrated with salinity contours, along-channel velocity, and suspended sediment (Figure 7-25). The salt had been expelled from the marsh channel during the ebb, and this section during the late flood shows the salt moving back into the estuary. The currents are weak at this time, but there is a slight enhancement of the flood at the bottom associated with the salt wedge at km 4. This feature indicates the input of sediment from the high-turbidity zone in the adjacent Frankfort channel in the main stem of the Penobscot.

The late ebb transect (Figure 7-26) shows the salt completely flushed out of the marsh, and uniform suspended sediments of about 60 mg/l in the marsh channel. Note that at this time the resuspension is intense in the Frankfort channel of the Penobscot.

During the May survey, the salt intrusion persisted though the tidal cycle, and strong salinity gradients were evident in both the horizontal and vertical directions. During the flood, an along-channel gradient developed in Mendall Marsh, driving the bottom water landward (Figures 7a-27 and 7a-28). Resupension of sediment in the Penobscot first occurred on the flank of Frankfort Flats, and resuspension progressed into Mendall Marsh in the next hour. This pattern of resuspension is suggestive of upwelling of channel water into Mendall Marsh, probably driven by the channel curvature effect.

During the ebb, the salinity in Mendall Marsh collapses, but it remains stratified along the base of the channel (Figure 7-29). Substantial resuspension occurs in the shallowest portion of the marsh that could be surveyed. Some resuspension occurs in the Penobscot channel, but not as intense as the flood.

The June data show similar patterns to May, but the CTD data were compromised by a sampling rate problem, so these data are not displayed.

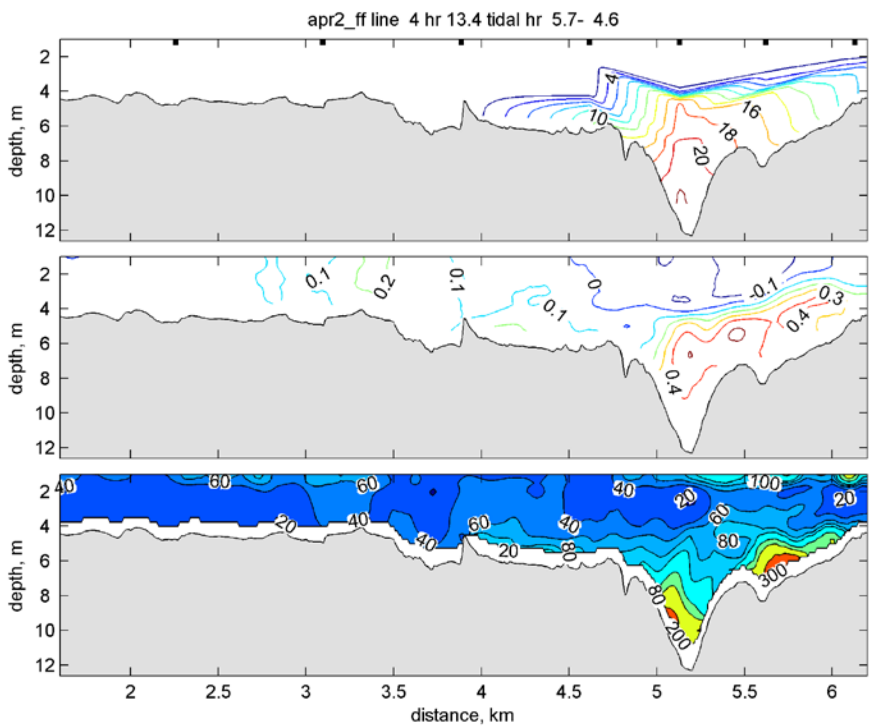


Figure 7-25. Mendall Marsh survey, April 2010, late flood. (top) Salinity, (middle) along-channel velocity (m/s), (bot.) suspended sediment from optical backscatter (mg/L).

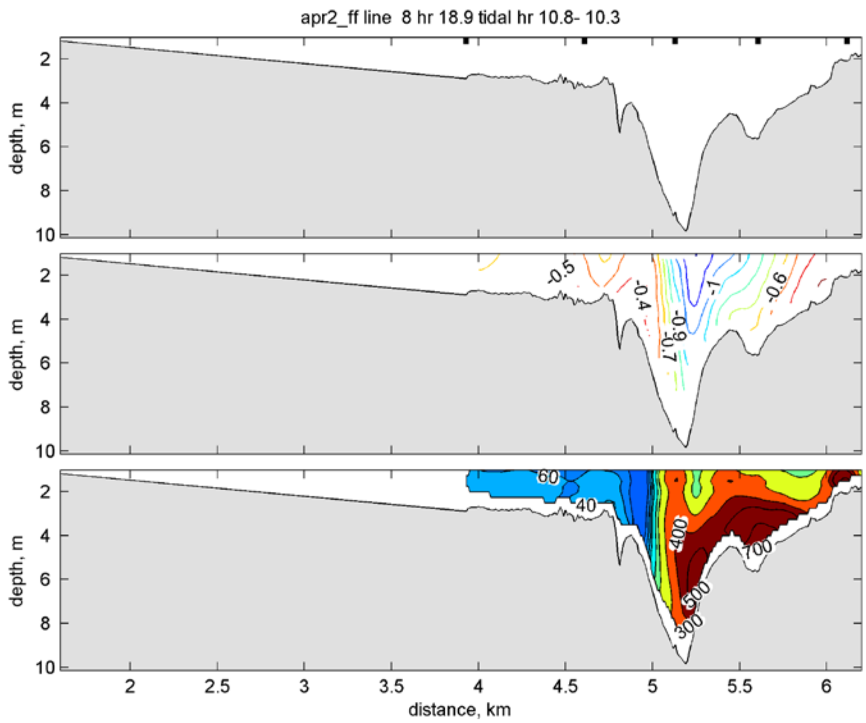


Figure 7-26. Mendall Marsh, April 2010, late ebb. (top) Salinity (psu), (middle) along-channel velocity (m/s), (bot.) suspended sediment from optical backscatter (mg/L).

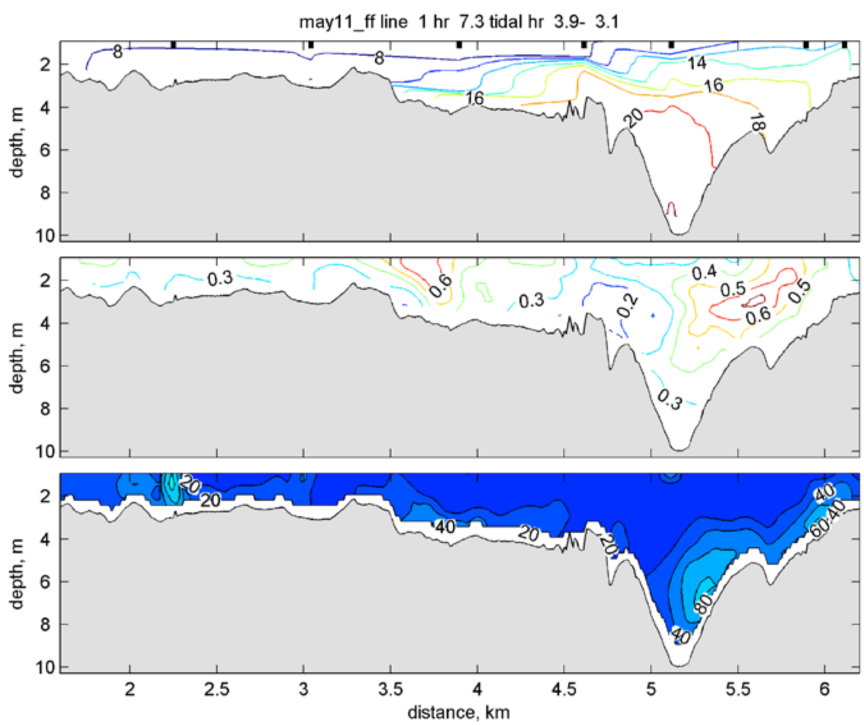


Figure 7-27. Mendall Marsh, May 2010, mid flood. (top) Salinity (psu), (middle) along-channel velocity (m/s), (bot.) suspended sediment from OBS (mg/L).

