

Cooperating Parties Group

LOWER PASSAIC RIVER RI/FS NEWARK, NEW JERSEY

APPENDIX M SEDIMENT TRANSPORT MODEL OF THE LOWER PASSAIC RIVER

Prepared by:



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1.0 INTRODUCTION

The RI/FS of the Lower Passaic River Study Area (LPRSA) conducted by the Cooperating Parties Group (CPG) includes the development of a Sediment Transport (ST) model of the Lower Passaic River (LPR) and Newark Bay (NB). The CPG's model development and calibration process followed the approach outlined in the LPR and NB Modeling Work Plan (MWP) documents (HydroQual 2006a, and HydroQual 2006b). Region 2 was periodically updated on the CPG's ST modeling efforts through presentations at the Semi-Annual Modeling Meeting and Modeling Collaboration Meeting forums. In addition, the CPG's ST system understanding, model development, and model calibration and performance were summarized in a report submitted to Region 2 in January 2013 (Moffatt & Nichol and Deltares, 2013). On April 5, 2013, Region 2 provided several comments to this report (US EPA, 2013). The CPG subsequently incorporated several of Region 2's comments, and made further refinements to the model setup and parameterization in an effort to improve model parameterization and performance. The revised ST model was documented in a memorandum provided to Region 2 in August 2014 (Moffatt & Nichol and Deltares, 2014), with comments received from Region 2 on November 18, 2014.

This report combines the information provided in the January 2013 report and the August 2014 memorandum and aims to provide a comprehensive documentation of the CPG's ST model setup, parameterization, and calibration performance. Additional model tests and simulations performed in response to comments made by Region 2 are also included. Note that the contents of this report are restricted to the ST model application to the LPRSA. The NB portion of the model has been refined to include certain processes specific to NB such as the impact of wind waves and navigation scour, as well as site-specific data collected in NB for model inputs such as sediment erodibility. The model refinement and application to NBSA is documented in the NBSA hydrodynamic and sediment transport model addendum (Moffatt & Nichol and Deltares, 2017). The remainder of this report describes the CPG's system understanding as it pertains to sediment transport in the LPRSA based on several lines of evidence including measurements in the water column, sediment, and bathymetry. Following the discussion of the system understanding, the ST model setup, calibration and results are presented.

2.0 SEDIMENT TRANSPORT SYSTEM UNDERSTANDING

The development and application of a model for a given site usually involves an assessment of the major processes relevant to the problem to be addressed with the model. In the case of the ST model described in this document, this assessment has been carried out using a number of datasets and tools, in particular:

- The hydrodynamic (HD) model developed by Region 2 (HydroQual 2008),
- A high-resolution HD model developed by the CPG,
- Data collected by Sommerfield and Chant (2010) at RM 1.4 as part of their Newark Bay monitoring study,
- Data from the Fall 2009 Physical Water Column Monitoring (PWCM) program,
- Data collected by Dr. Robert Chant of the Institute of Marine and Coastal Science, Rutgers University during a low-flow period in 2004 and during a 1 in 25-year event in March 2010,
- Data from the 1949 post-dredge bathymetric survey and 1966 bathymetric conditions survey, and
- Data from the 2007, 2008, 2010, 2011, and 2012 multi-beam bathymetric surveys.

The analyses allow for an empirical understanding of ST processes in the LPRSA, describe the major sediment transport processes to be reproduced by the model, and provide calibration targets for the ST model. This section describes the spatial domain, and the results of analyses to understand the major processes relevant for sediment transport in the LPRSA.

2.1 Spatial Domain

The spatial domain of the ST model is the same as the model grid developed for the HD model described previously in Appendix L. The domain includes the 17.4-mile tidal stretch of the LPR extending from Dundee Dam to its mouth in Newark Bay, the Hackensack River (including the Meadowlands wetlands) from Oradell Dam to its mouth in Newark Bay, Newark Bay, and the tidal inlets to Newark Bay, namely the Arthur Kill extending to Raritan Bay and the Kill van Kull extending to upper New York bay (Figure 1). In addition to the discharge and suspended sediments (SS) entering from the freshwater and open boundaries listed above, several minor tributaries (Second River, Third River, Saddle River), combined sewer outfalls (CSO), and storm-water outfalls (SWO) also discharge into the LPRSA.

Historically, the LPR was extensively used for shipping and dredged to depths well below the pre-industrial conditions (Chant et al. 2011). The reach above RM 6.8 in the LPR was last dredged in 1932 and between RM 6.8 – 2.5 in 1949. The navigation channel in the lower reach (RM 0 – 1.5), however, was dredged as recently as 1983. Following the decline of shipping activities in the LPR, the navigation channel was not maintained and has subsequently infilled with sediments. Areas of ongoing dredging are limited to isolated berthing facilities at the mouth of LPR, along with maintenance and capital dredging in the lower half of NB, the Kill van Kull, and Arthur Kill.

The model grid used for representing this network of inter-connected water bodies is shown in Figure 1; it derives from the grid developed by Region 2 for the HD model (HydroQual 2008). Within the LPR, the average grid size is 40 m wide and 180 m long, with the river typically represented with 4 cells across (decreasing to 3 cells above RM 4.4, and 2 cells above RM 15.7), and the former navigation channel represented by 1-2 cells. Lateral bathymetric gradients in the LPR are often steep, ranging from about 25 ft. below NGVD in the deepest parts of the former navigation channel, to a few feet below NGVD on the shallows, to NGVD in the intertidal areas. With only 4 cells to represent this wide range of depths, the HD model cannot reproduce the flow patterns, velocities, and shear stresses in great detail, especially in the vicinity of features such as river bends, and in-water structures such as bridge abutments. Furthermore, several of the erosional and depositional features that have been observed in the analysis of the recent multi-beam bathymetries (described subsequently) are sub-grid scale features compared to the size of the individual model grid cells. For these reasons, the ST model cannot be expected to fully resolve the spatial heterogeneity of the features and processes observed in the data. In order to develop a better understanding of the shear stress regime within the LPRSA, a high resolution HD model was developed as described in the following section.

2.2 High Resolution HD Model

A high-resolution HD model was developed in order to better quantify the distribution of velocities and shear stresses within the LPR. The increased resolution was necessary to resolve features and processes such as secondary flow in river bends, cross-channel variability in flow patterns, and the presence of in-river structures such as bridge abutments. While the spatial extent of the high resolution HD model was maintained the same as the ST model, the resolution was increased by roughly 4-5 times and 2-3 times in the longitudinal and lateral directions, respectively, in the LPR (average grid size is 18 m wide and 42 m long). The model bathymetry within the LPR was based on the USACE single-beam survey conducted in 2004.

The model was calibrated to hydrodynamic data (water levels, velocities, and salinity) collected by Rutgers University in 2004 (dataset also used for the calibration of the LPR/NB HD model; HydroQual 2008) which covered flows ranging from a few-100 cfs to 3000 cfs (for comparison the long-term average flow at Dundee Dam is estimated as 1200 cfs). The trade-off for higher grid resolution is increased simulation times, and consequently the high-resolution model could not be applied for a long-term simulation.

Rather, the calibrated high-resolution model was applied to a series of constant river discharges covering typical spring-neap tidal cycles to obtain shear stress maps under varying conditions. These maps also formed the basis of a look-up table of predicted shear stresses as a function of tide and discharge, which was used to estimate shear stresses for the high-resolution grid over a 20-year period beginning in 1989. These maps were used for an assessment of the spatial and temporal distribution of shear stresses and to inform the system understanding analyses.

Note that although a constant bathymetry (corresponding to the 2004 time-frame) was used in the high-resolution model, in general, within the LPR, temporal changes in bathymetry are small compared to the overall water depth, even after an extreme event such as Hurricane Irene. Hence, yearly variations in bathymetry will not strongly affect the overall flow patterns, although locally flow velocities and bed shear stresses may be affected.

2.3 Transport Processes

Hydrodynamic transport processes within the LPR are controlled by the tides, estuarine circulation, and freshwater discharge. Semi-diurnal tides entering Newark Bay through the Kill van Kull and Arthur Kill propagate through NB to LPR and to the head-of-tide at Dundee Dam. The tide propagates as a standing wave within the LPR, with maximum tidal currents typically occurring mid-tide. In addition to being a tidal river, the LPR is also an estuary, where freshwater inflow from Dundee Dam and other freshwater tributaries interfaces and mixes with the salt water propagating from NB. The difference in density associated with freshwater and saltwater causes a density-driven flow circulation referred to as estuarine circulation. The zone of transition from freshwater to brackish, referred to as the salt front, is also typically associated with the Estuarine Turbidity Maximum (ETM), a region characterized by relatively high SS concentrations (SSC) and sediment trapping (Dyer 1997). The salt front represents the upstream-most extent of the estuarine circulation process, and therefore the upstream-most extent of the SS originating from the down-estuarine portion of the river.

Hydrodynamic and sediment transport during normal tidal and discharge conditions in the LPR are also characterized by tidal asymmetry, with higher velocities and SSC during flood than on ebb. The combination of estuarine circulation and tidal asymmetry results in landward directed tidally-averaged near-bottom SS fluxes within the salt wedge (near-surface SS fluxes may be directed up- or down-estuary depending on the magnitude of freshwater flow) and directed seaward in the freshwater section. In addition to the tidal and estuarine processes, the LPR is also influenced by fluvial processes associated with freshwater inflow from Dundee Dam. During episodic high-flow events, the system is typically characterized by localized erosion (and deposition) within the LPR and export of sediments from the LPR. In contrast, the tidal and estuarine processes during low-flow conditions typically tend to be associated with the import of sediments from NB to the LPR and accumulation within the LPR. Given the bi-directional nature of the net SS flux within the LPR as a function of freshwater discharge, the exchange between the LPR and NB becomes an important element of the sediment dynamics within the LPR. Each of these

processes is further examined in the following sections. Although some of these processes relate to the hydrodynamics of the system, given its importance to sediment transport, they are described here in some detail.

2.3.1 Freshwater Inflow

HydroQual (2008) describes the various sources of freshwater inflow into the LPRSA. Dundee Dam, with an annual average discharge of 1200 cfs (calculated by drainage area proration from the long-term average discharge at Little Falls of 1140 cfs) represents the major source of freshwater entering the system, with several minor tributaries (Saddle River, Second River, Third River) contributing about 10% of the flow entering from Dundee Dam. Various CSOs and SWOs also contribute flow, primarily during rainfall events. The freshwater inflow from Dundee Dam follows seasonal trends, with low-flow periods typically in summer and fall, and high-flow periods typically in winter and spring. High-flow events are typically associated with rainfall and hurricane events, with peak discharge during such events reaching several times the annual average discharge. Appendix L describes the results of a discharge return frequency analysis. Accordingly, a 1 in 2-year event corresponds to a discharge of 7100 cfs, 16,000 cfs (similar to a discharge event occurring on March 16, 2010; an event with suitable data for use in model development) corresponds to a return period of 25-years, and Hurricane Irene in August 2011 with peak discharge of 20,800 cfs at Little Falls corresponds to a return period of 90-years.

2.3.2 Tidal Asymmetry – Currents

Tidal systems such as the LPR are characterized by periodic (semi-diurnal in this case) fluctuations in water level associated with the tide. The water level fluctuations also translate to similar fluctuations in flow (or alternatively the velocity), with flow directed up-estuary during the incoming or flood tide (period of increasing water levels in case of the LPR), and directed seaward during the outflowing or ebb tide (period of decreasing water levels in case of the LPR). In a purely tidal system, the volume of inflowing water on flood is balanced by the volume of outflowing water on ebb. However, the flow rates associated with flood and ebb need not be equal or symmetric. Flood and ebb velocities are a function of the duration of the flood and ebb phases, which can be influenced by the distortion of the tidal wave due to factors such as non-linearities in the propagation velocity of the tidal wave, reflection of the tidal wave at the head-of-tide, frictional effects, and intertidal storage (Friedrichs and Aubrey, 1988). The resulting inequality in peak flood and ebb currents is referred to as tidal asymmetry in currents, with the exact direction of the asymmetry (flood- or ebb-dominance) dependent on the system characteristics.

Figure 2, which includes data at several locations (shown with red circles in Figure 1) collected during the Fall 2009 PWCM ADCP and CTD sensors, shows the tidal asymmetry within the LPR. The information on the lower 5 panels represents the difference of the peak flood and peak ebb currents every tidal cycle, measured at the surface and the bottom (typically about 4' to 5' above the bed) of the water column at various locations within the

LPR, with positive values directed up-estuary and negative values directed down-estuary. The near-bottom (3' above the bed) salinity measurements at each location are also included on the corresponding panels. Note that the tidal asymmetry shown in Figure 2 also includes the contribution due to estuarine circulation discussed in the following section. In general, during normal tidal and discharge conditions, the stations within the lower 8 miles exhibit flood-dominant tidal asymmetry (more so for near-bottom currents than surface currents). Near-bottom tidal asymmetry at a given location is also a function of discharge, exhibiting flood-dominance at low discharge, with the magnitude of asymmetry decreasing and transitioning to ebb-dominance at higher discharges as the tidal currents are modified by increasing freshwater flow which is directed down-estuary. In contrast, the station at RM 10.2 shows flood dominance only during the low-flow (discharge of approximately 200 cfs) period at the beginning of the deployment. During the remainder of the deployment RM 10.2 and RM 13.5 (for the entire deployment) exhibit ebb-dominance. This tidal asymmetry in currents is of relevance given its importance to sediment transport, with the SSC exhibiting a similar asymmetry as discussed in a following section.

2.3.3 *Estuarine Circulation*

In addition to the periodic tidal fluctuations in water levels which drives the tidal exchange of water between LPR and NB, hydrodynamic transport within the LPR is also subject to salinity-driven circulation. Measurements along the thalweg of the LPR and NB show a pronounced longitudinal gradient in salinity, with relatively high salinity in NB, and decreasing with distance up-estuary into the LPR. Because of the density differences between saltwater and freshwater, the freshwater discharge from Dundee Dam tends to flow on top, subject to turbulent mixing with the denser saltwater entering from the Kill van Kull and Arthur Kill, resulting in a partially mixed water column within the LPR. The pressure gradient induced by the longitudinal salinity gradient generates a tidally-averaged near-bed flow directed up-estuary, and a tidally-averaged near-surface flow directed seaward – this is referred to as estuarine or gravitational circulation, and the mass flow induced is balanced by vertical mixing and entrainment processes.

Estuarine circulation is apparent when examining the tidally-averaged residual currents within the LPR. Figure 3 shows the vertical profile of the tidally-averaged (averaged over two tidal cycles in order to account for the inequality in the semi-diurnal tides) currents at various locations within the LPR on October 15 (data from the Fall 2009 PWCM ADCP moorings). The depth associated with the instantaneous current profiles was normalized by the instantaneous water depth at each station to enable a comparison over stations of variable water depths. During this period, the salt front is located in the vicinity of RM 10.2, and as a result, residual current profiles show near-bottom currents directed up-estuary at all the estuarine stations (RMs 1.4, 4.2, 6.7), with the estuarine null point (the location where the tidally-averaged bottom current is zero; Sommerfield 2011) located in the vicinity of RM 10.2. In contrast, near-surface currents at all locations as well as the entire profile at RM 13.5 are directed down-estuary. Figure 4 shows the time-series of the near-bottom and near-surface residual currents (calculated as the average over two tidal

cycles) at these same locations over the period of the entire deployment, with positive values directed up-estuary and negative values directed down-estuary. The near-bottom (3' above the bed) salinity measurements at each location are also included.

The direction of the near-bottom residual current is dependent on the salt front location – seaward of the salt front, near-bottom residual currents are directed up-estuary and landward of the salt front, near-bottom residual currents are directed down-estuary. The near-bottom residual current directed up-estuary reflects the influx of salt water driven by estuarine circulation. These features are most apparent at RM 6.7 which is the most dynamic location with respect to estuarine circulation over the deployment. From the beginning of the deployment through October 24 when the salt front is located landward of RM 6.7, residual near-bottom currents are directed landward (indicating estuarine circulation), and transitioning to seaward directed (indicating a freshwater dominance) as the salt front is pushed down-estuary with the discharge event on October 25. Subsequently, as discharge decreases and the salt front moves landward of RM 6.7 around November 10, near-bottom residual currents transition back to being landward-directed before changing direction with the discharge events starting on December 3. Some exceptions such as the sea-ward directed near-bottom currents at RM 6.7 between November 7 and 10 even when the salt front is located up-estuary of this location may be due to the fact that the salinity was measured at a slightly deeper point (about 1.5' deeper) in the water column than near-bottom currents.

2.3.4 Salt Front Dynamics

As indicated by the analyses in the preceding sections, the location of the salt front is indicative of a transition in the LPR from a tidal estuarine system to a tidal riverine system. The location of the salt front varies spatially and temporally. For discussion purposes in this section, the salt front is taken to be the location of the 2 ppt isohaline at the bottom of the water column. During normal tidal and discharge conditions, the salt front is within the LPR, at a location dependent on the freshwater discharge, inter-tidal timing (spring/neap), intra-tidal timing (flood/ebb), and offshore set-up/set-down events.

The HD model was used for an analysis examining the dynamics of the salt front location. This analysis has been discussed previously in Appendix L and is summarized here for completeness. Figure 5 shows the location of the salt-front as a function of the river discharge. The salt-front is situated up-estuary of RM 5 when discharge at Dundee Dam is below the annual average of 1,200 cfs (HydroQual 2006a; 1,140 cfs at Little Falls with drainage-area proration to calculate discharge at Dundee Dam). The salt-front location is pushed seaward with increasing flow and at 2,000 cfs it is found on average near RM 3. During a 1-year return flow of about 6,000 cfs, the salt front is pushed below RM 2, while a 5-year return flow of about 10,000 cfs pushes the salt front below RM 1, where the river widens rapidly. The location of the salt front is also a function of the tidal cycle, moving up-estuary during flood and moving down-estuary during ebb, with tidal excursion lengths on the order of 2.5 to 4.5 miles from low to high tide. The salt front location is also a function of spring-neap cycle, on average (tidally averaged) further up-estuary on neap

than on spring, primarily due to higher vertical mixing and lesser salinity stratification during spring tides than neap tides.

2.3.5 Tidal Variability and Asymmetry – SSC

Under normal tidal and discharge conditions, SSC data exhibit tidal asymmetry, intra-tidal variability, and inter-tidal variability driven by similar fluctuations in velocities. This is seen from a detailed examination of SS dynamics from the Fall 2009 PWCM deployment as shown in Figure 6. Figure 6 displays the near-bottom velocity (from the ADCP sensor, ~4-5ft above the bed), the near-bottom salinity (from the CTD sensor, 3ft above the bed), and near-bottom SSC (from measurements of Acoustic Backscatter, ABS, converted to SSC; see Attachment A for a discussion of SSC derived from ABS measurements) over a two-day period starting on October 13, 2009. Periods of flood and ebb currents and corresponding SSC have been distinguished by blue and red symbols respectively. As seen from Figure 6, under normal tidal and discharge conditions, SSC tend to closely follow the temporal variation in velocity, increasing as velocity increases, reaching a peak around maximum flood/ebb velocity, decreasing thereafter as velocity decreases, and reaching a minimum around slack-water when velocity is near-zero. As a consequence of the tidal asymmetry in velocities described previously, SSC are higher during flood than on ebb for all locations within the salt wedge (RM 1.4, 4.2, 6.7, and 10.2). In combination with a similar asymmetry in velocities, the asymmetry in SSC represents a net near-bottom landward SS flux (integrated over the tidal cycle) and is discussed in further detail in a following section. In contrast, the freshwater station (RM 13.5) shows relatively smaller variability in SSC within the tidal cycle and no coherence with respect to velocity fluctuations.

The intra-tidal variability in SSC and its correspondence with similar variability in velocities during both flood and ebb tides for all locations within the salt wedge is also indicative of the bed-water exchange processes. The rapid increase in SSC during the accelerating phase of the flood/ebb tide followed by the rapid decrease on the decelerating phase indicates resuspension and deposition from/to the sediment bed over tidal time-scales. This periodic resuspension/deposition is indicative of a pool of easily erodible sediment, termed a fluff layer, deposited on the bed during slack water and resuspended during the following flood or ebb tide. Similar sediment dynamics have been observed in other tidal and estuarine systems (Maa et al. 1998, Van Kessel et al. 2007, El Ganaoui et al. 2004, Wang 2003). Using the range in depth-average SSC within the flood tide of ~50 to ~150 mg/L at the various locations within the salt wedge, with tidally-averaged water depth of 5 m, and assuming a dry density of 300 Kg/m³ results in estimated fluff layer thickness of approximately 1-3 mm. The sediment mass contained within this fluff layer is more or less in equilibrium with the sediments suspended in the water column every tidal cycle.

The SSC data also exhibit inter-tidal variability. Figures 7 & 8 show the daily average surface and near-bottom SSC at various locations from the Fall 2009 PWCM data (Figure 7), and at RM 1.4 by Sommerfield and Chant (2010) in 2008-2009 (Figure 8). Both datasets

show spring-neap variability in SSC, with higher SSC during spring tides (tidal range of ~2m) than during neap tides (tidal range of ~1m) at all locations within the predominantly estuarine portions of the river (RMs 1.4, 4.2, and 6.7 during this deployment). This variability is driven by a similar variability in velocity over the spring-neap cycle. This dependency is indicative of a stronger bed-water column exchange of fines during spring tide, and/or more intense mixing over the water column. Furthermore, the time-series at RM 1.4 (Figure 7 second panel from top, and Figure 8) shows that SSC vary within a relatively constant range (~10-25 mg/L from neap to spring) when Dundee Dam discharge is less than ~2000 cfs. Only when discharge exceeds ~2000 cfs for some extended period (starting on December 5, 2009 in Figure 7, and between December 12, 2008 and January 15, 2009 in Figure 8) does SSC exceed the range of ~10-25 mg/L. This suggests that the bed-water exchange within the LPRSA is dominated by the fluff layer dynamics up to discharge of ~2,000 cfs at Dundee Dam, with suspended solids concentrations increasing as discharge increases beyond ~2,000 cfs. Comparing to the annual average discharge of 1,200 cfs at Dundee Dam suggests that fluff layer dynamics dominates sediment transport within the LPR most of the time. The response at discharge higher than ~2,000 cfs may indicate a combination of higher SS load from Dundee Dam and/or erosion of the more consolidated sediments underlying the fluff layer. Note that as the inflow from Dundee Dam increases, ebb-directed velocities increase as well.

2.3.6 *Estuarine Turbidity Maximum*

The hydrodynamic processes described previously (freshwater inflow and estuarine circulation) contribute to formation of an estuarine null point, the location where the near-bottom tidally averaged current is zero and which is typically associated with the location of the salt front within the LPR. Figure 3 shows the location of the estuarine null point in the vicinity of RM 10.2 on October 15, 2009, a location also coincident with the salt front during this time period. These processes, in combination with the net landward transport of SS (near-bottom) through the salt wedge and the delivery of SS from the head-of-tide at Dundee Dam, induce a convergence of fine sediments around the estuarine null point for fine sediments originating from both up-estuary (Dundee Dam) and down-estuary (Newark Bay) and all other sediment inputs. The resulting feature is referred to as the ETM and is characterized by relatively high SSC and is an area associated with sediment trapping (Dyer 1997). The ETM location at any given time is a function of the freshwater inflow, the spring-neap cycle, the tidal cycle, and offshore set-up and set-down events, moving up- and down-estuary in a manner analogous to the salt front.

Several data sources indicate the presence of a well-defined ETM associated with the salt front within the LPR and NB. Shipboard measurements of salinity and SSC along longitudinal transects of the LPR and NB (Chant et al. 2011) as well as analyses of the SSC measured during the Fall PWCM (Mathew et al. 2011) show both the presence of the ETM in the vicinity of the salt front, as well as the dynamic nature of the ETM location and concentrations. Figure 9 shows the salinity contours, and SSC measured during two different discharge conditions, the upper panel during low-flow conditions (June 23, 2005 with discharge of 250 cfs at Little Falls), and the lower panel during high-flow conditions

(16,000 cfs storm-event on March 16, 2010; both datasets measured by Dr. Robert Chant of the Institute of Marine and Coastal Science, Rutgers University). Both transects show higher SSC in the vicinity of the salt front than at locations up- or down-estuary of the salt front. During the low-flow survey, both the salt front and the ETM are located at RM 7, with depth-average SSC of ~ 75 mg/L within the ETM. In contrast, during the high-flow survey, the salt front and the ETM are pushed to RM 0 with much higher depth-average SSC of ~ 250 mg/L, a likely consequence of the higher river discharge combined with some resuspension. Around the slack phase of the tide, as flow velocities and shear stresses decrease, suspended sediments deposit from the water column, with the highest deposition fluxes expected within the ETM.

2.3.7 *Residual SS Transport*

The residual SS flux, calculated by integrating the instantaneous SS fluxes (calculated as the product of the instantaneous SSC and flow velocity) over tidal time-scales or longer gives an indication of the large-scale SS transport within the LPR and its dependency with various forcings. The residual SS flux integrates the effect of transport due to river flow, estuarine circulation, and tidal pumping (which includes the effects of tidal asymmetry, internal asymmetry, and slack tide asymmetry). The direction and magnitude of the net daily depth-integrated SS fluxes computed using paired measurements of SSC (estimated from ABS measurements) and velocities from the moored ADCPs during the Fall PWCM are shown in Figure 10 as a function of the measured daily discharge at Dundee Dam. Both SSC and velocity profiles measured by the ADCPs have been extrapolated to the unmeasured depths at the near-bottom and the near-surface of the water column (linear extrapolation in case of the former, assuming zero shear at the water surface for extrapolation of velocity to the unmeasured near-surface depth, and assuming a log-velocity profile for extrapolation of velocity to the unmeasured near-bottom depth). The ADCP measured vertical structure of the velocity and SSC have not been extrapolated across the width of the river; rather the fluxes are expressed per unit width of the river. In addition to the Fall PWCM data, data collected at RM 1.4 during 2008-2009 by Sommerfield and Chant (2010) have also been analyzed and are presented in Figure 10. At all the locations within the predominantly estuarine sections of the river (RMs 1.4, 4.2, and 6.7 during this deployment), below a certain discharge threshold, SS fluxes are directed up-estuary. Only at the freshwater station (RM 13.5) is the net flux consistently directed seaward. The discharge associated with the inflection in the direction of SS fluxes decreases in the landward direction, thus indicating the dominance of fluvial processes over tidal/estuarine processes at lower discharges with distance up-estuary. It should be noted that even though the daily depth-integrated SS flux at a given location may be directed seaward for a given discharge, near-bottom SS fluxes may still be directed landward as a consequence of estuarine circulation and/or tidal pumping. Moreover, the data in Figure 10 with respect to up-estuary transport may be conservative since the ADCP moorings being mounted on a tripod on top of the bed, does not measure the near-bottom depth interval which is approximately 20-25% of the total water depth. In addition, near the bed, SSC are high, and hence sediment flux would be high.

2.3.8 Exchange with Newark Bay

Given the availability of long-term monitoring data, for purposes of this document, the exchange between the LPR and NB is characterized at RM 1.4 in the LPR. Because of the tidal pumping and estuarine circulation processes described previously, the exchange between the LPR and NB is an important element of the solids balance for the LPR. Both the datasets presented in Figure 10 show that at RM 1.4, below a certain discharge threshold, the net-depth integrated SS fluxes are directed from NB into the LPR, i.e. infilling regimes, with net export from the LPR at higher discharges, i.e. exporting regimes. The exact discharge threshold associated with the inflection in net SS flux is slightly different for the two datasets, ~750-1000 cfs in case of the 2009 Fall PWCM data and ~1000-1500 cfs in case of the data collected by Sommerfield and Chant (2010). The data collected by Sommerfield and Chant (2010) were collected as part of an independent effort separate from the LPRSA RI process and so the difference with the PWCM data may in part be related to differences in the mooring locations, the quality of the correlation between ABS and SSC used to estimate SSC from the ABS measurements, sampling and analytical protocol used for the measurement of SSC used for developing the correlation of ABS and SSC, etc. Nonetheless, both datasets show the same general process, of the LPR importing solids from NB during low discharge conditions and exporting to NB under high discharge conditions. Furthermore, as mentioned in the preceding section, both datasets are likely conservative with respect to the river discharge associated with the transition in the direction of the net SS exchange between NB and LPR.

2.3.9 Infilling

In addition to SS data, several recent and historical bathymetric datasets show evidence of infilling within the LPR. Attachment B includes a detailed description of the analysis of the historical bathymetries summarized here. Historic data sources include the 1949 post-dredge bathymetry between RM 2.5 and RM 6.8, the 1966 bathymetric survey¹ between RM 2.3 and RM 7.8, and the 1983 post-dredge bathymetry between RM 1.5 and RM 0. Recent datasets include the 2007, 2008, 2010, 2011 and 2012 multi-beam bathymetries. Comparison of these historic bathymetries to the current conditions shows accumulations of as much as 15 ft. within the dredged channel. Comparison of the recent multi-beam bathymetries also shows infilling within the LPR during low-flow periods (described in further detail in the following section). The Environmental Dredging Pilot Study (EDPS; MPI 2007a) also showed rapid infilling of the excavation pit following the completion of dredging, at rates up to 3 mm/day.

2.3.10 Current Morphological Behavior

Attachment B includes an analysis of the various recent multi-beam bathymetries collected in the LPRSA as part of the RI process (2007, 2008, 2010, 2011 and 2012) and is

¹ The 1966 conditions bathymetry is generally consistent with the depth of the cesium peak measured in the CLRC (AECOM 2010) and Tierra (CLH 1995) coring programs

summarized here. The bathymetric surveys spanned a wide range of discharges at Dundee Dam, ranging from low flows of a few hundred cfs, to a 1 in 25-year event (16,000 cfs in March 2010 and 2011), and a 1 in 90-year event (Hurricane Irene in August 2011). The bathymetric data and the bathymetric changes over these varying discharge conditions allow for the evaluation of sediment dynamics in the LPR from a morphological perspective and provide confirmation of the trends identified from the analysis of hydrodynamic and SS data. In particular, similar to the conclusions from the analysis of the SS data, the comparison of the various bathymetries shows morphological behavior that is dependent on the hydrographic conditions. For instance, the 2010 and the 2011 surveys which followed a 16,000 cfs event and Hurricane Irene, respectively, show erosion in the vicinity of bridge abutments or features such as river bends, and deposition down-estuary of RM 2 where the river widens and shear stresses decrease. However, during low-flow periods such as between the 2007 and 2008, and the 2011 and 2012 surveys, areas that experience erosion during high-flow periods show deposition, whereas areas at the mouth of the river with deposition during high-flow periods show erosion during low flow periods, restoring the long-term morphodynamic equilibrium of the river.

The large-scale pattern of erosion or export of sediments from locations landward of RM 2 during high-flow periods and deposition or import of sediments to locations above RM 2 during low-flow periods shows the dynamic between fluvial processes responsible for erosion during high-flow conditions, and the tidal and estuarine processes responsible for infilling during low-flow conditions. This observation is analogous to the trends identified in the analysis of the net daily depth-integrated SS fluxes summarized in a preceding section, with net infilling at low discharges and net export of SS at high discharges. Similarly, the depositional features downstream of RM 2 during the high-flow periods are due to depositional conditions in this reach of the LPR during some of the high-flow discharges captured by the bathymetric survey data, and the relative dominance of tidal and estuarine processes compared to fluvial processes down-estuary of RM 2, in particular down-estuary of RM 0.9 where the LPR widens rapidly. This increase in cross-sectional area is accompanied by a corresponding decrease in bed shear stresses during high-flow conditions leading to the predominance of depositional features in this reach of the LPR during high-flow conditions.

The alternating erosional and depositional temporal features landward of RM 2 as well as the depositional features between RM 0-2 during high-flow conditions are explainable considering relative dominance of fluvial and tidal/estuarine forcings varying over temporal and spatial scales. In contrast, the erosional features between RM 0 and RM 2 during low flow conditions are somewhat atypical and not explainable considering either fluvial or tidal/estuarine forcings. For instance, bed shear stresses in this reach over the full range of tidal conditions from neap to spring as well as during high river flows are too low to mobilize bed sediments; rather depositional processes dominate in this reach during both high flow conditions (as seen from bathymetric data as well as HD model simulations) as well as during low flow conditions (as seen from HD model simulations). Therefore, the reach between RM 0-2 is expected to always be a sink for fine sediments. This is indeed the case during high river flow conditions, when sediments are mobilized up-estuary and

flushed towards the mouth followed by deposition between RM 0-2. During low flow conditions, despite low hydrodynamic shear stresses and the import of SS from Dundee Dam and Newark Bay, the bathymetric data show erosional features between RM 0-2. Hence the erosional features during low-flow conditions are anomalous. An analysis of maritime traffic (mostly restricted between RM 0 and RM 1.5) indicates that these erosional features are likely related to navigational processes; this is further elaborated in the following section and also in Attachment B.

In summary, the analysis of the bathymetric surveys suggests that on average, the LPR, except for the lower 1.5 miles, is more or less in morphodynamic equilibrium, though variations around this equilibrium may occur in response to a series of high-flow events, or prolonged periods with low-moderate flows from Dundee Dam. The bathymetric features at any given point in time may reflect the preceding hydrographic conditions (infilling or erosional). The lower part (<RM1.5) of the LPR is not in morphodynamic equilibrium with respect to the hydrodynamic forcings. Only when the sediment load is large, as during high river flow events, fine sediments can settle in this part of the river. The accommodation space of this part of the river is of course governed by the hydrodynamic forcing during that event. Or in other words, the mouth may shallow up to the level at which the hydrodynamic shear stresses reach a level preventing further siltation in this part of the river. At that equilibrium, the remainder of the fines transported down the LPR likely may end up in NB. During low-flow conditions, between RM 0-1.5, as described subsequently, maritime activities are hypothesized to create and maintain a state of morphodynamic equilibrium with respect to navigation processes (near-bed currents induced by ship/tug-boat propellers) rather than hydrodynamic processes (river discharge, tidal and estuarine currents).

2.3.11 Navigation Scour

As mentioned in the previous section, the analysis of the recent multi-beam bathymetries shows that the lower 2 miles of the LPR are characterized by deposition during high-flow conditions and erosion during low-flow conditions. However, examination of shear stress maps generated from the high-resolution HD model suggests that the erosion at the mouth of the river during the low-flow periods cannot be explained from hydrodynamic forcings (tidal velocities, freshwater discharge, or wind-wave generated shear stresses). Rather, the erosional features may be a consequence of scour associated with ongoing shipping activities in the navigation channel and around the shipping terminals. Historically, the LPR was used for commercial shipping extensively, with a Federally mandated navigation channel authorized up to RM 15.4. However, with the decline of industrial activities along the LPR, commercial shipping within the LPR has declined and is currently limited to the lower 1.5 miles, with a number of terminals and berths located in this reach (USACE, 2010).

Examination of the bathymetric data and the bathymetric difference maps show the presence of somewhat randomly distributed (spatially) and irregular erosional features which were attributed to navigation scour, as well as regular features typical of dredging

works in the vicinity of some of the terminals. The possibility of scour induced by shipping activities was confirmed by examining information on the types of shipping vessels and ship tracks in this reach of the LPR, as well as the propeller-induced bottom velocities and shear stresses relative to normal hydrodynamic processes. The mass of sediment erosion attributable to navigation scour was also calculated using the bathymetric surveys and compared to the SS loading from Dundee Dam during the corresponding period, and the SS flux at RM 1.4 from a preliminary model simulation that did not include navigation scour (but otherwise considered to be calibrated). This comparison provided an assessment of the significance of navigation scour in the overall solids balance for the LPRSA. Accordingly, the SS load from navigation scour was found to be comparable to or even larger than the SS contribution from Dundee Dam as well as the SS flux at RM 1.4. This analysis is described in further detail in Attachment B. The analyses suggest that the solids load associated with navigation scour is a significant source of solids to the lower miles of the LPR, and is a significant internal source of solids within the LPR that needed to be accounted for within the process-based modeling framework used for the LPRSA RI/FS. Navigation scour has therefore been included within the CPG's ST modeling framework.

2.4 System Understanding Summary

The net transport of fine sediment in the water column of the LPR is governed by tidal asymmetry, gravitational circulation and river flow. As mentioned previously at low river flow, tidal asymmetry and gravitational circulation are dominant and favor conditions of fine sediment trapping; these sediments may have entered the river over Dundee Dam, from tributaries and/or from Newark Bay; the latter may contain fines washed out of the river during a preceding ebb tide. As the river flow increases, river-induced advection dominates the effects of tidal asymmetry and gravitational circulation, and suspended fine sediments are washed out of the river. It is expected that under these conditions, the riverbed itself remains stable. Only at even more energetic conditions (very high river run-off, possibly in conjunction with spring tide and rapid set-up/set-down events) scouring of the riverbed at specific locations may be expected. These arguments yield the conceptual picture sketched on the top panel of Figure 11 in which three hydro-sedimentological regimes are defined:

- Regime 1: low energetic conditions (low river flow) under which fine sediments are trapped in the river, partly in the ETM, partly through settling elsewhere on the river bed
- Regime 2: medium energetic conditions (moderate river flows) under which fine sediments accumulated in the water column (ETM) and/or in the fluff layer on the bed, are flushed out of the river into Newark Bay
- Regime 3: high energetic conditions (high river flow, possibly in conjunction with spring tide and/or rapid set-up/set-down) under which the riverbed may scour at specific locations

It is noted that Regimes 1 and 2 are mainly governed by hydrodynamic forcings. However, under Regime 3 conditions, erosion rates are governed equally by the hydrodynamic forcing and the bed sediment properties in general, and its erosion properties in particular. As cross-sectional area and tide-induced flow rates vary along the river the transitions between the regimes sketched in Figure 11 vary along the river. Another important observation is that the hydrodynamic conditions (river discharge, in conjunction with tide and set-up/set-down conditions, as previously discussed) at which all saline water is flushed out of the river do not coincide with the Regime 1-2 transition, but are expected to lay somewhere within Regime 2.

While this picture is representative for the major part of the LPR, the sedimentary regime in the lower 1.5 miles are different. The cross section of this part of the river is off-equilibrium with respect to the hydrodynamic forcing – it is far too wide. This large width/depth is likely maintained by the effect of shipping.

A few decades ago, following the construction of the navigation channel in the LPR, the picture in the top panel of Figure 11 was quantitatively different, as flow velocities in the river were substantially smaller because of the larger water depths (river cross-section). The transitions between the various regimes would shift to the right as sketched in the bottom panel of Figure 11. This explains why sedimentation rates in the post-dredging period (i.e. after 1949) were much larger than today as sedimentation-favorable conditions were more frequent, and erosional conditions, induced by high river flows, were less frequent.

The data and analyses reported herein inform the relationship between sediment transport and various forcings such as freshwater discharge from Dundee Dam, estuarine circulation, tidal asymmetry, and intra- and inter-tidal fluctuations. The data also inform on processes such as the location of the ETM and the exchange between the LPR and NB under various flow and tidal conditions. At river flows less than ~750 cfs, because of tidal pumping and estuarine circulation, the LPR can be considered to be net infilling with suspended solids transported down-estuary from Dundee Dam and up-estuary from NB. Net export from the LPR only occurs at discharge greater than ~750 cfs. Note that this transitional river discharge is expected to be somewhat larger, as near-bed data are missing. On average, the LPR up-estuary of RM 1.5 is more or less in morphodynamic equilibrium, though variations around this equilibrium may occur in response to a series of river floods, or prolonged periods with average or below-average flows.