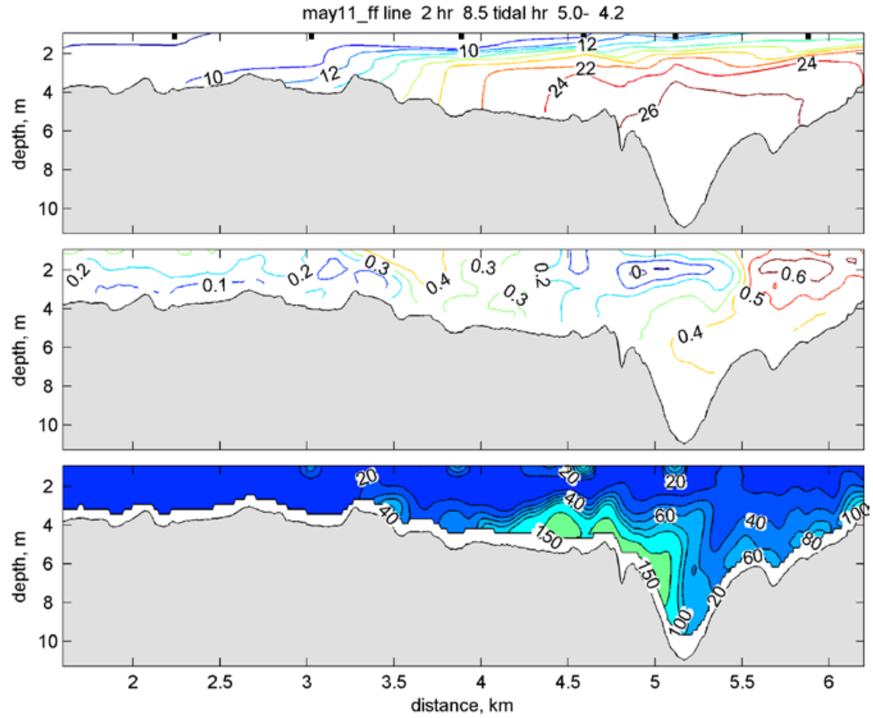


Figure 7-28. Mendall Marsh, May 2010, late flood. (top) Salinity (psu), (middle) along-channel velocity (m/s), (bot.) suspended sediment from OBS (mg/L).

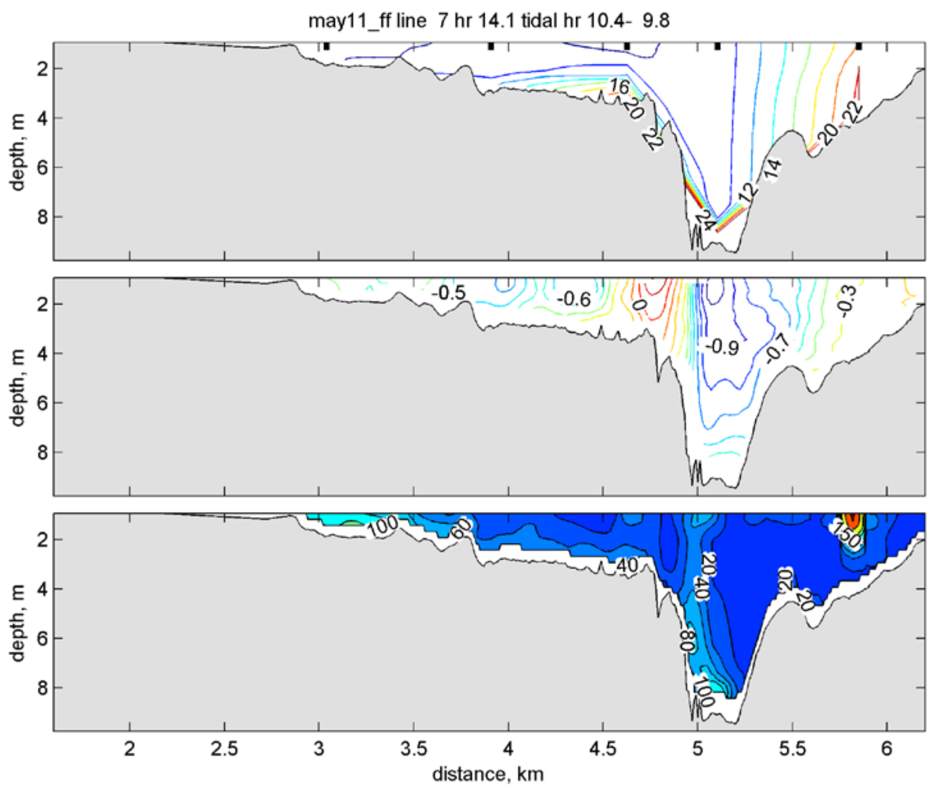


Figure 7-29. Mendall Marsh, May 2010, ebb. (top) Salinity (psu), (middle) along-channel velocity (m/s), (bottom) suspended sediment from optical backscatter (mg/L).

4.3.4 Orland Line

During the April survey, strong salinity gradients were evident in the Orland line. During the flood (Figure 7-30), strong near-bottom currents caused intense resuspension, although its height was limited by stratification. All of the sediment settled back to the bed at the end of the flood (Figure 7-31).

During May, again strong resuspension was evident during the flood, but because the near-bottom stratification was weaker, the suspended sediment extended farther up in the water column, and the flood velocities were stronger due to less freshwater outflow (Figure 7-32). During the ebb, a patchier pattern of resuspension occurred, probably because of the variation of near-bottom stratification. The Orland River itself did not exhibit significant suspended sediment.

In June, conditions were similar to May, but there were patches of resuspension within the Orland River (Figure 7-33). The tides were slightly stronger during the June survey, so this may explain the difference.

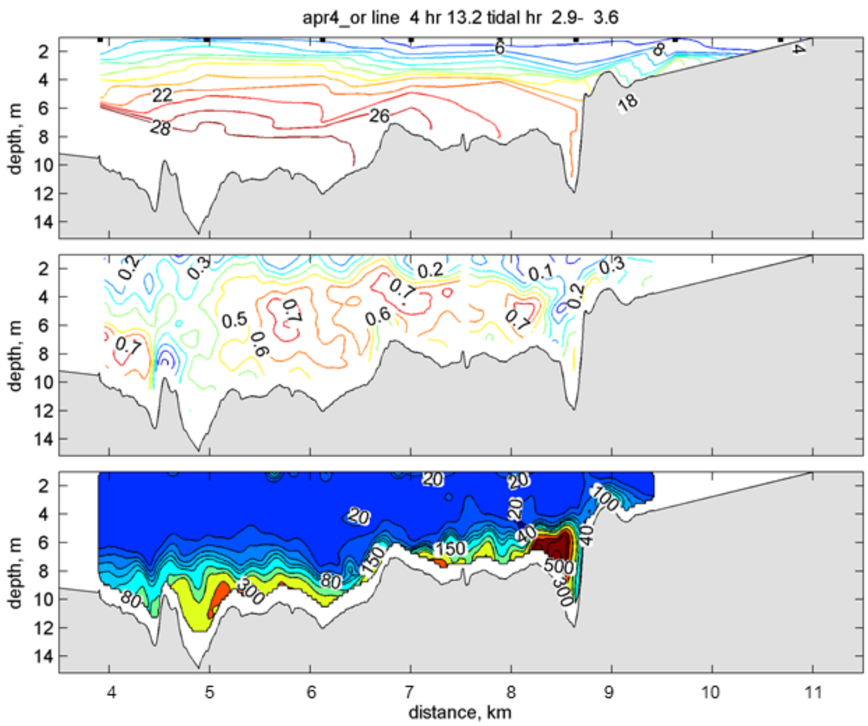


Figure 7-30. Orland River survey, April 2010, flood. (top) Salinity (psu), (middle) along-channel velocity (m/s), (bottom) suspended sediment from OBS (mg/L).

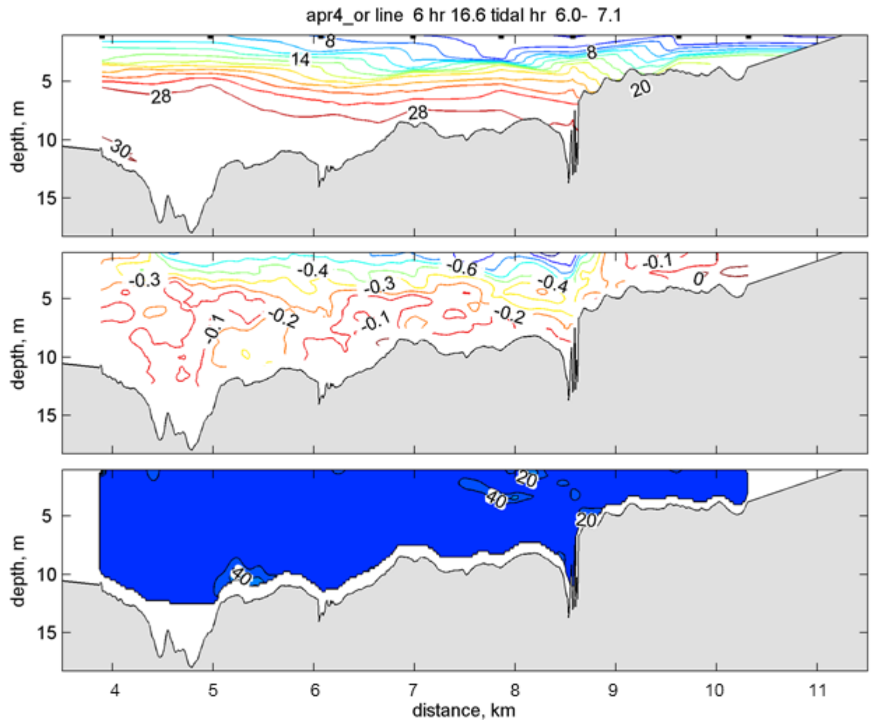


Figure 7-31. Orland River survey, April 2010, end of flood. (top) Salinity (psu), (middle) along-channel velocity (m/s), (bottom) suspended sediment from OBS (mg/L).

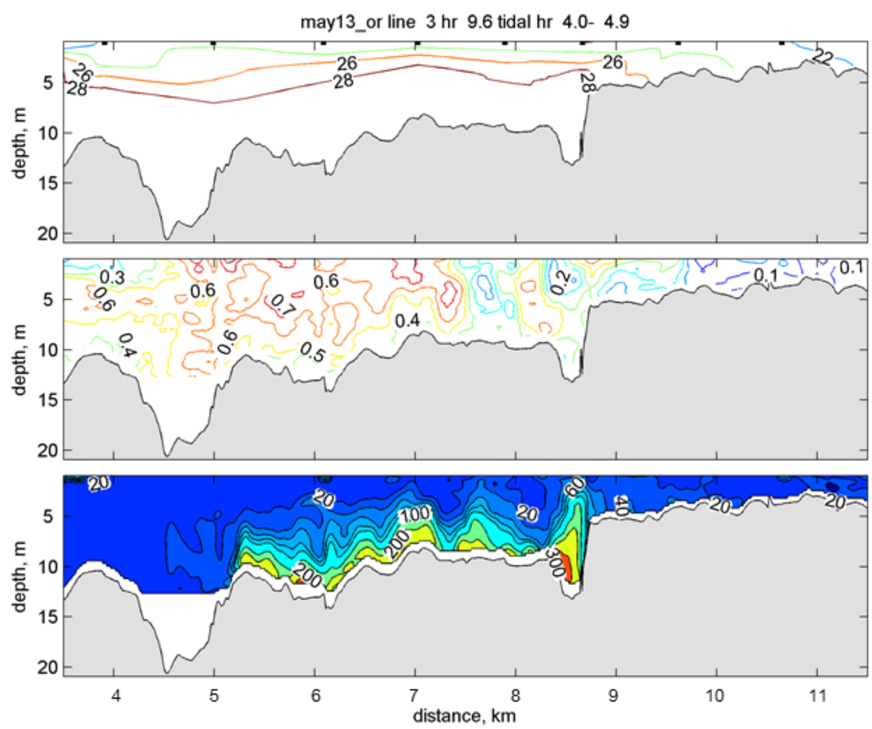


Figure 7-32. Orland River survey, May 2010, mid-flood. (top) Salinity (psu), (middle) along-channel velocity (m/s), (bottom) suspended sediment from OBS (mg/L).

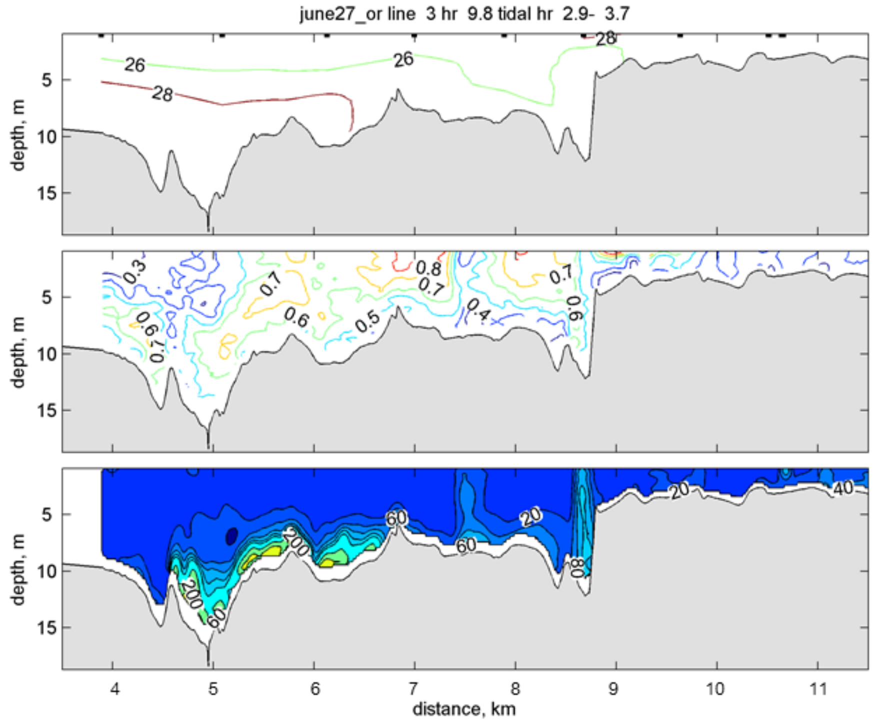


Figure 7-33. Orland River survey, June 2010, mid-flood. (top) Salinity (psu), (middle) along-channel velocity (m/s), (bottom) suspended sediment from OBS (mg/L).

4.3.5 Verona Line

The Verona line was sampled more comprehensively during the 2011 surveys, so the data from 2010 do not add significantly to the story. One example of the conditions in May 2010 shown in Figure 7-34 indicates the strong velocity shear during the ebb (middle panel). Just as in the 2011 data, the high turbidity is carried upward by the shear flow, but it settles out within 5 km of the Frankfort trapping zone. The decrease in the height of the suspended sediment between 9 and 7 km provides an opportunity to obtain an approximate settling velocity for this time-period, based on the assumption that the spatial structure is due only to advection and settling. Based on the observed velocities and the general downward slope of the 20 mg/l contour, we obtain an estimated settling velocity of 2-3 mm/s. The average settling velocity is probably greater for the near-bed sediment, which probably contains more sand. This is suggested by the abrupt changes in concentration of the near-bottom sediment, although it is possible that temporal/spatial variations of sediment resuspension also contributed to this variability.

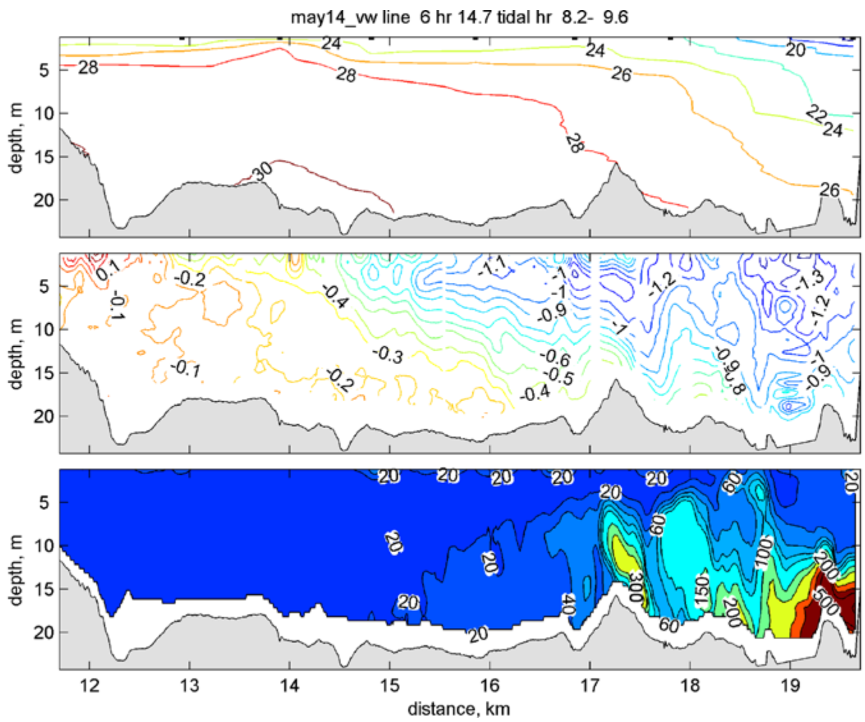


Figure 7-34. Verona Island survey, May 2010, mid-ebb. (top) Salinity (psu), (middle) along-channel velocity (m/s), (bottom) suspended sediment from OBS (mg/L).

4.3.6 Summary of Suspended Sediment Distributions, 2010

The spatial distribution of near-bottom sediment resuspension for the three sampling periods of 2010 is shown in Figure 7-35. These data confirm the Frankfort and Bucksport trapping zones, and they also indicate that the channel to the south of Verona Island is a significant trapping zone.