These analyses, in conjunction with other data sources, provide necessary information to parameterize and calibrate the ST model within the LPR and the exchange between the LPR and NB. In particular, processes that can be considered key to reproducing the sediment dynamics of the LPR include the location and SSC within the ETM, the intra- and inter-tidal variability in SSC, residual SS fluxes, and infilling. Infilling is an especially important process because of the presence of hydrograph-dependent alternating erosional and depositional features in the LPR. In addition, some of the remedial alternatives to be considered as part of the RI/FS process may include dredging to the Federally-mandated navigation channel depth at selected locations within the LPR. In such a scenario, the

model's ability to reproduce infilling is essential in being able to simulate the post-dredge morphological evolution.

3.0 MODEL FRAMEWORK

The ST model framework applied to the LPRSA follows the approach outlined in the LPR and Newark Bay MWP documents (HydroQual 2006a, and HydroQual 2006b). The model framework is identical to the one used by Region 2 for their 8-mile Proposed Plan and revised Focused Feasibility Study for the lower 8-miles of the 17-mile LPRSA (FFS; Louis Berger 2014) and involves an implementation of the SEDZLJ bed model developed by Jones and Lick (2001) within the computational framework of the ECOM HD model. During the course of its application to the LPRSA, SEDZLJ has been further developed by Region 2 to include a bed consolidation model developed by Sanford (2008). The combined HD and ST modeling framework is referred to as the ECOM-SEDZLJS model. The ST model development and calibration reported herein are based on model code and input files received from Region 2 in November 2011 and which were modified in several aspects as described subsequently in this report.

Because the overall ST model framework and formulations are similar to the model used by Region 2 for the FFS (Louis Berger 2014), these are not described here in detail. During the course of the CPG's model application to the LPRSA, the model was modified in several respects. These modifications are described in detail in Section 4.3. The next section provides a high-level overview of the ECOM-SEDZLJS model formulations; these are described in more detail in the FFS report (Louis Berger 2014).

3.1 ECOM

The ECOM sub-module of ECOM-SEDZLJS refers to the HD model. ECOM is a three-dimensional time-variable HD model originally developed by Blumberg and Mellor (1980, 1987) and has been applied in a variety of systems ranging from oceanic, coastal, to estuarine settings. The application and calibration of ECOM to the LPRSA and Newark Bay was performed by Region 2 (HydroQual, 2008). The model was calibrated and its performance compared against a number of datasets and metrics collected at various locations and at different times in the LPRSA and Newark Bay. The calibration metrics included water levels, salinity, velocity, and temperature. ECOM calculates the temporally, spatially, and depth-varying flow-velocity, horizontal and vertical turbulent mixing coefficients, salinities, and temperatures and the spatially and temporally varying water depths and passes it to the ST model.

3.2 SEDZLJS

The SEDZLJS sub-model of ECOM-SEDZLJS derives from the SEDZLJ model developed by Jones and Lick (2001) and the consolidation model of Sanford (2008). SEDZLJS is essentially a model that defines the spatially and temporally varying bed mechanics (sediment layering and composition, erodibility, consolidation) and the bed-water exchange processes (shear stresses, erosion, and deposition). In other words, the formulations of SEDZLJS relate to the sediment properties in the bed, and its resuspension and deposition processes. Once the sediments are in suspension, its near-field and far-field

transport is calculated using the advection and dispersion rates calculated by the ECOM HD model. The various key features of the SEDZLJS model framework are summarized here.

3.2.1 Bed Model

The bed model in SEDZLJS is structured as a spatially and temporally varying multi-layer and multi-sediment class model. One of the key features of SEDZLJ is the ability to define the erosion properties of the sediments at a given site using measurements measured from Sedflume erosion experiments (McNeil et al., 1996; Jepsen et al., 1997; Roberts et al., 1998) on cores collected at the given site. The Sedflume experiments measure the critical shear stress for erosion (a measure of the resistance to erosion) and the erosion rate as a function of the imposed shear stress at the bed-water interface. Since the Sedflume experiments allow the measurement of erosion properties with depth into the core, the effect of consolidation processes in the field can be measured and included in the model. The effect of consolidation is typically seen as a depth-dependent increase in the critical shear stress for erosion and/or as a decrease in the erosion rate associated with a given bed shear stress. This depth-dependent variation in erodibility can be input to and represented in the model by means of a multi-layer model bed structure. SEDZLJ uses this information to calculate the time-variable and depth-dependent erosion rates as a function of the time-variable shear stresses imposed by the HD model. Furthermore, the erosion measurements performed by Sedflume reflect measurements of gross erosion properties on bulk sediments at a given point in time. As such, these are a function of the instantaneous sediment composition (amongst other sediment properties such as the degree of consolidation). In nature, sediment composition may show changes in time in response to the shear stress regime, coarsening during high-shear stress periods such as during high river flow events, or show changes in space with coarser sediments in high-shear stress areas, and becoming finer as shear stresses decrease in space and/or time. The effect of such temporally and spatially variable composition is included in the model by means of a multi-class formulation, with the ability to represent a number of particle size classes ranging from fine sediments (cohesive; $<63 \mu\text{m}$) to sandy sediments (non-cohesive; $>63 \mu\text{m}$). From the perspective of the dynamics within the bed, these size classes are distinguished by their threshold for initiation of motion (the critical shear stress for erosion, calculated using the Shields Parameter; Van Rijn, 1984), increasing with particle size. SEDZLJ incorporates the effect of variable composition on erosion rates by limiting the erosion of a given particle size class only when the gross critical shear stress of the layer (measured from Sedflume experiments), as well as the critical shear stress of the given size class are both exceeded by the shear stress imposed at the bed-water interface.

3.2.2 Erosion – Resuspension and Bedload

The erosion behavior of the cohesive and non-cohesive size classes is somewhat different. For the cohesive size classes, upon erosion, they are resuspended from the bed and entrained in the water column, and subsequently subject to advection and dispersion by the hydrodynamic transport processes. The non-cohesive size classes, in addition to

resuspension and entrainment are also subject to bedload movement (the transport of individual particles in contact with the sediment bed by rolling, sliding, and/or saltating motion). The total mass eroded for a given non-cohesive particle class (calculated using the approach described in the preceding section), is fractionated into resuspended and bedload components using a formulation derived from the measurements of Guy et al. (1966).

3.2.3 Settling and Deposition

In the water column, particles in suspension are subject to vertical advection and vertical turbulent mixing both of which are calculated based on the HD model. Particles are also subject to settling through the water column, at particle specific settling velocities. The non-cohesive particles are assumed to settle discretely, with settling velocities calculated using the formulation of Cheng (1997). The settling velocity of the cohesive classes can be assigned either as a function of concentration (in an approximation of flocculation effects as done in the FFS model by Region 2), or assigned constant settling velocities with an alternate way of including the effects of flocculation. The latter approach was developed and implemented by the CPG as part of the model application to the LPRSA and is further described in Section 4.3.

Sediments in suspension near the bottom of the water column may deposit to the bed at a rate that is a function of the settling velocity and a probability of deposition. The probability of deposition for cohesive sediments is calculated using the formulation of Krone (1962), and the probability of deposition for non-cohesive sediments is calculated using the formulation of Gessler (1967).

3.2.4 Consolidation

Following deposition, the sediment particles become a part of the bed. Although the composition of such bed layers formed by deposition can be determined from mass balance, the erodibility of these layers is a more complex function of time and depth in the bed. In nature, freshly deposited sediments (mainly for fine sediments) tend to be more erodible than sediments at depth in the bed or sediments have been residing in the bed for some time. These depth-dependent and time-dependent effects are mainly a result of bed consolidation effects. SEDZLJS incorporates the consolidation model framework of Sanford (2008) which calculates the time-and depth-dependent dry density of the sediment layers as a reversible function of the sediment mass overlying a given sediment layer. In other words, the dry density increases with depth into the sediment and with time, and if the overlying sediment mass above a given layer decreases in time, the dry density also decreases. SEDZLJS also includes a function that relates the erosion properties (critical shear stress for erosion and the erosion rate associated with a given bed shear stress) as a function of the dry density. Thus, the effect of consolidation and therefore the erodibility of the sediments deposited over the course of the model simulation is represented as a time-variable process.

3.2.5 *Shear Stress*

The total shear stress imposed by the HD model at the bed-water interface is considered to be the sum of two separate components: (1) the form drag which expresses large-scale river bed features including sand waves, vegetation, debris, etc., and (2) the skin friction which is the shear stress fraction acting on the individual sediment particles at the bed-water interface, and the forcing responsible for the surface erosion measured in the Sedflume experiments used to define the model inputs. SEDZLJS includes a formulation that calculates the skin friction component of the total shear stress as a function of the sediment composition in the surficial bed layer. The skin friction component is adjusted for the flow regime (smoothed turbulent, transitional, or fully rough turbulent) following Winterwerp and van Kesteren (2004), and to account for the formation and decay of bedforms in predominantly non-cohesive areas during sufficiently large shear stress events following van Rijn (1993).

4.0 MODEL SETUP AND DEVELOPMENT

Model setup, development, and calibration are inherently an iterative process. Application of the model initially focused separately on high and low-flow conditions, i.e., exporting and importing regimes. For instance, the low-flow application involved a model of only the LPR forced with the measured tides and suspended sediment data at RM 1.4 from the Fall 2009 PWCM dataset, whereas the high-flow application was only focused on reproducing the suspended solids data measured during the 16,000 cfs event on March 16, 2010. This was followed by a combined application to both high and low-flow conditions as well as to long-term periods. Only the resulting model framework and parameterization are presented in this document along with an explanation of the rationale for the model parameterization and code modifications. The model setup and parameterization is also a consequence of comments provided by Region 2 as part of the periodic Semi-Annual Modeling Meeting and Modeling Collaboration Meeting forums, and comments provided on an intermediate report submitted to Region 2 in January 2013 (Moffatt & Nichol and Deltares, 2013). The CPG subsequently incorporated most of Region 2's comments, and also made further refinements to the model setup and parameterization in an effort to improve model performance. The revised ST model was documented in a memorandum provided to Region 2 in August 2014 (Moffatt & Nichol and Deltares, 2014). The model setup was subsequently modified to include a few minor changes suggested by Region 2 during review of the draft version of this report, and to include refinements within the NB portion of the model domain developed as part of the model application to NB (documented in Moffatt & Nichol and Deltares, 2017).

This remainder of this section describes the time-periods chosen for the model calibration, the various model inputs and parameters, and the model formulations including changes implemented as part of the application to the LPRSA.

4.1 Time Periods Modeled

The time-period chosen for the ST model application and calibration was intended to bracket the periods with the largest amount of data for model-data comparisons and model calibration. Accordingly, these periods correspond to calendar years 2007, 2008, 2009, 2010, 2011, 2012, and 2013 covering the recent multi-beam bathymetry datasets, the 2009 Fall and 2010 Spring PWCM data, the data from the 16,000 cfs event on March 16, 2010, the 2008-09 NB deployment by Sommerfield and Chant (2010), and Chemical Water Column Monitoring (CWCM) program. In addition, given the objective of supporting the long-term calibration and application of the contaminant fate and transport model, the ST model was also applied over a long-term simulation from water year (WY)² 1995 through WY2013. The first year of the long-term simulation is treated as a spin-up period, mainly for the sediment composition and erodibility specified as averages over large spatial

² The water year begins on October 1 of the preceding calendar year and ends on September 30 of the given calendar year.

reaches in the model initial conditions to equilibrate with the localized hydrodynamic and shear stress regime. Model results for WY1995 are therefore not presented in this report.

4.2 Model Inputs

The ST model requires a number of inputs defining and parameterizing the various inputs and processes in the model framework. These inputs and parameters include:

- The number of sediment classes and the corresponding particle sizes
- Mass fraction of each sediment class in the sediment bed per model cell
- Sediment bed dry density per model cell
- Boundary conditions for SS
 - Inflow at Arthur Kill and Kill van Kull
 - Inflow at Dundee Dam
 - Inflow from LPR tributaries (Saddle River, Second River, and Third River), the Hackensack River, and the CSOs and SWOs
- Grain size distribution of SS associated with the inflowing boundaries
- Erosion properties (erosion rate parameter as a function of shear stress and critical shear stress for erosion) per model cell
 - Fluff layer
 - Parent layers
 - Deposited layers
- Settling velocity of each sediment class
- Sediment bed discretization in depth
- Navigation scour parameters

4.2.1 Particle Size Classes and Effective Diameters

The trend in SSC within the tidal cycle presented in Figure 6 suggest the presence of SS with very different settling velocities within the LPR – a class with higher settling velocity within the estuarine section and a slower settling class within the freshwater section. The slower settling class is indicative of fine sediments associated with the sediment load from

Dundee Dam and the faster settling class indicative of solids originating from marine or estuarine sources and transported up-estuary into the LPR by tidal pumping and estuarine circulation. The faster settling particles in the down-estuary part of the river are the result of spatial segregation and flocculation in the saline environment. The model parameterization considering flocculation is described in a following section. The sediment classes in motion during such normal tidal and discharge conditions (as the data in Figure 6) are expected to be fine sediments, (particle size <63 μm) given the relatively muddy sediment substrate within the LPR, especially in the lower 8 miles. Therefore, two solids classes were used to represent the fines within the LPR and NB, with size classes corresponding to <4 μm (clays), and 4-63 μm (silts). In contrast to the lower reaches of the LPR, the areas above RM 8 are predominantly sandy, especially within the former navigation channel. In addition to the core data, the bed forms and sand waves observed within the upper reach in some of the recent multi-beam bathymetry datasets suggest a sandy substrate with non-cohesive transport during storm events. In order to achieve a reasonable depiction of non-cohesive transport processes such as bed armoring, three sand classes were chosen corresponding to 63-450 μm (fine-medium sand), 450-2000 μm (coarse sand), and >2000 μm (gravel).

The sediment grain size distribution data from core samples were used to evaluate the diameter associated with each of the five particle size classes. Data from several sampling programs listed below were used in this analysis:

- 2013 LRC-SSP2 program (AECOM 2014)
- 2012 LRC-SSP program (AECOM 2013)
- 2008 CPG Low-res coring program (AECOM 2010)
- 2007 Newark Bay RIWP Phase 2 SI
- 2005 Newark Bay RIWP Phase 1 SI
- 2000 Spring RI-ESP Sampling Program
- 1999/2000 Minish Park Monitoring Program
- 1999 Late Summer/Early Fall RI-ESP Sampling Program
- 1999 Preliminary Toxicity Identification Evaluation Study

The particle size for each class was assigned as the median of the class size computed for the individual core samples and is shown in Table 1.

Table 1. Effective Diameters for Particle Size Classes in the LPR and NB ST Model Application

Size Class	Effective Diameter (um)
Clays (<4 um)	2
Silts (4-63 um)	17
Fine-Medium Sand (63-430 um)	155
Coarse Sand (430-2000 um)	760
Gravel (>2000 um)	4025

4.2.2 Mass Fractions in Sediment Bed

The sediment mass fraction within each of the size classes was also evaluated using the datasets used to calculate the particle diameters. Spatially, the data were segregated into distinct areas based on geomorphic characteristics – inside and outside the former navigation channel, a delineation that roughly corresponds to areas outside and inside the shoals and margins identified by Region 2 as part of their FFS model (Louis Berger 2014), respectively. In addition, predominantly silty areas, all located above RM 8 and termed “silt pockets” were identified using the “silt” category in the 2005 Side-Scan Sonar data (Aqua Survey, 2006) and using the probing data collected as part of the various RI sediment sampling programs. These three geomorphic categories were also mapped to the model grid, with each model cell assigned to one of the three categories. Figure 12 shows a map of the model grid along with its geomorphic characterization.

The sediment data located in these three spatial categories were treated separately, and also examined for along-channel trends (for the data located inside and outside the channel). Measurements of grain size distribution were used to calculate the mass fractions associated with each of the particle size classes within the ST model. Figure 13 shows the resulting fractionation by particle class for data from the top 15 cm of the bed, and in Figure 14 for data from the 15-45 cm depth-interval. Laterally within the LPR, the main feature seen is a distinction between the data inside and outside the former navigation channel, with coarser sediments within the former navigation channel and finer sediments outside, especially in the silt and fine-medium sand classes. The main longitudinal feature is a coarsening of the sediments with distance up-estuary within the former navigation channel. Additional features include the relatively coarse substrate between RM 7.8-8.3, and the relatively fine sediments within the silt pockets delineated using the “silt” category in the 2005 Side-Scan Sonar data (Aqua Survey, 2006) and using the probing data collected as part of the various RI sediment sampling programs. These features were included within the initial conditions for the ST model by developing averages separately for the data inside and outside the former navigation channel over distinct longitudinal reaches (RM 0-2, RM 2-4, RM 4-6, RM 6-7.8, RM 7.8-8.3, RM 8.3-9.3, RM 9.3-13, and RM >13), and a single average value for all the data within the silt pockets. The model grid cells within each

spatial reach were assigned to the averages derived for inside or outside the channel in that reach, or to the average for the silt pockets depending on the spatial overlay of the model grid, the navigation channel, and the silt pockets. This process was followed for the depth intervals 0-15 cm and 15-45 cm to define the model initial conditions.

4.2.3 Dry Density

The sediment bed dry densities were determined from solids content measurements from core samples (from the datasets described previously for grain size distribution) and assuming particle specific gravity of 2.65. The data were averaged over the same lateral and longitudinal spatial resolution as the grain size distribution data described above. The values for the individual core samples as well as the averages computed for the model inputs are shown in Figure 15 and show similarities with the grain size distribution. As expected given the coarser sediments within the former navigation channel, dry density is higher in these sections than areas outside the former channel and in the silt pockets. Areas within the silt pockets tend to show the lowest dry density as expected given the relative bias towards fine sediments in these areas. These dry density averages were assigned to the individual model cells using the same procedure described previously for the grain size distribution.

4.2.4 Boundary Conditions

The boundary conditions of the ST model relate to the SSC associated with the various freshwater and marine inflows to the LPR and NB model domain. In addition to the SSC, the fractionation of the inflowing SS in terms of the various particle size classes represented in the model also needs to be defined. The following sections describe the development of the SSC associated with the inflows at the Kill van Kull, Arthur Kill, Dundee Dam and other freshwater/SWO/CSO inflows, and the grain size distribution associated with the SS in the inflowing waters. Since the ST model is meant to be applied over periods beyond the window of time with available measurements of SSC associated with the various inflows, the development of the boundary conditions included the development of rating curves relating SS loads/concentrations to other physical parameters such as velocity, flow, tidal range, etc. Using these rating curve relationships, the SS boundary conditions during other periods was estimated using either measured or calculated (by the HD model) values for velocity, flow, tidal range, etc. as described subsequently.

Pre-deepening – Kill van Kull and Arthur Kill

As mentioned previously, the calibration period used for the ST model encompassed WY1995 through WY2013. During this period, the navigation channel in the Kill van Kull and Arthur Kill (and Newark Bay) were deepened from 45' to 50' MLW. As a result, tidal velocities, residual circulation, and sediment fluxes in the Kill van Kull and Arthur Kill have changed in time (Sommerfield and Chant, 2010). Chant (2006) describes a series of deployments in the Kill van Kull and Arthur Kill, near their entrance to Newark Bay, and conducted over 2000-2002, a period before the deepening project and reflective of pre-

deepening SS loadings. These deployments included ADCPs measuring currents and ABS (and converted to SSC) over the water column.

Region 2's FFS model (Louis Berger 2014) relied on rating curves developed using the 2000-2002 data from Chant (2006) to define the SS boundary condition at the Kills for the period from WY1995-WY2004. Rating curves for the periods after WY2005 were developed using similar measurements in 2008-2009 by Sommerfield and Chant (2010); these data are reflective of the post-deepening condition. For the 2008-2009 data, which the CPG had analyzed and developed rating curves for as well (this is described in the following section), the overall methodology between the two modeling teams is similar. For instance, both sets of rating curves for the Kill van Kull included dependencies with currents and tidal range, and separate functions for periods of accelerating flood velocity and decelerating flood velocity. Although the rating curve functions were somewhat different for the Arthur Kill, as described subsequently, the SS influx from Arthur Kill is about an order of magnitude lower than the influx from Kill van Kull, thus reducing the significance of this difference. Given the overall similarity in approach between the two teams for the recent dataset, it was decided to use the boundary conditions developed by Region 2 for the pre-50' deepening periods (WY1995-WY2004).

Post-deepening – Kill van Kull

Rating curves for the inflowing sediment concentrations at the open boundaries for the post-deepening conditions (WY2005 onwards) were developed based on an analysis of data collected by Sommerfield and Chant (2010). Sommerfield and Chant deployed a series of ADCP moorings at a couple of locations in Newark Bay, at RM 1.4 in the LPR, at the mouth of the Hackensack River, and in the Kill van Kull and Arthur Kill near their entrance to Newark Bay. Figure 16 shows the locations of the various moorings. The ADCPs measured velocity and ABS (converted to SSC using a relationship developed using paired measurements of ABS and SSC) during April 2008-August 2008, and from September 2008 to March 2009. These data were filtered to eliminate possible contamination of the data due to periodic ship traffic. The resulting dataset was examined for dependencies with a number of independent variables, with functional relationships identified between SSC/loads and flow velocity, tidal range and the seasons as described below.

Figure 17 shows a 12-day snapshot of the SSC data at Kill van Kull, with the concentrations on the flood tide (inflowing water; blue line) distinguished from the concentrations on ebb (red line). Comparison to the velocity in the same bin and tidal range on the upper panel suggests a dependency with velocity and tidal range, with SSC increasing as velocity increases within the flood tide and decreasing as flood velocity decreases. SSC also tends to increase from neap to spring. Both these dependencies are seen more clearly in Figure 18 which shows the dependency with velocity on the upper panels (separated into periods of accelerating and decelerating velocity), with tidal range (lower left panel), and over the course of the seasons (lower right panel). In general, SSC increases as velocity increases, with the shape of the response following a power-law for the accelerating flows and a linear relationship for the decelerating flows. The positive relationship with tidal range also suggests a dependency in addition to the positive relationship with velocity. Finally,

seasonal trends are also apparent in the data, with higher concentrations in winter and early spring and lower concentrations in mid-late spring, summer, and fall.

These correlations with flow velocity, tidal range, and the seasonality was incorporated into a rating curve for sediment flux at the Kill van Kull, which was prescribed by fitting the following curve to the data:

$$\text{SS Load} = a * U^b * \text{TR}^c * \text{SF}$$

where U = velocity in m/s, TR = tidal range in meters, Load^3 in $\text{g/m}^2/\text{s}$, SF = seasonality factor (applicable during the months of December to April), and a , b , and c are parameters fit by least-squares optimization. Separate functions were developed for the accelerating and decelerating phases of the flood tide. The rating curve was developed for SS load rather than SSC in order to reproduce the SS load into Newark Bay.

Figure 19 shows an example comparison of the rating curve estimated SS load versus the measured load, and the SSC back-calculated from the rating curve estimated SS load versus the measured concentration, for the accelerating and decelerating flood velocity cases. In general, the rating curve performs well in reproducing the SS load, with bias on the order of 2% (estimated using the slope of the regression of estimated and measured) and a good correlation coefficient ($R^2 > 0.8$). Equivalent comparisons for SSC show more scatter between the estimated and measured values, possibly because the data may include some fluctuations related to reasons beyond the dependencies considered in this analysis. Nonetheless, the comparison of the estimated and measured load provides confidence that the overall mass loading into Newark Bay from the Kill van Kull can be reproduced with this approach. Figure 20 shows a time-series comparison of the measured and estimated SS load and concentrations for the same time-period as shown in Figure 17. Square and circle symbols are used to denote the rating curve derived estimates for accelerating and decelerating velocities. In addition, a subset of data during neap tides exhibit currents directed into NB during ebb tide (defined as period of decreasing water levels for this analysis); these are shown with a triangle symbol with the rating curve estimates derived using either accelerating or decelerating functions as applicable. In general, the rating curve performs well in reproducing the temporal trends (both on intra-tidal as well as inter-tidal time-scales) as well as the magnitudes of SS load and concentrations.

Table 2 lists the rating curve coefficients for each of the sigma levels (water column layers; layer 10 is at the bottom and layer 1 at surface of the water column) used to prescribe the solids boundary condition at the Kill van Kull. The time-variable concentration associated with the inflowing water at Kill van Kull over the ST model application period was subsequently developed using these rating curve functions along with the velocity calculated by the HD model for each sigma layer in the model along with the corresponding tidal range and seasonality factor.

³ Terms flux and load, both of which refer to the same physical parameter, have been used interchangeably in this document.

Table 2. Rating curve functions for the solids boundary condition at Kill van Kull

Sigma Level	a	b	c	SF
Case: Accelerating Flood Tide				
10	110.94	1.91	-0.05	1.38
9	68.38	1.84	0.06	1.31
8	43.17	1.93	0.14	1.26
7	23.68	1.81	0.69	1
6	14.05	1.85	1.16	1
5	12.01	1.90	1.15	1
1 to 4	13.76	1.88	0.65	1
Case: Decelerating Flood Tide				
10	66.93	1.37	0.55	1.38
9	51.11	1.40	0.67	1.31
8	32.32	1.33	0.86	1.26
7	22.32	1.27	1.27	1
6	15.84	1.27	1.62	1
5	13.44	1.28	1.70	1
1 to 4	13.13	1.32	1.35	1

Post-deepening – Arthur Kill

The rating curve used to develop the boundary condition at Arthur Kill was developed using the same Sommerfield and Chant (2010) dataset described previously. Figure 21 shows a 12-day snapshot of the SSC data from the bottom-most ADCP bin at Arthur Kill, with the concentrations on the flood tide (inflowing waters; blue line) distinguished from the concentrations on ebb (red line). Comparison to the velocity in the same bin and tidal range on the upper panel shows that in contrast to the Kill van Kull, SSC at Arthur Kill do not indicate a relationship with flow velocity. The concentrations also exhibit unexplained variability as seen from the spikes on October 10, 12 and 13. The only trend that could be identified is a low-frequency positive linear relationship of SSC with the tidal range as shown in Figure 22. This was fit using a function of the form:

$$SSC = m * TR + c$$

where SSC is in mg/L, TR = tidal range in meters, and m and c are coefficients fit by least-square optimization.

Table 3 lists the rating curve coefficients for each of the sigma levels (water column layers) used to prescribe the solids boundary condition at the Arthur Kill. These rating curves were used to develop solids boundary conditions time-series using the tidal range calculated by the HD model for any given period.

Table 3. Rating curve functions for the solids boundary condition at Arthur Kill

Sigma Level	m	c
10	7.09	6.55
9	4.42	5.07
8	3.04	3.97
7	2.78	3.32
6	2.12	3.28
5	1.55	3.19
4	1.46	2.84
3	1.82	2.33
2	2.52	1.77
1	3.41	1.19

Figure 23 shows an example comparison of the rating curve estimated SSC versus the measured concentration, and the SS load calculated from the rating curve estimated SSC versus the measured load. Regression lines quantifying the relationship between measured and estimated values, and relevant equations and correlation coefficients are also included in each of the panels in Figure 23. Given the dependency with only tidal range (as indicated from Figure 22), the estimated concentrations vary within a narrow range of ~15-30 mg/L even though the data varies over a larger range (~10-125 mg/L). However, as explained previously, much of the measured variability is unexplainable, a point also seen from the comparison of estimated versus measured SS load in Figure 23. In this case, both estimated and measured values vary over similar ranges, with most estimated values within a factor of two of measured values. Figure 24 shows a time-series comparison of the measured and estimated SS load and concentrations for the same time-period as shown in Figure 21. The circle symbols denote the rating curve derived estimates. In general, the rating curve performs reasonably well in reproducing the temporal trends (both on intra-tidal as well as inter-tidal time-scales) as well as the magnitudes of SS load (with the exception of the spikes stemming from the unexplained variability in SSC). Comparing the measured SS loads in Figures 24 and 20, it should be noted that the SS load from Arthur Kill to Newark

Bay is about an order of magnitude smaller than the load from Kill van Kull to Newark Bay. Therefore, even though the rating curve does not explain the full range of variability in SSC in the Arthur Kill, the overall approach (including the rating curve development in Kill van Kull) performs reasonably well in capturing the dominant SS loadings to Newark Bay.

Dundee Dam

The boundary condition at Dundee Dam was developed using a rating curve developed by relating SS measurements at Dundee Dam to the discharge over Dundee Dam. The SS rating curve developed for Dundee Dam includes data from a number of sources:

- Water samples collected as part of the Fall 2009 and Spring 2010 PWCM program
- Water samples collected as part of the CWCM events from 2011 through 2013
- Water samples collected by Malcolm Pirnie (MPI 2007a; MPI 2008a; MPI 2008b)
- SS estimated from Optical Backscatter (OBS) measurements of turbidity during the Fall 2009 and Spring 2010 PWCM program. The OBS data were screened to exclude spurious data indicative of sensor fouling. The OBS measurements of turbidity were converted to SSC using the turbidity-SSC correlations developed for the Fall 2009 and Spring 2010 PWCM datasets as described in Attachment A.
- Water samples collected by the PVSC/NJHDG (obtained from the US EPA's STORET database website on Nov. 20, 2013). Only measurements since October 2007 are included given the availability of USGS measurements of discharge at Dundee Dam only after this date.

The SS data were paired with 15-min discharge measurements reported by the USGS at Dundee Dam (except for the MPI data which were measured prior to the deployment of the USGS flow gage at Dundee Dam in 2007 and were therefore paired with daily discharge at Little Falls scaled to Dundee Dam by drainage area proration). Figure 25 shows the relationship between SS and discharge at Dundee Dam (SS load on left panel, SSC on right panel). SS load is noted to increase with discharge, with a change in the slope of the trend at approximately 2000 cfs. SSC are relatively flat below 2000 cfs and increase linearly with discharge beyond 2000 cfs. There may be inverse relationship below 2000 cfs, with SSC increasing as discharge decreases; one possible hypothesis for this trend may be the impact of primary production within Dundee Lake especially since residence time in Dundee Lake is expected to increase as discharge decreases. However, this issue was not investigated further. The OBS-derived SS data were further screened and processed as described below:

- Measurements from the high flow event between March 24 and April 10 2010 when discharge peaked at 10,000 cfs are excluded. Occurring only two weeks following a 16,000 cfs event (a 25-year return frequency event) it is likely that the river bed upstream of Dundee Dam may have armored and been depleted of the more easily

erodible sediments. Therefore, the solids load during this event may likely have been somewhat atypical and biased low compared to other events of similar magnitude. In order to avoid incorporating a low bias into the rating curve as a consequence of such non-linear sediment dynamics in the reaches above Dundee Dam, only the data from the period following April 10, 2010 when the discharge decreased below 2000 cfs is included in the rating curve development.

- The OBS data represents a high-frequency dataset (with a measurement every twelve minutes) over a fairly short time period of a few months whereas the water sample data represent a low-frequency dataset (typically no more than one sample per day) over a period of several years. In order to avoid biasing the rating curve towards the OBS-derived SS data (given the much larger sample size of the OBS data compared to the water sample data), the OBS data were binned by discharge (binned separately for the Spring 2010 and Fall 2009 PWCM OBS datasets). The procedure involved dividing the range of discharges in base 10 log-space (231-10,300 cfs) available for the OBS data into equidistant bins, with the bin size (bin size of 0.014 in base 10 log-space) chosen such that the resulting total number of bins were approximately equal to the number of water-sample/discharge pairs (n=147). The Spring and Fall OBS-SSC/discharge time-series were binned separately using this binning interval, yielding a dataset of 87 binned OBS-SSC/discharge pairs for the Spring dataset and 53 pairs for the Fall dataset.

The revised rating curve was developed by relating SS load to discharge using a “hockey-stick” relationship to describe the different slope in the load-discharge trends above and below ~2000 cfs, nominally referred to as flood and non-flood regimes, respectively. Separate relationships have been derived for the flood and non-flood regimes with the discharge threshold same as the rating curve used in Region 2’s FFS model (Louis Berger 2014). The calculated loads were also corrected for the bias introduced by fitting the load-discharge relationship in log-space (Ferguson 1986). The rating curve function is listed below (Q is the discharge at Dundee Dam in m³/s and L is the SS load in MT/day) and the parameters are listed in Table 4.

$$\ln\left(\frac{L}{L_m}\right) = A * \ln\left(\frac{Q}{Q_m}\right) + B + C$$

The parameters A, B, and C are chosen depending on whether flow is in flood ($Q > 2 * Q_m$) or non-flood condition ($Q < 2 * Q_m$). Figure 25 includes the SS load rating curve on the left panel, and the SSC back-calculated from the rating curve on the right panel.

Figure 26 shows a time-series of the rating curve-derived SSC during the PWCM periods and a comparison to the OBS-derived SSC at Dundee Dam during the Fall 2009 and Spring 2010 PWCM program. In general, the rating curve is comparable to the OBS data although less variable than the data at low discharges. Finally, for purposes of developing model inputs, during the periods when OBS-derived SS time-series data are available (the Fall 2009 and Spring 2010 PWCM periods), the OBS-derived SS data are used to define model inputs rather than SS estimates calculated from the rating curve. During all other periods,

the model input at Dundee Dam is derived using the rating curve. Figure 27 shows the time-series of flow, SSC, and SS load at Dundee Dam over the duration of the long-term model calibration (WY1995-WY2013).

Table 4. Rating curve parameters for the solids loading at Dundee Dam

Parameter	Non-Flood	Flood
Q_m	30.3	
A	1.02	1.75
B	0.73	0.42
C	0.12	0.16
L_m	11.76	

Other Sources

The boundary conditions for the various freshwater tributaries entering the LPR (Saddle River, Second River, and Third River), the Hackensack River, and the CSOs/SWOs were set the same as Region 2's FFS model (Louis Berger 2014).

Grain Size Distribution of SS Loadings

The previous sections described the development of rating curves to support the specification of SSC boundary conditions for the ST model. The rating curve estimated SSC are a measure of the total SSC (sum of all particle size classes). In order to fractionate the total SSC into the five particle size classes in the ST model, measurements of the grain size distribution in a subset of the water samples collected as part of the CWCM events were reviewed and analyzed. Water samples taken at the freshwater boundaries at Dundee Dam, Second River, Third River, Saddle River, and the tidal boundaries at Kill van Kull and Arthur Kill during CWCM Small Volume Routine Events 1, 2, 3, 4, and 5, the CWCM Small Volume Low Flow Event, and the High Volume Event 1 were subject to deflocculation and laser diffraction to measure the grain size distribution of the SS. The grain size distribution data was analyzed to calculate the mass fractions within each of the five particle classes in the CPG's model parameterization.

Figure 28 shows the calculated mass fractions of clays, silts, and fine sand (none of the samples reported any classes larger than the smallest sand class) for the water samples at each of the boundaries from the various CWCM events. The mass fractions are plotted as a function of the measured Dundee Dam discharge for the data at Dundee Dam, Second River, and Third River, as a function of the Saddle River discharge for the data at that location, and as a function of the tidal range at the NOAA tide gage at Bergen Point for the data at the Kill van Kull and Arthur Kill. The mass fraction data at all locations only show variability within a small range of values and do not show a dependency with discharge (over the range ~300 cfs to ~2,500 cfs) at the freshwater boundaries) or tidal range (ranging

from neap to spring) at the Arthur Kill and Kill van Kull. Therefore, the mass fraction data from the various CWCM events at a given location were averaged and used to assign the composition associated with the solids at that boundary. Table 5 shows the average composition measured at each of the locations measured in the CWCM events and used to define the composition of the inflowing SS at these boundaries in the CPG's model. The composition tabulated in Table 5 is applied under all tidal range (and flow) conditions at the tidal boundaries at the Kill van Kull and Arthur Kill, and during low-medium flow conditions (flows less than 2,500 cfs at Dundee Dam, and less than 190 cfs at Saddle River, Second River, and Third River) at the freshwater boundaries. During high flow conditions at the freshwater boundaries (flows greater than 2,500 cfs at Dundee Dam, and greater than 190 cfs at Saddle River, Second River, and Third River), the solids composition derives from a combination of Region 2's FFS model inputs (16% fine sand), and the CWCM event data (maintaining the same relative proportion of clays and silts as seen in the low flow data tabulated in Table 5).

Table 5. Grain size distribution associated with the solids boundaries (at low flow conditions for freshwater boundaries and all conditions for tidal boundaries)

Location	Clay (<4um; %)	Silt (4-63um; %)	Sand (63-430um; %)
Dundee Dam	15.8	82.0	2.2
Second River	16.7	78.2	5.1
Third River	14.9	83.5	1.6
Saddle River	14.1	85.1	0.8
Kill van Kull	17.1	82.0	0.8
Arthur Kill	16.5	82.4	1.1

The average composition tabulated in Table 5 indicates ~15% clays, ~80% silts, and a small fraction of sands entering from all the boundaries to the LPR and NB study areas, i.e. the majority of the solids entering from both freshwater and tidal boundaries are silts. At the same time, a couple of observations and a theoretical consideration, as described below, suggest a difference in the settling characteristics of the sediments from the freshwater and marine boundaries:

- The intra-tidal temporal trends presented in Figure 6 which shows less intra-tidal variability indicative of SS with lower settling velocity at the predominantly freshwater station (RM 13.5) as compared to the predominantly estuarine station (RM 1.4).
- The settling velocity analysis (presented in Attachment F) which shows lower median settling velocities at the freshwater station (RM 13.5) compared to the predominantly estuarine station (RM 1.4).

- Theoretically, given the role of salinity in promoting flocculation (Winterwerp and Van Kesteren, 2004), the sediments entering the LPR and NB from the Kill van Kull and Arthur Kill are expected to be flocculated (and therefore associated with relatively higher settling velocity). In contrast, the sediments entering from the freshwater boundaries are expected to be poorly flocculated and associated with relatively lower settling velocity.

These arguments support the idea that the SS entering from the tidal boundaries are likely flocculated (with relatively higher settling velocities) and the SS entering from the freshwater boundaries are likely poorly-flocculated (with relatively lower settling velocities). Therefore, in order to represent these two different SS types, flocculated versus poorly-flocculated, entering from the tidal and freshwater boundaries respectively, the ST model was modified to include two additional classes of clays and silts – poorly-flocculated clays and silts entering from the freshwater boundaries, and flocculated clays and silts entering from the tidal boundaries. The model application therefore includes a total of seven solids classes. The settling velocities assigned to these four cohesive classes are described in a following section.

Furthermore, in nature, when a poorly-flocculated particle from the water column is deposited to the sediment bed, over time it is subject to various physical, chemical, and biological processes that can lead to the aggregation of individual particles and effectively an increase in its settling velocity. In an approximation of such processes, within the context of the CPG's ST model, when poorly-flocculated particles that have settled to the sediment bed are subsumed beneath the fluff layer (layer schematic as described in a following section), they are assumed to instantaneously transform to a flocculated particle. This approximation takes into consideration the longer residence times achieved beneath the fluff layer (average residence time within the fluff layer is only on the order of 6 hours or half a tidal cycle). In practical terms, within the context of the CPG's ST model, this instantaneous change in flocculation state only results in an instantaneous change in settling velocity, from the lower settling velocities associated with poorly-flocculated sediments to the higher settling velocities associated with flocculated sediments. Following a similar rationale, the silts and clays in the sediment bed input to the model at initialization are assumed to be flocculated i.e. associated with higher settling velocities.

4.2.5 Erosion Properties

The process of model setup and calibration was an iterative process and included a number of modifications to the original ECOM-SEDZLJS framework. Although described in additional detail in the following section, one such modification involved the vertical discretization of erosion properties within the sediment bed. Conceptually, the original model framework was modified to include a fluff layer overlying more consolidated bed layers. In other words, a low strength (or easily erodible) fluff layer overlying a stronger or less erodible layer (strength in this context is meant to refer to the critical shear stress for erosion). The erosion properties (the critical shear stress for erosion and the erosion rate

parameter) of both layers were derived from site-specific data and are described in the following sections.

Fluff Layer

Erosion properties for the fluff layer were derived from an analysis of SS data from the Fall PWCM. Review of the Fall PWCM data showed some consistent patterns – during all periods when the salt front and therefore the ETM were located above RM 4.2, SSC at RM 4.2 during the flood tide is on average (averaged over the flood tide) higher than at RM 1.4 (as seen in Figure 6). The concentrations were also noted to be positively correlated with the flow velocity within the tidal cycle. This increase in concentrations was considered to be associated with erosion between RM 1.4 and 4.2 during the given flood tide. Considering only the period of accelerating velocity on the flood tide (which is also the period of increasing SSC), the increase in concentrations from RM 1.4 to 4.2 likely represents gross erosion rather than net erosion. However, since the analysis uses SS measurements rather than direct measurements of erosion, the analysis is presented in terms of the entrainment process rather than the erosion process. The increase in concentrations in time was converted to an entrainment rate and related to the velocity and shear stress regime. Considering only the data during normal discharge and tidal conditions when fluff layer dynamics are considered to dominate sediment transport within the LPR, this entrainment represents erosion from the fluff layer and therefore inform the erosion properties of the fluff layer. The results of this analysis are summarized here; the analysis is described in further detail in Attachment C.

The Fall 2009 PWCM program included continuous (every 12 minutes) measurements of velocity, salinity, water depth, and the SSC profile at RM 4.2 amongst other locations. The increase in depth-average SSC from one measurement to the next was converted to an entrainment rate over that time-interval using the measured water depth and a dry density of 327 Kg/m^3 (which is the surficial dry density used by the model; this is described subsequently) for the fluff layer. The resulting entrainment rate was paired with the skin friction calculated by the HD model over that time period (the pairing with skin friction is described in further detail in Attachment C). The entrainment rate calculation was restricted to the period of minimum to maximum SSC at RM 4.2 during the flood tide, only for periods not affected by advection from RM 1.4 (neglecting dispersion), and for periods in the Fall PWCM when the salt front and therefore ETM are located above RM 4.2 (October 11–24, 2009 and November 21–28, 2009).

The paired entrainment rate and skin friction data are shown in Figure 29. Since the entrainment rates were calculated from high-frequency water column suspended solids measurements, they are susceptible to variability in the suspended solids concentrations resulting in negative entrainment rates. However, the variability (as seen in the range of entrainment rates as well as negative entrainment rates) is restricted to a relatively small subset (<20%) of the entire dataset and is more pronounced at the lower shear stresses (expected around low-water slack) when SSC are relatively low compared to other periods within the accelerating flood tide. The negative entrainment rates were not included in the subsequent analysis to infer the erosion properties of the fluff layer. The entrainment rate

data were also binned over shear stress intervals and used to develop a functional relationship similar to the Sedflume erosion rate formulation, $E = A\tau^n$ (where E =erosion rate in cm/s, τ =shear stress in dynes/cm², and parameters A and n are empirically determined from the data). The relationship is approximately linear ($n=1.01$), with binned erosion rates ranging from $\sim 2 \times 10^{-6}$ to $\sim 3 \times 10^{-5}$ cm/s over the entire range of normal tidal shear stresses. Another important erosion property apparent from Figure 29 is the threshold for resuspension or the critical shear stress for erosion; appreciable entrainment is noted to occur at shear stress greater than ~ 0.25 dynes/cm² which suggests the critical shear stress for the fluff layer within the LPR/NB ST model framework. This critical shear stress is also comparable to measurements for the fluff layer at other sites (0.5 dynes/cm² reported by Wang 2003; 0.25-0.5 dynes/cm² reported by El Ganaoui et al. 2004; 0.5 dynes/cm² reported by Maa et al. 1998). The erosion rates ranging from $\sim 2 \times 10^{-6}$ to $\sim 3 \times 10^{-5}$ cm/s over the range of normal tidal conditions also overlap with reported values for other sites (constant 10^{-6} cm/s reported by Wang et al. 2003; $10^{-7} - 8 \times 10^{-6}$ cm/s reported by El Ganaoui et al. 2004 over the same shear stress range). The results of the entrainment rate analysis were used to define the erosion properties for the fluff layer in the LPR/NB ST model – the critical shear stress for erosion was defined as 0.25 dynes/cm² and the erosion rate (in cm/s) was defined as a power function of the shear stress with coefficient $A=1.06 \times 10^{-5}$ and exponent $n=1.01$. The fluff layer thickness is set to 1 mm, based on the value estimated from the PWCM data (using dry density of 327 Kg/m³, a value consistent with model definition for unconsolidated sediments).

The fluff layer erosion properties thus parameterized using the PWCM data were also compared to measurements from the Gust microcosm experiments (Chesapeake Biogeochemical Associates, 2006). This analysis and comparison is described in detail in Attachment D and is only summarized here. The Gust microcosm experiments included a series of erosion tests in an annular flume to measure the erosion properties of surficial sediments. Shallow cores from a number of locations within the LPR were collected in 2005 and analyzed in the Gust microcosm. The resulting measurements of the erosion rate parameter for surficial sediments (analogous to the fluff layer schematization in the CPG's ST model framework) are comparable to the erosion rate parameter derived from the analysis of the PWCM data. The depth profile of the critical shear stress for erosion measured in these experiments show, in general, lower critical shear stress at the surface of the cores, increasing by approximately an order of magnitude within the top few millimeters of the bed. This increase in the strength of the sediment bed is similar to and supportive of the bed layering schematic adopted in the CPG's ST model with a thin layer of easily erodible sediments (the fluff layer) overlying a less erodible bed.

Parent Layers

The parent layers in ECOM-SEDZLJS refer to the stack of consolidated sediment layers initialized in the model. Erosion properties for these layers were defined using data collected during the LPR Sedflume program (Borrowman et al 2006). Data from the LPR Sedflume core tests were analyzed for the dependency between erosion rate and shear stress. Attachment E provides a detailed description of the analyses summarized here. A

function of the form $E = A\tau^n$ (where E =erosion rate in cm/s, τ =shear stress in Pa, and parameters A and n are empirically determined from the data) was fit to each of the shear stress sequences run through the Sedflume device for each core. The resulting functions were used to calculate the critical shear stress for erosion, calculated as the shear stress corresponding to erosion rate of 10^{-4} cm/s for each shear stress sequence run for each of the Sedflume cores; this is a relatively standard approach in the analysis of Sedflume erosion data.

The resulting erosion properties were analyzed for vertical and spatial heterogeneity. In general, the individual cores showed erodibility (as indicated by both erosion rate and the critical shear stress for erosion) decreasing with depth, a qualitatively reasonable expectation given that sediments at depth would be more consolidated than surficial sediments and therefore more resistant to erosion. However, spatially, the cores showed a high degree of variability with no apparent correlation with location within the LPR, organic carbon content, sand content, or bulk density; even duplicate cores taken at the same location showed a high degree of variability. Given this unexplained variability, and the lack of any objective criteria to map this variability in erosion properties to the entire LPR domain, the erosion properties measured in the individual Sedflume cores were averaged to develop a single set of parameters for use in the LPR/NB model. Table 6 shows the erosion properties over depth for the average core developed from the Sedflume data. These properties were assigned to the predominantly cohesive parts of the model domain: the lower 7.8 miles of the LPR, the silt pockets above RM 8, and areas outside the former navigation channel between RM 8.3 and RM 14.7 in the LPR. Erosion properties for the predominantly non-cohesive parts of the domain (i.e., the areas within the navigation channel above RM 8, and areas between RM 13 and RM 14.7) were based on the values published in Roberts et al. (1998), which relates erosion properties to median diameter (D_{50}) of the sediments. Due to the paucity of grain size distribution data above RM 14.7 (as seen in Figure 13), and the prevalence of gravel and boulders in this portion of the river, the parent layers up-estuary of RM 14.7 were defined as non-erodible.

Initial model runs using the average core properties derived from the Sedflume data showed erosion on the order of 15-20 cm within the former navigation channel in much of the lower miles of the LPR even under normal tidal and below-average discharge conditions. This was an unexpected result since the erosion properties used to define the consolidated strata underlying the fluff layer were expected to result in a relatively stable bed under normal tidal and below-average discharge conditions. Furthermore, extending the initial application to the 16,000 cfs event on March 16, 2010 following an appropriate spin-up simulation resulted in significant over-prediction compared to the measured SSC data. Taken together, these results suggested an inconsistency between the shear stresses imposed by the model and the defined erosion properties of the parent layers, resulting in over-prediction of erosion under low as well as high-flow conditions. This result may likely be a consequence of under-estimating the critical shear stress for erosion as shown in Figure 30, which shows a comparison of the critical shear stress computed using the

standard approach with the empirical⁴ critical shear stress in each of the shear stress sequences run for the Sedflume cores. Lines indicating perfect agreement (1X) between calculated and measured values, and under-estimation of measured values by several factors (2X, 4X, and 6X) are also included in Figure 30. This comparison shows that most calculated values tend to be up to 6 times lower than the measured critical shear stress for erosion. Therefore, the critical shear stress of the parent layers was used as a calibration parameter and increased primarily to adjust the response of the model to the 16,000 cfs event of March 16, 2010.

Table 6. Erosion Properties for Parent Layers Derived from Sedflume data and Calibration

Depth Interval (cm)	A (cm/s)	N	τ_{Cr} (Pa)	
			Calculated ⁵	Calibrated
0 - 2.5	134×10^{-4}	2.14	0.1	0.4
2.5 – 5	62×10^{-4}	2.54	0.2	0.5
5 – 10	24×10^{-4}	2.71	0.31	1.35
10 – 15	24×10^{-4}	2.93	0.34	1.76
15 – 20	7.9×10^{-4}	3.25	0.53	1.66
20 – 25	4.4×10^{-4}	3.48	0.65	1.81
25 – 30	3.4×10^{-4}	3.39	0.69	1.67
>30	5.5×10^{-4}	2.79	0.54	2.56

Figure 31 shows the depth profile of the calculated critical shear stress (using the standard Sedflume approach at erosion rate of 10^{-4} cm/s; shown with black filled circles), the range between the highest shear stress with no erosion (τ_0) and the lowest shear stress with some erosion (τ_1) for all the Sedflume shear stress sequences within a given depth interval (shown with grey bars), the range and average (shown with red bars and red symbols respectively) of the measured critical shear stress for erosion (calculated as the average of τ_0 and τ_1). Therefore, the critical shear stress profile input to the model was parameterized via calibration as a multiple (1.5X) of the average measured critical shear stress (red

⁴ Empirically, the critical shear stress can be considered to be bounded by the highest shear stress with no observed erosion and the lowest shear stress with some observed erosion in each of the shear stress sequences run for the Sedflume cores

⁵ The standard approach to calculate critical shear stresses analyzing Sedflume data consists of fitting a function of the form $E = A\tau^n$ where E=erosion rate in cm/s, τ =shear stress in Pa, and parameters A and n are fit to the Sedflume erosion data. The resulting function is used to calculate the critical shear stress for erosion as the shear stress corresponding to erosion rate of 10^{-4} cm/s.

diamonds) for each bed layer for which erosion properties were developed from the Sedflume data. The re-parameterization was consequence of a calibration exercise such that the parent layers are not susceptible to erode under low discharge and normal tidal conditions when only fluff layer dynamics are expected to dominate sediment transport in the LPR. The resulting critical shear stress profile is shown with blue squares in Figure 31 and is within the bounds of the measured values (red bars) at all depth intervals. A similar empirical approach for deriving the critical shear stress for erosion was also used in the Housatonic River ST model (Weston 2004).

Deposited Layers

The deposited layers refer to sediment bed layers developed by deposition in a given cell during the course of the model simulation. At model initialization, only the parent layers and a fluff layer are defined. Following initialization, as the simulation progresses, any deposited sediments are tracked in a separate stack referred to as the deposited layers. This is purely a computational heuristic to allow newly deposited sediments to be tracked separately from the parent layer sediments, which are more consolidated than the freshly deposited sediments. ECOM-SEDZLJS includes a time-variable model of bed consolidation (following Sanford, 2008) that acts on the depositional layer stack to calculate the time-variable bed density profile and the effect of density on the erosion properties of sediments deposited over the course of the simulation. The consolidation model was parameterized such that the deposited layers reproduce the erosion properties (critical shear stress and erosion rate as a function of shear stress) specified for the parent layers. In addition, since the dry density associated with the deposited layers will control the sedimentation rate achieved by the model, an output of direct relevance to the behavior of the contaminant fate and transport model, the consolidation model was re-parameterized to use dry density profiles derived from the LPR core data as described below.

Sediment coring data from the various sampling programs that were used for developing initial conditions as described in a preceding section were used to constrain the dry density profile in the consolidation model. The upper panels in Figure 32 show an example of the dry density data available for the top 6" of the sediment bed. The data show the expected dependency with cohesive content (fraction <63 μ m), with dry density increasing as the cohesive content decreases. Since the consolidation model in ECOM-SEDZLJS is applied to only predominantly cohesive layers, the data were screened to only include the cores with >50% cohesive, and with dry density <1gm/cm³ (a small subset of atypical cores with high dry density, >1gm/cm³, and high cohesive content are not included for purposes of this analysis). This analysis was also restricted to cores with >50% cohesive content in order to minimize effect of particle size on dry density as seen in the upper left panel in Figure 32. In other words, as cohesive content decreases (and sand content increases), due to the larger particle sizes associated with sand (as compared to the cohesive classes), porosity decreases, thus increasing dry density. Restricting the analysis to the fraction of cores with >50% cohesive content avoids this artifact. The screened data were averaged to develop the average dry density associated with the top 6" of the sediment bed. A similar procedure was applied to develop the average dry density over the depth intervals 15-45 cm, 45-75 cm, 75-105 cm, and 105-165 cm as shown in the lower right panel of Figure 32.

A sensitivity analysis showed that including cores with >15% cohesive content increased the average dry density by less than 5% in all depth intervals (except the 15-45 cm interval which increased by 7%). The consolidation model was parameterized by constraining the parameters such that the erosion properties calculated for the depositional layers reproduce the Sedflume-derived erosion rate and critical shear stress profile defined for the parent layers (left and middle panel on bottom row in Figure 32) as well as the dry density profile (right panel on bottom row in Figure 32). The consolidation rate associated with the transition from the freshly deposited, unconsolidated state to the completely consolidated state is based on the consolidation experiments performed using LPR sediments (SEI 2008).

4.2.6 Settling Velocity

The settling velocities associated with the individual sediment classes within the ECOM-SEDZLJS model are treated separately based on particle size and source (for the cohesive classes). For the non-cohesive classes (diameter >63 μ m), settling velocity is calculated by the model as a function of the particle diameter using the formulations in Cheng (1997). However, for the cohesive classes, given the influence of processes such as flocculation that are not explicitly included in the model, the settling velocity has to be specified as a site-specific input. The settling velocity of the clays and silts in the model were defined based on the analysis of data on the vertical distribution of SS and flow velocities from Sommerfield and Chant's (2010) data collection effort, and from the Fall 2009 PWCM program. The settling velocity analysis is described in Attachment F and is summarized here.

Ignoring effects on vertical mixing by vertical salinity gradients, and assuming small longitudinal gradients in flow and SSC, the vertical SSC profile is expected to follow the logarithmic Rouse distribution (Van Rijn, 1984). The bulk settling velocity estimates of the total suspended sediments were therefore derived from the parameters of the fit of the data to this vertical distribution. By computing the bulk settling velocity on each vertical profile, the mean and median statistics were obtained over the entire time-series covered by each dataset. Figure 33 shows cumulative probability distributions of the calculated settling velocities at each of the mooring locations from the 2009 Fall PWCM program and the Sommerfield and Chant (2010) location at RM 1.4 in the LPR. The majority of the calculated settling velocities are in the 0.2-5 mm/s range, with medians computed at different stations along the river ranging from about 0.6 mm/s at RM 13.5 to about 1.5 mm/s closer to the mouth of the river. These computed settling velocity estimates were also found comparable also to the estimates from the EDPS experiment lending further credence to this analysis.

The settling velocity analysis is inclusive of all the SS types and size classes (possibly including sands as well as some of the higher discharges) within the water column. In addition, there are certain assumptions about mixing processes inherent in the Rouse-profile which are somewhat different from the ECOM-SEDZLJS numerical model.

Therefore, the results from this analysis were used only as a general guideline during the model calibration process.

The main features noted in the settling velocity analysis include (1) a positive relationship between settling velocity and near-bottom flow velocity (including within individual tidal cycles), and (2) a longitudinal gradient in settling velocity, with lower values at RM 13.5 and higher values at RM 1.4. The former feature indicates the presence of particles (flocs) with higher settling velocity at higher flow velocity, and is probably indicative of higher critical shear stresses for erosion associated with such particles. Note that none of the available erosion data in the LPR (Sedflume, Gust, entrainment rate analysis) lend themselves to the identification of particle class-specific erosion properties. However, the range of settling velocities noted in the data has been approximated in the model by including cohesive classes with a range of settling velocities as described subsequently. The second main feature noted in the data, the longitudinal gradient in settling velocity, may possibly indicate the presence of particles varying in their degree of flocculation. The suspended sediments originating from the freshwater inputs to the LPR (predominantly Dundee Dam) are expected to be relatively poorly-flocculated and associated with relatively low settling velocity. In contrast, the suspended sediments originating from the marine sources to the LPR (Kill van Kull and Arthur Kill via Newark Bay), are expected to be flocculated and associated with relatively high settling velocity. This source-dependent distinction in settling velocity is also included in the model by assigning varying settling velocities to the cohesive sediments originating from the freshwater and marine sources. Note that in principle, the spatial and temporal dynamics noted in settling velocity may also be numerically approximated by using a concentration-dependent settling velocity and associated with a single cohesive class in the model. Using multiple cohesive classes associated with varying settling velocities as a function of particle size and origin (flocculation effects) has the advantage of tracking sediment classes by origin.

Table 7. Settling velocities associated with the various sediment classes in the model.

Size Class	Effective Diameter (um)	Settling Velocity (mm/s)
Poorly Flocculated Clays (<4 um)	2	0.05
Poorly Flocculated Silts (4-63 um)	17	0.25
Flocculated Clays (<4 um)	2	0.08
Flocculated Silts (4-63 um)	17	0.4
Fine-Medium Sand (63-430 um)	155	13
Coarse Sand (430-2000 um)	760	90
Gravel (>2000 um)	4025	273

In accordance with the above features noted from the settling velocity analysis, settling velocity for the poorly-flocculated clay fraction was set to a relatively low 0.05 mm/s and

the settling velocity of the poorly flocculated silt fraction as 0.25 mm/s using the settling velocity formulation of Cheng (1997) included in ECOM-SEDZLJS. The settling velocity of the flocculated clays and silts was set to 0.08 mm/s and 0.4 mm/s, respectively, as the result of a calibration exercise as described in a following section. This represents a 60% increase from the settling velocity calculated for the poorly-flocculated clay and silt fractions; this increase reflects the impact of flocculation. Table 7 lists the settling velocities associated with the various sediment classes in the ST model.

4.2.7 Sediment Bed Discretization with Depth

The sediment bed discretization in depth refers to the number and thickness of the bed layers initialized in the model as well as the resolution of the deposited layers. The discretization of the bed layers defined at model initialization derives from the vertical structure in erosion properties measured in the Sedflume cores described previously. As shown in Table 6, erosion properties were discretized over 0-2.5 cm, 2.5-5 cm, 5-10 cm, 15-20 cm, 20-25 cm, 25-30 cm, and >30 cm depth intervals from the Sedflume data. In addition to erosion properties, the definition of initial conditions for bed grain size distribution and dry density (for the parent layers) also corresponded to these depth intervals, and were specified using the data-derived values described in a preceding section. The erosion properties, mass composition, and dry density derived for the >30 cm depth-interval were considered to apply over a deep bed, defined so that the model performance would not be constrained by the availability or the lack thereof, of sediments below the 30 cm depth-interval. In addition, the depositional layers which contain the sediment strata created by deposition over the course of the model simulation, were parameterized with a 1 mm discretization in order to achieve a smooth transition in consolidation and erosion properties with depth. The fluff and transitional layers were also initialized with a thickness of 1 mm each.

4.2.8 Navigation Scour

The implementation of navigation scour in the ST model involved the following three aspects: (1) identification of the area potentially subject to navigation scour, (2) the conditions under which navigation scour occurs, and (3) the scour rate. The parameterization of navigation scour in the model is based on analysis of the recent and historical bathymetry data as described below.

The portion of the LPR (and the corresponding model cells) subject to navigation scour are located between RM 0-1.4, and were identified by comparing the 2007 to 2008 surveys and the 2011 to 2012 multi-beam bathymetric surveys. Figure 34 shows the area within the LPR considered to be impacted by navigation scour as evidenced by erosional trends in comparing the bathymetric change during the 2007-2008, and 2011-2012 periods (left and middle panels) and the right panel shows the corresponding model cells considered to be subject to navigation scour.

For the model grid cells potentially subject to navigation scour, the concept of an “equilibrium-depth” or a water depth in dynamic equilibrium with the existing local ship traffic was used, with any sediment accumulation above the equilibrium depth being subject to scour. A qualitative analysis of the evolution of bathymetry from 1983 through 2012 (single-beam bathymetries in 1983, 1989, and 2004, LPRSA multi-beam bathymetries from 2007, 2008, 2010, 2011, and 2012, and NBSA multi-beam bathymetry from late 2012) was performed to look for any convergence patterns over time that might indicate the existence of such an equilibrium depth. Figure 35 shows the temporal evolution of bathymetry at four different transects located at the mouth of the LPR from 1983 through 2012. This analysis which was repeated for other transects in this reach, showed the depth at most locations tending approximately to the 2008 bathymetry, with notable exceptions being in locations of dredging events (for instance location 11 which shows a dredging event between the 2010 and 2011 surveys) or locations exhibiting deposition during Hurricane Irene in 2011 (for instance locations 12 and 13) and subsequently showing a continuing increase in water depths through 2012. Based on this analysis, the equilibrium-depth for each of the selected model cells was set to the observed depth from the corrected 2008 multi-beam survey (the correction of the 2008 survey has been described in detailed during several CPG-EPA oversight modeling meetings).

The temporal trend apparent in the transects shown in Figure 35 were also analyzed to fit an exponential time-function to the depth of scour in the selected model cells computed from the bathymetric changes between the 2007 to 2008 surveys, and between the 2011 to 2012 surveys. The scour rate input to the model is the average of the scour rate calculated for the individual cells multiplied by a factor to account for the fact that the scour rate calculated on the basis of the bathymetry data reflects net scour whereas the model input is in terms of the gross scour (the multiplicative factor was calibrated to a value of 10).

The magnitude of navigation scour calculated by the model is a function of time. The model is initialized with a given bathymetry, and as the model simulation progresses in time, the instantaneous bathymetry is compared to the equilibrium depth to determine the possibility of navigation scour. If so, the bathymetric change due to navigation scour over the following simulation period is calculated using the exponential function and scour rate described previously, and the bathymetric change incorporated in the model and the corresponding sediment mass scoured is released evenly throughout the water-column as a point source load at the location of scour. The inclusion of navigation scour in the ST model did not involve any code modifications; rather, this was performed in a pre-processing step and by definition of appropriate model inputs. For instance, as mentioned previously the sediments resuspended due to navigation scour was input as a point source load, essentially an input to the model simulation.

4.3 ECOM-SEDZLJS Modifications

As mentioned previously, the model setup and calibration was an iterative process that included a number of modifications to the ECOM-SEDZLJS code received from EPA. Although the model algorithm has changed somewhat from the version received from EPA,

the erosion, deposition, and consolidation formulations that are at the heart of the ECOM-SEDZLJS framework have not changed. Rather, the code modifications for the most part are incremental in nature and represent an enhancement of the model capabilities to ensure the reproduction of the key sediment transport processes that have been identified in the LPR (see Section 2). The code modifications fall into two broad categories: (1) related to the schematization of the bed layering, and (2) related to the decoupling of the HD and ST models and the bathymetric feedback between the decoupled models.

4.3.1 Schematization of Bed Layering

The model application to long-term periods involving a range of discharge conditions initially focused on the erosion properties of the parent layers. As described previously, the critical shear stress of the parent layers was adjusted through a process of calibration resulting in a sediment bed that is relatively stable during low discharge and normal tidal conditions, and which results in a good comparison of predicted and measured suspended sediment concentrations during high-flow conditions. The calibrated erosion properties are such that erosion from the parent layers and from the consolidated deposited layers occurs primarily during episodic storm events. Consequently, during low-to-average discharge and normal tidal conditions, the model did not reproduce processes such as the intra- and inter-tidal variability, tidal pumping, infilling, and the exchange with Newark Bay. Since sediment transport under such conditions in the LPR is dominated by the dynamics of the fluff layer, and since the entrainment rate analysis (supported by the Gust microcosm data) provides information to support the parameterization of the fluff layer, the bed discretization in ECOM-SEDZLJS was modified to include a fluff layer overlying the parent and/or deposited layers. Similar schematizations of the bed involving a more erodible fluff layer overlying a more consolidated layer have been applied at other sites as well (El Ganaoui et al. 2004; Van Kessel et al. 2007).

Figure 36 shows a schematic of the revised bed layering along with a conceptual description of the hydrodynamic conditions that can potentially scour through the various strata. The fluff layer is located underneath the active layer (which is the layer at the interface between the bed and the water column) and is subject to erosion and deposition through the active layer. Under erosional conditions (e.g., the first half of the flood tide), the fluff layer may disappear due to resuspension. During the following depositional condition (e.g., the second half of the flood tide and high-water slack), the depositing sediments first recreate the fluff layer. When the fluff layer exceeds its pre-determined maximum thickness, the excess sediment is transferred to the underlying layer. Given the order of magnitude difference in strength between the fluff layer and the underlying parent or deposited layer, in order to avoid a discontinuity in strength and also for a better model-data comparison especially during spring tides, a transitional layer (with same thickness as the fluff layer) with intermediate strength was also introduced into the bed structure. New depositional layers are created immediately underneath the transitional layer, and under depositional conditions, sediment is transferred from the fluff layer through the transitional layer to the new depositional layer underneath. The deposited layers are subject to consolidation as described previously. Under erosional conditions, the layer depletion

proceeds in a logical manner with the fluff layer eroded first, followed by the transitional layer and subsequently by the deposited or parent layer, as the case may be.

4.3.2 Other Modifications

Additional minor code modifications made during the course of the CPG ST model development are listed below:

- Originally, the active layer erosion properties (critical shear stress and erosion rate function) were either set as the value at the surface of the depositional layers or based on the results of Roberts et al. (1998) in case the active layer is calculated as non-cohesive (no-cohesive criterion described in the next bullet). This was modified such that the active layer assumes the erosion properties (critical shear stress and erosion rate) of the bed layer it is exchanging sediments with. This can be either the fluff or transitional layer, or a deposited or parent layer, depending on the preceding history of deposition/resuspension.
- The time-variable behavior of the active layer as cohesive or non-cohesive (with respect to erosion properties), was modified to include a criterion based on the cohesive content being <15%, in addition to the original criterion of D50 being >200 μm for the layer to be treated as non-cohesive.
- The D50 used for the calculation of skin friction from the total bed shear stress is based on the grain size distribution of the surficial sediments at model initialization rather than the time-variable grain size distribution within the active layer, to prevent high frequency oscillations in the active layer composition from yielding unrealistic effects, and also because initial test runs using time-variable D50 to calculate skin friction yielded SSC and bathymetric changes substantially larger than measured values during certain high-flow periods.
- The formation of bed forms and its effect on reducing skin friction was restricted to the part of the model domain defined as predominantly non-cohesive at model initialization, i.e. between RM 7.8-8.3, areas within the navigation between RM 8.3-13, and all the model cells above RM 13.
- The settling velocity of the cohesive classes was modified as a constant input value rather than the concentration-dependent formulation originally implemented in the model.

4.3.3 HD and ST Decoupling

The ECOM-SEDZLJS code and inputs originally received from Region 2 were set up to simulate both HD and ST simultaneously (i.e. coupled HD and ST). However, the runtime associated with coupled HD and ST runs was prohibitively long, on the order of about 3-4 days per year of simulation. In an effort to reduce the ST model runtimes, especially with

respect to the long-term (18 years) simulations necessary for calibrating the ST and contaminant models, the HD and ST simulations were decoupled. The HD model is run independently of the ST model and its transport solution saved as a 15-minute average during the course of the simulation. The ST model subsequently reads the saved HD output and is run independently, with time-steps three to four times larger than the HD model simulations, resulting in average runtimes of about 36 hours per year of simulation. ECOM-SEDZLJS already included the capability to run decoupled HD and ST; during the course of the CPG's application to the LPR and NB, this feature was tested and debugged.

4.3.4 HD and ST Bathymetric Feedback

As mentioned in the preceding section, the HD and ST models were decoupled in the interest of computational efficiency. Since the ST model calculates changes in sediment bed thickness and therefore bathymetric change in response to erosion, deposition, navigation scour, consolidation, and swelling processes, and since this bathymetric change can have an impact on subsequent flow patterns, a protocol was developed to incorporate bathymetric changes calculated by the ST model into the HD model.

The sequence of computations in the decoupled HD and ST models is as follows. Both models are run for discrete time periods which range from as much as 30 days (more typically 15 days) during low to average flow conditions to as little as 1 day during high-flow conditions. The HD model is run first, the HD transport solution saved and used to run the ST model. The bathymetric changes computed by the ST model during a given time period are incorporated into the HD simulations for the following periods. In the interest of computational efficiency for the combined HD and ST models, the bathymetric changes computed by the ST model are incorporated into the subsequent HD simulations with a lag of one time period. For instance, the bathymetric changes computed during a simulation from day 0-15 are incorporated not in the following period (day 15-30), but rather in the simulation from day 30-45. This enables the HD model to be run for the time-period from day 15-30 in parallel with the ST model run for day 0-15. This is a reasonable approximation since the bathymetric changes within a given time period are typically on the order of a few millimeters to centimeters which is small compared to the water depth in individual grid cells (typically on the order of meters). The runtime for the combined HD and ST runs, run decoupled and with bathymetric feedback in the manner described above, is approximately 36 hours per year.

5.0 MODEL CALIBRATION, PERFORMANCE, AND VALIDATION

The CPG's ST model has been applied and calibrated against a number of datasets collected as part of the LPRSA RI program. This section describes the model calibration process, the calibration parameters, the calibration metrics, and the model calibration performance. Certain model-data comparisons (as described subsequently) also represent model validation since those comparisons were not examined in developing the model parameter calibrations. In addition, the calibrated model was also applied to simulate the historical infilling of the LPR since the last major dredging events. The resulting model-data comparisons represent a validation of the model performance.

5.1 Calibration Run Setup

The results presented here are taken from a long-term simulation starting in October 1994 (WY1995) and run through September 2013 (WY2013). In addition to incorporating the bathymetric changes computed by the ST model as described previously, the bathymetry in NB and the Kills was also updated periodically to reflect the various maintenance and capital dredging projects in those areas during the simulation period.

5.2 Calibration Metrics and Periods

The model performance has been assessed by comparing model results to the following datasets:

- Fall 2009 PWCM – SSC and SS fluxes
- Sommerfield and Chant (2010) – SS fluxes⁶
- 16,000 cfs event on March 16, 2010 – SSC
- Spring 2010 PWCM – SSC⁷
- CWCM – salinity and SSC
- Bathymetric changes over the periods covering the 2007, 2008, 2010, 2011, and 2012 multi-beam surveys
- Surficial bed sediment composition from the various datasets listed in Section 4.2.1⁸

⁶ This comparison represents a validation of the model performance since this dataset was not used during the model parameter calibration process.

⁷ This comparison represents a validation of the model performance since this dataset was not used during the model parameter calibration process

⁸ This comparison represents a validation and check on the model performance and parameterization.

Taken together, these model-data comparisons allow the assessment of model performance over a range of discharge conditions from low-flow conditions of ~100 cfs (Regime 1) to the 16,000 cfs event on March 16, 2010 (a 1 in 25-year event; Regime 3). Further, the comparison of predicted and measured bathymetric changes between the 2010 and 2011 multi-beam surveys also allows for an assessment of model performance during a period including an extreme event (Hurricane Irene; Regime 3), when discharge at Dundee Dam peaked at 24,000 cfs, a 1 in 90-year event.

5.3 Calibration Parameters

The model inputs adjusted as part of the calibration process include the critical shear stress of the parent layers (and by extension also the deposited layers) as described in Section 4.2.5, and the settling velocities of the flocculated clay and silt classes. As mentioned previously, the critical shear stress defined for the parent layers was adjusted in order to achieve a favorable comparison between the model calculations of SSC and the measurements during the 16,000 cfs event on March 16, 2010 which represents an extreme high-flow condition when erosion dominates the measured SSC signal within the LPR.

The settling velocity of the flocculated clays and silts (entering from the Kill van Kull and Arthur Kill) was calibrated by examining model-data comparisons only during low-moderate flow conditions when the parent layers are largely inactive with respect to erosional processes, and erosion is mainly restricted to the fluff layer. The calibration process involved incrementing the settling velocity of the flocculated clay and silt classes from values calculated using the respective particle diameters (equivalent to the settling velocity of the poorly flocculated clays and silts). The calibration process resulted in a 60% higher settling velocity for the flocculated clays and silts than the poorly-flocculated clays and silts entering from the freshwater loadings. The dataset used for calibrating the settling velocity was primarily the Fall 2009 PWCM and the CWCM data. In other words, the deposition and erosion parameters were calibrated under mutually exclusive conditions. Furthermore, the parameter calibration was also constrained within the range of measured values in the case of the critical shear stress for erosion of the parent layers (discussed in Section 4.2.5), and within the range of values from the settling velocity analysis (discussed in Section 4.2.6) in the case of the settling velocity of the flocculated clays and silts.

5.4 Calibration Performance – Model-Data Comparisons

5.4.1 SSC, Fall 2009 PWCM

Figures 37 through 41 show model-data comparisons of salinity, and the depth-average, surface, and bottom SSC at RMs 1.4, 4.2, 6.7, 10.2, and 13.5 during the Fall 2009 PWCM period. In general, with some exceptions as noted subsequently, the model reproduces major features noted in the data: intra- and inter-tidal (spring-neap) variability in SSC as well as the presence of an estuarine turbidity maximum (ETM) associated with the salt front. Within the predominantly estuarine portion of the LPR (RMs 1.4, 4.2, and 6.7 during the Fall 2009 period), the model performs reasonably well in reproducing the temporal

trends in SSC. Major exceptions include the near-bottom SSC at RM 1.4, and within the ETM (immediately landward and seaward of the salt front) at all three locations. These discrepancies are further explored subsequently.

Most calculated depth-average SSC are within a factor of two of the measured values. In particular, at RM 1.4, which is representative of the exchange with Newark Bay, the model performs reasonably well in reproducing the depth average SSC during both spring and neap tide conditions, and over the full range of flows observed during this period. However, during certain periods such as the spring tides around October 18 and November 3, the model tends to over-predict depth-average concentrations. At RM 4.2 and RM 6.7, with some exceptions as discussed subsequently, depth-average SSC calculated by the model is either comparable to or lower than the data. However, at RM 10.2 which is predominantly freshwater during this period, the model tends to under-predict the depth-average SSC and does not show intra-tidal variability to the same degree as seen in the data (for example, during the period from November 1 through 15). In contrast, at RM 13.5 which is in the freshwater zone through this period, the model-data comparisons are more favorable, with similar depth-average SSC as well as similar intra-tidal variability under all flow conditions.

Part of the discrepancy between model and data may originate from discrepancies within the HD model, especially in the location of the salt front. Notable discrepancies between the measured and calculated near-bottom salinity (and therefore the location of the salt front) occur around October 27 and November 25 at both RM 4.2 and RM 6.7 locations. At RM 4.2, during the spring tide on October 18 when the salt front (and therefore the ETM) is located up-estuary, the depth-average SSC are comparable to the data. However, following the two flow events on October 24 and October 28, the model under-predicts the salinity values at this location, i.e., the ETM is calculated to be further downstream in the model, and therefore the model under-predicts the measured SSC up to the first week of November. During periods when the salt front is correctly reproduced by the model (before October 24, and around November 17 and December 1), model calculated SSC are comparable to the data at RM 4.2. In contrast, at RM 6.7, prior to the flow events of October 24 and October 28, the model reproduces the measured near-bottom salinity but over-predicts the SSC within the ETM zone. Following the two flow events on October 24 and October 28, the salt front is pushed down-estuary; however, the model does not capture the intra-tidal variability in SSC and tends to be biased low compared to measured values.

In general, at both RM 4.2 and RM 6.7, and to a lesser extent at RM 10.2, the model reproduces the observed depth-average SSC reasonably well during the periods when the ETM is located at or up-estuary of these locations, while it tends to under-predict when the ETM moves down-estuary. In other words, the model tends to under-estimate the SSC at the upper (freshwater) end of the ETM. This may be related to certain dynamics of the fluff layer apparent in the data but not reproduced by the model. Conceptually, the fluff layer represents a pool of easily erodible sediments resuspended during flood as well as ebb tides and the signature of this tide induced resuspension is the occurrence of four SSC peaks per day, as seen in the time-series measurements before October 25 at RM 10.2. During the flow events of October 24 and 28, the time-series of measurements suggest that the normal

fluff layer dynamics are altered such that only two peaks are apparent per day from October 25 to November 1, following which the SS signal slowly reverts to the typical pattern of four peaks per day. A similar feature is seen in the measurements at RM 6.7, where the period preceding October 25 is characterized by four SS peaks per day, the period from October 25 to October 29 by two peaks per day, followed by a transition to four peaks per day. This transition occurs before the salt front moves up-estuary, and is also accompanied by a build-up of SSC within the ETM. The exact processes governing these dynamics may not be entirely known (part of discrepancy between the model results and the data may also be related to grid resolution), but it is important to note that when the salt front is located at RM 6.7, such as around November 15 and December 1, model results for depth-average SSC are comparable to the data. This suggests that the discrepancy between the model and the data during such periods may be a transitory phenomenon and perhaps not significant over long-term simulations.

Another point to consider in assessing the model performance relative to data is the fact that the Fall PWCM data represent estimates of SSC from surrogate measurements of Acoustic Backscatter (ABS). The ABS data are converted to SSC using a regression of ABS to SSC developed using a limited number of SSC measured in water samples. As such, the regression tends to the mean when applied to estimate SSC from the ABS time-series. The variability observed around the regression relationship can be included in the estimates of the measured SSC by means of prediction intervals to better assess model performance and deviations beyond the bounds of the estimated SSC. Figures 42 through 46 show a detailed time-series of model results and data (including the prediction interval) for SSC at the various PWCM mooring locations (upper 5 panels in both columns show comparisons per water column layer in the model), Dundee Dam discharge and the measured and model calculated tide (bottom left panel), and the measured and model calculated bottom salinity (3' above bed; bottom right panel). The time-series are shown for a one week period (from October 19th through 25th; similar comparisons for the entire PWCM period are included in Attachment G) when the tide transitions from spring to neap, with below-average discharge of about 500 cfs for most of the week and increasing to about 3500 cfs at the end of the week. During this period, the salt front and the ETM are located between RM 6.7 and RM 10.2 during the flood tide, and moving seaward of RM 6.7 with the ebb tide. The results and the comparison to data in Figures 42 through 46 can be reviewed with respect to the phase, intra- and inter-tidal variability, ETM dynamics, and response to the discharge event on October 24th.