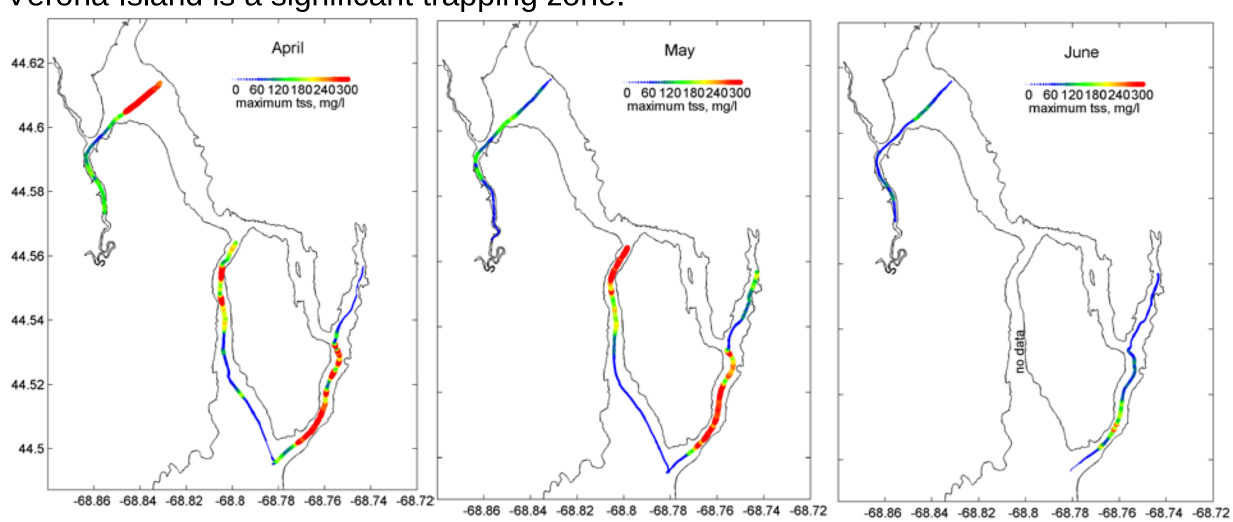


Figure 7-35. Maximum suspended sediment concentrations during 2010 surveys**.**

4.4 Grab Sampling Results

The distribution of fine sediment is shown in Figgure 7a-36. Fine sediment is generally found in the side embayments, notably Mendall Marsh, Fort Point Cove, and the Orland River. Fines are also found in patches the upper river north of Winterport (latitude 44.63), but these are likely to be seasonal patches of deposition. Note that all of the samples north of latitude 44.65 were obtained during low discharge conditions in August, 2011, when the salt intrusion extended through most of the upper tidal river.

A similar pattern is observed with the distribution of sediment classes (Figure 7-37), using the sediment color allows the “new mud” to be distinguished from “old mud”. The “new mud” is sediment that has been deposited recently enough that the iron has not been reduced, and thus the color is light brown rather than black or gray. Most of the Mendall Marsh samples have new mud, as does the channel to the east of Verona, parts of the Orland River, and the fine patch to the north of Winterport. Thick layers of new mud were found in the channel adjacent to the mouth of Mendall Marsh, with thickness of at least 10 cm based on entirely filling the grab sampler. Isolated patches of new sediment were found in the sheltered parts of Fort Point Cove.

The organic fraction (based on loss on ignition) is roughly correlated with the fine fraction (Figure 7-38), with some notable exceptions. Those exceptions are samples dominated by wood chips (circled in Figure 7-38). Other than the wood chips, the fine sediment end member has approximately 15% organic fraction, and the coarse end member has 1% to 5% organic fraction. The scatter in the distribution is due in part to the varying fraction of wood chips in the various samples.

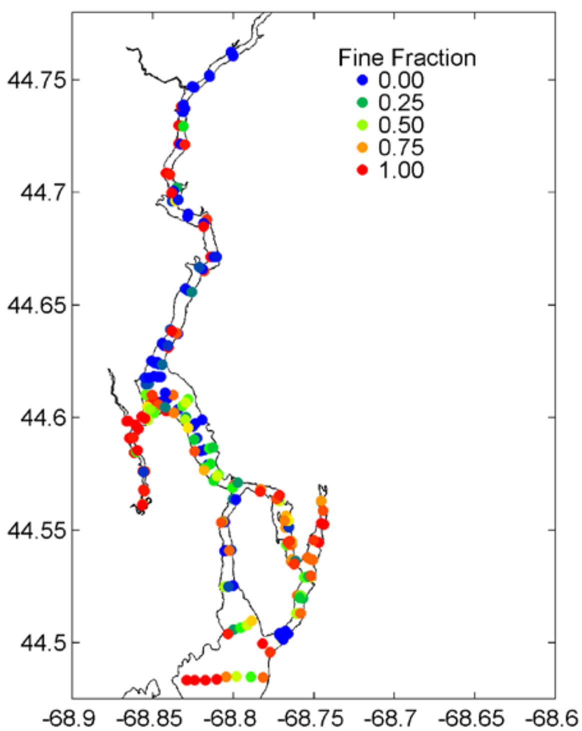


Figure 7-36. Mass fraction of bed sediment grab in the fine sediment class.

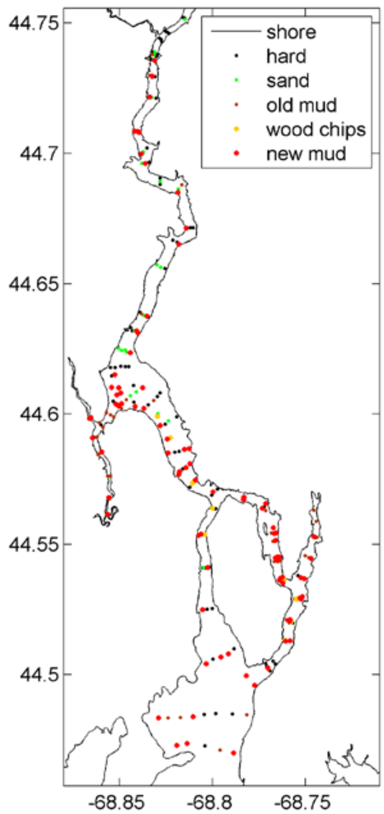


Figure 7-37. Map of grab sample classification**.**

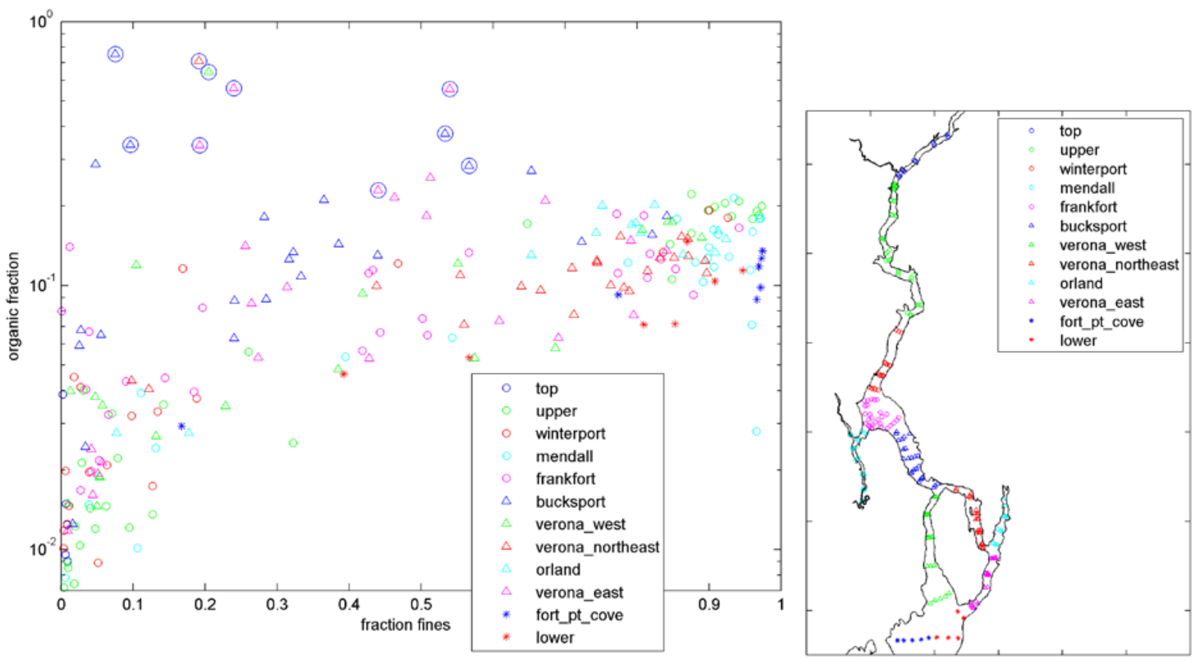


Figure 7-38. Bed grab sample organic fraction vs. mass fraction in the fine sediment class, with the markers indicating sample location (see map panel).