In particular, at RM 1.4 (Figure 42), at the beginning of the week, the model results are seen to be in phase with the data, exhibiting similar intra-tidal variability with flood-dominant SSC as the data. The model results also show inter-tidal variability, with average SSC decreasing with the transition from spring to neap. The discharge event towards the end of the day on October 24th coincides with a disruption of the tidal signal, a trend not entirely reproduced by the model. The fluctuation in measured SSC around this time (the last flood tide on October 24) may be related to this disruption of the tide, a phenomenon not entirely captured by the model. In contrast, during the ebb tide on October 25th, a period likely reflective of the SS loading and any potential resuspension induced by the discharge-

event as the flood wave travels down from Dundee Dam, SSC are more comparable to the measurements and within the range of the prediction interval. Another notable discrepancy at this location relates to the vertical gradient in SSC, with near-surface concentrations better reproduced by the model than near-bottom concentrations which are typically over-predicted. However, it is important to note that the data represent measurements at a specific location within the cross-section of the river whereas the model results represent an average across the width of the grid cell at this location. Therefore, the model calculates a spatially integrated average concentration over a larger portion of the cross-section than measured by the data. Consequently, even though the model-data comparisons for SSC presented here suggest a bias in model performance for this metric, the potential for a bias in overall model performance can also be assessed by comparison against other metrics such as short-term and long-term bathymetric change presented subsequently.

With some exceptions as discussed subsequently, RM 4.2 (Figure 43) show in general similar results as RM 1.4. The beginning of the week, the model calculates a longer ebb peak in SSC than indicated by the data, with maximum ebb concentrations equal to or larger than maximum flood concentrations, a trend opposite of that seen in the data. This may be a consequence of the model calculating lower salinity during ebb than seen in the data, and the difference in ebb concentrations and apparent phase difference may reflect the ETM moving down to the vicinity of RM 4.2 during ebb in the model. Towards the latter part of the week (around October 22), as the salt front and ETM move up-estuary, the model results transition to being in phase with the data, with similar magnitude and occasionally also showing flood dominance in SSC. The setup event on October 24 shows a larger impact in the data at this location than at RM 1.4, a trend captured by the model. However, some fluctuations in SSC seen to occur in parallel with a disruption of the first ebb tide on October 25 are not reproduced by the model. SSC during the second ebb tide on October 25 are within the range of the prediction interval, albeit with a slight phase difference. The exaggerated vertical gradient in SSC noted at RM 1.4 are less prominent. For example, during October 22-24, when the salt front is located up-estuary, model results for all sigma layers are generally within the range of the prediction interval over the entire tidal cycle.

The model-data comparisons at RM 6.7 (Figure 44) are dominated by the presence of the salt front and ETM for most of the week. Peak concentrations on both ebb and flood are over-predicted by the model, indicating that the sediment inventory in the water column within the ETM zone is over-estimated by the model. As mentioned previously, the model typically tends to under-predict SSC immediately up-estuary of the salt front, as seen following the high-flow event on October 25. Although the fluctuations associated with the setup event on October 24 are not captured, the impact of the flood wave as it moves down from Dundee Dam are well captured during the two ebb tides on October 25th.

The model results at RM 10.2 (Figure 45), which is located up-estuary of the salt front during this week show similar patterns as seen in the data, with SSC fluctuations over tidal time-scales. However, the model tends to be biased low compared to the mean estimated SSC, although, still within the lower bound of the prediction intervals. Although the fluctuations associated with the setup event on October 24 are not captured, the impact of

the flood wave as it moves down from Dundee Dam are well captured during the two ebb tides on October 25 and model results are seen to be comparable to the data.

In contrast to the downriver stations, at RM 13.5 both model and data show relatively low SSC and low variability in time (Figure 46). The data varies typically in the range of 5-15 mg/L, with the model results only slightly more variable (range of 5-20 mg/L) during most of the week. During the discharge event of October 24-25, the data show an increase with the upper bound of the prediction interval up to 70 mg/L whereas the model shows a pronounced but short-lived spike with near-bottom values of up to 150 mg/L. It should be noted that the SSC at Dundee Dam during this period only corresponds to a maximum of about 25 mg/L, so any increase beyond that value reflects resuspension within the LPR. During a significant portion of the discharge event of October 24-25, model results are within the prediction interval range.

The detailed review of the model results and comparison to the measured SSC indicate that on average the model performs reasonably in terms of several metrics such as the phasing of the tidal concentration signal, the inter- and intra-tidal variability, ETM concentrations, and overall response of the river to a minor discharge event, all of which are features relevant to reproducing the long-term sediment mass balance of the system. However, the detailed time-series comparisons of model and data also indicate several artifacts in the model performance (eg., the exact timing and location of the salt front is slightly different in the model and data which has a bearing on the ETM timing and location, the model tends to over-estimate the SS inventory in the water column seaward of the salt front, the model tends to under-predict SSC landward of the salt front, the model tends to over-predict near-bottom SSC at RM 1.4). The impact of these short-term discrepancies can be assessed by reviewing model performance over long-term and short-term period for additional metrics such as residual SS fluxes and bathymetric changes. The residual SS fluxes and bathymetric changes represent a relevant metric to examine the integrated model performance and assess the mass transport of SS. This is presented in a subsequent section.

5.4.2 SSC, High Flow Conditions

On March 16, 2010, flow over Dundee Dam peaked at 16,300 cfs, equivalent to a 1 in 25-year event in the LPR, providing an opportunity to measure the response of the river under such extreme high flow conditions. Dr. Robert Chant of the Institute of Marine and Coastal Science, Rutgers University conducted a series of longitudinal transects along the thalweg in the LPR and within the navigation channel in NB during the peak of the storm event. The data consists of CTD and OBS casts measuring the water depth, temperature, salinity and SSC (OBS measured, converted to SSC by means of an OBS-SSC relationship) over depth in the water column. A total of three such longitudinal transects were collected over half a tidal cycle, with the first transect collected at the beginning of the ebb tide, the second transect collected around the middle of the ebb tide, and the third transect collected around the following low-water slack. At the same time, water samples were collected for laboratory measurements of SSC. These samples were collected at the water column

surface, over a course of about 8 hours, from just before the first transect to the end of the third transect.

On average, the measured SSC tend to increase from the first to the third transect following the expected trends in net flow velocity – during flood and high-water stages, river flow and tidal flow are in opposing directions thus reducing the net velocity; they are aligned in the same direction during the ebb tide, with the highest net velocities expected during mid-ebb tide and low-water slack. Measured SSC range over an order of magnitude from about 20 mg/L (primarily in NB), to about 400 mg/L which occur primarily at the bottom of the water column within the ETM. Figure 9 presented previously shows the data from the second transect, and shows the presence of a well-defined ETM associated with the salt front around RM 0. The ETM extends for approximately 3 miles, from RM 0 to RM 3, with near-bottom SSC of ~400 mg/L and near-surface concentrations of ~200 mg/L within the ETM.

The model application and comparison to the salinity and SSC measured in this event are a measure of the model's capability to capture the response of the river to such extreme high-flow events and represents the model calibration to SSC under high-flow conditions. Figure 47 shows model-data comparisons of SSC for the three longitudinal transects measured by Dr. Robert Chant, and for the water sample data collected during this event. Most model-calculated values are seen to be within a factor of two of the measured values; only transect #2 shows an appreciable fraction of the measured values being over-predicted by more than factor of two compared to the measured values.

The model results for salinity and SSC over the period corresponding to the collection of the three transects have also been plotted along the longitudinal axis of the LPR and NB and compared to the data as shown in Figures 48 through 50. The model performs reasonably in reproducing the spatial patterns in concentrations, reproducing the relatively low concentrations found in NB, the high concentrations found within the ETM, as well as the temporal variability, with the highest concentrations found in the second and third transects. The model reproduces the salt front location approximately at the same location as seen in the data with some minor discrepancies (model-calculated salt front is about quarter mile down-estuary in case of transect #1, and about half-mile up-estuary in case of transects #2 and #3 when compared to the data). The model also shows an ETM associated with the salt front, with concentrations similar to measured values with most results within a factor of two of measured values as seen in Figure 47. However, the model-data comparisons for individual transects show some discrepancies. For instance, the model tends to under-predict SSC for transect #1, over-predict concentrations within the ETM as well as down-estuary of the ETM (in NBSA) for transect #2, and calculates two turbidity maxima for transect #3 (one centered around RM 0.5, and another one centered around RM 5). While the short-term impact of these discrepancies is apparent in the model-data comparisons presented in Figures 47 through 50, the large-scale impact of these discrepancies can be assessed by comparing the measured and calculated bathymetric changes. This is further discussed in a following section.

5.4.3 *SSC, Spring 2010 PWCM*

Figures 51 through 55 show model-data comparisons of bottom salinity, and the depth-average, surface, and bottom SSC at RMs 1.4, 4.2, 6.7, 10.2, and 13.5 during the Spring 2010 PWCM period. The estimates of SSC for data are based on ABS measurements from the ADCP moorings at these locations. Attachment A describes the development of SSC from the ABS measurements. The comparison of the model performance relative to this dataset also represents a validation of the model performance since the model parameter calibration process did not include this dataset.

The Spring 2010 PWCM deployment started about one week following the 16,000 cfs event (1 in 25-year event) on March 16, 2010. During this event, the salt front and the ETM are pushed to the vicinity of RM 1, following which the data shows the salt front gradually moving up-estuary as the Dundee Dam flow decreases. At the beginning of the deployment, the salt front is located around RM 1.4, moving up-estuary during flood and moving down-estuary during ebb. During the 10,000 cfs event that peaks on March 31, 2010, the salt front is briefly (for one tidal cycle) pushed entirely down-estuary of RM 1.4 before moving up-estuary around April 10 with the decreasing river flow. During a minor storm event starting on April 25, the salt front is pushed down to RM 1.4 before moving back up-estuary in the first week of May. Similar discharge dependent temporal dynamics in the salt front and ETM location are also apparent up-estuary, with the salt front moving up to RM 10.2 towards the end of the deployment in early July. Occurring immediately after a 16,000 cfs event, measured depth-average SSC during the 10,000 cfs event on March 31 only reach about 20 mg/L at RM 13.5, and increasing to about 70 mg/L at RM 1.4. The 16,000 cfs event on March 16, 2010 represents an event typical of Regime 3, when the fluff layer is completely depleted and with some localized erosion. As a result, at the beginning of the Spring PWCM deployment, the normal tidal signal of four peaks in SSC per day (typically around mid-flood and mid-ebb in the semi-diurnal tide) is reduced to only two peaks per day, typically during ebb tide. This suggests that the SS signal is dominated by fluvial processes, including the loadings from Dundee Dam and potentially erosion in the LPR. As the river discharge decreases, and the river transitions from ebb dominant tidal asymmetry in currents to normal tidal conditions (flood dominant tidal asymmetry in currents), fluff layer dynamics become re-established, resulting in the typical four peaks per day signal in SSC. This is most apparent in the data at RM 6.7, with the transition from two peaks to four peaks occurring around April 10. Subsequently, as the salt front reaches RM 6.7, around May 10, peak tidal depth-average SSC increase up to about 80 mg/L (during spring tides; somewhat lower during neap tides). When the salt front, and therefore the ETM, moves up-estuary of RM 6.7, SSC decline. Similar temporal dynamics are seen at all the stations (with the exception of RM 13.5 which is always located in the freshwater portion of the river during the entire deployment). This dataset therefore represents the recovery of normal tidal and estuarine SS dynamics (controlled by the fluff layer) in the LPR following the 16,000 cfs event of March 16, 2010.

Review of the model-data comparisons presented in Figures 51 through 55 shows that certain trends noted in the model performance during the Fall 2009 PWCM are apparent in this comparison as well. The vertical gradient in SSC is seen to have similar bias between

the model and data at RM 1.4, with near-bottom SSC over-predicted by the model, especially during spring tides. However, depth average concentrations are usually better reproduced by the model than the vertical gradient, especially when the ETM is located at the mooring location. At all locations, the model also reproduces the transition from two peaks to four peaks in SSC per day as well as the spring-neap variability in SSC, both indications that the model has re-established the fluff layer resulting in similar intra- and inter-tidal variability in SSC as seen in the data. However, there is a lag seen in the model results – for instance at RM 6.7, the ETM dynamics are apparent in the data starting around May 10. However, the model result tends to lag in this respect, with the ETM concentrations increasing attaining the range of measured values only around May 27. Thereafter, model results are comparable to the measured values. Model results at RMs 1.4, 4.2, and 10.2 also exhibit a similar lag, although to varying degrees. This lag is similar to the trend noted previously in the model-data comparisons using the 2009 Fall PWCM data, where the model is seen to under-predict SSC immediately up-estuary of the salt front.

At RM 1.4, the model performs well in reproducing the depth-average SSC, suggesting that the exchange with Newark Bay is well reproduced by the model, albeit with some over-prediction during spring tide conditions. At RM 4.2, although the model does reproduce the pattern of four peaks per days, the peak SSC tend to be under-predicted by the model, especially during neap tides. At RM 10.2, although the model calculates SSC that tend towards measured values most of the time from the beginning of the deployment to mid-May and again in early-mid July when the salt front is located here, the model does not capture the daily mean nor the intra-tidal variability in SSC from mid-May onwards as well as in mid-late July after the salt front is pushed down-estuary. This is true of the model-data comparisons at RM 13.5 as well, although not to the same degree as at RM 10.2 in terms of the relative discrepancy between model and data. One possible explanation for this may be that the data may show the effect of tidal pumping in transporting SS from down-estuary locations to RM 10.2 and RM 13.5 to a larger degree than captured by the model. The fact that this discrepancy is mostly limited to one location (RM 10.2), and similar to the lag in the timing of the ETM dynamics as noted at RM 6.7 previously, would seem to suggest that this is a transient phenomenon and perhaps not significant over long-term simulations. Another relevant issue to consider in this regard is that the Spring PWCM data represent estimates of SSC from measurements of ABS converted to SSC using a regression of ABS to SSC. The prediction interval bounding the regression relationship can be included in the estimated SSC time-series in the same fashion as done for the Fall PWCM data. Attachment G includes detailed comparisons of the model results for each sigma layer to the ABS-derived SSC along with the prediction intervals.

In summary, despite the artifacts noted in the model performance, especially with regard to the timing of the ETM dynamics, the overall model performance appears to be reasonable. More importantly, it performs well in capturing the transition of the river from Regime 3 conditions where the fluff layer has been flushed out of the LPR, to a Regime 1 condition where the fluff layer dynamics and normal tidal dynamics in SSC have been re-established. Over time, model predictions of the magnitude of SSC, and the intra- and inter-tidal variability in SSC tend to approximate the range of values seen in the data. As

mentioned previously, the Spring PWCM dataset was not included in the model parameter calibration exercise. Therefore, the ability of the model in reproducing many of the processes observed in the data, especially as the river recovers from a somewhat extreme discharge event (1 in 25-years), is taken to be an indication of the validity of the model calibration and the robustness of the model framework, especially the bed schematization involving a easily erodible fluff layer overlying more consolidated strata, which is a refinement of the original ECOM-SEDZLJS formulation and implemented during the application of this model to the LPRSA. The ability of the model to recover from such extreme events and re-establish an entirely different mechanism controlling the transport dynamics under typical discharge conditions provides confidence in the applicability of the model to long-term simulations such as the 18-year calibration simulation, or the decadal scale projection simulations.

5.4.4 Residual SS Transport

Figures 56 and 57 show model-data comparisons of the direction and magnitude of the daily net depth-integrated SS flux as a function of discharge for the Fall 2009 PWCM period and for the period in 2008-2009 measured by Sommerfield and Chant (2010) at RM 1.4. Since the data represents a point measurement at the mooring location, the estimates of SS fluxes have not been extrapolated to the entire cross-section. Rather, the fluxes are expressed in terms of mass per unit width of the river. The model calculated flux for the grid cell at the mooring location has been normalized by the cell width for an equivalent comparison to data. These comparisons show that, although not identical, in general, the model performs well in reproducing the processes of up-estuary transport by tidal pumping and estuarine circulation within the LPR, the trend toward down-estuary transport as discharge increases, as well as the exchange between the LPR and NB. The general trends observed in the model results at RM 1.4 show reasonable agreement with those from the data which indicates that the exchange between the LPR and NB is correctly simulated by the model. Within the predominantly estuarine stations during this deployment (RM 1.4, 4.2, and 6.7), the slope of the flux-discharge relationship in the model tends shallower than the data, suggesting that the model calculations of resuspension may be biased low during conditions when daily discharge at Dundee Dam are less than 4000 cfs. At the same time, the model-data comparisons during the high-flow event on March 16, 2010 presented in a preceding section suggested that the model performed reasonably well under those conditions. It is possible that the model performance relative to the data may exhibit a continuum, with the model biased low during moderate flow events, and comparable to the data during high flow events such as the March 16, 2010 event. In contrast, the flux-discharge relationship calculated by the model at the freshwater stations (RM 10.2 and 13.5) agree well with the data in terms of the slope of the relationship and the magnitude of the flux for a given discharge.

Furthermore, the model-data comparisons using the data from Sommerfield and Chant (2010) at RM 1.4 represents a validation of the model performance since this dataset was not considered in developing the model calibration. Rather, this dataset has only been used to evaluate the model performance following the development of the model calibration

parameterization. Therefore, from the perspective of testing the model performance independently of the model calibration datasets, the comparison to the data from Sommerfield and Chant (2010) represents a validation of the model parameterization and performance. In addition, the Sommerfield and Chant (2010) deployment occurred following a 16,000 cfs event in April 2007, an event similar to the event in March 2010 immediately preceding the Spring PWCM deployment. Similar to the conclusion from the model performance during the Spring 2010 PWCM period, the comparison of the model results to Sommerfield and Chant's (2010) data also shows that the model is able to capture the transition from a Regime 3 condition to a Regime 1 condition and re-establish the equilibrium and infilling under normal tidal and discharge conditions.

At RM 1.4, model performance against data from both datasets shows that the model tends to calculate more net up-estuary transport than suggested by the data. However, it should be noted that the SSC used to calculate SS fluxes were derived from ABS data using an ABS-SSC relationship. The uncertainty inherent in this relationship was previously examined using prediction intervals; however, that uncertainty has not been propagated to the estimated net daily SS fluxes. In addition, the data represent measurements at a specific location within the cross-section of the river whereas the model results represent an average across the width of the grid cell at this location. Therefore, the model calculates a spatially integrated average concentration over a larger portion of the cross-section than measured by the data. Consequently, even though the model-data comparisons for SS fluxes presented here suggest a bias in model performance for this metric, the potential for a bias in overall model performance can also be assessed by comparison against other metrics such as short-term and long-term bathymetric change presented subsequently.

5.4.5 CWCM Model-Data Comparisons

The water samples collected as part of the CWCM program were characterized for SSC in addition to salinity and contaminant concentrations. Since the water samples were collected over a range of discharge (ranging from ~200 cfs to 4000 cfs) and tidal conditions (with measurements over the tidal cycle as well as spring-neap cycle) at several locations within the LPR, these measurements provide an additional dataset to judge the performance of the ST model.

The comparison of the measured salinity versus the model-calculated salinity for the various events and locations is presented in Appendix L with the model performing well in reproducing the salinity measurements. Figure 58 shows comparisons of the model calculated and measured SSC during these events. Most predictions are within a factor of two of the measured values, with no apparent bias during any single event. The only bias in model performance appears to be an over-prediction of the near-bottom SSC at RM 0 and RM 1.4, a feature better seen in the probabilistic comparisons of the model-predicted and measured SS values shown in Figures 59 and 60. Each panel in Figures 59 and 60 shows all the model-data pairs available for the given location, with the stations at RM 10.2, 6.7, and 4.2 located within the freshwater portion of the LPR during the periods of sampling, stations at RM 0 and 1.4 within the estuarine portion of the LPR, and floating

stations Tidal 1 and Tidal 2 located near the salt front and halfway between the salt front location and RM 1.4 respectively. It should be noted that the location of the salt front was variable over the course of the sampling, and so the locations of Tidal 1 and Tidal 2 were not fixed over the various sampling events. Nonetheless, the model-data comparisons show a good comparison between model and data at all the freshwater stations, with a slight bias (less than a factor of two) towards under-prediction. In the estuarine portion of the LPR, near-surface model predictions are comparable to the data. However, near-bottom comparisons are more variable, with Tidal 1 and Tidal 2 well reproduced, but RM 1.4 and RM 0 generally over-predicted by the model. The over-prediction of near-bottom SSC in the lower 1.4 miles of the LPR is a trend also noted in the comparisons to the 2009 Fall and 2010 Spring PWCM data. This over-prediction is likely related to the complex nature of the interaction between the LPR, Newark Bay, and the Hackensack River. The exchange between these water bodies is further explored in the NBSA Modeling Addendum (Moffatt & Nichol and Deltares, 2017).

5.4.6 Bathymetric Comparisons

Figures 61 through 64 show maps of the bathymetric change measured in the 2007-2008, 2008-2010, 2010-2011, and 2011-2012 multi-beam surveys (left panels), and model calculations during the corresponding periods within the lower miles of the LPR. The bathymetric difference data were averaged over the model cells. These bathymetric comparisons span low-flow periods (2007-2008, and 2011-2012), and high flow periods (2008-2010, and 2010-2011) showing distinct spatial and temporal patterns of erosion and deposition. The bathymetry difference data were also averaged laterally and longitudinally (in ~0.1-mile long sections) for a comparison of large-scale morphological patterns in the data to model results. Figures 65 and 66 show the results of this analysis; only the portion of the data with at least 70% coverage with any given model grid cell is included in the cross-sectional and longitudinal averages (top panels), with model results shown for corresponding cells (bottom panels).

Both the data and model show distinct morphological responses depending on the flow regime, with the low flow periods characterized by deposition above RM 2 and scour below RM 2 (somewhat lesser in the model), and the high-flow periods characterized by erosion above RM 1-2 and deposition below RM 1-2. Comparing the areal extent of erosional features in the model and data, in particular for the 2010-2011 period, shows that on average, the model tends to predict erosion about 0.5 mile down-estuary than seen in the data. This relative bias in the location of salt front during discharge events has been noted previously in the discussion of the model-data comparisons using the Fall PWCM data as well as the March 16, 2010 event data. As a consequence, the depositional features during the high-flow periods also tend to be shifted down-estuary by ~0.5 mile. Because deposition between RM 0-2 during the high-flow conditions provides the source material for navigation scour during subsequent low-flow conditions, any bias in the location and amount of deposition between the model and data during high-flow conditions also affects model calculations of navigation scour during subsequent low-flow conditions. The mismatch in this feedback likely explains the relatively lower magnitude and prevalence

of navigation scour in the model during the low-flow periods between the 2007-2008 and 2011-2012 surveys.

The analysis of the year-to-year bathymetric change observed in these multi-beam bathymetry data (see Attachment B) has shown the presence of several areas that behave in a cyclical manner, with erosion during high-flow periods and infill during low-flow periods. For instance, areas that exhibit infilling during the 2007-2008 low-flow period typically tend to show erosion during the 2008-2010 high-flow period. These areas are typically in the vicinity of bridge abutments or features such as river bends. However, the spatial scale of these features is too small to be resolved by the HD and ST model grid. Therefore, in the comparisons of model and data, the model under-represents these erosional features and therefore also the associated depositional features both at the mouth of the LPR during the 2008-2010 high-flow period as well as the infilling of the local scour holes during the 2007-2008 low-flow period. It is estimated that about 20-40% of the measured signal during the 2008-2010 period reflects erosional and depositional processes due to such sub-grid scale processes. In contrast, during the 2010-2011 high-flow period, the model tends to over-predict erosion at several locations – between RM 9-10.5, between RM 8-4, and between RM 1.5-0.5. This may be due to the lack of erosion data at depth, with the erosion properties measured in the Sedflume cores (described in Section 4.2.5) restricted to depths of about 1'. However, the over-prediction of erosion is restricted to the high-flows during Hurricane Irene which was a 1 in 90-year event. During smaller events, the erosion depths calculated by the model are relatively lesser.

Figure 67 shows another comparison of the measured and model-calculated bathymetric change over the periods corresponding to the various multi-beam bathymetric surveys. The measured bathymetric change was mapped to the model grid and used to calculate an average change per cell, including only cells with >70% coverage with bathymetric data. The probabilistic comparisons in Figure 67 offer another perspective on the large-scale model performance relative to the measurements, without explicitly considering the spatial correspondence between model results and data. The comparisons show that with the exception of the 2010-2011 comparison, on average the model response tends to be less variable than the data. However, during 2007-2008 and 2011-2012, the model and data distributions are similar over the majority of the domain. Deviations between the model and data are restricted to the lower and upper 5-10% of the distributions. The comparison over 2010-2011 shows good agreement between the model and data distributions, with deviations towards the lower and upper 5-10% of the distribution. The average bias for the middle 80% of the distribution is on the order of 5-10 cm. Similarly, the comparison over 2011-2012 show good agreement between the model and data distributions, with appreciable deviations only in the lower ~10% and the upper ~2% of the distribution. In contrast, the model-data comparisons over 2008-2010 show the biggest discrepancy, with the data showing erosion over approximately half the domain and deposition over the remaining area. The model does not capture the spatial extents of erosion and deposition seen in the data; most changes calculated by the model are relatively small. This may likely be due to a couple of factors – the lack of suitable Sedflume data to define spatially variable erosion properties, and limitations imposed by grid resolution which prevent the

reproduction of areas of cyclical local scour and deposition behavior (as described in Attachment B). Finally, the comparison over 2007-2012 for the most part show a good correspondence between the measured and calculated bathymetric changes. The data shows the erosional and depositional areas distributed evenly in the LPR during this period. Both the relative distribution of erosional and depositional areas as well as the magnitudes of erosion and deposition are well reproduced by the model.

The measured and calculated bathymetric changes have also been compared volumetrically over RM 2-14 and RM 0-2 (the spatial breakpoint chosen this because of the flow-dependent morphological behavior in these two reaches, with net erosion during high-flow periods and net deposition during low flow periods in RM 2-14, and the opposite trends in RM 0-2). Volumetric accumulation in RM 0-2 are also shown including the accumulation in a half-mile reach (accounting for the half-mile offset in the location of the salt front in the model compared to the data) within the former navigation channel in Newark Bay. The resulting comparisons are shown in Figure 68 for comparisons where only data and model results from grid cells with 70% bathymetry data coverage are included, and in Figure 69 for comparisons where all data and all model results from grid cells with any bathymetry data are included. The comparisons are shown over the periods bounded by the individual multi-beam bathymetry surveys, and over the entire period bounded by the first and last multi-beam bathymetry surveys (2007-2012). During the 2010-2011 high-flow period, the model predicts net erosion and net deposition above and below RM 2 (including the half-mile offset), respectively. However, during 2008-2010, the model mostly calculates net accumulation over these spatial scales, albeit with local areas of limited erosion. Overall, the magnitude of erosion and deposition during 2008-2010 is under-predicted (about 20-40% of the signal measured in the data is estimated to reflect sub-grid scale localized scour and resulting deposition). In contrast, during 2010-2011 the model over-predicts erosion above RM 2. As mentioned previously, the half-mile offset in the depositional areas during high-flow periods affects the calculation of navigation scour during low-flow period since the areas subject to navigation scour in the model were developed based on observations of navigation scour in the bathymetry surveys. As a result, although individual cells between RM 0-2 during these periods are subject to navigation scour; the net change over RM 0-2 is seen to be either slightly erosional or slightly depositional during the low-flow periods. In the absence of navigation scour in the model, these areas would be calculated to be more depositional. Model calculations of infill volumes above RM 2 are seen to be comparable to the data during the low-flow periods.

Comparison of the bathymetric changes over 2007-2012 allows for a long-term and large-scale assessment of the model performance relative to data over a range of flow conditions. During this period (for the case where all data and all model results from grid cells with any bathymetry data are included), the data shows approximately 3 million ft³ of net erosion above RM 2 and 3.8 million ft³ of net deposition below RM 2. The model shows similar spatial trends, with 3.8 million ft³ of net erosion above RM 2 and 3.1 million ft³ of net deposition below RM 2 (including the volume of sediment deposited in the channel up to 0.5 mile below RM 0). These results suggest that the model reproduces the large-scale spatial and temporal behavior of the LPR seen in the multi-beam bathymetry surveys, with

infilling during low-average flow conditions and erosion during high-flow conditions, and with the upper miles (>RM 2) showing net erosion and the lower miles (<RM 2) showing net deposition during the five years spanning the various multi-beam bathymetric surveys.

In addition to the model-data comparisons using the recent multi-beam bathymetric surveys, model performance has also been assessed by comparison to estimates of bathymetric change over the 1995 to 2004 time-period. The estimates of bathymetric change over the 1995 to 2004 time-period are based on a probabilistic analysis (conditional simulations) conducted by Region 2 (Louis Berger, 2014) using single beam bathymetry data, resulting in mean estimates of measured bathymetric change averaged over the spatial scale of a model grid cell. These estimates are limited to the areal extent of the bathymetric surveys, i.e., between RM 1.5 to RM 7. Mean estimates of measured bathymetric change along with the model calculated bathymetric change during this time period are shown in Figure 70 (as a map), and probabilistically and volumetrically in Figure 71. The data indicate large areas of infilling along with erosion in specific areas such as along the outer bends at RM 2, RM 3.3, RM 5, and RM 6.5. Although the model predicts similar spatial patterns and magnitude of infilling as noted in the data, it tends to under-predict the magnitude of erosion. Measured erosion ranges up to about 30 cm, whereas model-calculated erosion only ranges up to about 7 cm. Both model and data show similar magnitudes of maximum infilling, ranging up to about 100 cm. However, the data shows infilling in about 20% more grid cells than calculated by the data. In other words, in a subset of the domain, the model tends to under-predict both erosion and deposition, and reproduces approximately similar magnitudes of deposition in the remainder of the domain. Qualitatively, this is a similar trend as noted in the comparison of the multi-beam bathymetries, where between 20-40% of the signal measured in the data is estimated to reflect sub-grid scale localized scour and resulting deposition, features that are finer than the spatial discretization of the model. Comparing the volumetric change calculated by the model to the data shows that the model under-predicts net sedimentation during this period by 20% between RM 2-7.5, by 50% between RM 2-1.5, and a total under-prediction of 30% over RM 1.5-7.5.

5.4.7 Model Bed Composition Evolution – Comparison to Core Data

As mentioned previously, the long-term calibration simulation from WY1994 through WY2013 involved a continuous simulation with time-variable bed compositional changes calculated by the model based on the time-variable erosion and deposition fluxes. Although the model is initialized with a certain bed composition for the various sediment size classes included in the model, review of the changes over time and its comparison to LPRSA core data serves as a check on the overall performance of the model with respect to its initialization and can serve as a qualitative check on model performance and identify any long-term temporal deviations.

The review of the evolution of bed composition in the model has been performed by comparing the initial and final calculated bed composition (cohesive fraction of the top 15 cm of the sediment bed) in the LPRSA relative to various core/grab sample data as shown

in Figure 72. The comparisons are presented over 2 mile sections of the LPR. In the upper miles, between RM 6-18, the model shows relatively small deviations from the initial condition, indicating that the model conserves the initial condition in time and suggesting that the model initial conditions are in general agreement with the localized shear stress regimes. In the lower 6 miles, the model calculates changes from the initial conditions, with the changes for the most part approximating the range of measured values and the shape of the measured distribution. However, there are some exceptions, notably at the upper and lower tails of the distributions where the model tends to calculate finer and coarser surficial sediments, respectively, than seen in the data. These are restricted to the lower 10% of the distribution in both RM 0-2 and RM 2-4, and the upper 30% of the distribution in RM 4-6. Both the tendency to create surficial sediments that are somewhat finer in composition than measured values in a fraction of the domain between RM 0-6 and the coarsening between RM 0-4 may be an artifact related to the composition of the SS at the freshwater boundaries during high-flow conditions. As mentioned in Section 4.2.4, this was done on the basis of very limited data following an analysis performed by Region 2, and which assumed that the non-cohesive loads are entirely composed of the smallest sand class (which is the fraction responsible for the coarsening in these areas). However, the presence of coarser sand fractions measured in the surficial sediments is an indication of the uncertainty associated with this assumption on the composition of the boundary condition during high-flows.

Despite the differences noted above, it is important to note that the model reproduces a similar composition as seen in the data for the majority of the model domain within RM 0-6 and within the overall LPRSA as well. In addition, the model also represents and maintains the large-scale spatial gradient in composition, with predominantly fine sediments in the lower miles of the LPR, and coarsening with distance up-estuary. Therefore, the model performance with respect to the temporal and spatial evolution of the bed composition can on average be considered representative of the measured composition in the LPRSA.

5.5 Model Performance – Mass Flux Summaries

The results of the long-term calibration simulation described in the preceding sections have also been analyzed and reviewed with respect to understanding the mass balance of the LPRSA, specifically the import and export of sediments, and the bed-water exchange processes. Figures 73 through 75 show the water column advective and bed-water exchange fluxes calculated by the ST model within the LPRSA during the WY1996-WY2013 long-term calibration period. The results are presented for the cohesive fractions (clays and silts) in Figure 73, for the non-cohesive (sand) fractions in Figure 74, and for total sediments in Figure 75. The loadings to the LPRSA from Dundee Dam, loadings from the tributaries (Second River, Third River, Saddle River, and McDonald Brook), loadings from the CSOs/SWOs, advective transport over various reaches, advective transport into and out of the LPRSA, and the bed-water exchange fluxes (erosion, deposition, and navigation scour in selected areas of the LPRSA) are shown.

Non-cohesive transport (Figure 74) within the LPRSA (in terms of external loadings as well as advective fluxes) is generally at least 2 orders of magnitude lower than equivalent cohesive transport terms (Figure 73). In contrast, the gross erosion and deposition fluxes are considerably higher for non-cohesives, particularly above RM 2, reflecting the strong influence of high flow events in these reaches.

Spatially within the LPRSA, the upper miles (>RM 8) are net erosional and the lower miles (<RM 8) are net depositional with respect to both cohesive (clays and silts), and non-cohesive sediments during the long-term calibration period. As expected, these spatial patterns also exhibit hydrograph dependent variability, with the high-flow years being typically erosional (>RM 2 and >RM 8) for the cohesive and non-cohesive fractions respectively, and the low-flow years being depositional over the entire LPRSA for both sediment types.

On an annualized basis over the duration of the long-term calibration period, the total solids loading from all the upstream sources is approximately 29,400 MT/year, of which Dundee Dam contributes about 21,600 MT, the tributaries about 6,400 MT, and the CSOs/SWOs about 1400 MT/year (Figure 75). Net export from the LPRSA to Newark Bay during this same period amounts to 19,200 MT/year, with the LPRSA accumulating on average about 10,200 MT/year. However, a significant portion of these annualized fluxes reflects the influence of a relatively extreme event, Hurricane Irene, a 1 in 90-year event, in 2011. Excluding the results from WY2011, the annualized mass fluxes are quite different. For instance, about 55% of the net export of 19,200 MT/year at RM 0 occurs during WY2011. Similarly, the Dundee Dam load decreases from 21,600 MT/year to 18,800 MT/year, and tributaries and CSOs/SWOs from a combined total of 7800 MT/year to 6300 MT/year. Consequently, net deposition in LPRSA increases to 16,500 MT/year.

The inter-annual variability in the trapping dynamics of the LPRSA as a sink or source of sediments as well as the magnitude of infilling is driven by the freshwater discharge from Dundee Dam, a point apparent in reviewing the flux summaries in relation to the river flows as shown in Figure 76. The upper panel shows the annual average flow at Dundee Dam over the period WY1996-WY2013, the middle panel shows the total SS (sum of cohesive and non-cohesive) load entering the LPRSA from Dundee Dam and the tributaries/CSOs/SWOs, and the net advective flux of total SS at RM 0, and the bottom panel shows the net annual change in the LPRSA (erosion/deposition). WY2011 and WY2002 represent two extremes with respect to the hydro-sedimentological behavior, with the high-flow year WY2011 characterized by net erosion (seen on the bottom panel) and net export (seen on the middle panel) from the LPRSA (past RM 0), and the low-flow year WY2002 characterized by net sedimentation (as seen on the bottom panel) with SS imported from both Dundee Dam (and the tributaries/CSOs/SWOs) as well as from Newark Bay (as seen in the up-estuary flux at RM 0 for this year on the middle panel). Other high-flow years such as WY2007 (with a 16,000 cfs event in April 2007), WY2010 (with a 16,000 cfs event in March 2010) also less net infilling in the LPRSA due to more gross erosion during high flow conditions. During the other years, the LPRSA is net depositional, with the exact magnitude of deposition a function of the solids loading from Dundee Dam and the tributaries/CSOs/SWOs, and also a function of the magnitude of the

events occurring during the given year. For instance, WY1996 and WY2005 both had discharge events in excess of 10,000 cfs and are associated with somewhat lower sedimentation. In contrast, other years with similar annual average discharge such as WY1997, WY2003, WY2004, etc. which did not experience events greater than 10,000 cfs tend to experience more deposition. Similarly, the occurrence of an event in excess of 10,000 cfs may also explain why WY1999 shows relatively lower accumulation despite having a below-average annual average discharge. These hydrograph-dependent patterns of erosion and sedimentation are consistent with the three hydro-sedimentological regimes presented in Section 2.4, with most years falling into Regime 1 (low-energy, trapping conditions), certain years such as WY2007 and WY2010 falling into Regime 2 (medium energy, flushing conditions), and the high-flow years such as WY2011 falling into Regime 3 (high energy, exporting conditions).

The trapping dynamics presented in Figure 76 also indicate that exchange between the LPRSA and Newark Bay is hydrograph dependent, with low-flow years such as WY2002 exhibiting a net import of solids from Newark Bay into the LPRSA, and high-flow years showing net export from the LPRSA into Newark Bay. The spatial and temporal trends in trapping and the exchange with Newark Bay calculated by the ST model are consistent with the process-based description of sediment transport in the LPRSA, in particular the interplay between the tidal, estuarine, and freshwater forcings, and also consistent with observations from the various multi-beam bathymetric surveys conducted as part of the RI.

5.6 Model Validation: Simulation of Historical Infilling

In addition to the model-data comparisons presented in the preceding sections, the model was applied for a qualitative test of its ability to represent the historic infilling of the LPR following the last major dredging event. The setup and results of this historical infill simulation are described next.

5.6.1 Historical Infill Simulation – Setup

Given the availability of data (described subsequently) for validating the results of this simulation, it was only run for 15 years, using boundary conditions identical to that used for the long-term calibration run (from WY1996 through WY2010) described in the preceding section. The distribution of discharge during this 15-year period is comparable to the long-term record at Little Falls suggesting its suitability for long-term model applications beyond the window of short-term model-data comparisons.

The model bathymetry used for this simulation is an approximation of the conditions in the LPR, NB, and the Kills around the time of the last major dredge event in 1949 within the LPR. Accordingly, model bathymetry within the navigation channel in the lower 8 miles of the LPR was set at the federally mandated navigation channel depths (RM 0-2.6: 30 ft, RM 2.6-4: 20 ft, RM 4-7.8: 16 ft; depths relative to MLW). Within NB and the Kills, the bathymetry was approximated based on maps showing the historical evolution of Newark Bay (USACE 2006) – major features represented are a 30 ft (relative to MLW) channel in

the Kills leading to Port Newark and the LPR, and the absence of the Port Elizabeth, Port Elizabeth pier-head, and Port Elizabeth channels with the bathymetry in these areas set at 5 ft (relative to MLW). Other inputs specific to this historical infill simulation relate to the solids loadings from Dundee Dam, Kill van Kull, and Arthur Kill. Given the objective of simulating the historical infill following the 1949 dredging in the LPR, the solids loadings from both Dundee Dam and the Kills were defined to be representative of the historical loadings rather than the loadings under current conditions used for the calibration run. The solids loadings from Dundee Dam were defined using the SS load-discharge rating curve developed by Region 2 for the FFS model, which as described in the August 2014 memorandum may likely be more representative of loadings in the 1960s than current conditions. Similarly, the SS loadings from the Kills were defined using the rating curves derived by Region 2 for the FFS model using data collected by Chant (2006) in 2000-2002, prior to the implementation of the 50' channel deepening project in NB and the Kills. All other model inputs and parameters were as defined for the calibration simulation.

5.6.2 Model Performance, Historical Infill Simulation – Infill Rates and Patterns

The results from this simulation and its comparison to the measured infill are shown in Figure 77. The measured sedimentation rates were determined by comparison of the post-dredge bathymetry to the next available bathymetry survey which between RM 2.5 and 6.8 involved comparing the 1949 and 1966 surveys, and below RM 1.4 involved comparing the 1983 and the 2004 surveys. The bathymetric change for both model and data are presented as an annualized sedimentation rate. It should be noted that there are several sources of uncertainty inherent in such a hindcast simulation of historical sedimentation patterns in the LPR. These include model artifacts such as uncertainty in historical erosion rates for the fluff layer and underlying parent layers, impacts of navigation which historically was more widespread within the LPRSA than currently, as well as uncertainties associated with historical loadings from Dundee Dam, the various tributaries, CSOs and SWOs, and well as from the Kill van Kull and Arthur Kill. Considering these sources of uncertainty, a relative comparison of the spatial patterns of infilling rather than the absolute magnitude of infill rates is perhaps more appropriate for an assessment of model performance.

Spatially, both data and model show much higher infill rates in the lower miles than at locations further up-estuary, with sedimentation rates occasionally in excess of 15 cm/yr below RM 1.5. Similarly, in both model and data, sedimentation rates show a slight decrease from RM 1 to RM 0, a feature likely related to shipping activities and associated scour in this reach of the LPR. Above RM 2.5, both the model and data show relatively high infill rates along the southern edge of the navigation channel between RM 2.5 and 3.2 (and somewhat lower infill rate in the center of the channel), and in the inner bend at RM 4, and towards the shoal at RM 4.2. Similarly, both the model and data show lack of infill in the outer bends at RM 3.3 and RM 4.7, and in the vicinity of the Bridge St, Clay St, and I280 bridges (RM 5.5-6.5). Notable locations with a discrepancy between model and data include the vicinity of RM 5, RM 7, the inner bend at RM 3.5, and northern edge of the channel between RM 2.5-3, with model-calculated infill rates lower than measured values.

In addition, the model also does not capture the channel-wide infilling between RM 1.5-1, with the model generally calculating more infilling in the center of the channel and less infilling along the edges and outside the channel. However, as mentioned previously, there are a number of factors and sources of uncertainty that may affect model performance in reproducing the historical infill rates. Therefore, this simulation can only be examined qualitatively for an assessment of the model's overall ability to reproduce the large-scale infill observed since the last major dredging event in the LPR. Overall, the model can be said to reproduce both the magnitude of infilling in several places, as well as the spatial patterns of infilling noted in the data.

5.6.3 Model Performance, Historical Infill Simulation – Bed Composition

The evolution of the bed composition (cohesive fraction of the top 15 cm of the sediment bed) in the LPRSA has been assessed relative to various core/grab sample data and presented in Figure 78. The comparisons are presented over 2 mile sections of the LPR. In the upper miles, between RM 6-18, the model shows relatively small deviations from the initial condition, with the deviations tending towards the distribution of the measured cohesive content. In the lower 6 miles, which are predominantly depositional in this particular simulation, although the model calculates a distribution that is similar in shape to the data distribution, the model has a tendency to calculate a finer composition than measured. This may likely be related to the uncertainty in the composition of the historical solids loadings from Dundee Dam, the tributaries, as well as from CSOs and SWOs. The historical infill simulation relied on recent water column composition measurements for low-average flow conditions, and the approach developed by Region 2 for high-flow conditions. As mentioned previously, the solids loadings at Dundee Dam appears to have changed from the 1960s to current conditions; however, the composition associated with the loadings in the 1960s is unknown. In addition, the model also captures the large-scale spatial gradient in composition, with predominantly fine sediments in the lower miles of the LPR, and coarsening with distance up-estuary.

5.6.4 Summary of Historical Infill Simulation

An exact match is not to be expected between the model and the data for reasons such as the fact that the system never had a bathymetry as exactly simulated with the complete mandated navigation channel all dredged at the same time, the differences in the hydrograph during the years spanning the data versus the hydrograph used in the simulation, lack of accurate information on the historical SS loadings and composition, differences in sedimentation rate over time (sedimentation rates would be expected to be highest during the period immediately following dredging and decrease subsequently), as well as uncertainties associated with the interpolation and comparison of the historical single-beam transect data used to estimate the river-wide sedimentation rates. Therefore, this comparison is mainly useful for a qualitative assessment of the patterns of infilling and for a high-level assessment of whether the model as formulated and parameterized is capable of reproducing the infill expected following a dredging event. Considering also the model's tendency to reproduce more or less similar distributions of bed composition

(small-scale as well as large-scale patterns) as seen in the data, in general, the model, can be said to reproduce the infill process that has been historically observed within the LPR.

5.7 Summary of Model Calibration and Application

The CPG's ST model has been calibrated and compared against a number of metrics and datasets including water column SSC and fluxes, bathymetric change, and bed composition. The model results have also been reviewed and compared to data over a variety of time-scales – intra- and inter-tidal, and under a variety of flow regimes, ranging from low-flow conditions characterized by depositional processes, to extreme high-flows such as a 1 in 25-year and 1 in 90-year event. The model performance has also been assessed for a number of processes identified in the data. The model calibration process was also chosen such that the two parameters adjusted as part of the calibration process, namely the critical shear stress of the parent layers in the bed and the settling velocity of the sediment entering from the Kill van Kull and Arthur Kill, could be calibrated independently. In other words, the regimes under which these parameters were calibrated were mutually exclusive, ensuring that the choice of the value for one parameter does not influence the resulting calibration achieved for the other parameter. In addition, the parameter calibration was also constrained within the range of site-specific values established from measurements and data analysis. This also served to ensure a realistic set of parameter calibration values. The calibrated model has also been applied to simulate the historical infill that has been observed within the navigation channel of the LPR since the last major dredging events in 1949 and 1983.

6.0 SUMMARY

The CPG's ST model application has been developed and calibrated and compared to a variety of datasets collected as part of the LPR RI/FS program. Calibration metrics included in the assessment of model performance include SSC measured in water samples, SSC estimated from ABS and OBS, SS fluxes estimated from ABS-derived SSC and ADCP velocity measurements, bathymetric changes, and bed composition. Model-data comparisons have also been performed over a range of discharge and tidal conditions. On average, the model reproduces the measured SSC and SS fluxes over a range of flow conditions ranging from a 1 in 25-year event to extremely low-flow conditions. The direct comparisons of model performance to bathymetry data show mixed results, with certain features such as the large-scale infilling above RM 2 during low-flow periods and deposition below RM 2 during 2010-2011 better reproduced than others such as the exact footprint and magnitude of navigation scour. The model in some locations over-predicted scour in several areas of the LPR during Hurricane Irene. In addition to the comparisons to data, the model performance has also been reviewed relative to the major sediment transport processes identified in the data.

The model performance is subject to the artifacts and constraints imposed by a number of factors including (1) grid resolution, which limits the ability of the model to predict small-scale features such as the local scour noted around bridge abutments within the LPR, in other words a spatially accurate reproduction of bed shear stresses over a range of flow conditions, (2) the lack of spatial variability in the Sedflume erosion data which may account for the over-prediction of scour during Hurricane Irene, and (3) the temporal uncertainty in the Sedflume erosion properties defined for the parent layers which pertains to the fact that when previously buried layers get exposed following a storm event, in nature unconsolidation and bioturbation processes may enhance the erodibility of the exposed layers over time. However, the model does not include this, rather it maintains the exposed layers at its pre-exposure consolidated state with respect to erodibility. Overcoming these artifacts and limitations will require not only a change in model framework used by both Region 2's FFS Model and the CPG's ST Model as well as a significant data collection effort with uncertain prospects for the relative improvement in model performance. The CPG's revised ST model includes the major processes relevant to the fate and transport of sediments, and with certain exceptions such as the over-prediction of scour during Hurricane Irene, the exact spatial location of the salt front/ETM, the transient temporal dynamics of the fluff layer, etc., performs well in reproducing the major transport features and processes observed in the data.

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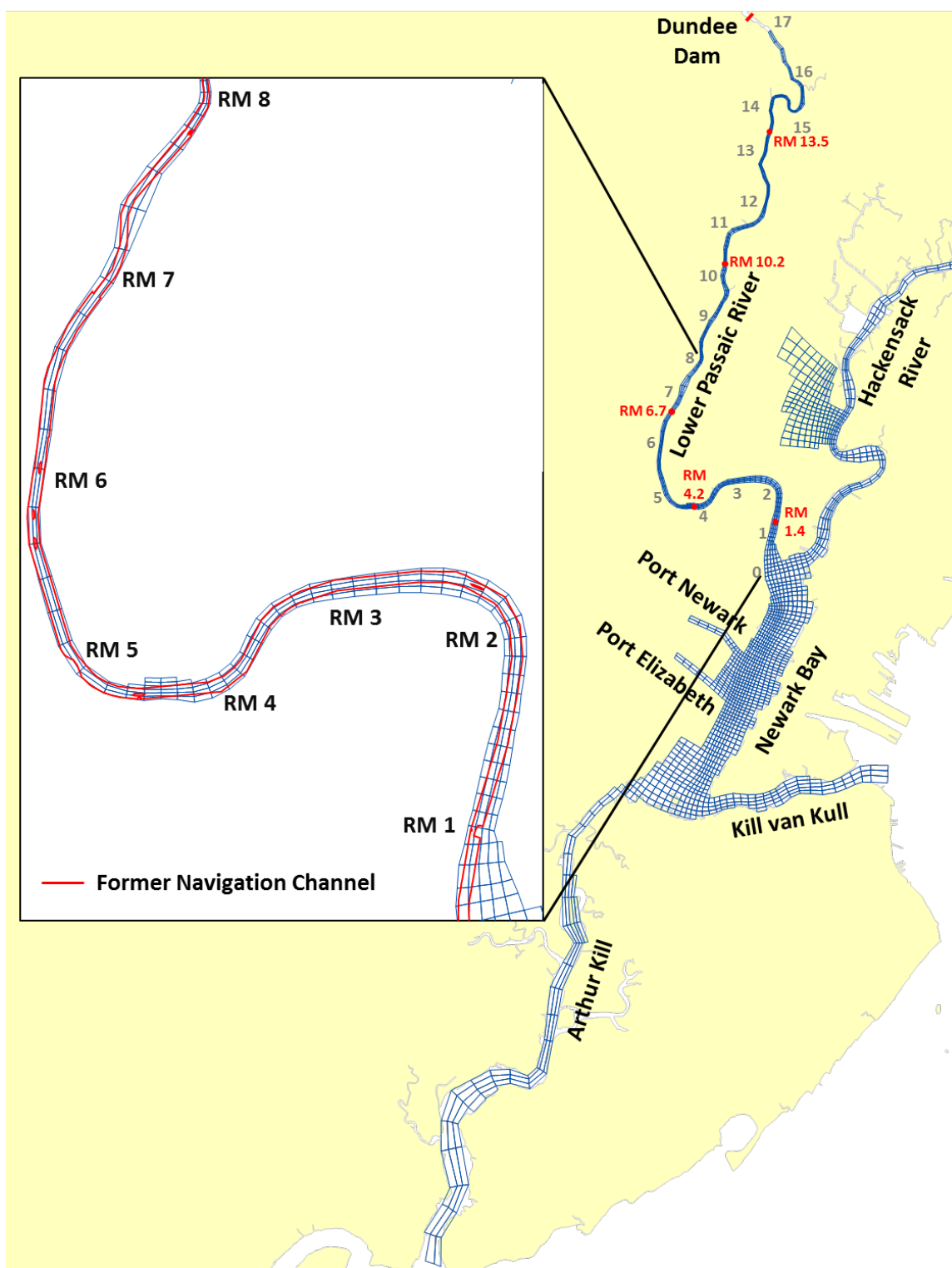


Figure 1. The Lower Passaic River and Newark Bay modeling domains, along with the computational grid for ECOM-SEDZLJS

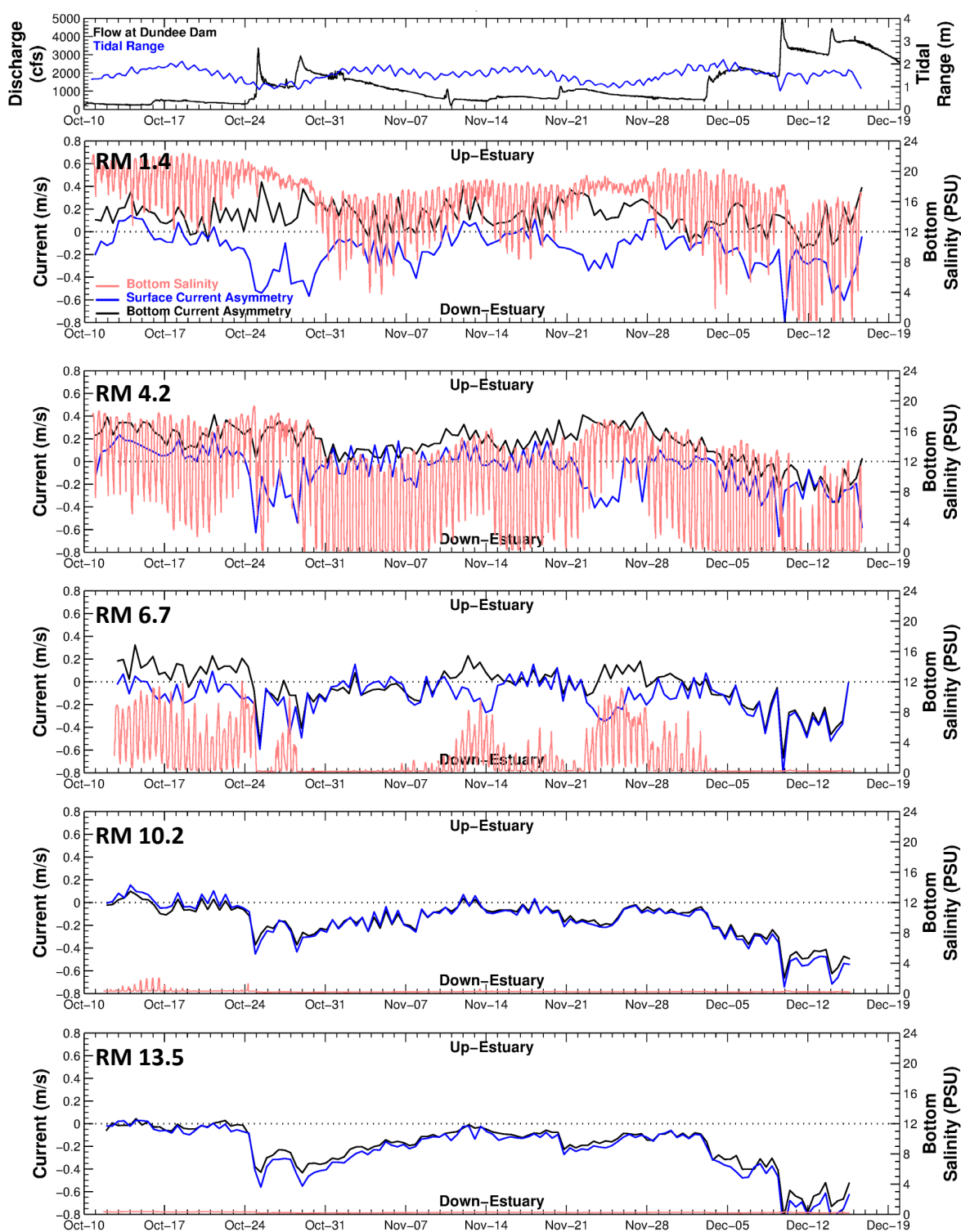


Figure 2. Tidal asymmetry in peak flood and peak ebb currents and dependency with discharge in the LPR

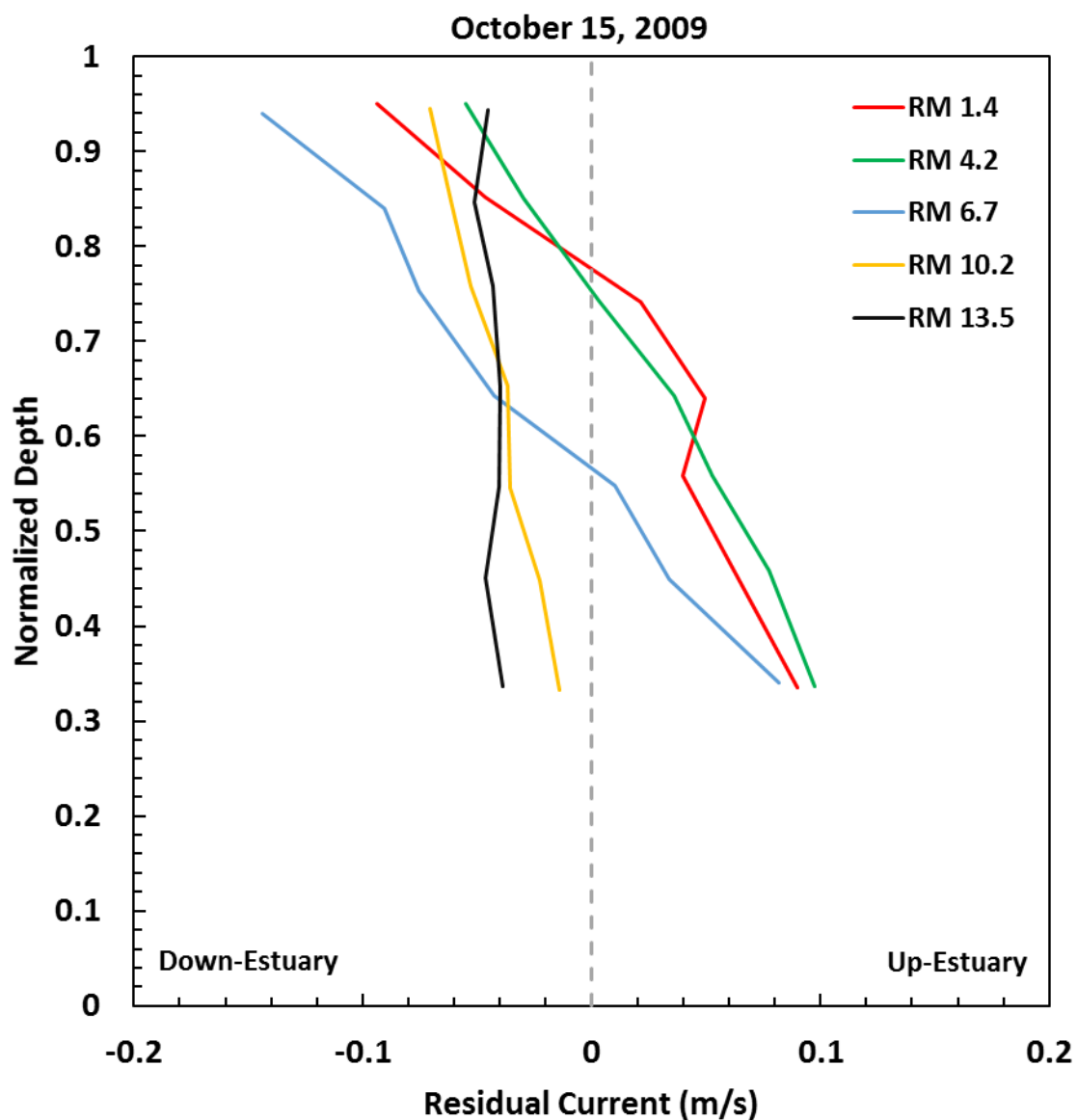


Figure 3. Residual current profile in the LPR over two tidal cycles on October 15, 2009

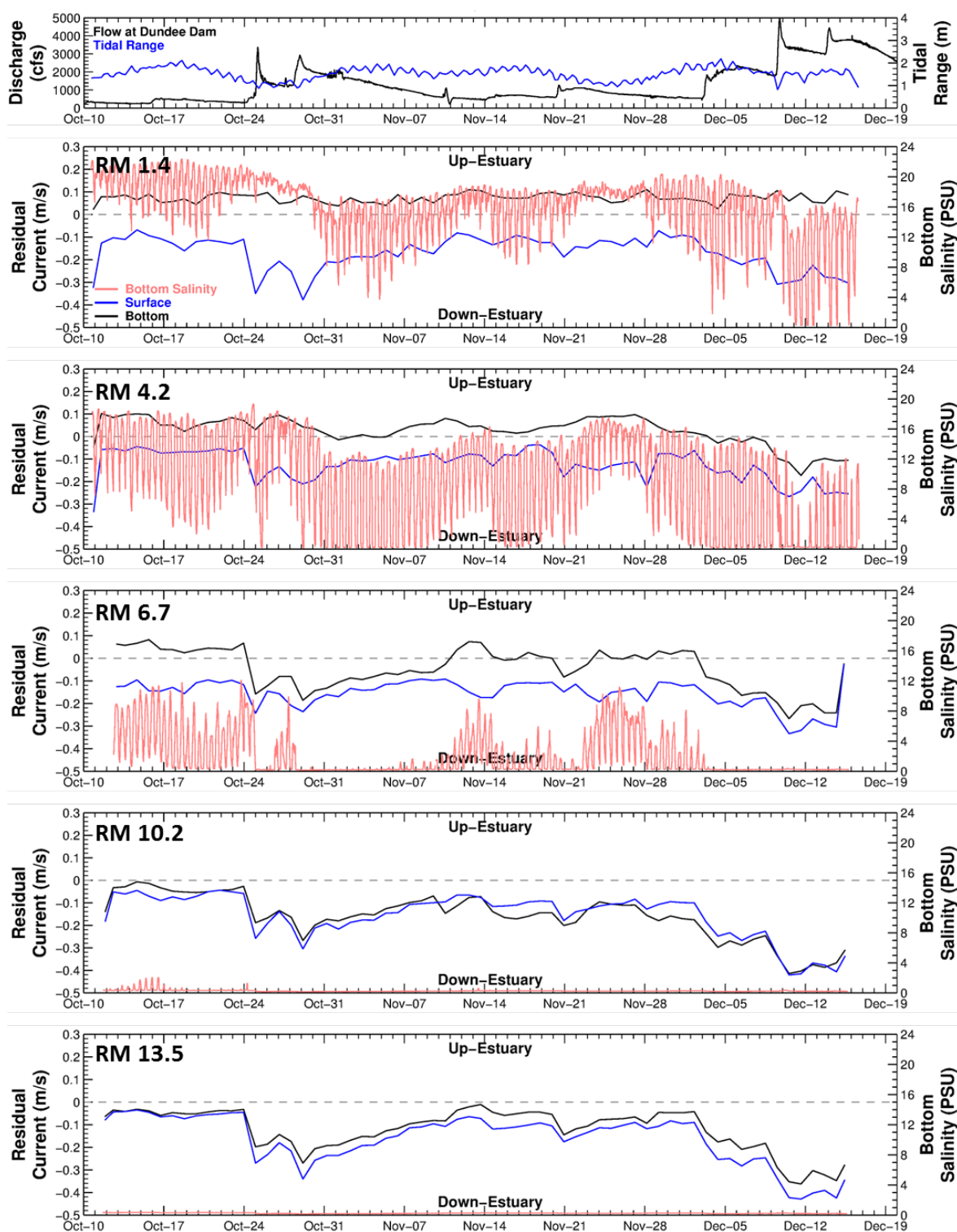


Figure 4. Near-bottom and near-surface residual currents and dependency with salt front location and discharge in the LPR

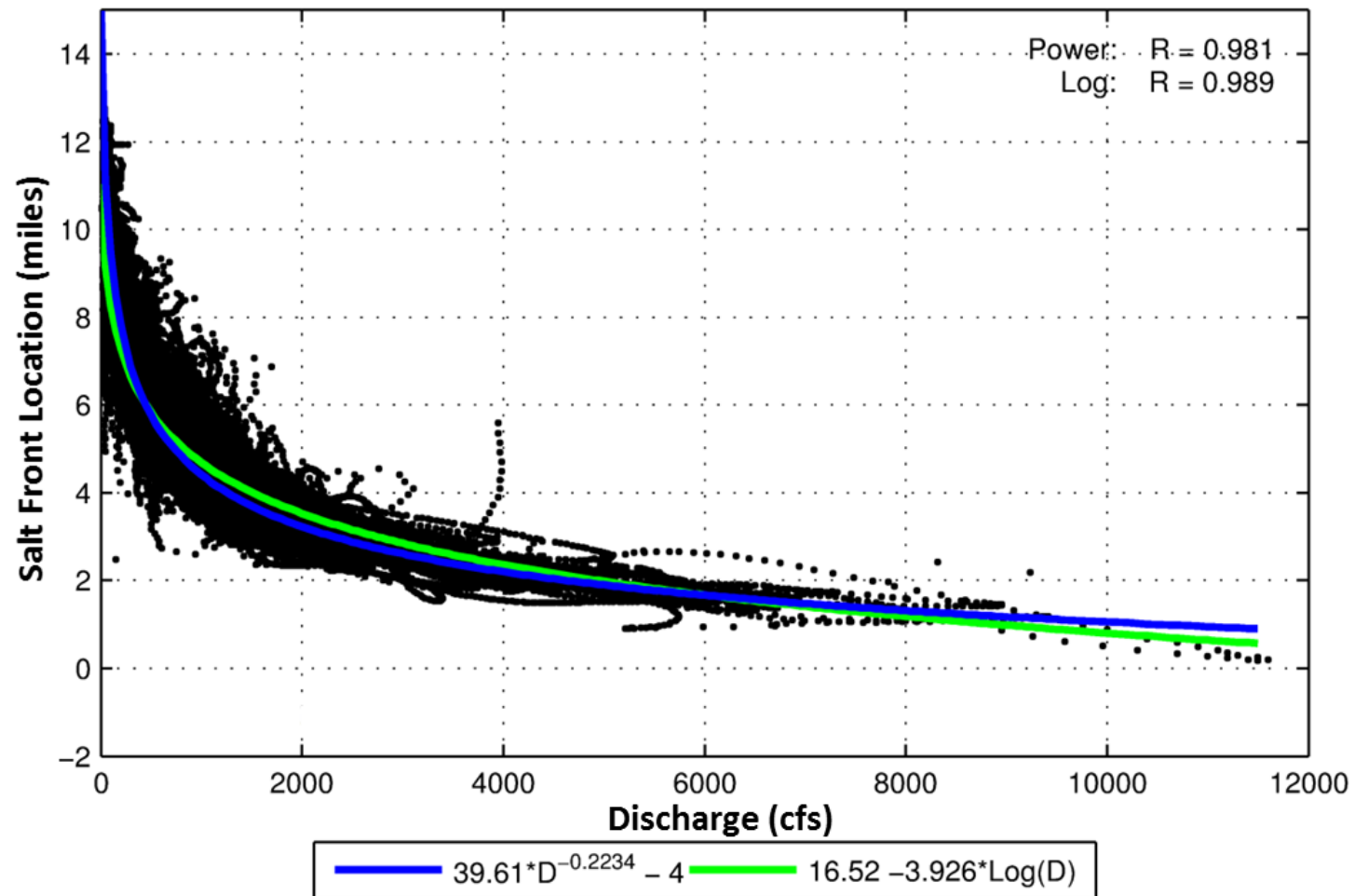


Figure 5. Salt front (defined as 2 ppt at the bottom of the water column) location as a function of discharge at Dundee Dam

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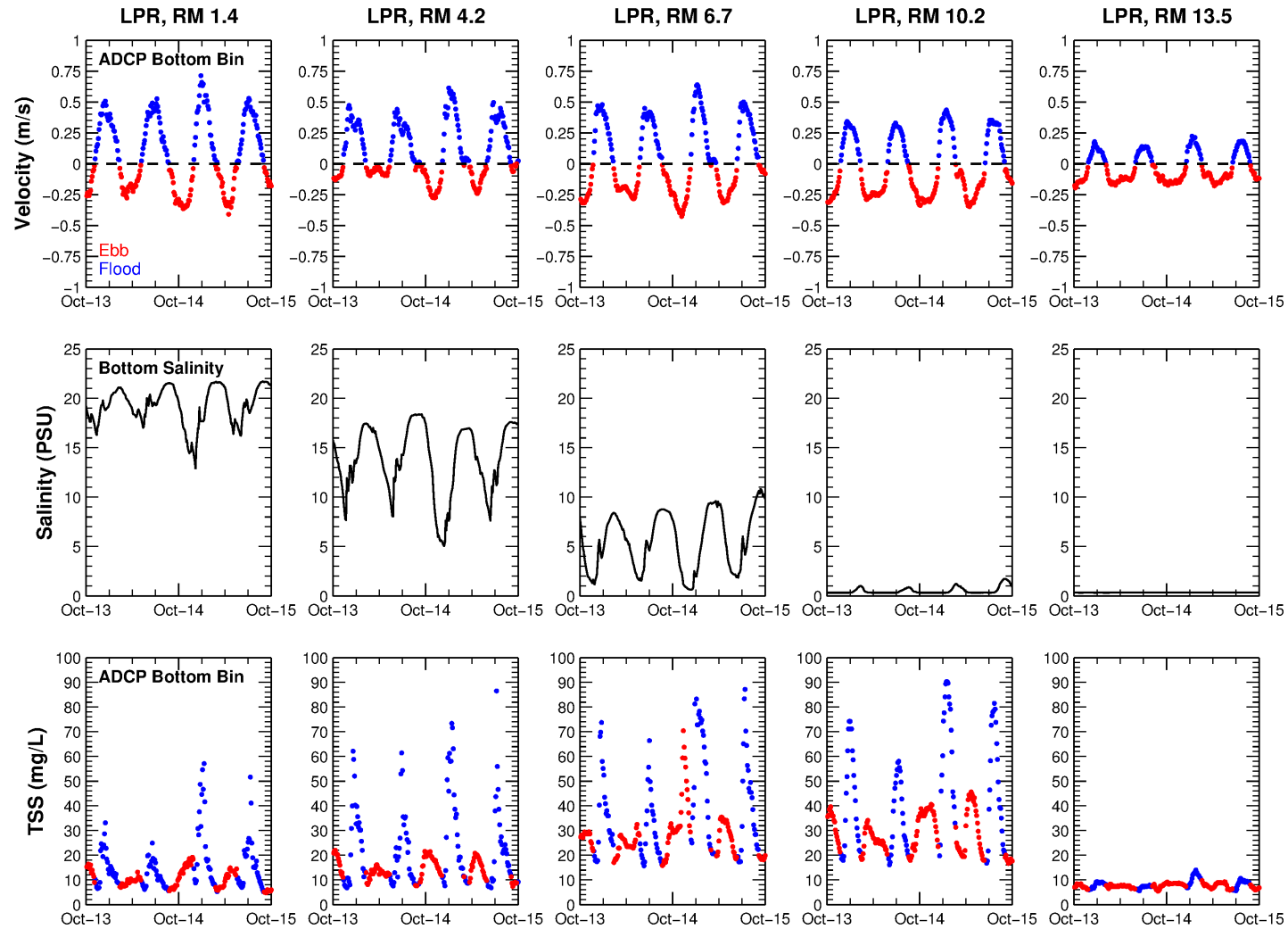


Figure 6. Near-bottom velocity, salinity, and SSC measured at RM 1.4, 4.2, 6.7, 10.2, and 13.5 during the Fall 2009 PWCM deployment

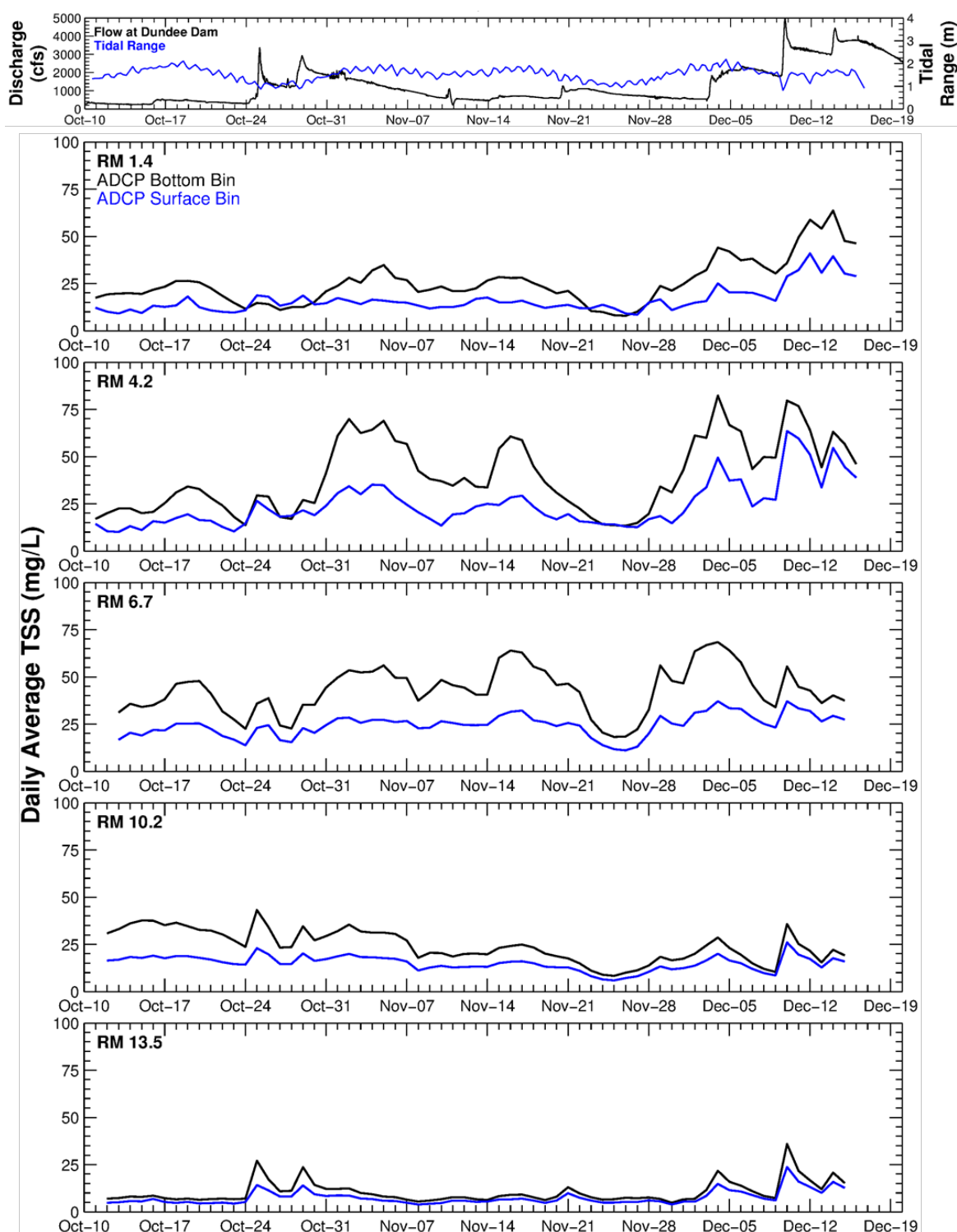


Figure 7. Inter-tidal variability in SSC, its relationship to the spring-neap cycle and discharge. From top to bottom, panels for RM 13.5, 10.2, 6.7, 4.2, and 1.4. Data from Fall 2009 PWCM

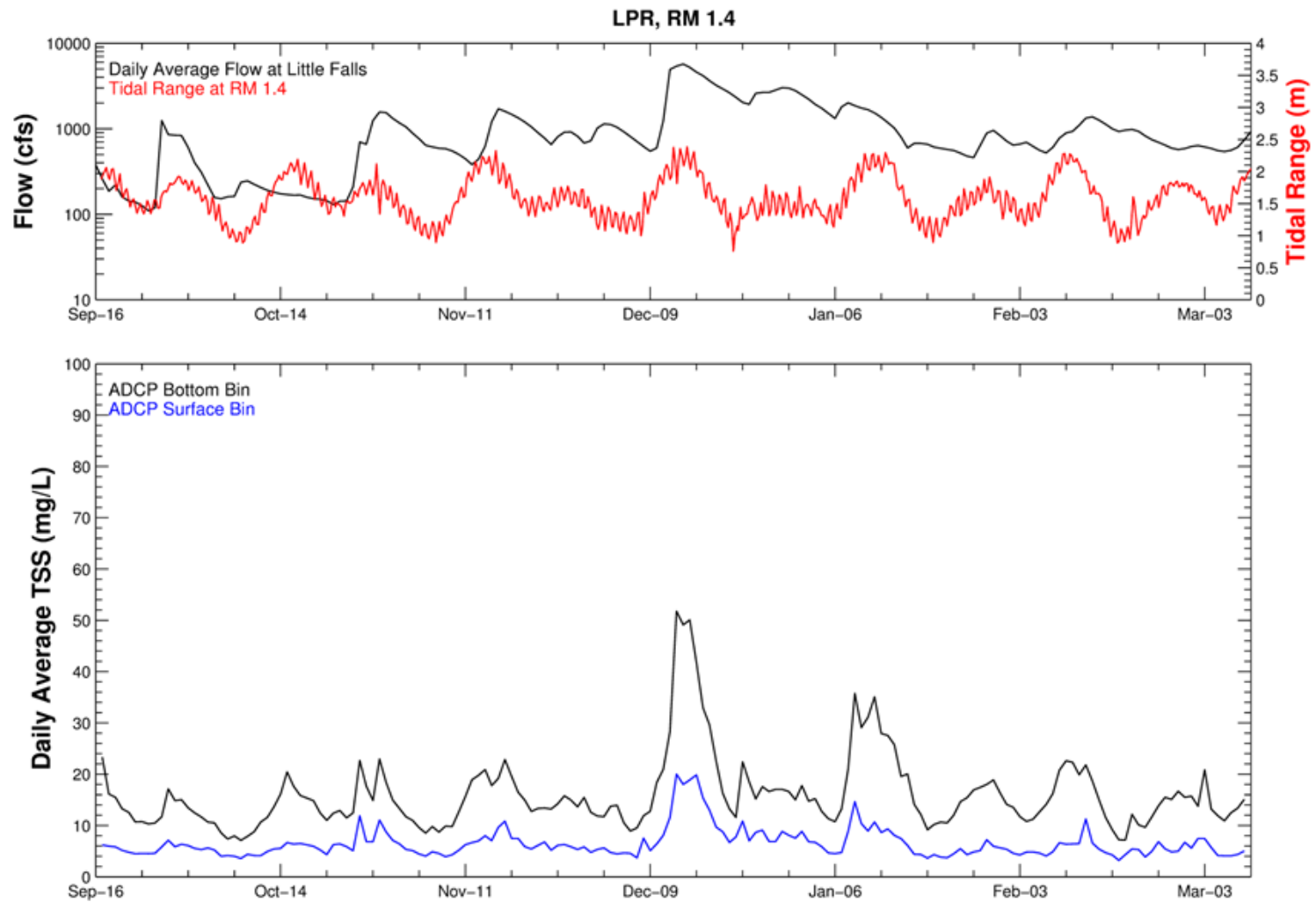


Figure 8. Inter-tidal variability in SSC, its relationship to the spring-neap cycle and discharge. Data from Sommerfield and Chant (2010)