5 ANALYSIS

5.1 Sediment Budget

5.1.1 Sediment Inputs

An analysis of the sediment loading from the watershed was based on the USGS turbidity sensor at the Eddington Station on the Penobscot River. We used the analysis by Dianne Kopek of the relationship between the optical backscatter in Formazin Nephelometric Units (FNU, a standard measure of turbidity) to the concentration in mg/l (Figure 7-39), using the conversion:

$$C(mg/l) = FNU \times 1.77$$

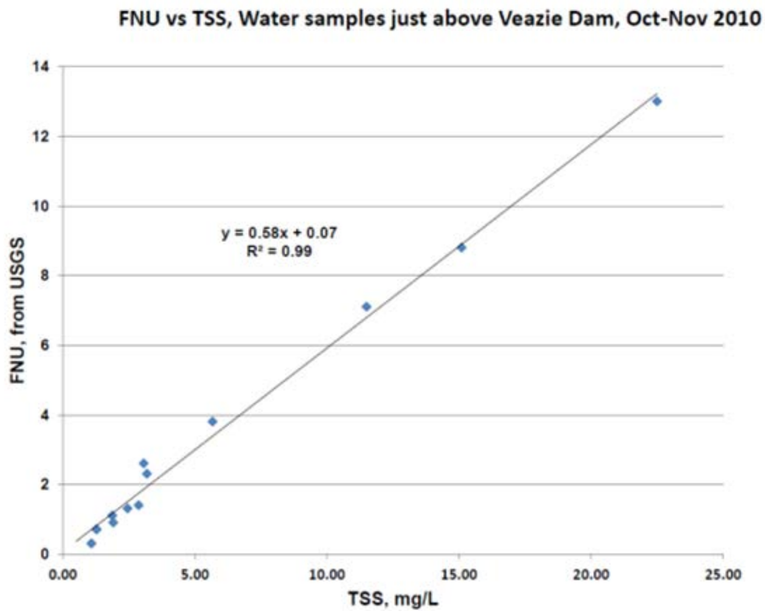


Figure 7-39. Regression between optical backscatter sensor and suspended sediment concentration at Veazie Dam**.**

We then determined the relationship between concentration and discharge based on the data from Feb. to Dec., 2010, which are shown in Figure 7-40. The data indicate a change in slope for higher discharge, which is typical of sediment yield curves. A third-order fit and a "hockey stick" bilinear fit both provide similar representations of the available data. We chose to use the bilinear fit as a more conservative (lower maximum concentration) approach to estimating the yield. The relationship between sediment and flow for this curve is as follows:

$$C(mg/l) = Q(m^3/s) \times C_o / Q_o : Q < Q_o$$
$$C(mg/l) = C_o + (Q - Q_o) \times C_m / Q_m : Q < Q_o$$

where $C_o = 9 mg/l,\ Q_o = 1700\ m^3/s,\ C_m = 37 mg/l,\ Q_m = 1270\ m^3/s$

This rating curve provides a crude estimate of the sediment input, due to the small number of high concentrations observed. It also provides no information about historical changes in loading due to dams and changes in land use. However it does provide an indication of the quantities and variability that can be ascribed to changes in river flow. As more data are obtained at higher discharge rates, the present loading rates will be better constrained, but for now, this is as well as we can due to estimate sediment loading.

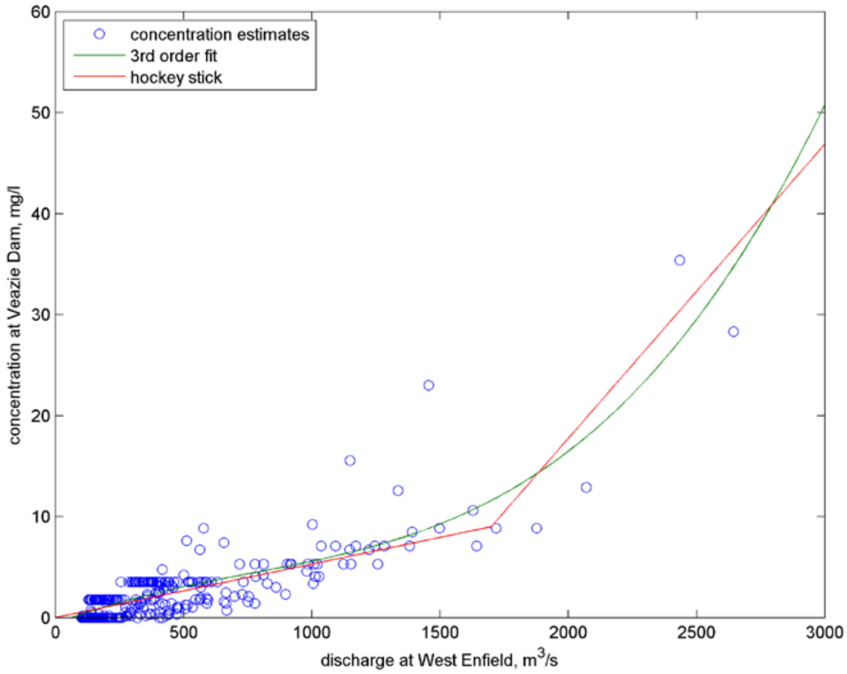


Figure 7-40. Sediment concentration vs. discharge relationship at Veazie Dam**.**

Based on this relationship, the loading for the entire 109 year record from 1902 to 2011 is shown in Figure 7-41. The average loading is 43,000 tons/y, with a maximum of 145,000 tons in 1973 and a minimum of 10,000 tons in 1983. In 2010, we estimate that 60,000 tons were discharged, in the 82nd percentile of loading.

A more detailed view of recent loading, the cumulative loading between 2009 and 2011 is shown in Figure 7-42, with the period of the field observations bounded by the vertical dashed lines. The 2010 freshet only provided moderate loading (about 20,000 tons), so the large cumulative loading for 2010 is due mainly to the storms late in the year that provided almost 40,000 tons of additional loading. The loading during the 2011 freshet observation period was about 40,000 tons, accounting for most of the sediment supplied during 2011.

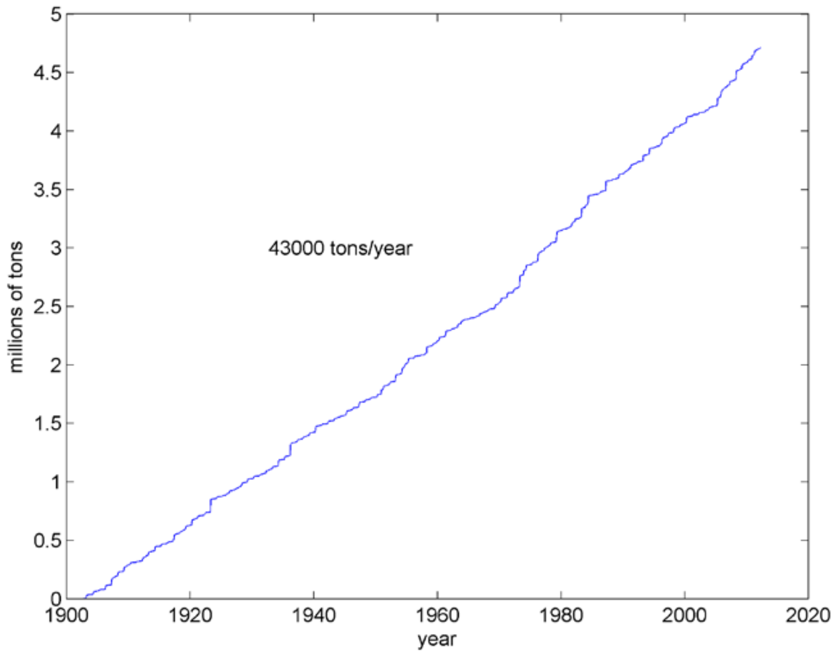


Figure 7-41. Cumulative sediment flux at Veazie Dam (1902-2011), based on discharge-concentration relationship**.**

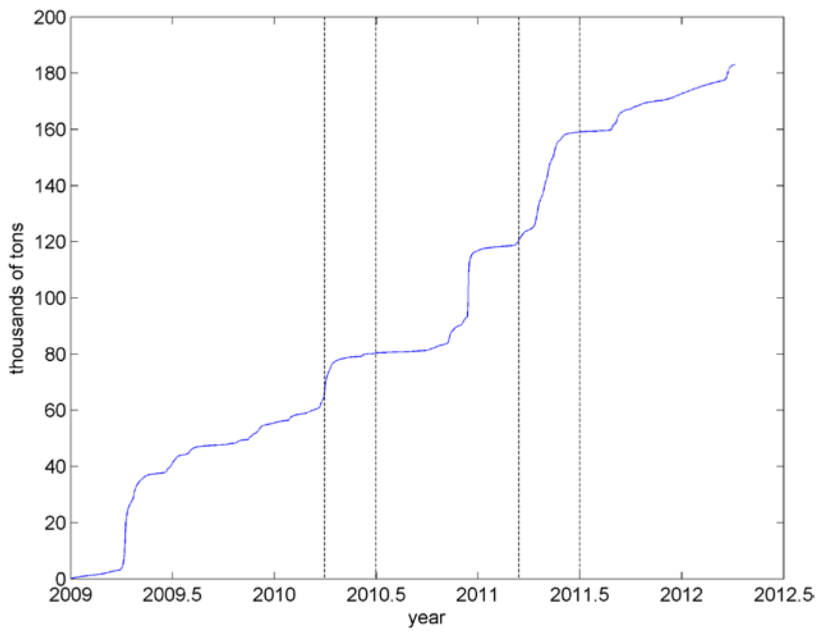


Figure 7-42. Cumulative sediment flux at Veazie Dam (2009-2011), based on discharge-concentration relationship. Vertical lines indicate the observation periods.