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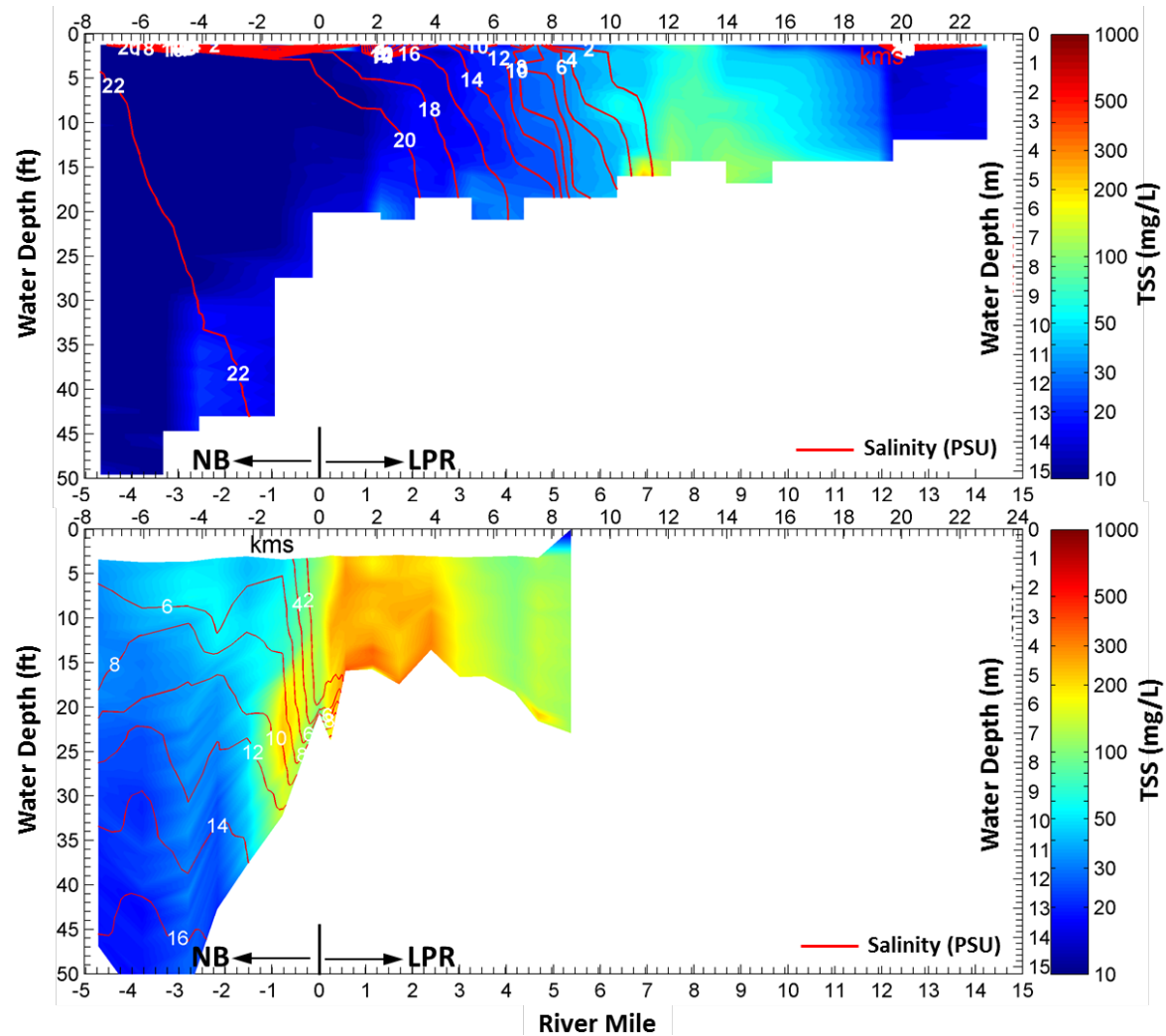


Figure 9. Transects of salinity and SSC along the longitudinal axis of the LPR and NB for a low-flow condition (250 cfs on June 23, 2005; upper panel) and for a high-flow condition (16,000 cfs on March 16, 2010; lower panel)

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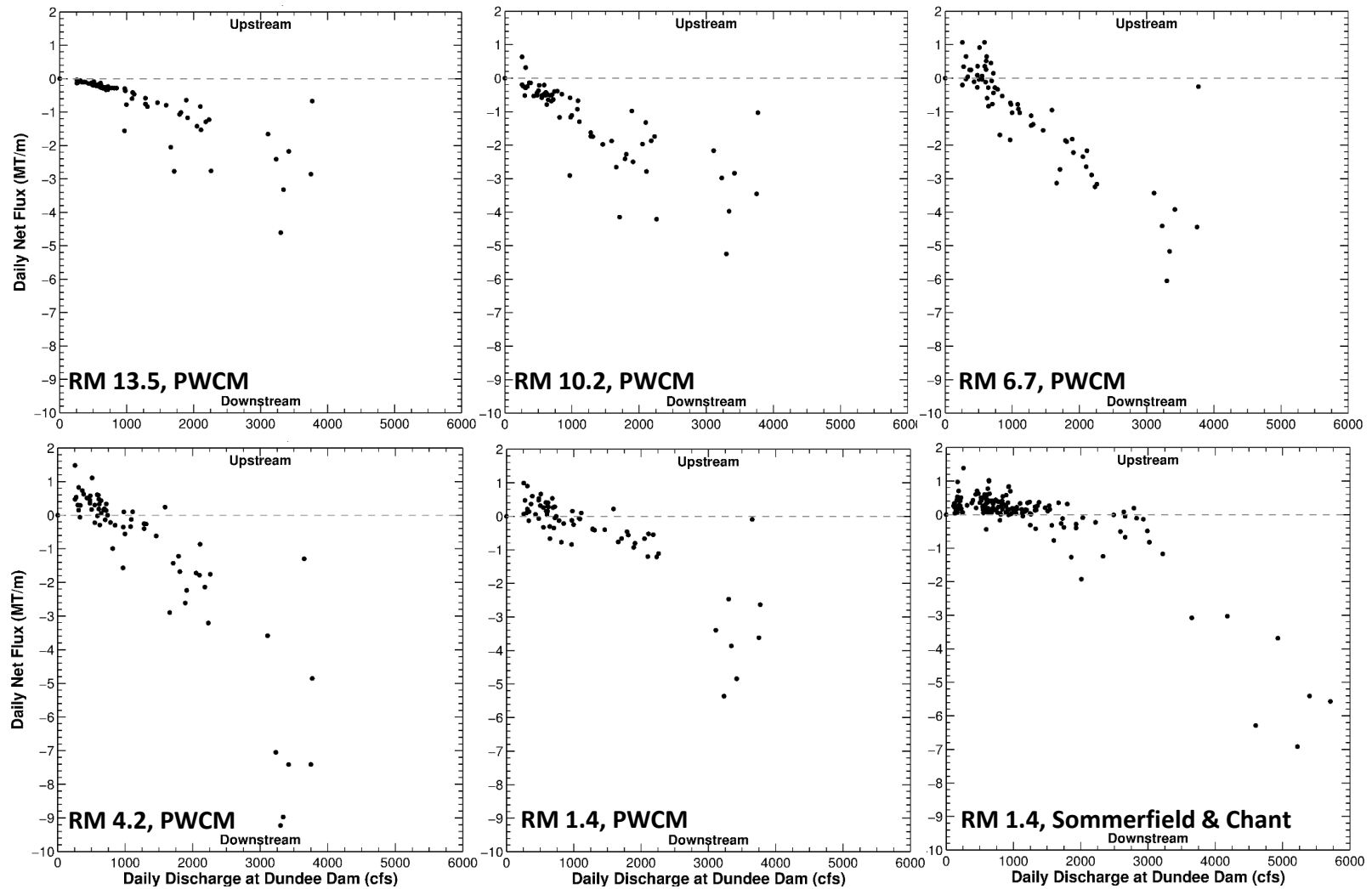


Figure 10. Net daily depth-integrated SS flux versus discharge from Fall 2009 PWCM, and from Sommerfield and Chant (2010)

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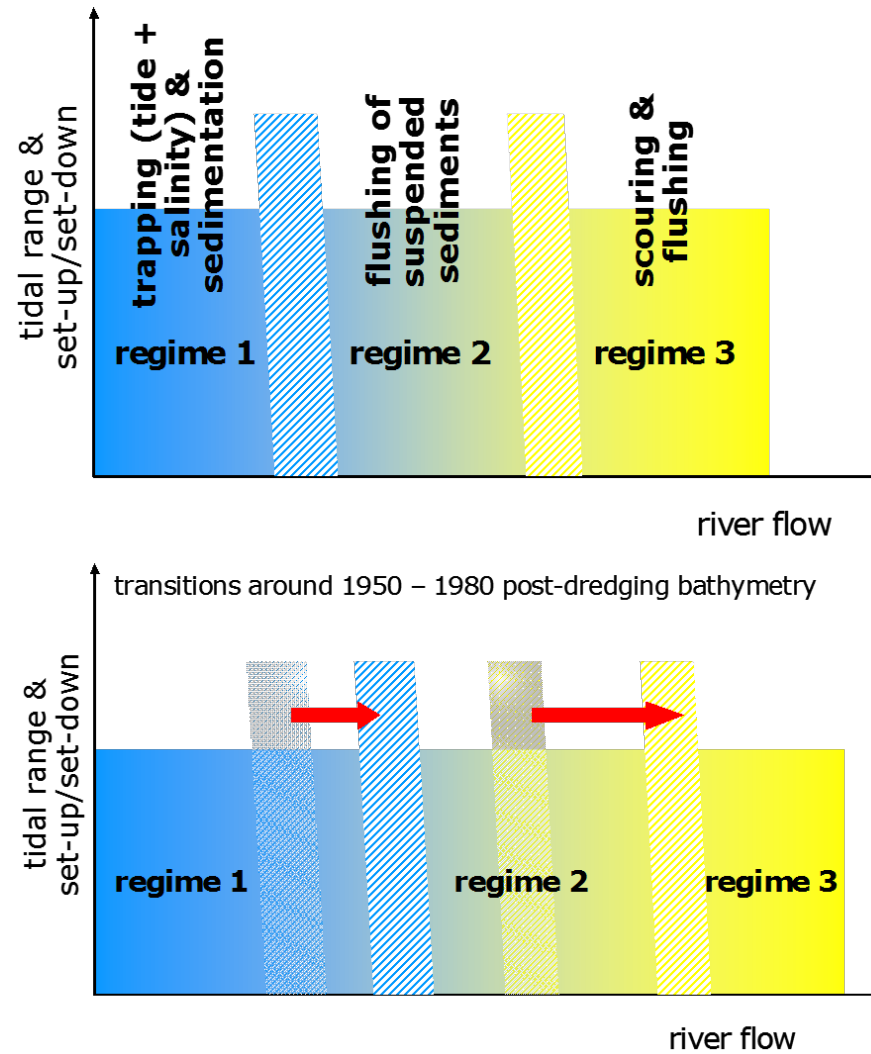


Figure 11. Conceptual picture of hydro-sedimentological conditions in the Lower Passaic River (top panel). Same as top panel but for the post-dredging bathymetry (bottom panel).

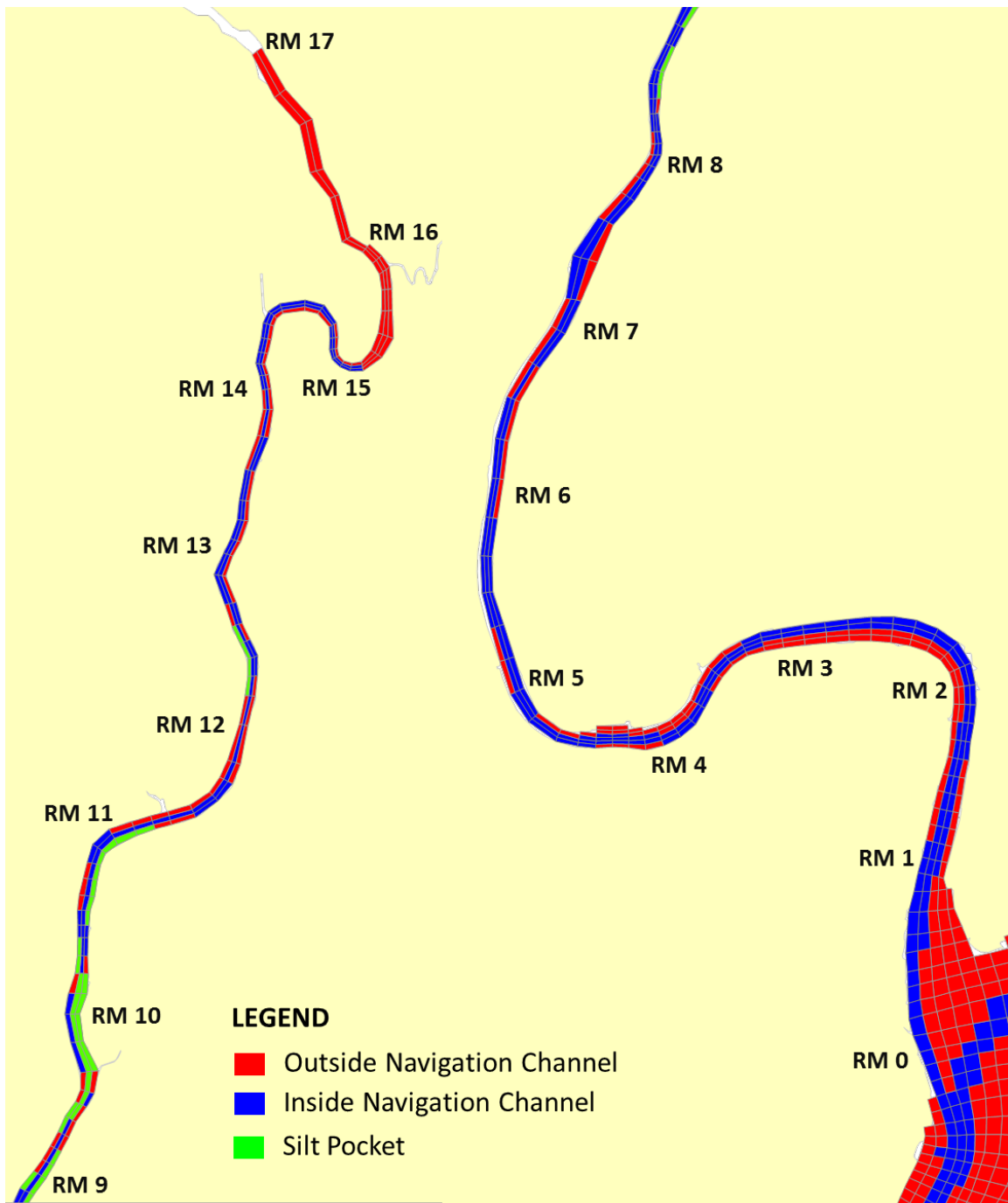


Figure 12. Geomorphological assignment of model cells - inside navigation channel, outside navigation channel, and in silt pockets.

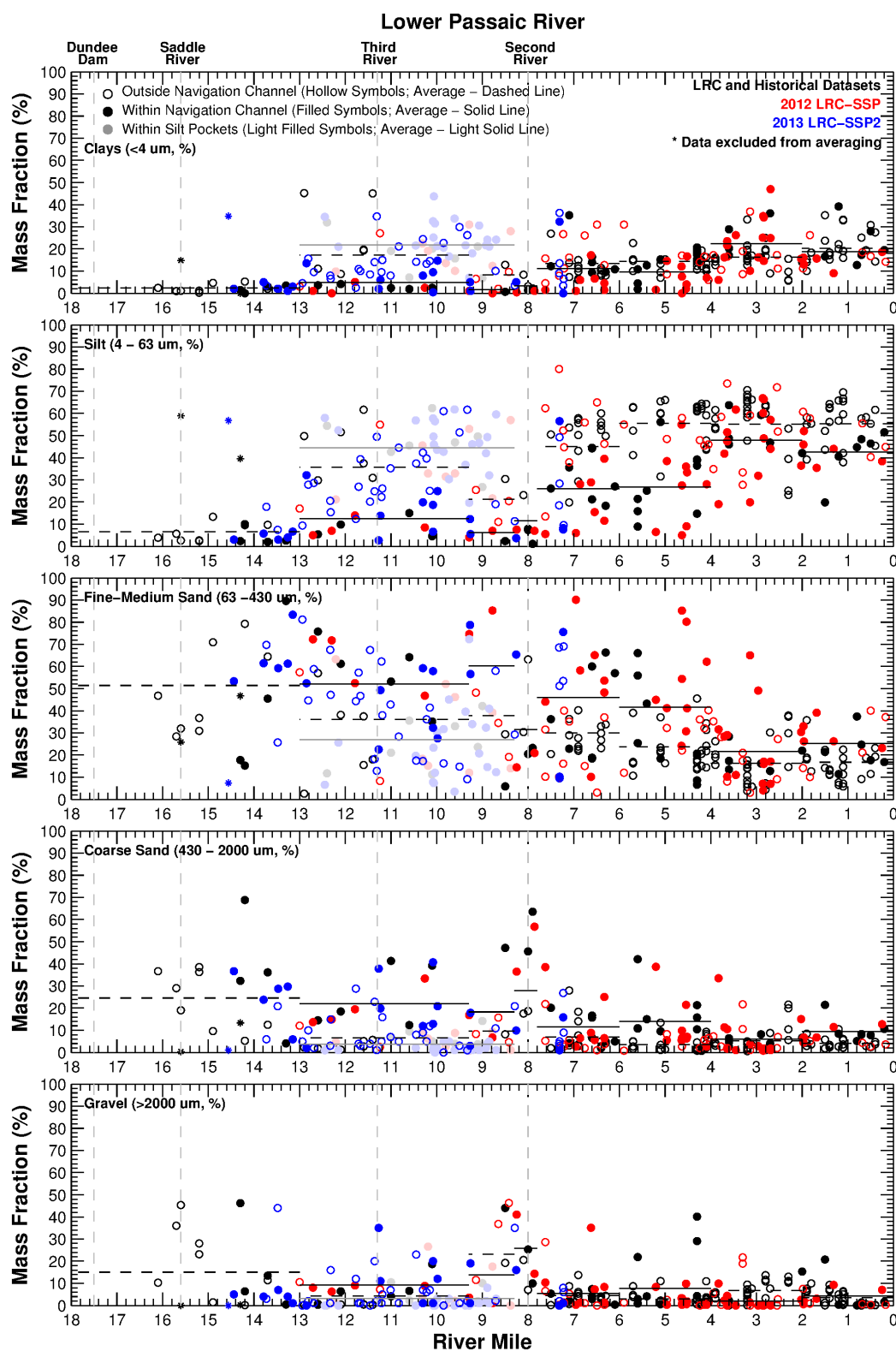


Figure 13. Grain size distribution data and model initial condition for surficial sediments (top 15 cm of bed) in the LPR

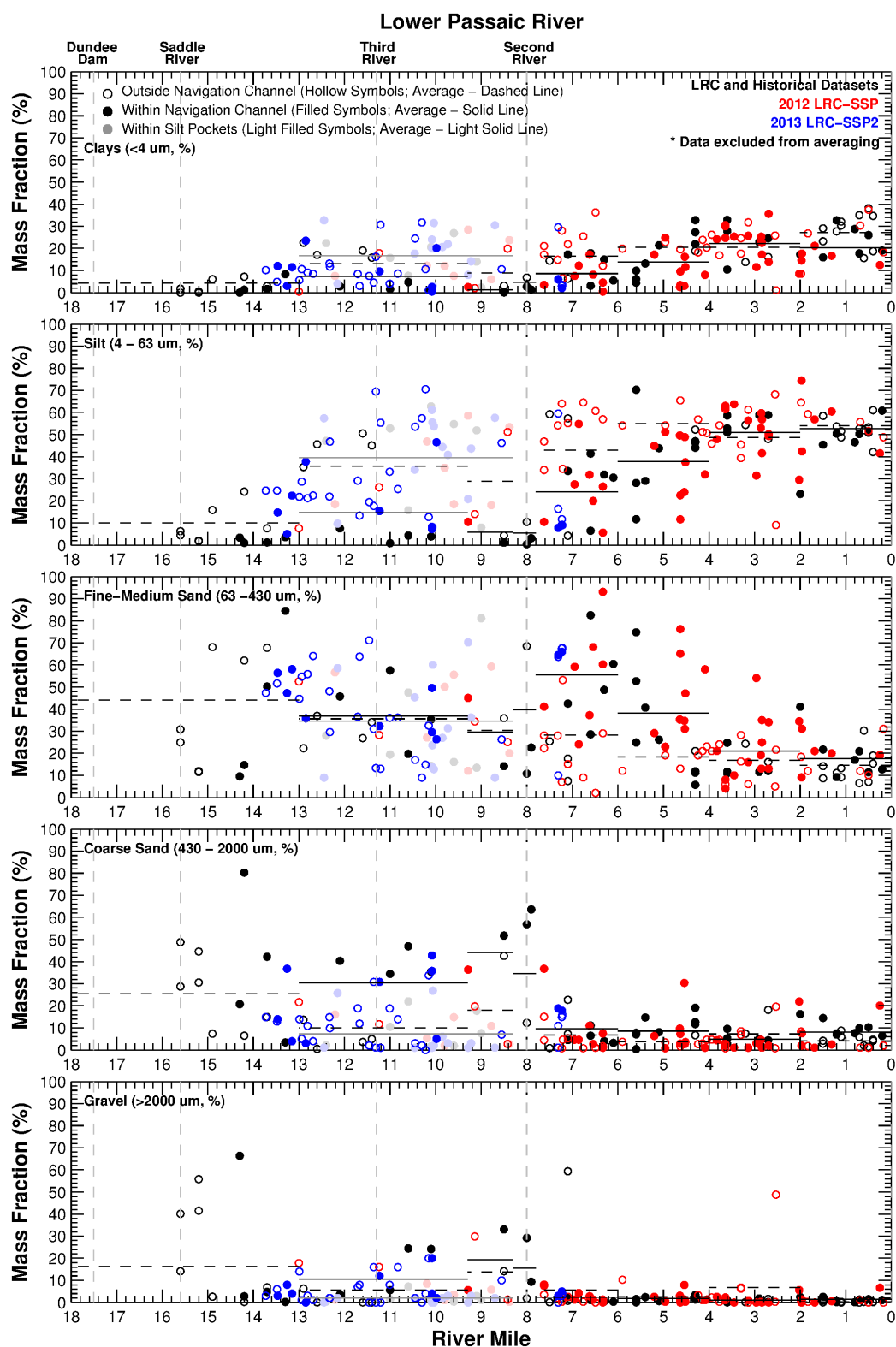


Figure 14. Grain size distribution data and model initial condition for the 15-45 cm depth-interval in bed in the LPR

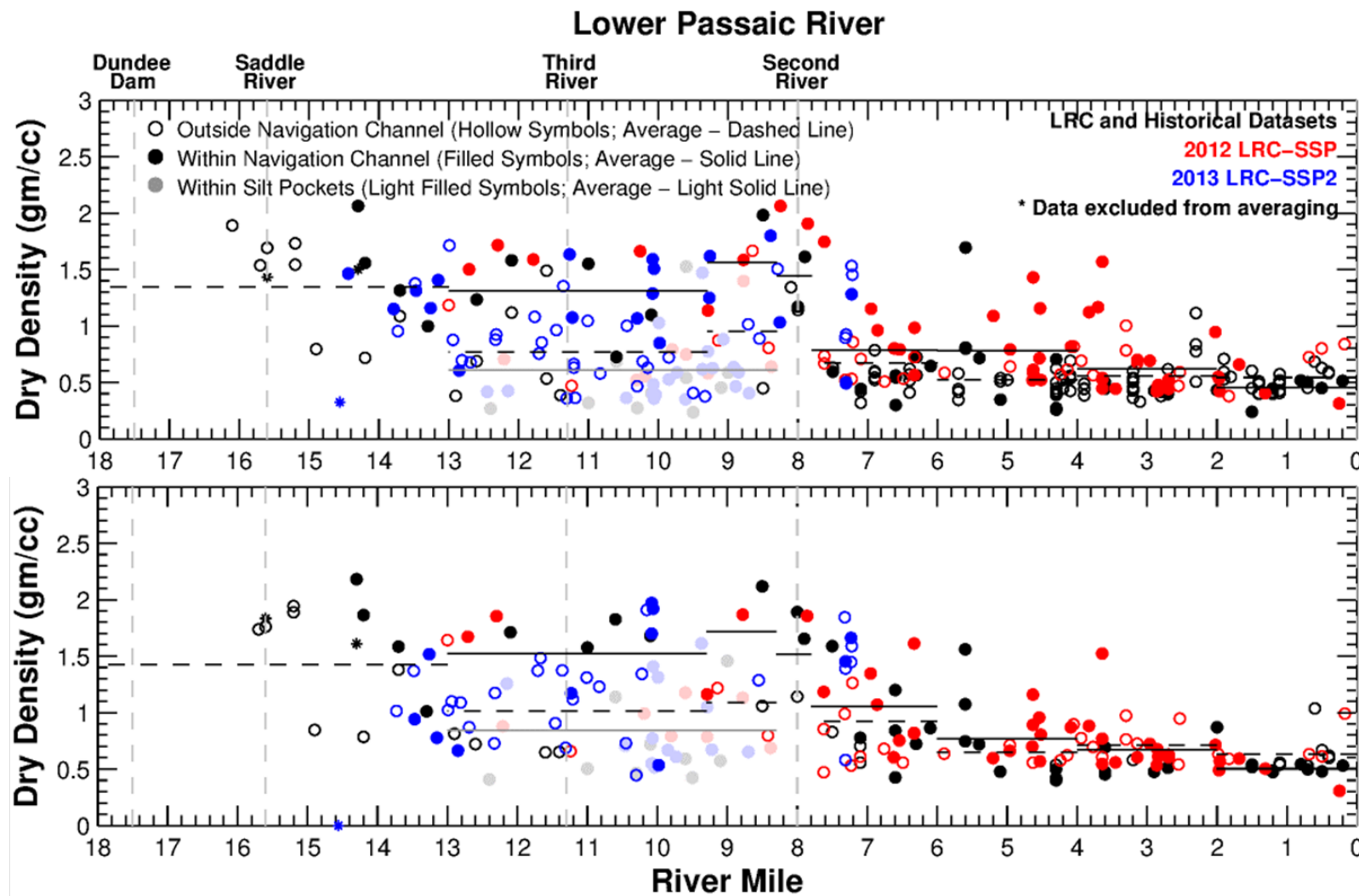


Figure 15. Longitudinal plot of dry density initial condition for surficial sediments (top 15 cm of bed; upper panel), and for the 15-45 cm depth interval in bed in the LPR (lower panel)

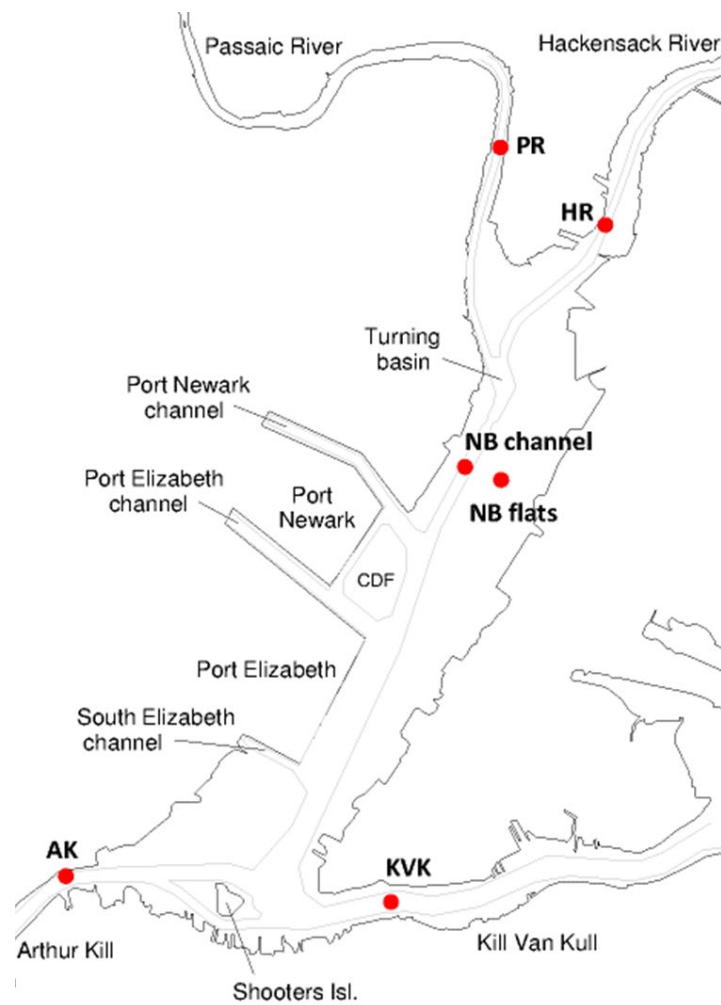


Figure 16. Location map of mooring deployments during 2008-2009. Adapted from Sommerfield and Chant (2010) .

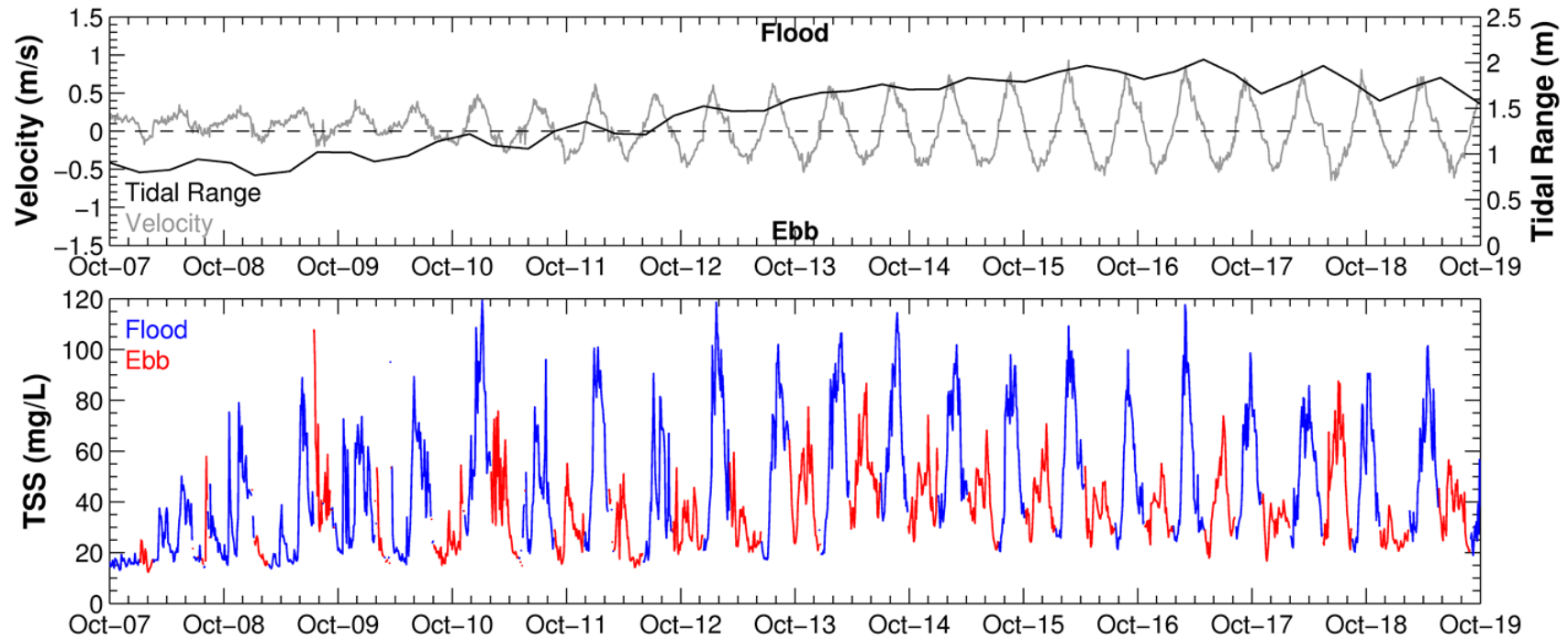


Figure 17. Example time-series of SSC at Kill van Kull from bottom-most ADCP bin. Data from Sommerfield and Chant (2010).

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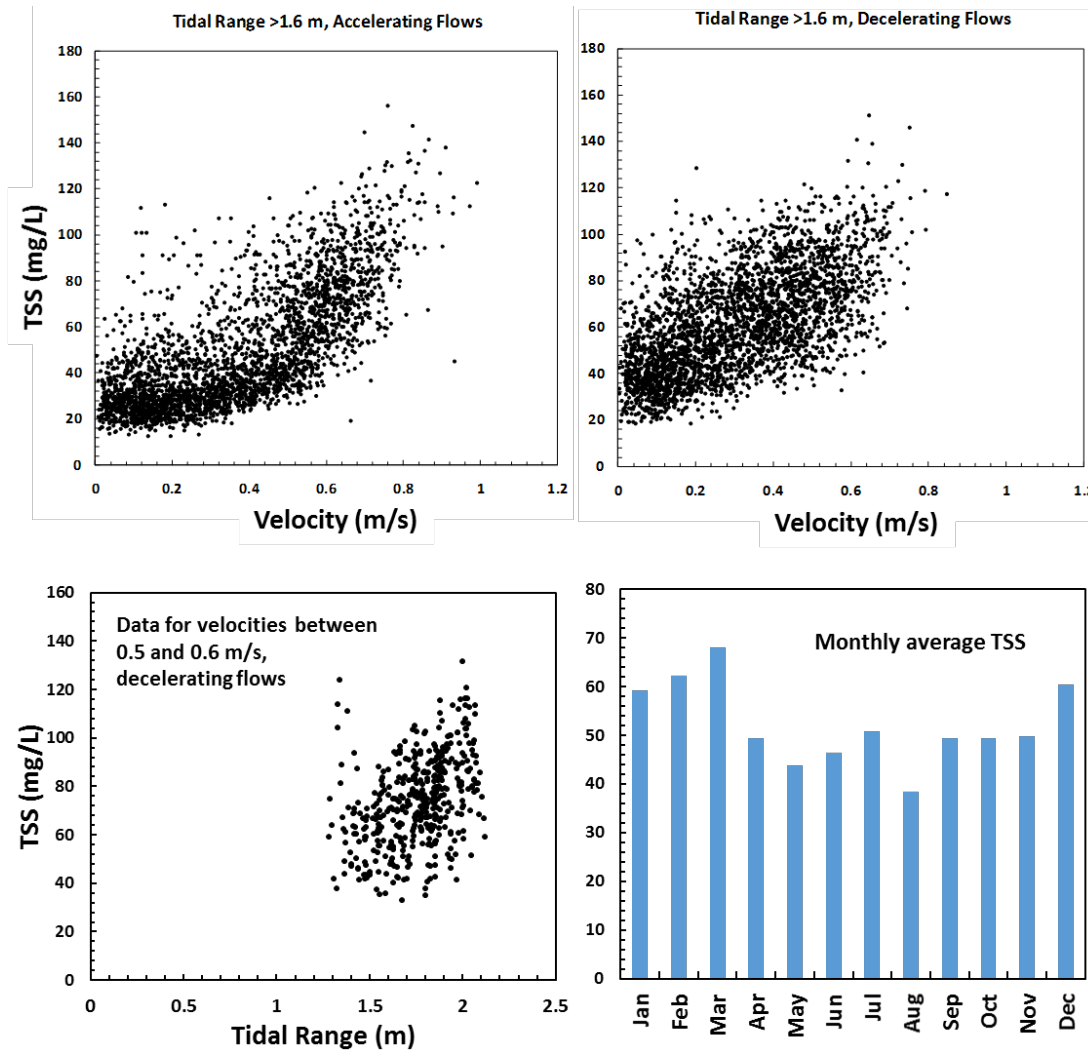


Figure 18. Functional dependencies for inflowing SSC at Kill van Kull. Data from bottom-most ADCP bin, Sommerfield and Chant (2010).

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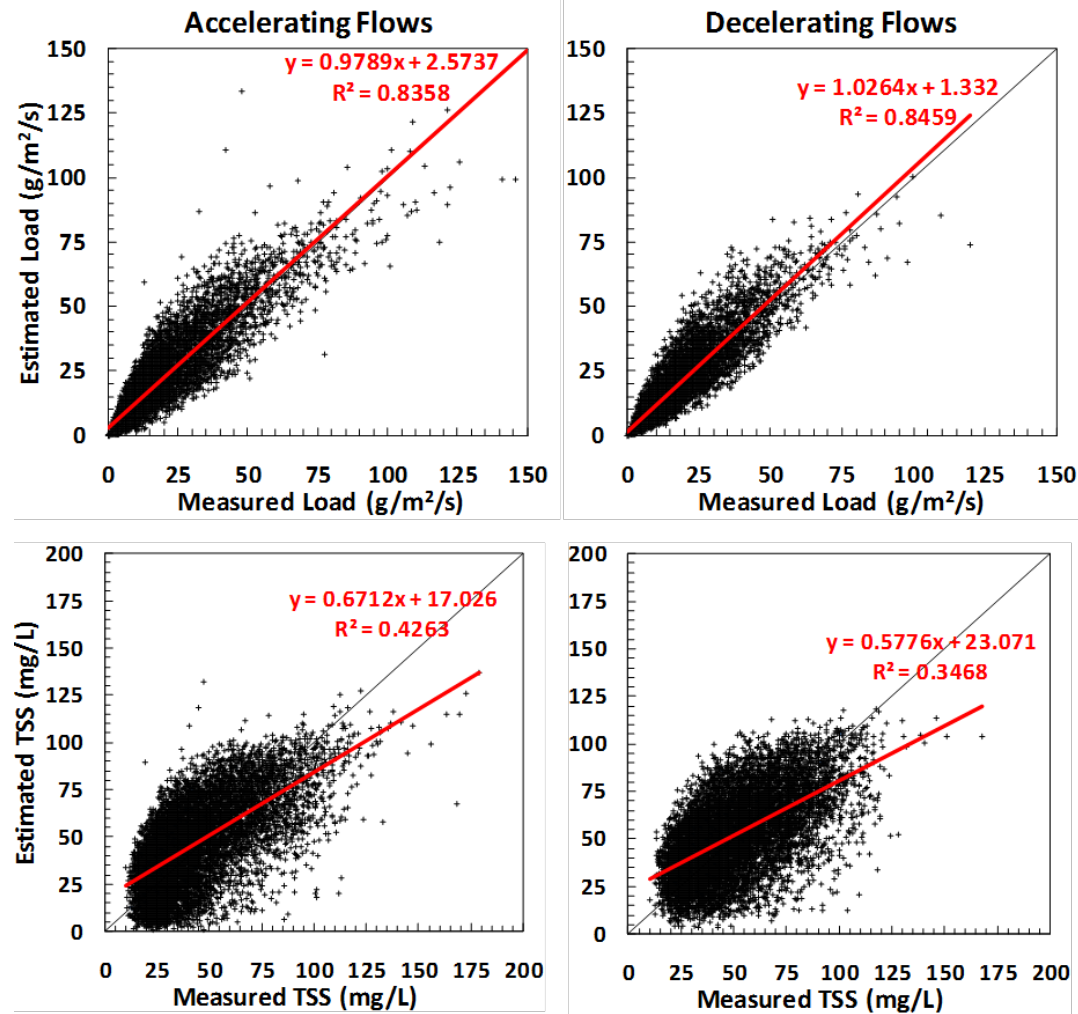


Figure 19. Example comparison of rating curve derived SS load and concentrations to measured values in ADCP bottom-most bin at Kill van Kull. Data from Sommerfield and Chant (2010). Red lines indicate regression of measured and estimated quantities, with the regression equations and correlation coefficients also on each panel.

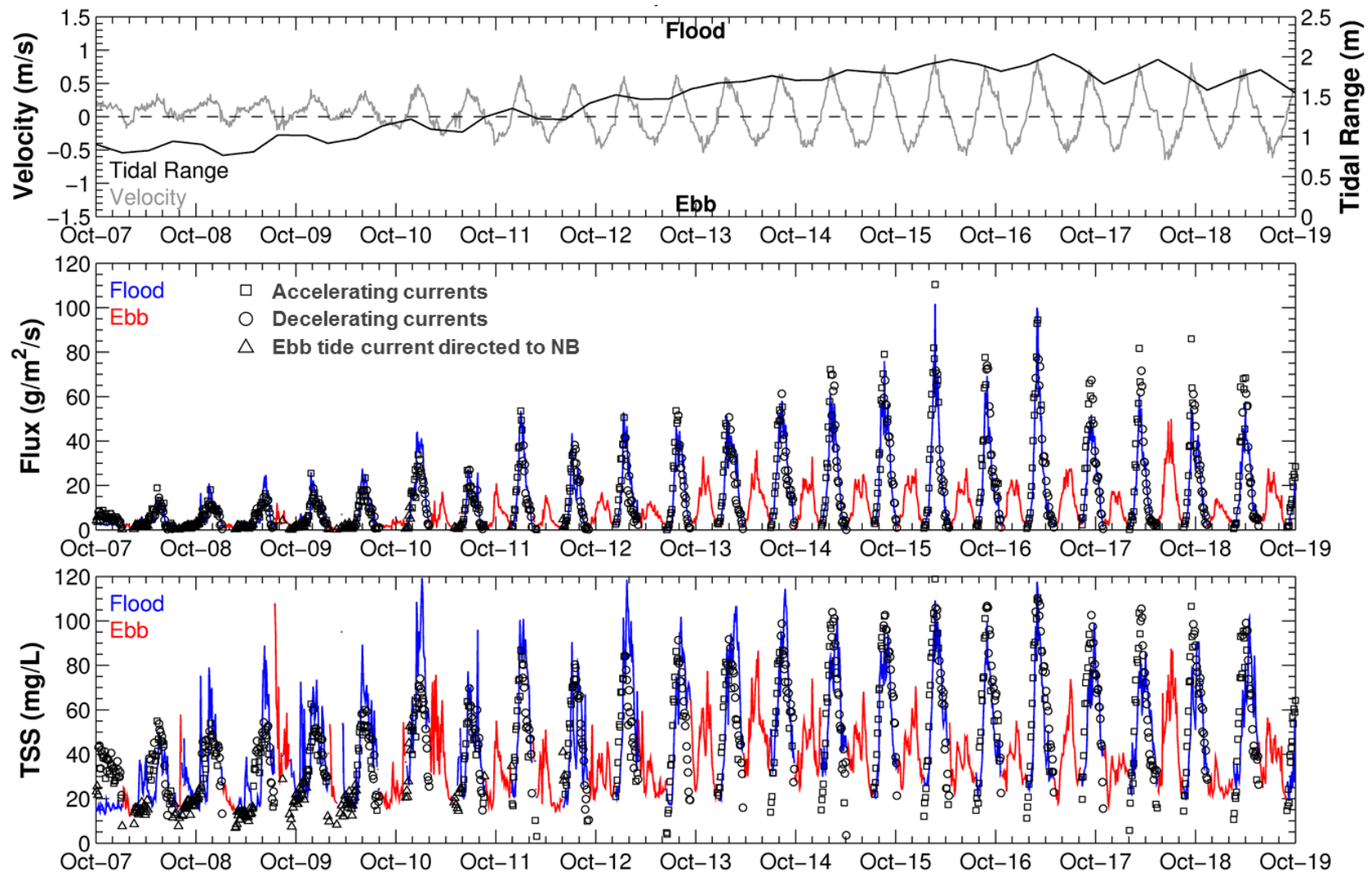


Figure 20. Example time-series comparison of measured and rating curve derived SS load and concentrations for ADCP bottom-most bin at Kill van Kull. Data from Sommerfield and Chant (2010).

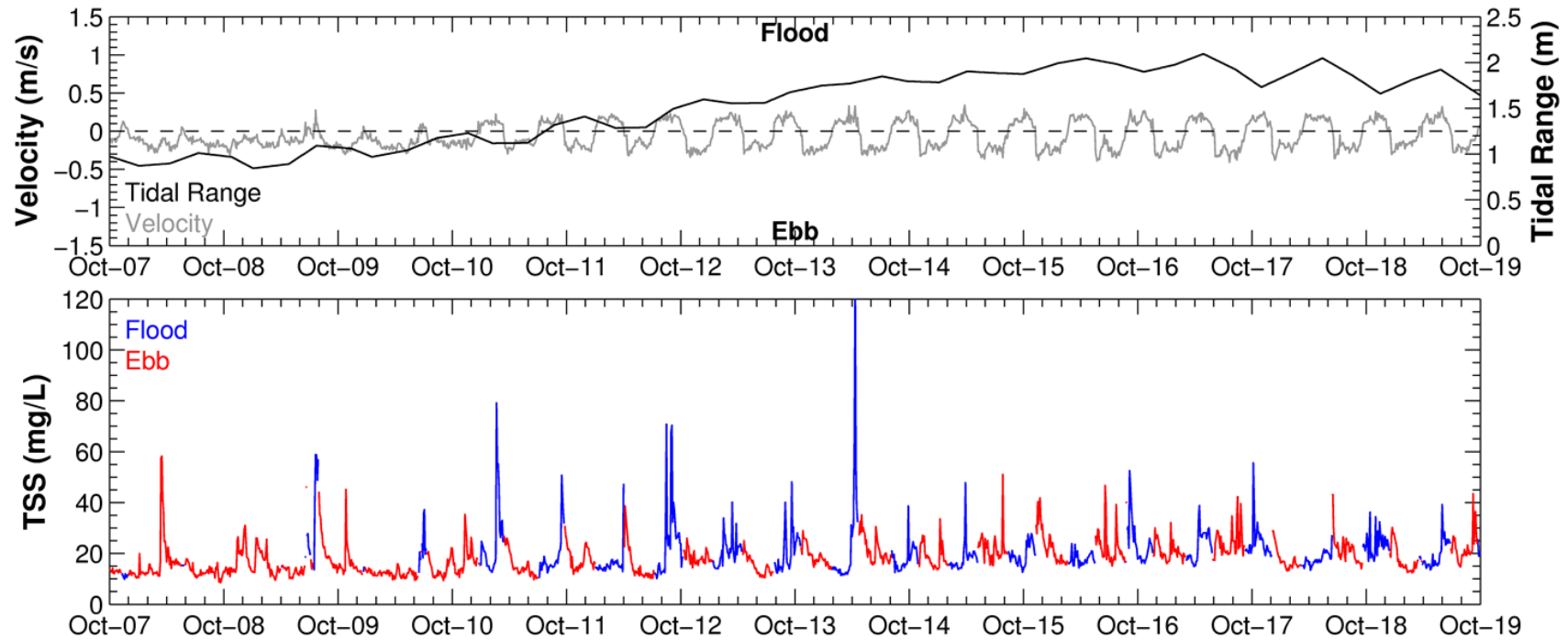


Figure 21. Example time-series of SSC at Arthur Kill from bottom-most ADCP bin. Data from Sommerfield and Chant (2010).

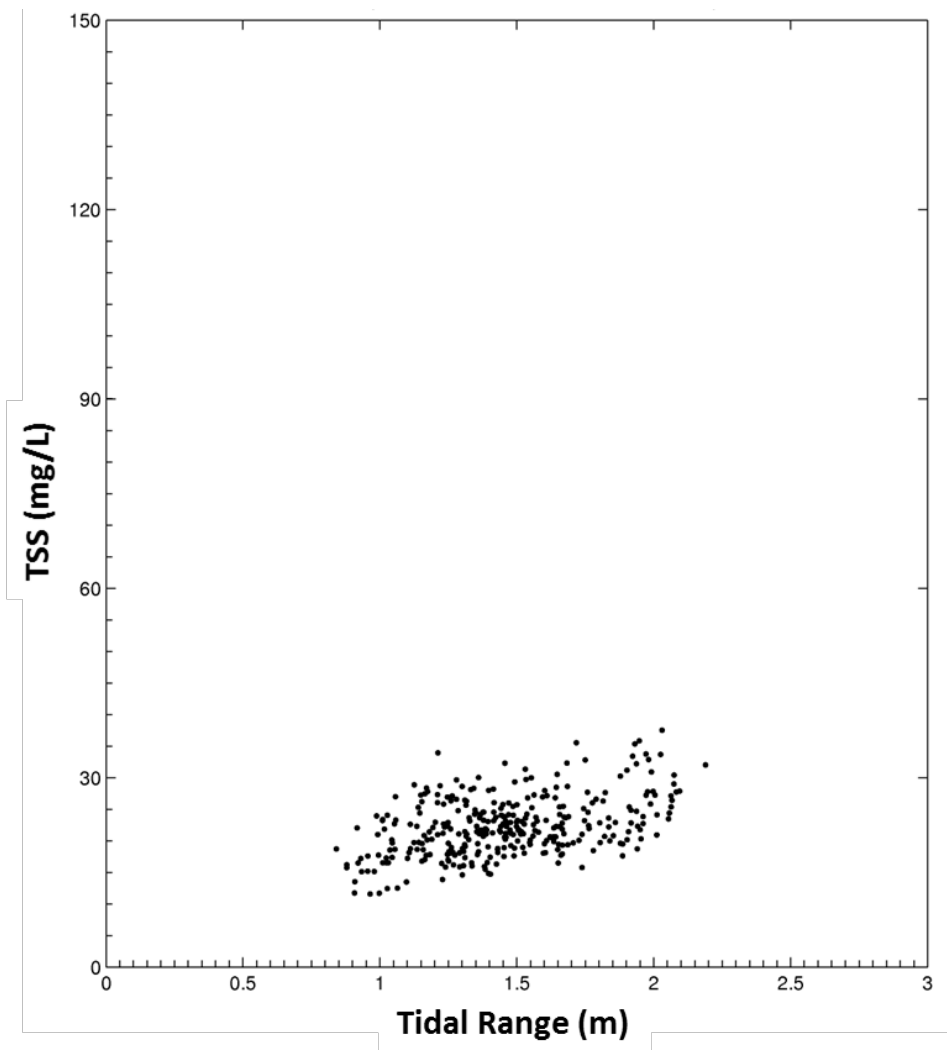


Figure 22. Functional dependency for inflowing SSC at Arthur Kill. Data from bottom-most ADCP bin, Sommerfield and Chant (2010).

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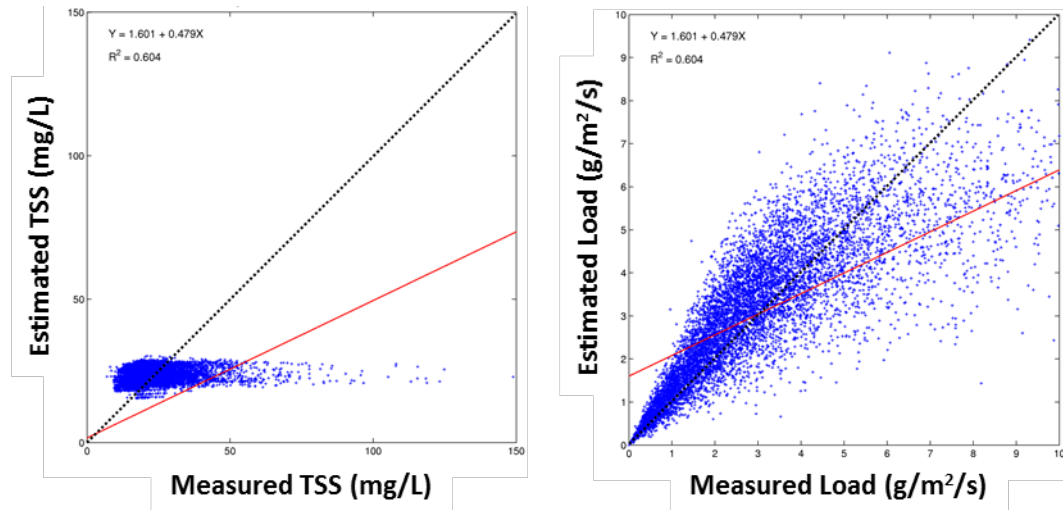


Figure 23. Example comparison of rating curve derived SS load and concentrations to measured values in ADCP bottom-most bin at Arthur Kill. Data from Sommerfield and Chant (2010). Red lines indicate regression of measured and estimated quantities, with the regression equations and correlation coefficients also on each panel.

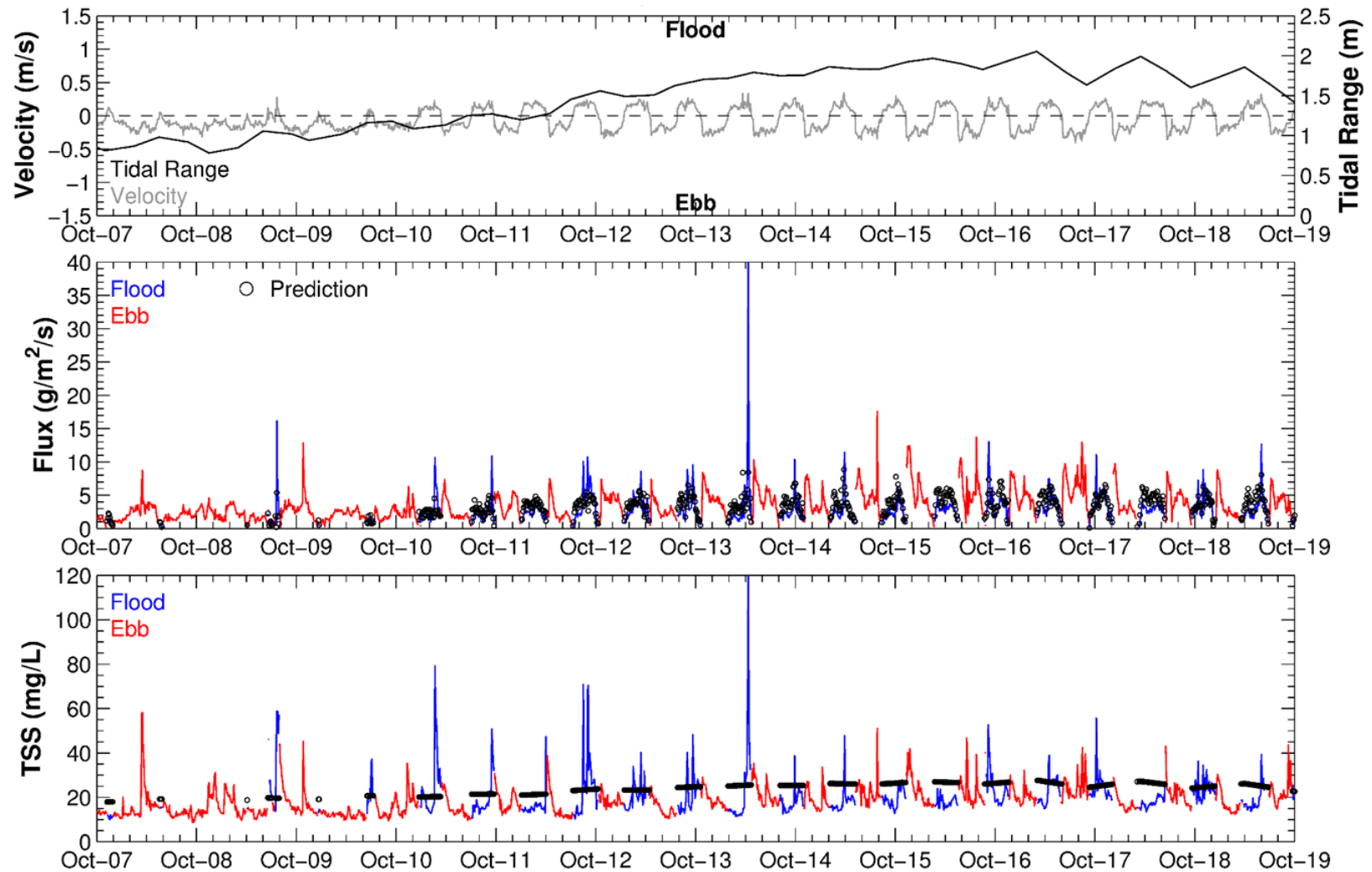


Figure 24. Example time-series comparison of measured and rating curve derived SS load and concentrations for ADCP bottom-most bin at Arthur Kill. Data from Sommerfield and Chant (2010).

Draft Sediment Transport Model of the Lower Passaic River

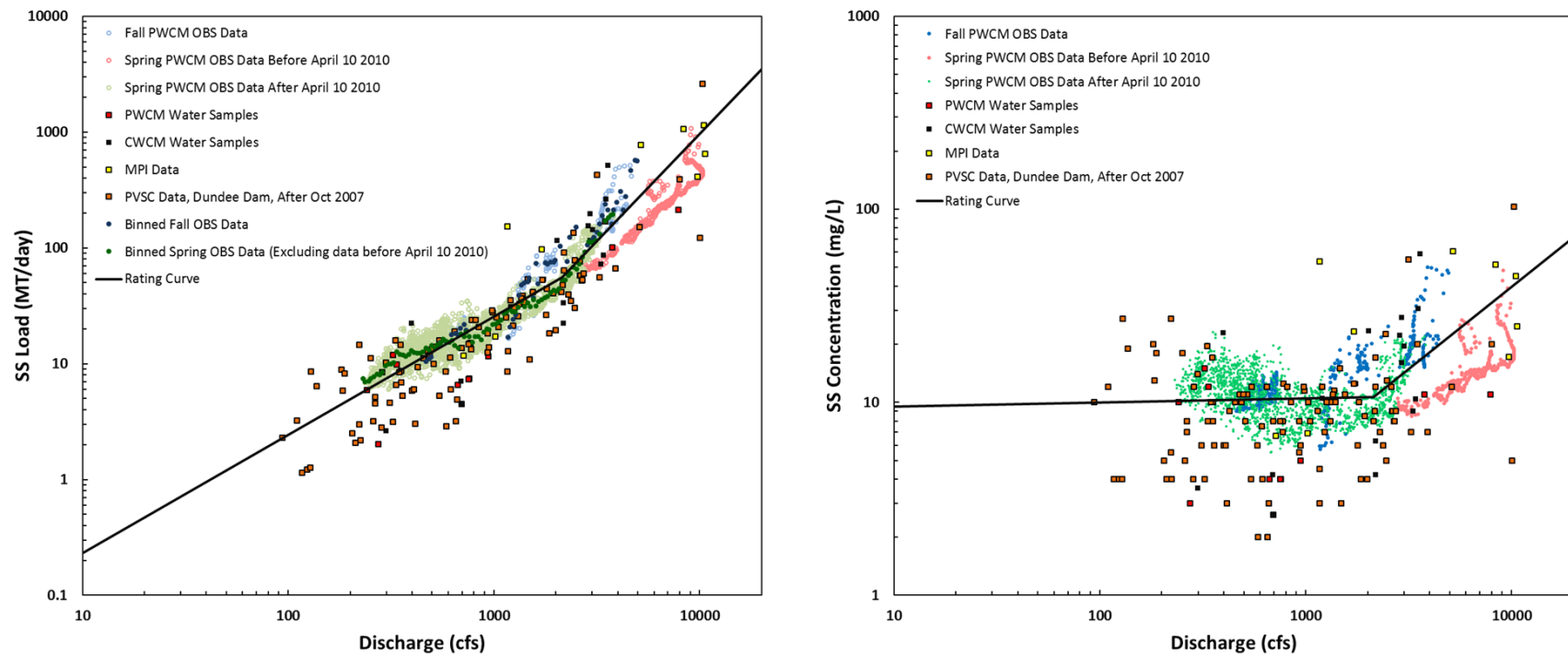


Figure 25. Rating curve for SS load and concentration as a function of discharge at Dundee Dam

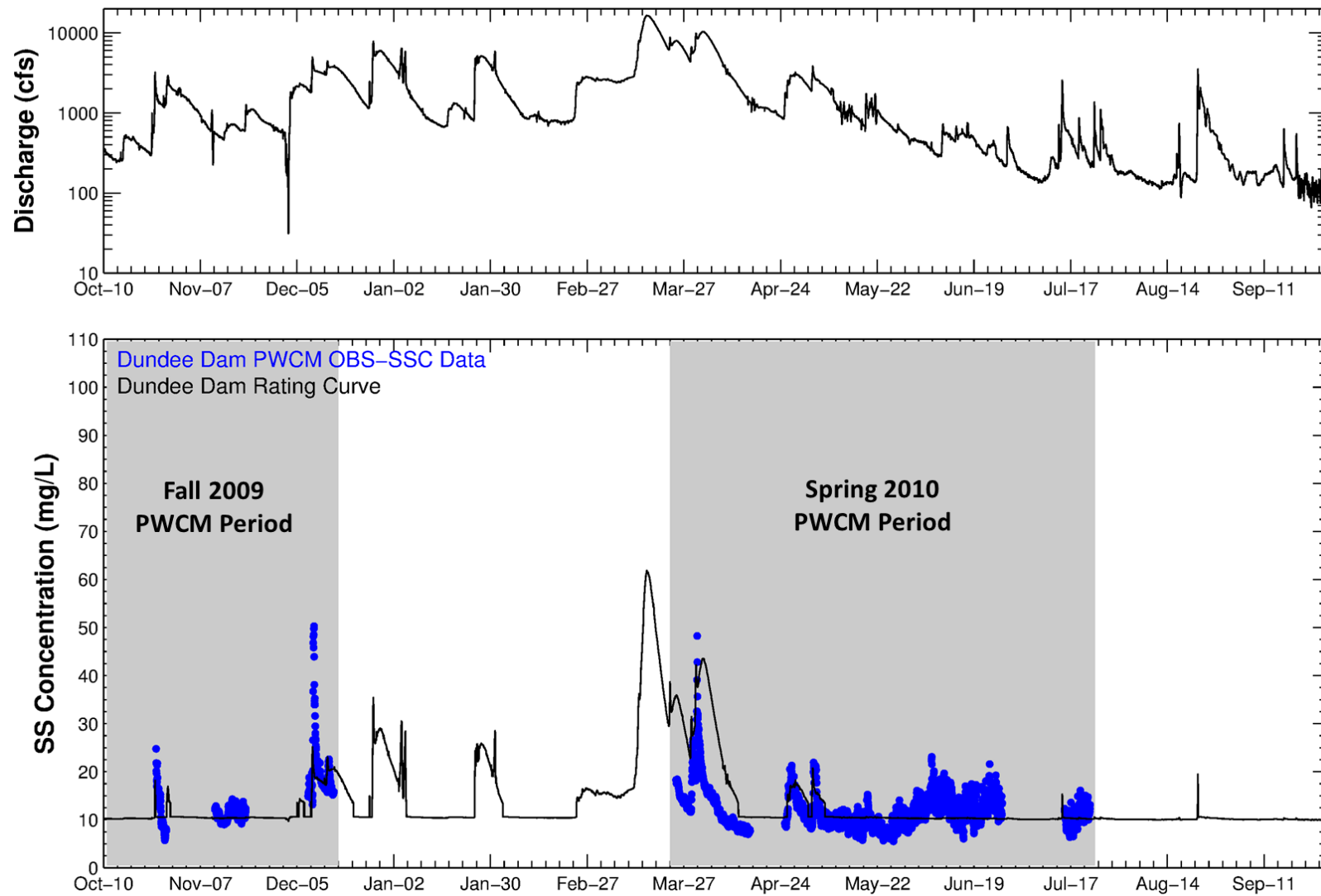


Figure 26. Rating curve-derived SSC and comparison to OBS-derived concentrations

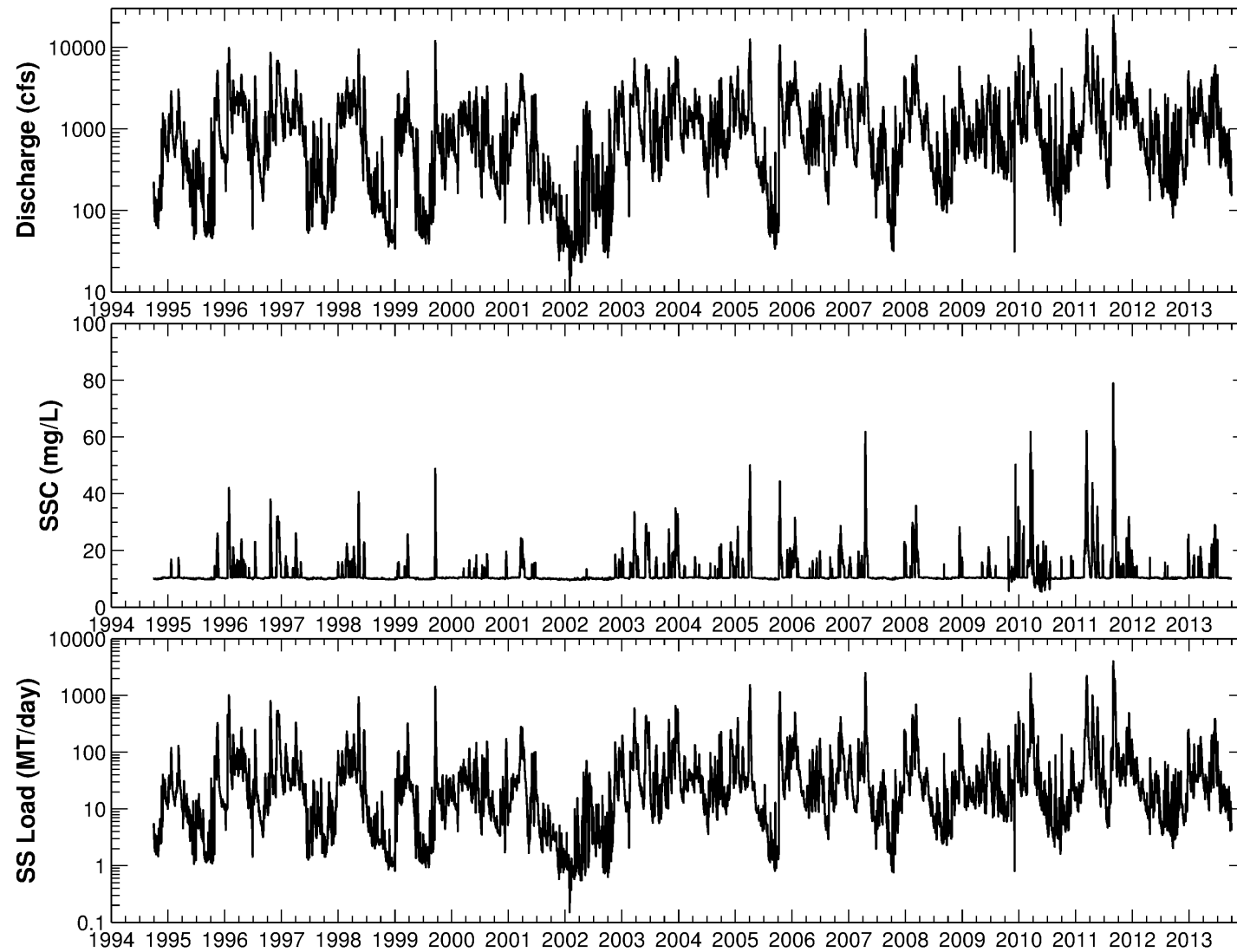


Figure 27. Time-series of flow, SSC, and SS load at Dundee Dam during the long-term calibration period.

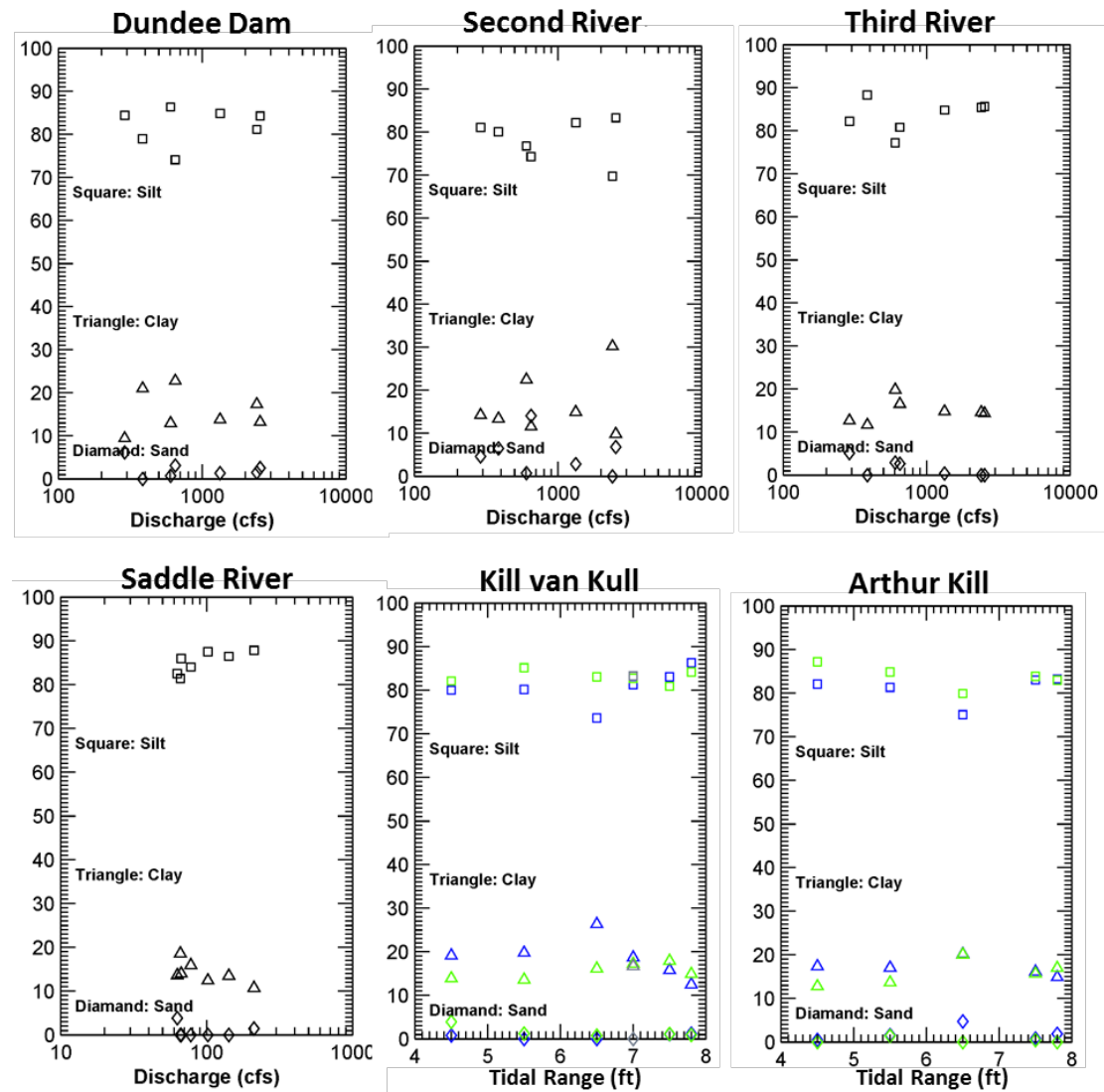


Figure 28. Sediment mass fractions in water samples from the CWCM events.

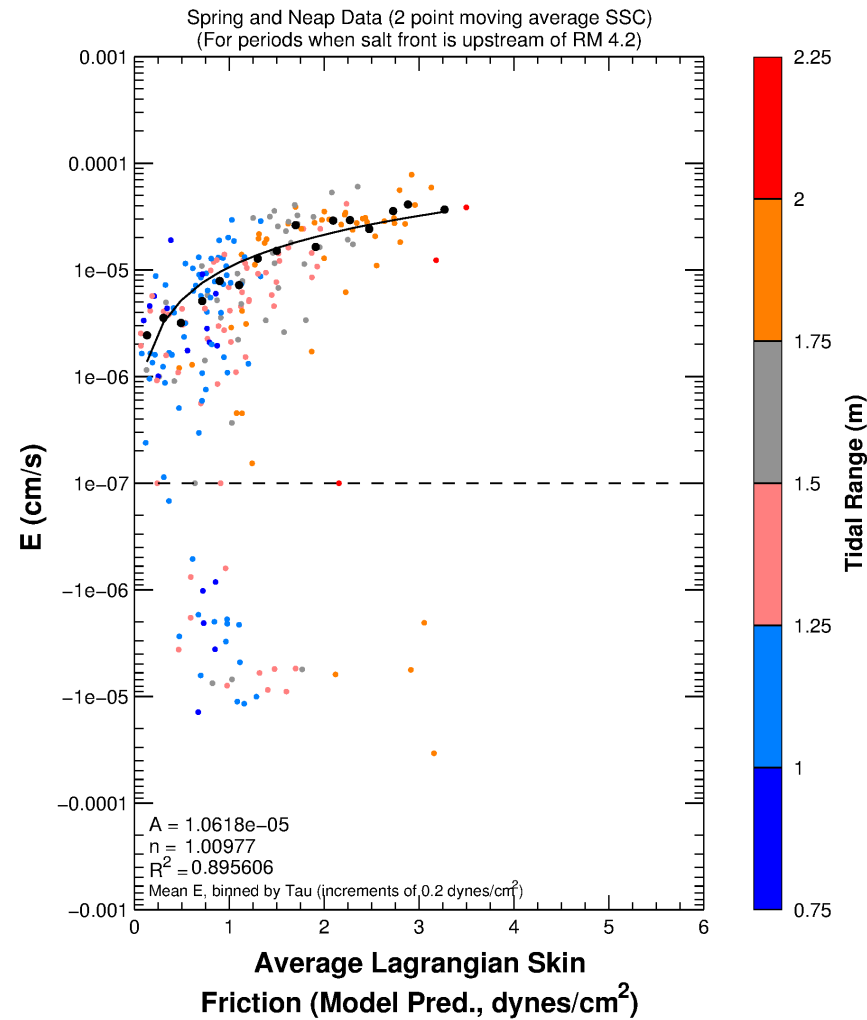


Figure 29. Fluff layer erosion rate as a function of shear stress. PWCM data shown with filled circles. Erosion data binned by shear stress (binned values shown with unfilled circles). Erosion rate function used for model input calculated from regression of binned data.