There may be other sources of loading of sediment to the estuary, such as bluff erosion and inputs from Penobscot Bay. The data from the Fort Point mooring indicate that the Bay is not a significant source of suspended sediment. Bluff erosion could be a significant source relative to watershed loading. For example, if 10% of the shoreline of the estuary were eroding 0.5 m/year, with a typical relief of 10 m, this would provide a loading of 45,000 cubic meters per year. At a mean bulk density of 1 ton/m^3, this would be comparable to the riverine input. However that rate would represent local widening of the river by 50 m in a century, which would be readily identified over the period of accurate surveying. The possible role of bluff erosion should be considered further, but it probably represents less than 30% of the total loading.

Another possible historical loading source is the wood products industry, which has provided a large input of saw dust and wood fragments over the last century, with the present rate probably much lower than the historical high. This loading is not relevant for the supply of inorganic sediment to the estuary, but wood chips and saw dust still represent a significant fraction of the mobile material in the estuary. For the present analysis we are not considering this source, however.

5.1.2 Sediment Export

The average concentration at Fort Point is approximately 3 mg/l, based on the moored data from 2010. The estimate was not strongly constrained by calibrations, as there were no bottle samples at Fort Point in 2010, and only two surface bottles in 2011, one with 8 mg/l and the other with 11 mg/l. These are higher than any of the 2010 near-surface estimates, so the calibration is suspect. However, these are still very low concentrations, and the survey data indicate that the high suspended sediment concentrations observed at the trapping zones fall out of the water column long before they reach the mouth of the estuary. We expect, with some uncertainty, that the concentrations are typically in the range of 5-20 mg/l, and also that near-bottom concentrations tend to exceed near-surface values. These estimates are also consistent with water sampling in 2006-7 in Fort Point Cove, where concentrations averaged 3 mg/L (Phase I report, Fig. 15).

An estimate of the sediment flux at Fort Point based on integrating the product of the velocity and the 2010 suspended sediment concentration actually indicates an influx of sediment, due to a net bottom inflow of around 0.05 m/s and stronger near-bottom than near-surface suspended sediment concentrations. However other studies have shown that the sediment flux depends strongly on lateral position in the estuary (Ralston et al. 2012), and so the flux at the Fort Point mooring may not be representative. It is possible that there is a fraction of very fine sediment that exits the system during high flow events, but this study does not provide direct evidence. Based on the available evidence, it is likely there is a slight import of sediment from Penobscot Bay, but this input would not have much relevance to the “mobile pool” of sediment 10 km farther up the estuary.

5.1.3 Estimation of the size of the mobile pool

A key question for determining the remediation of the estuary is to determine the size of the mobile pool, because it appears to be a major reservoir of Hg. The size of the mobile pool was determined based on the observed distribution of new mud in the estuary. Because the new mud was found to have relatively uniform Hg concentration, and the characteristics of the mud indicate recent deposition, we deemed that this constitutes the mobile pool of sediment. Wood chips were included in the estimate of the mobile pool. For class 3 (mixture of new mud and other material), we assumed that ½ of the sample was new mud.

The areal distribution of the new mud is reasonably well resolved by the grab sampling, but its depth was not well known. In some cases, the new mud extended over the entire 10 cm depth of the grab sample, and in other cases it only constituted several cm at the top. For the purpose of estimating the mass, we assumed that on average, the new mud was 5 cm thick. The uncertainty of that estimate is probably a factor of 2-i.e., it is probably not less than 2.5 cm and not more than 10 cm, averaged over the entire estuary, based on the grab samples. The estuary was divided into 12 segments, shown in Figure 7-38. The area of each segment was calculated from a numerical planimetric calculation.

Figure 7-6: Calculation of Mass of Mobile Pool

Segment	Area, km^2	Fraction new mud[1] or wood-chips	Mass in tons[2]
Upper	5.47	0.28	38,000
Winterport	2.47	0.18	11,400
Mendall	1.38	0.27	9,300
Frankfort	5.21	0.31	40,500
Bucksport	4.95	0.46	57,000
Verona west	7.88	0.33	65,700
Verona east	2.99	0.68	50,800
Orland	2.33	0.38	22,400
Verona south	1.99	0.46	22,900
Fort Point Cove	5.42	0.50	67,700
Lower	10.60	0.43	113,600
Total	52.09	0.38	499,100

[1] Assumes that mixtures of new mud and other material have ½ new mud

[2] Assumes 5 cm thickness, 500 kg/m^3 bulk density

Note that although the highest concentrations of mobile sediment occur between Bucksport and Frankfort, the largest mass of mobile sediment appears to be in the lower estuary. This is due mainly to the large area of the lower estuary. Unfortunately, this part of the estuary was not well resolved, so the calculation of mass is more uncertain for this region.

5.1.4 Estimated Residence time

We have estimated that on average, 43,000 tons of sediment are entering the estuary from the watershed. A large fraction of that sediment is incorporated into the mobile pool, but some fraction is sequestered in area of permanent deposition (such as on the surface of marshes), and some small fraction may leave the estuary as wash load. If we assume that 75% of the sediment that enters becomes incorporated into the mobile pool, we obtain a residence time of sediment in the mobile pool of

$$T_{res} = \frac{M_s}{Q_s}$$

where M_s is the mass of mobile sediment and Q_s is the input, 75% of 43,000 tons/year or 32,000 tons/year. Based on Figure 7-6, the pool size (from Bangor to Fort Point) is 500,000 tons (with an uncertainty of 50%, so T_{res} is 6 to 25 years, depending on the actual thickness of the mobile pool. This estimate is within the uncertainty of the geochemical calculations that have been provided by other members of the Study Group.

It is interesting to compare the rate of sedimentation to the regional sea level rise of 2-3 mm/y. The area of the estuary is 52 km^2, and using a bulk density of 0.5 tons/m^3, the average accretion is 1.2 mm/y (again assuming a 25% loss of input). Thus under the present sea-level rise conditions, there is more than enough accommodation space to keep up with sea level rise. The long term fate of the sediment is burial, but the energy of the estuary provides enough mobilization to retard the burial process by 1 to 2 decades.

5.2 Analysis of Sediment Resuspension and Flux

The tidal cycle surveys provide information about the spatial distribution of the velocity and suspended sediment for the different sampling intervals, and the moorings provide continuous records of velocity and suspended sediment at discrete locations through the estuary. In combination, the data can be used to quantify the tidal and residual fluxes of sediment through the estuary.

5.2.1 Near-bottom velocity

The near-bottom velocity is important for determining the bottom stress and the net direction of sediment transport, thus it is a key variable for assessing the transport and trapping of sediment. In the main stem of the river, the maximum near-bottom tidal velocities were around 1 m/s at the Winterport and Frankfort Channel moorings (Figures 7a-4 and 7a-5). Near bottom velocities are strongly modulated by the position of the salinity intrusion, which in turn depends on the river discharge and the tidal forcing. During periods of high discharge, the river flow pushes the salinity intrusion seaward, removing the source of the estuarine circulation that would otherwise drive landward near-bottom flow. The high river velocities also add to the seaward flux during ebb tides and retard flood tides. The estuarine circulation depends on the tidal amplitude, as strong turbulent mixing during spring tides breaks up the two-layer exchange. Combining these factors, near-bottom velocities in the estuary are enhanced in the seaward direction during high discharge periods and spring tides, and conversely landward near-bottom flow is enhanced during low discharge and neap tide periods. The evidence of this is most apparent at the Winterport and Frankfort Channel moorings in the upper estuary, where the presence of the salinity intrusion is variable and a narrow, shallow bathymetric cross-section increases the river and tidal velocities (Figures 7a-5 and 7a-6). In the lower estuary at the Verona Island and Fort Point stations, the salinity intrusion is always present and the estuarine circulation makes the near-bottom velocities always landward (Figure 7-6).

In the side embayments, the tidal velocities are much weaker, with maxima typically around 0.5 m/s (Figure 7-4). The Mendall Marsh and Orland River stations do exhibit a similar response of the near-bottom velocity to the seasonal variation in discharge, as early in the deployment the elevated river flow reduces the salinities and shifts the near-bottom velocities seaward compared with the lower discharge periods later in the deployment (Figures 7a-6 and 7a-8).

While the moorings provide excellent temporal coverage of the response of the near-bottom currents to changing forcing conditions, they are necessarily limited to fixed locations. To assess spatial variability, the shipboard ADCP can be used to provide a representative estimate of the near-bottom velocities, as it resolves to within 10% to 15% of the water depth, or roughly 1-2 m from the bottom. As seen at the mooring, the near-bottom currents in Mendall Marsh were generally less than 0.5 m/s, with the exception of ebbing near-bottom currents during the freshet, which reached 0.7 m/s near the mouth (km 4) (Figures 7a-25 to 7a-29). In the Penobscot River adjacent to Mendall Marsh, the strongest near-bottom currents occurred during the freshet ebb, during which they exceeded 0.8 m/s. In non-freshet and neap tide conditions, currents were generally less than 0.5 m/s.

For the Orland River, the both ebb and flood currents reached maxima of 0.3-0.5 m/s (Figures 7a-30 to 7a-33). Along the Penobscot channel to the south of Verona Island, maximum currents were slightly greater than 0.5 m/s. An apparent decrease in velocities during the April and June observations is mainly due to the lack of sampling during maximum ebb, although the May data indicate that the near-bottom currents were slightly flood-dominant.

Along the Verona line, the conditions during the freshet were not fully resolved during the ebb, but flood currents reached a maximum of ~0.8 m/s at the north end of the line. During non-freshet conditions (in May 2010), the flood currents exceeded 1 m/s at the north end of the line, and ebb currents reached 0.7 m/s. This difference between flood and ebb is due to the strong influence of the estuarine circulation at this location, which resulted in enhancement of the near-bottom inflow. The currents were significantly weaker at the south end of the Verona line, consistent with the wider and deeper cross-section.

5.2.2 Suspended Sediment

Tidal resuspension of sediment depends on the bottom stress and on the availability of bed sediment. The effect of the spring-neap variation in tidal velocity is evident in the near-bottom suspended sediment concentrations. At the Winterport and Frankfort Channel stations, concentrations range from 300 to over 1000 mg/L during spring tides, while concentrations are much lower during neap tides, typically less than 100 mg/L (Figures 7a-9 and 7a-10). The sediment availability depends on how much sediment has been input to the estuary recently by the river, and locally the availability of bed sediment depends on how much sediment has been trapped by the flow convergence associated with the salinity intrusion. Both factors likely contribute to the remarkably high sediment concentrations seen early in the record at Frankfort Channel, as the spring freshet supplied new sediment to the system and the intense frontal trapping (seen in the along-estuary surveys, Figure 7-16) focused sediment in that region of the estuary. Sediment concentrations are much lower in the lower estuary, due both to the weaker tidal velocities and to the fact that the sediment trapping in the upper reaches of the estuary limited the delivery of sediment to the lower estuary (see along-estuary surveys, Figures 7a-18, 7a-20, and 7a-22). Near-bottom sediment concentrations at the Verona Island mooring are higher than at Fort Point despite similar tidal velocities, consistent with the spatial gradient in available sediment associated with the trapping by the salinity gradient (Figures 7a-4 and 7a-10).

In the side embayments, sediment concentrations are lower than in the main stem, with maximum near-bottom concentrations around 200 mg/L during spring tides and less than 50 mg/L during neap tides (Figure 7-11). The spring-neap variability associated with the bottom stress is the dominant signal in mooring records, with seasonal shifts associated with the changing river discharge and locations of sediment trapping being more subtle. The survey data can be used to assess the location of trapping zones and how the trapping pattern varies with river discharge (Figure 7-35). During April, high suspended sediment concentrations are observed in the main stem of the Penobscot in association with the high loading of the river outflow. The only exception is the river to the SW of Verona Island. Moderate concentrations are observed in Mendall Marsh, but not in the Orland River. In the May observations, the concentrations are no longer elevated in the Penobscot near Frankfort Flats, but higher concentrations are observed at the north and south ends of Verona Island. These are regions of high velocity where tidal resuspension is intense. In June, the concentrations are generally lower than May, apparently due to shifting of the salinity intrusion farther landward and due to winnowing of the available sediment by deposition in lower energy environments.

5.2.3 Sediment fluxes

Combining the velocity and suspended sediment data provides an indication of how sediment moves through the estuary. At the Frankfort Channel mooring in 2011, the tidally averaged sediment fluxes are strongly seaward during the high discharge and spring tide periods early in the record (Figure 7-43), top panel). During neap tides early in the deployment the direction of net sediment flux reverses to be landward, and as the discharge decreases later in the deployment the net fluxes are almost entirely landward. Integrating the fluxes at Frankfort Channel, the spring tides during high discharge move 40,000 to 50,000 tons seaward, similar to the entire annual input from the river at Veazie Dam in an average year. The amplitude of the fluxes decreases during the lower discharge period of May and June, but cumulatively the landward transport moves a similar mass of sediment back up the river over this period.

Note that these flux calculations used the velocity profile from the ADCP and suspended sediment observations from surface and bottom OBSs, so assumptions were required for vertical profile of suspended sediment. The sediment profile can be related to settling velocity, and the results shown here span a range of settling velocities from 0.5 to 2 mm/s, the typical range of settling velocities inferred from bottle samples taken during the CTD surveys. Greater settling velocities lead to higher near-bed sediment concentrations, and consequently more landward flow due to the estuarine circulation. The flux calculations have additional uncertainty in that they do not incorporate lateral gradients in velocity or sediment concentration, which have been shown in other estuaries to be important. However, the central concept of a seasonal cycle of seaward fluxes during high discharge and landward fluxes during low discharge is robust.

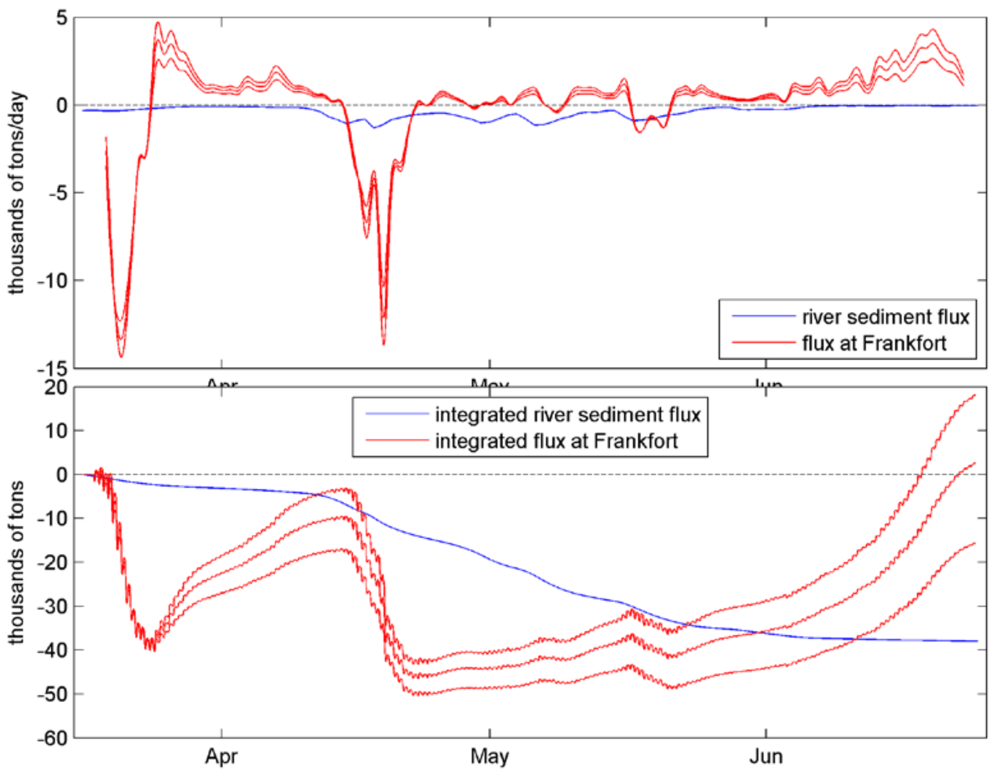


Figure 7-43. Sediment flux at Frankfort Channel mooring, 2011. (top panel) Tidally averaged fluxes (red) using different assumptions for sediment settling velocity (between 0.5 and 2 mm/s), along with sediment input at Veazie Dam (blue). (bottom) Cumulative sediment fluxes with the same assumptions. Seaward fluxes are negative.

The mooring at Winterport in 2010 tells a similar story. The maximum discharge was at the beginning of the deployment, corresponding with strongly seaward sediment flux (Figure 7-44). As discharge decreased, sediment flux shifted landward with the return of the salinity intrusion in the second half of the deployment. In this case, the fluxes past Winterport during the first month of the deployment were several times greater than the sediment input over the dam during that period, likely indicating remobilization of sediment from the tidal river upstream of Winterport that had been deposited during previous low discharge periods. Note that the net sediment flux is the difference between the ebb and flood phases of the tide, which can be seen as the wiggles in the plot of cumulative sediment flux (Figure 7-44). The tidal fluxes are much greater than the tidal average, particularly during spring tides, presenting observational challenges.

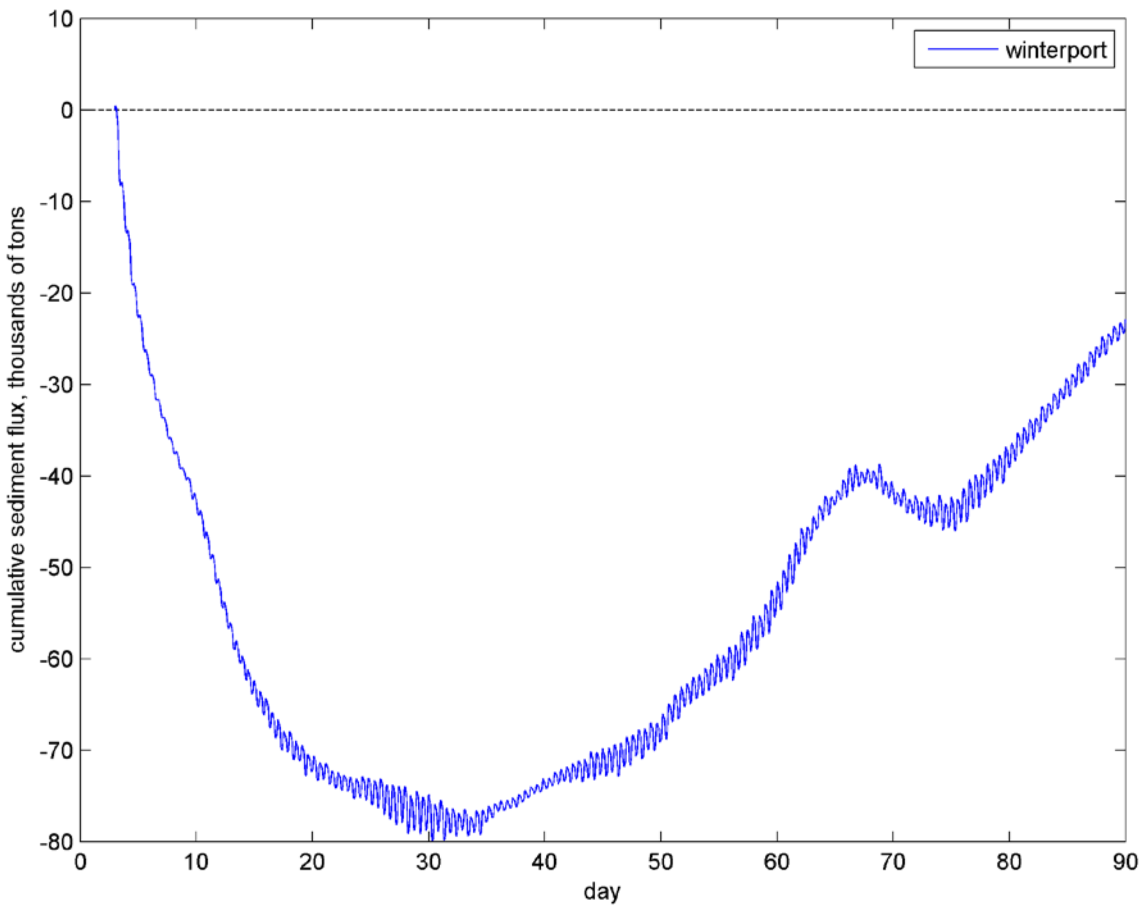


Figure 7-44. Cumulative sediment flux at Winterport mooring, 2010 . Seaward fluxes are negative.

In the side embayments, the initial seaward flux of sediment during the high discharge period is not as pronounced because the local inputs of runoff and sediment are much less for the Mendall Marsh and Orland River embayments than the main stem of the river (Figure 7-45). At the beginning of the deployment in 2010, discharge from the local watersheds of Mendall and Orland produced net flux out at each mooring, but as the local discharges decreased, the sediment fluxes in both system became landward. The pattern is similar at the main stem moorings, but the integrated fluxes at Winterport and Frankfort Channel nets out to be around zero over the deployment periods. In contrast, the side embayments are depositional regions where integrated sediment fluxes are strongly landward. The cumulative fluxes by the end of the deployment were calculated to be 500 to 1000 tons. This mass of sediment is small compared to the integrated fluxes in the main stem, but it is much larger than the fluxes coming from the local watersheds. This is consistent with the idea that Penobscot River sediment is trapped in the main stem at frontal regions in the vicinity of these two side embayments, and tidal processes deliver relatively high concentrations during flood tides that lead to permanent deposition in Mendall and Orland. These results are also consistent with other observations in the study that Mendall Marsh is a net sink for particles from the main stem of the Penobscot River (see Chapter 10).

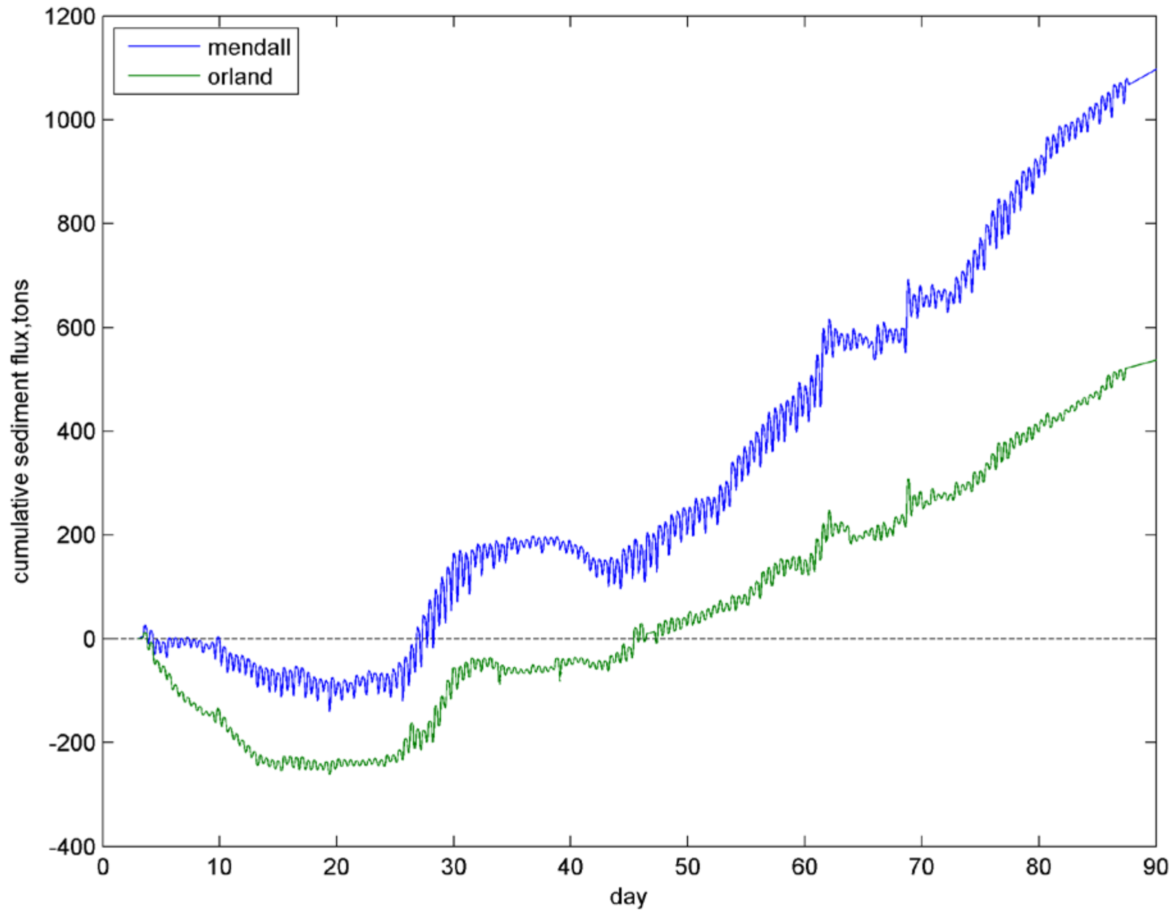


Figure 7-45. Cumulative sediment flux at Mendall Marsh and Orland River moorings in 2010. Seaward fluxes are negative.

6 REFERENCES

Ralston, D.K., W.R. Geyer, and J.C. Warner. 2012. Bathymetric controls on sediment transport in the Hudson River estuary: lateral asymmetry and frontal trapping. Journal of Geophysical Research. 117, C10013, doi:10.1029/2012JC008124.