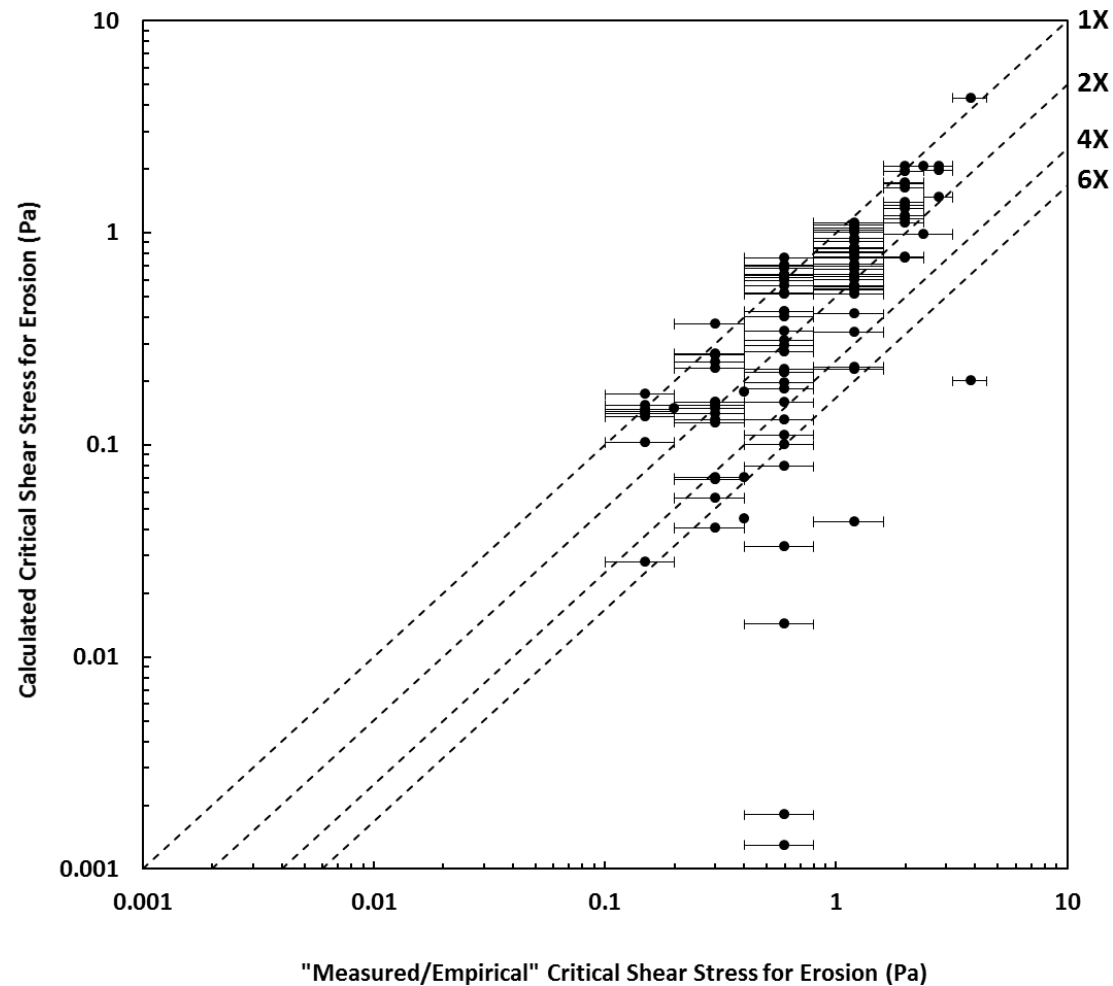


Figure 30. Calculated critical shear stress for erosion (corresponding to erosion rate of 10^{-4} cm/s) versus measured or empirical critical shear stress for erosion. Measured critical shear stress taken as the average of measured highest shear stress with no erosion and lowest shear stress with some erosion (range indicates the two values used in the computation of the average)

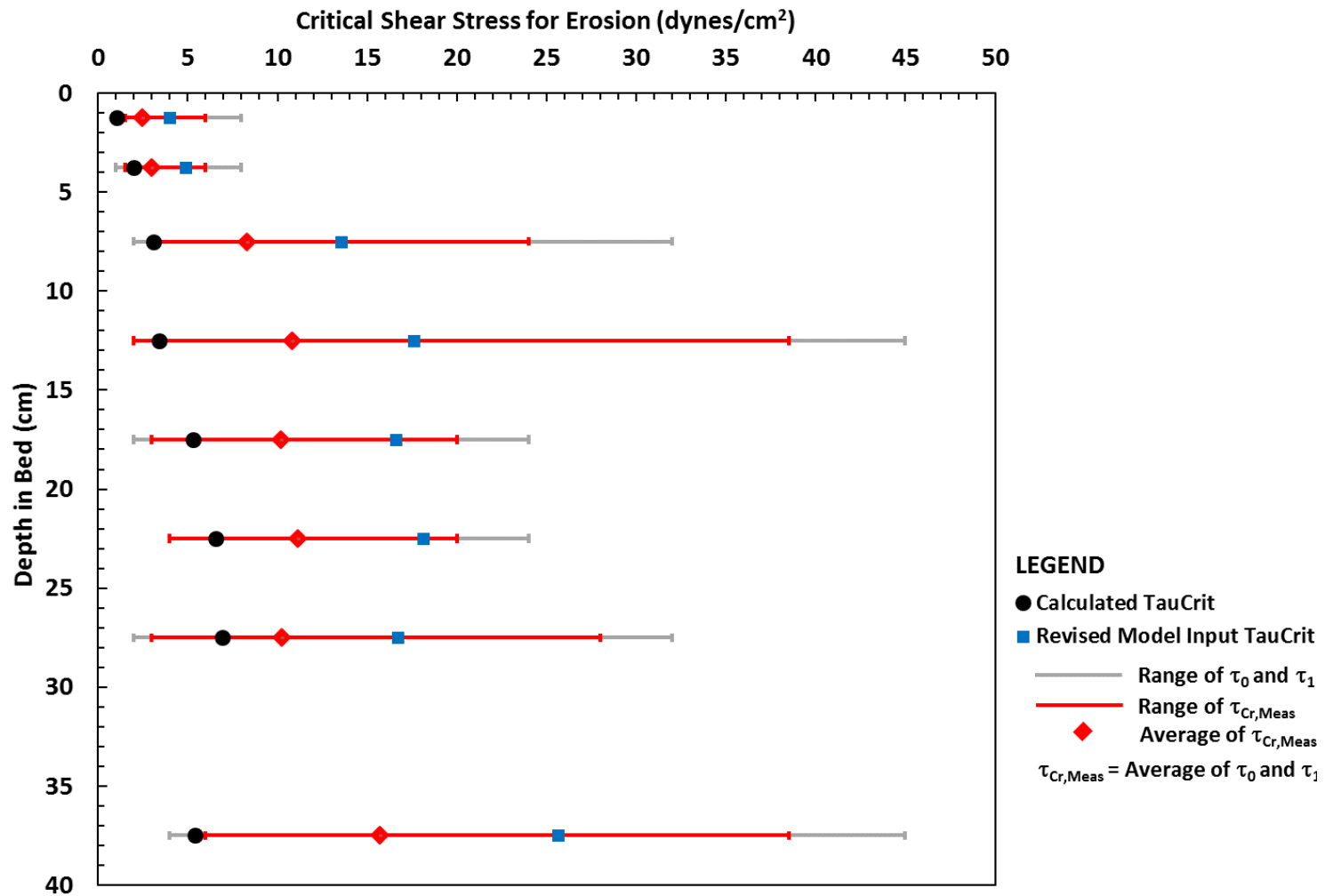


Figure 31. Depth profile of critical shear stress from the Sedflume data, and model input critical shear stress

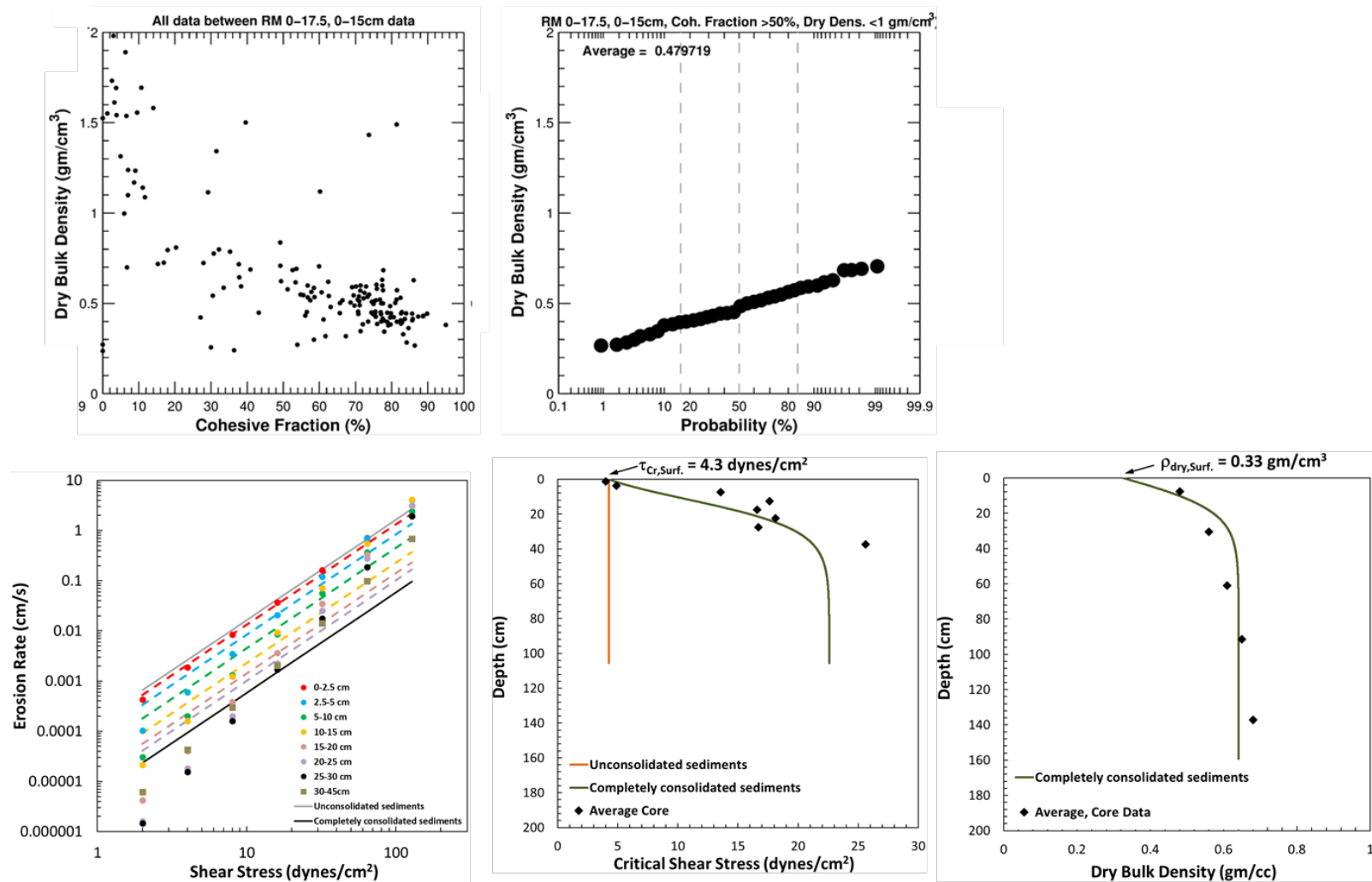


Figure 32. Dry density data used (example for top 6" of bed) to parameterize consolidation model (upper panels); and consolidation model fits relative to Sedflume erosion rate and critical shear stress data, and relative to dry density profile data (lower panels)

Draft Sediment Transport Model of the Lower Passaic River

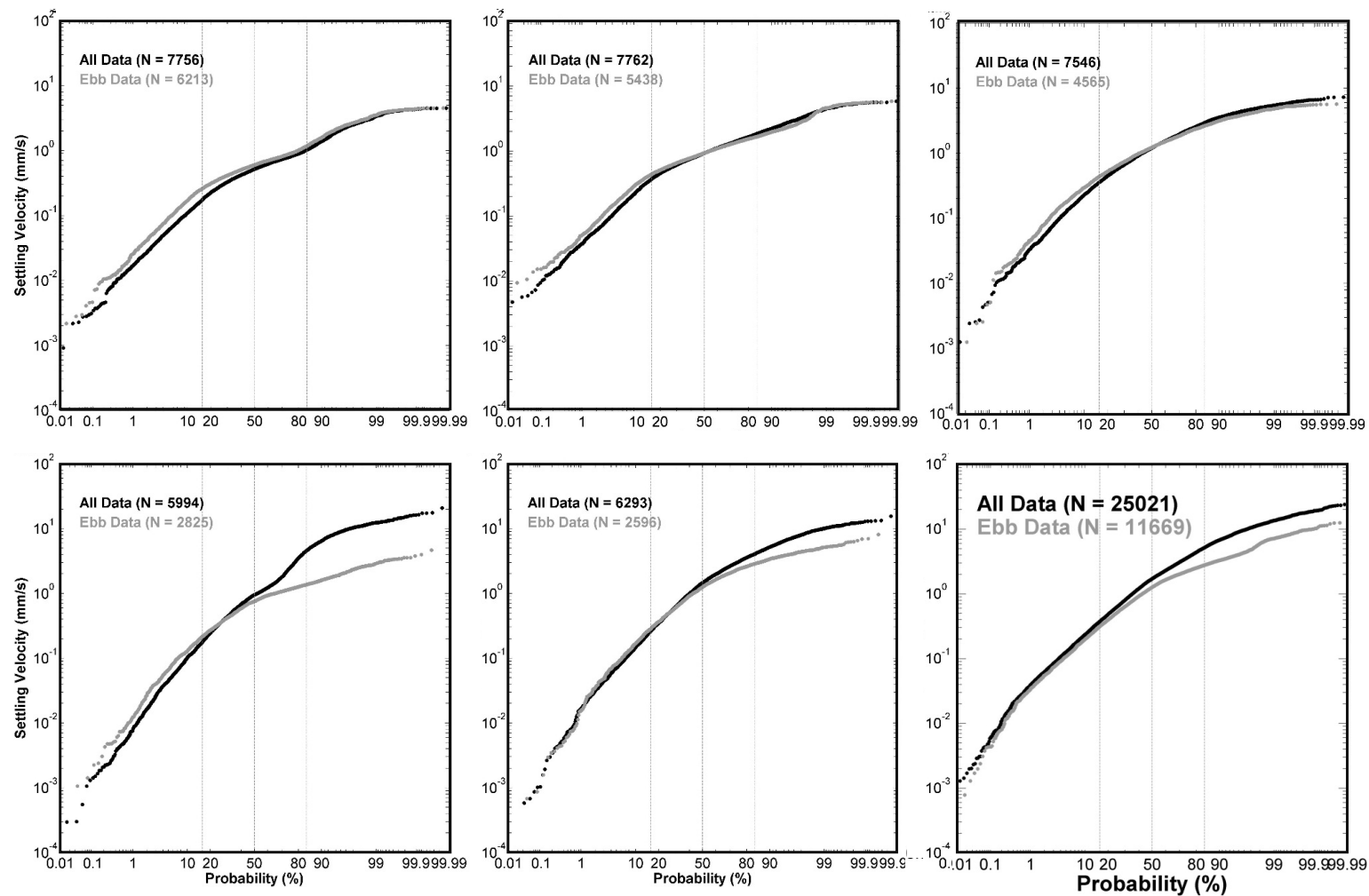


Figure 33. Distribution of calculated settling velocities from Fall 2009 PWCM data and Sommerfield and Chant (2010) data. Upper panels from left to right - RM 13.5, 10.2, and 6.7 from Fall 2009 PWCM. Lower panels from left to right - RM 4.2 and 1.4 from Fall 2009 PWCM, and RM 1.4 from Sommerfield and Chant (2010)

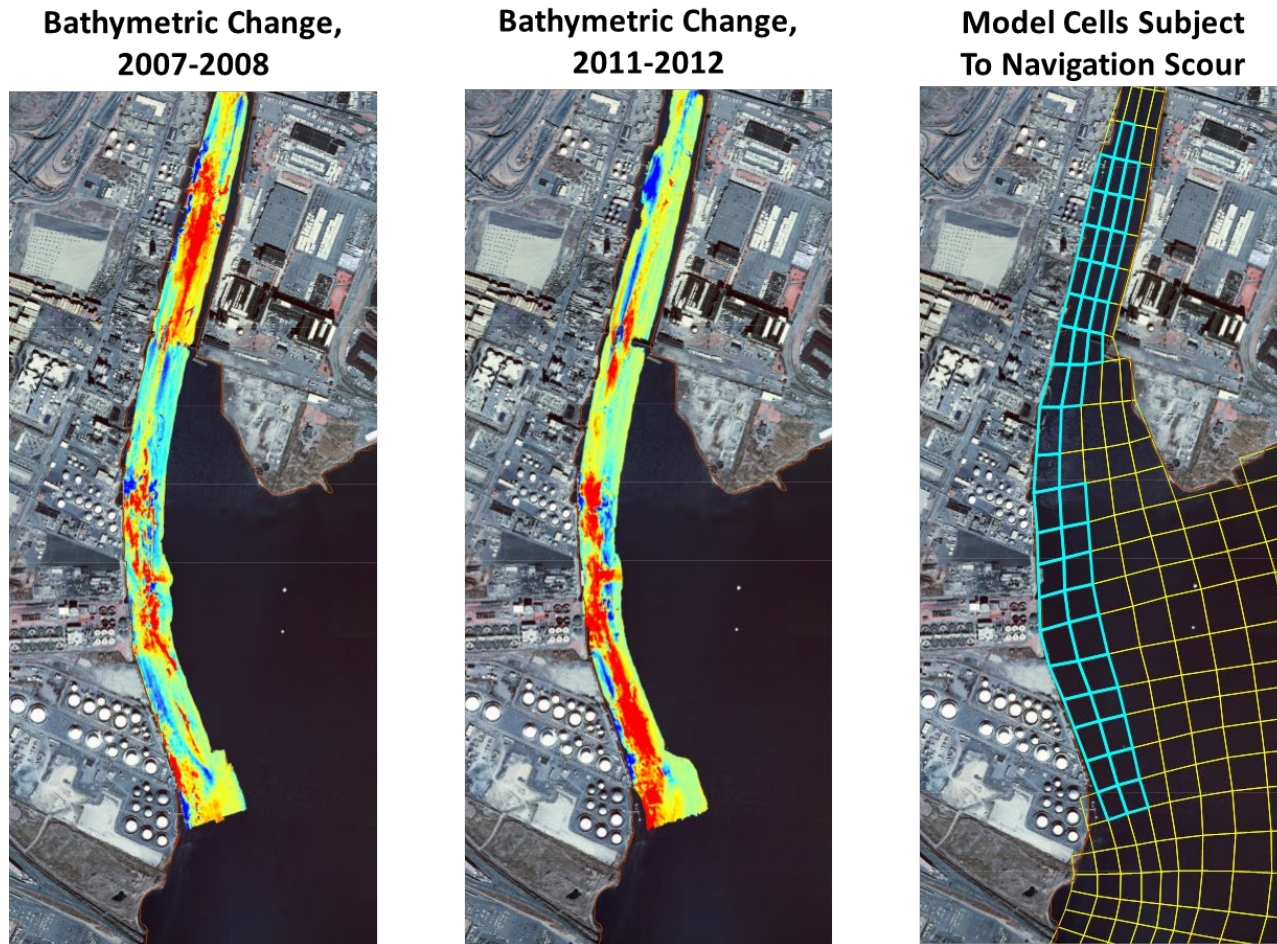


Figure 34. Areas with navigation scour as evidenced by erosional patterns during the low-flow bathymetric surveys (left and middle panels, areas shown in red, orange, and yellow shades), and model cells subject to navigation scour (right panel, cyan outlined cells).

Draft Sediment Transport Model of the Lower Passaic River

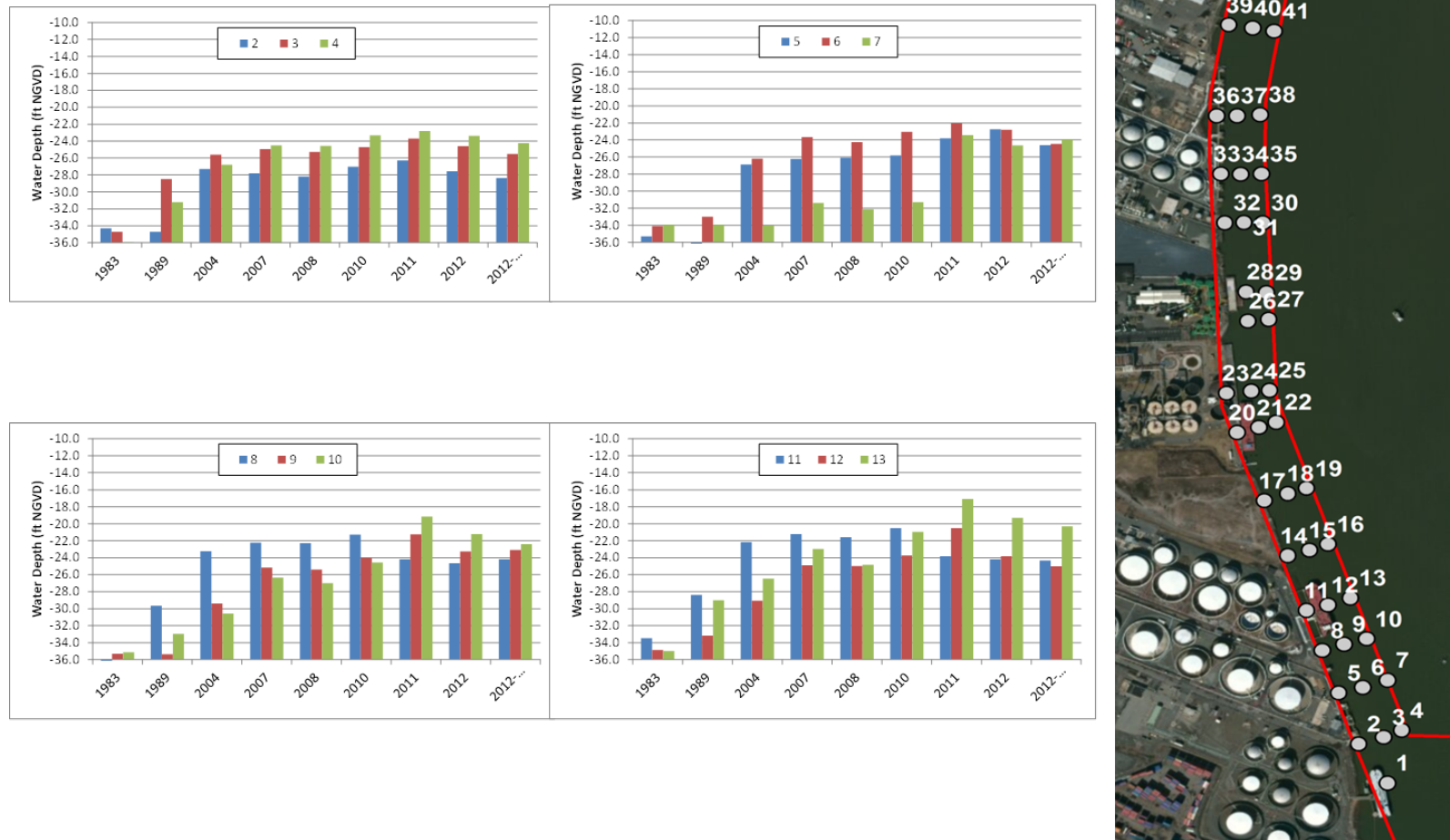


Figure 35. Evolution of bathymetry from 1983 to 2012 at four different transects, with the locations of the observation points identified in adjoining map.

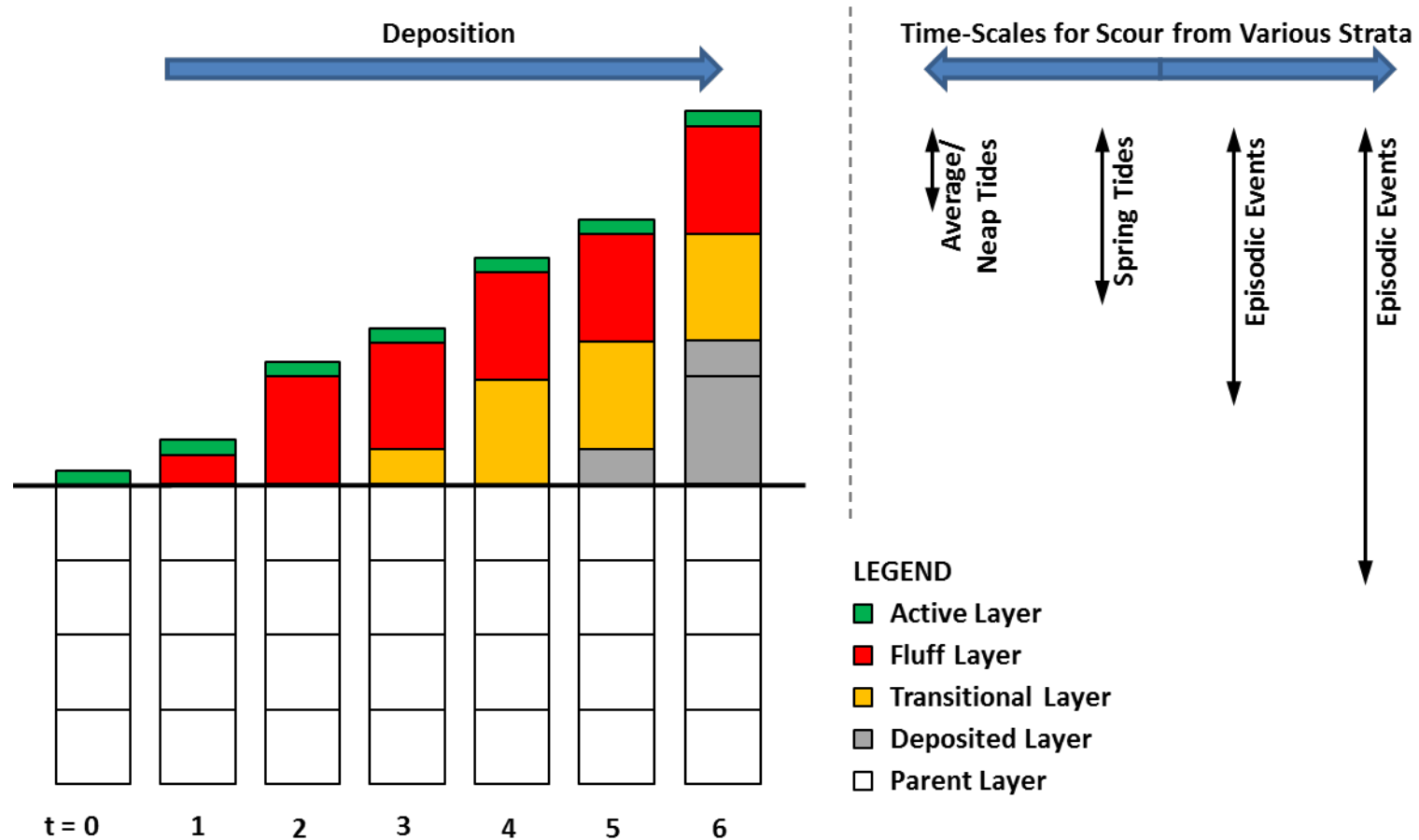


Figure 36. Schematic of revised bed layering in ECOM-SEDZLJS and conceptual representation of hydrodynamic conditions potentially responsible for erosion from various strata.

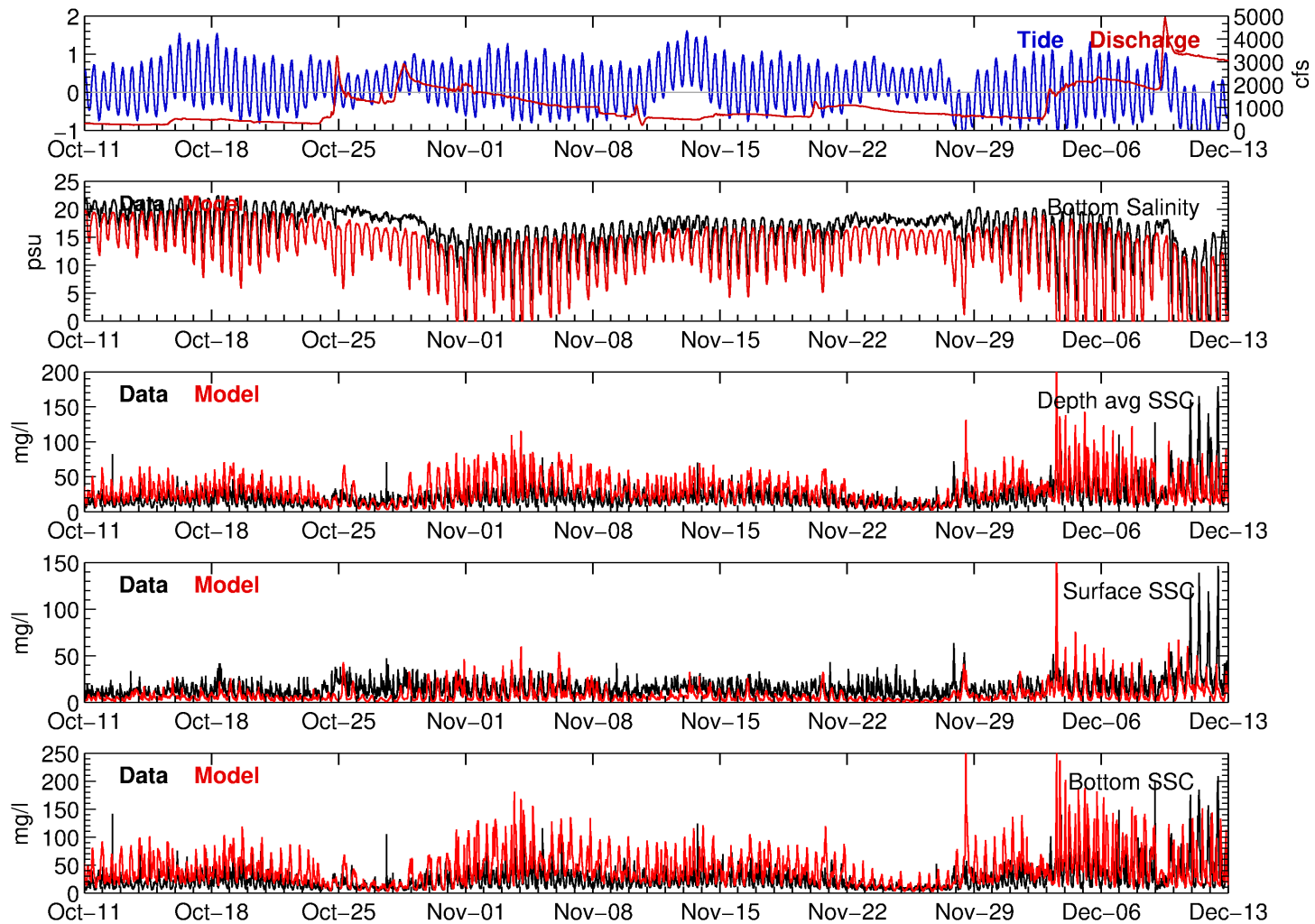


Figure 37. Time-series of model results and data during the Fall PWCM at RM 1.4

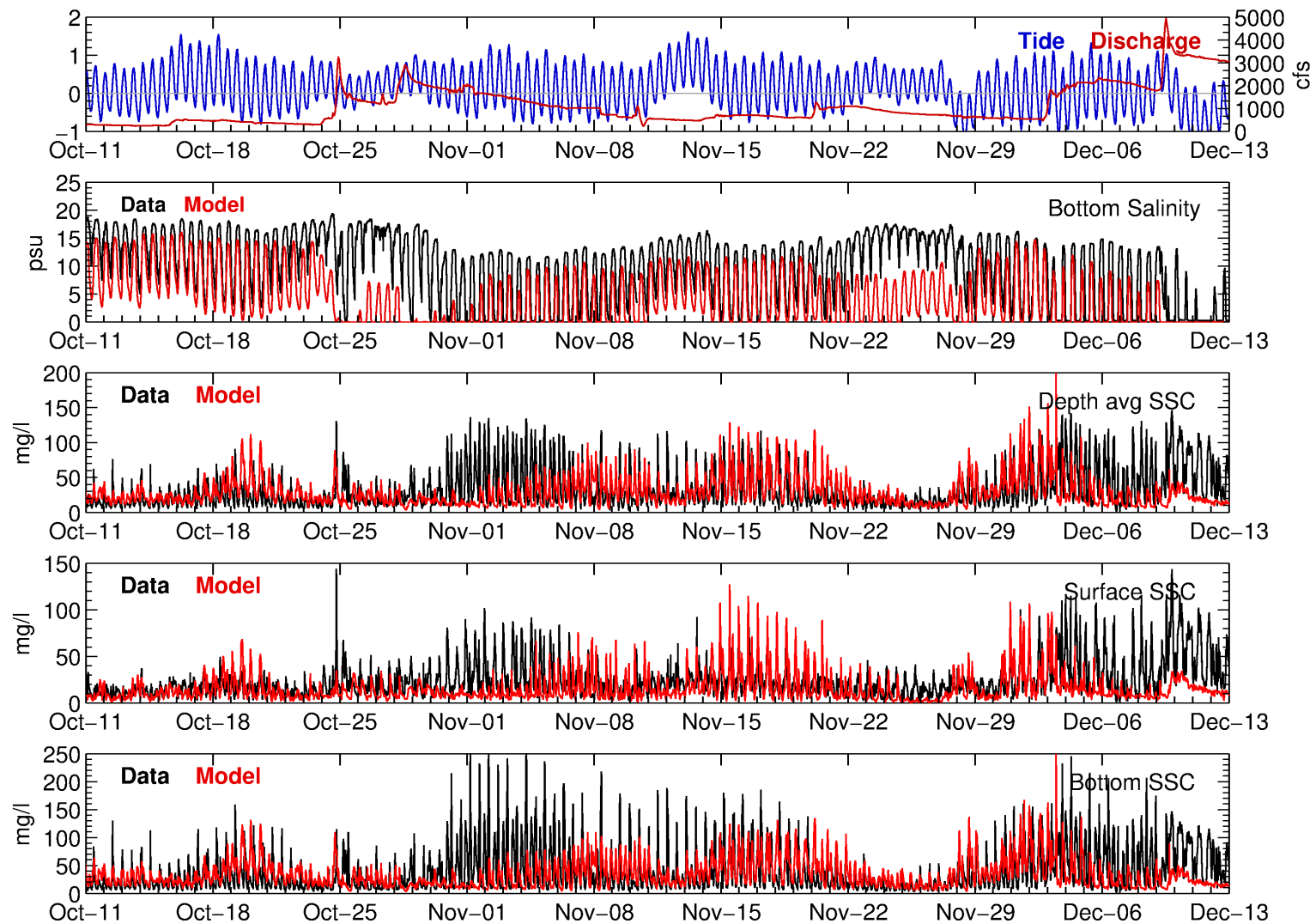


Figure 38. Time-series of model results and data during the Fall PWCM at RM 4.2

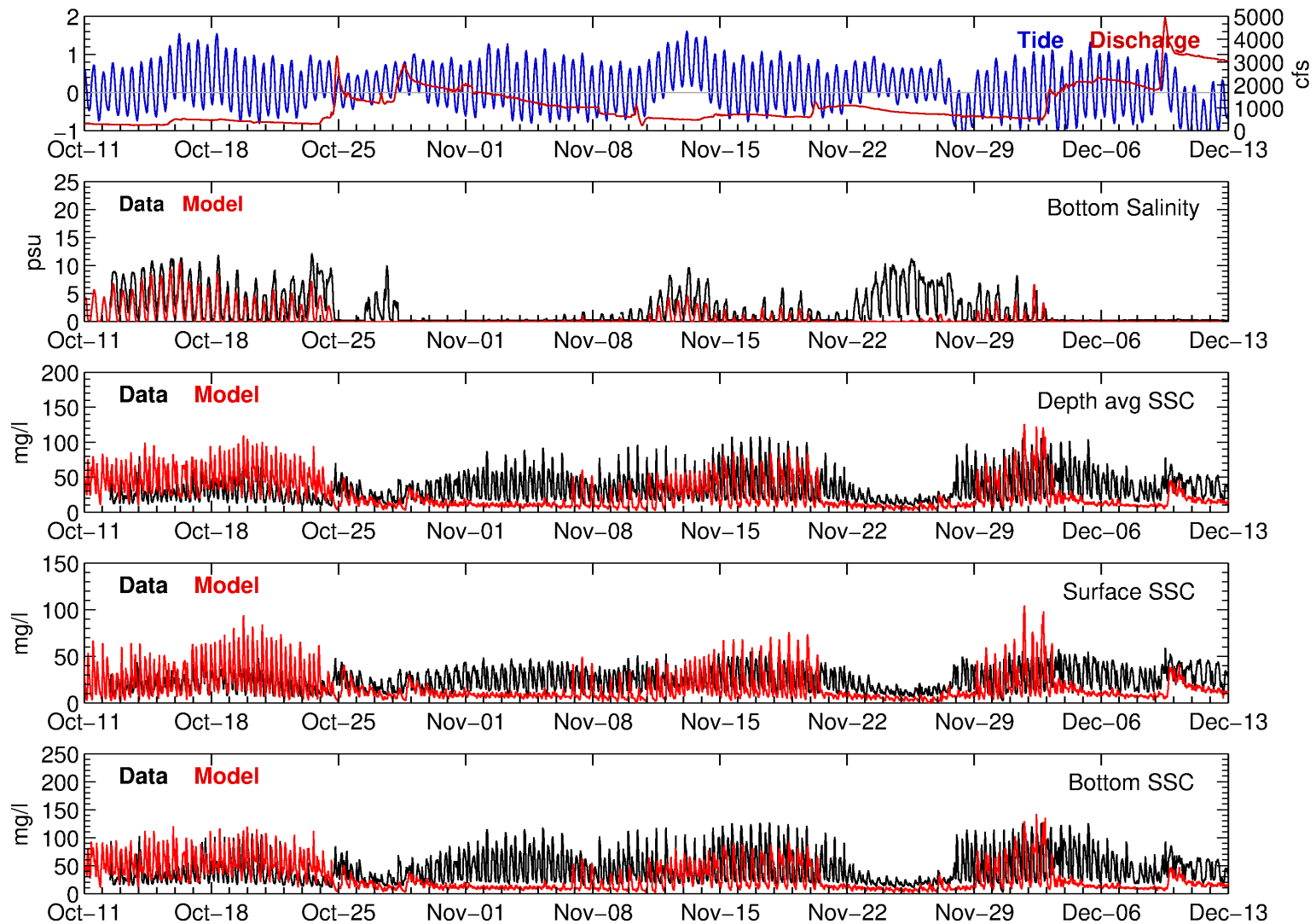


Figure 39. Time-series of model results and data during the Fall PWCM at RM 6.7

Sediment Transport Model of the Lower Passaic River

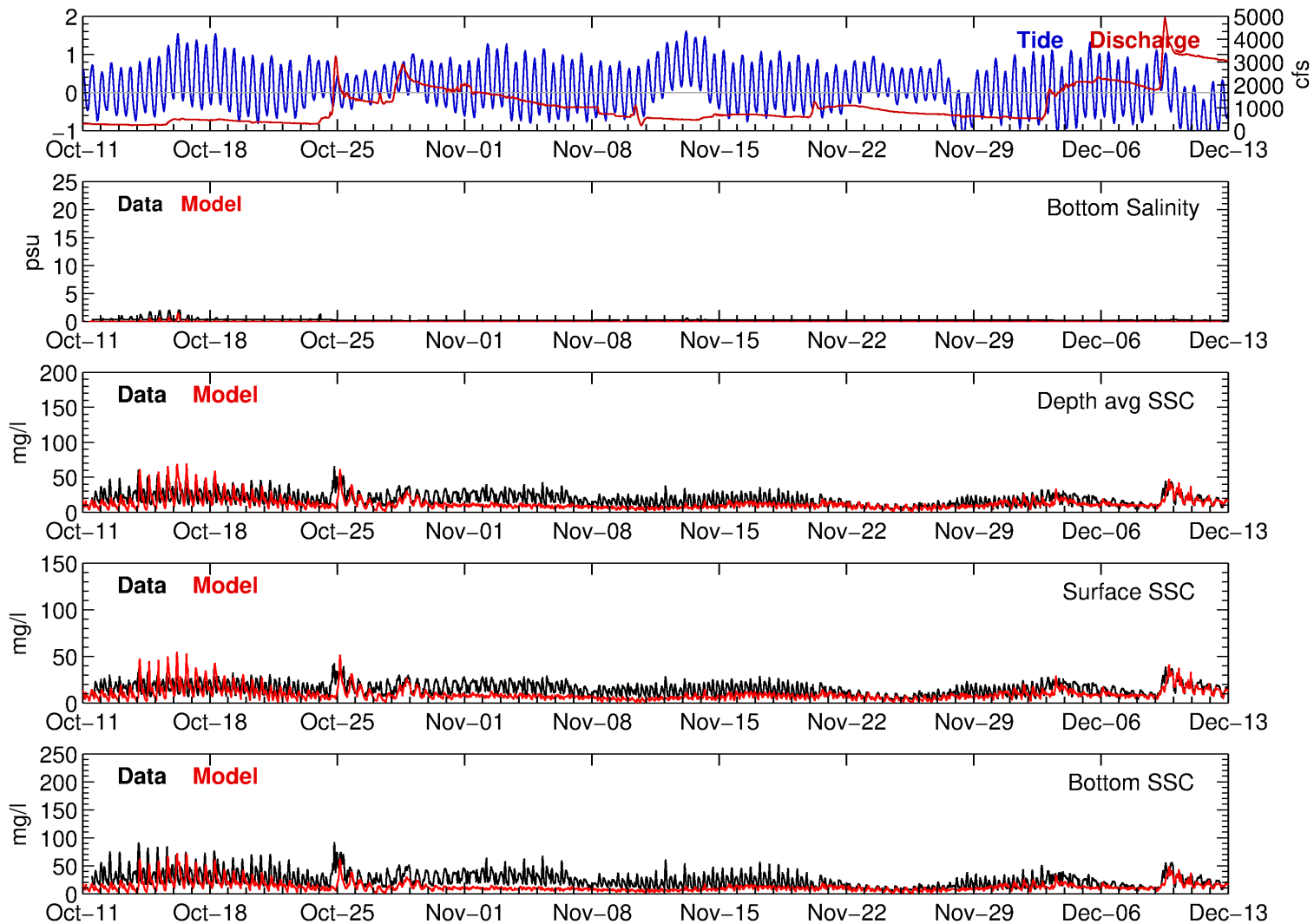


Figure 40. Time-series of model results and data during the Fall PWCM at RM 10.2

Sediment Transport Model of the Lower Passaic River

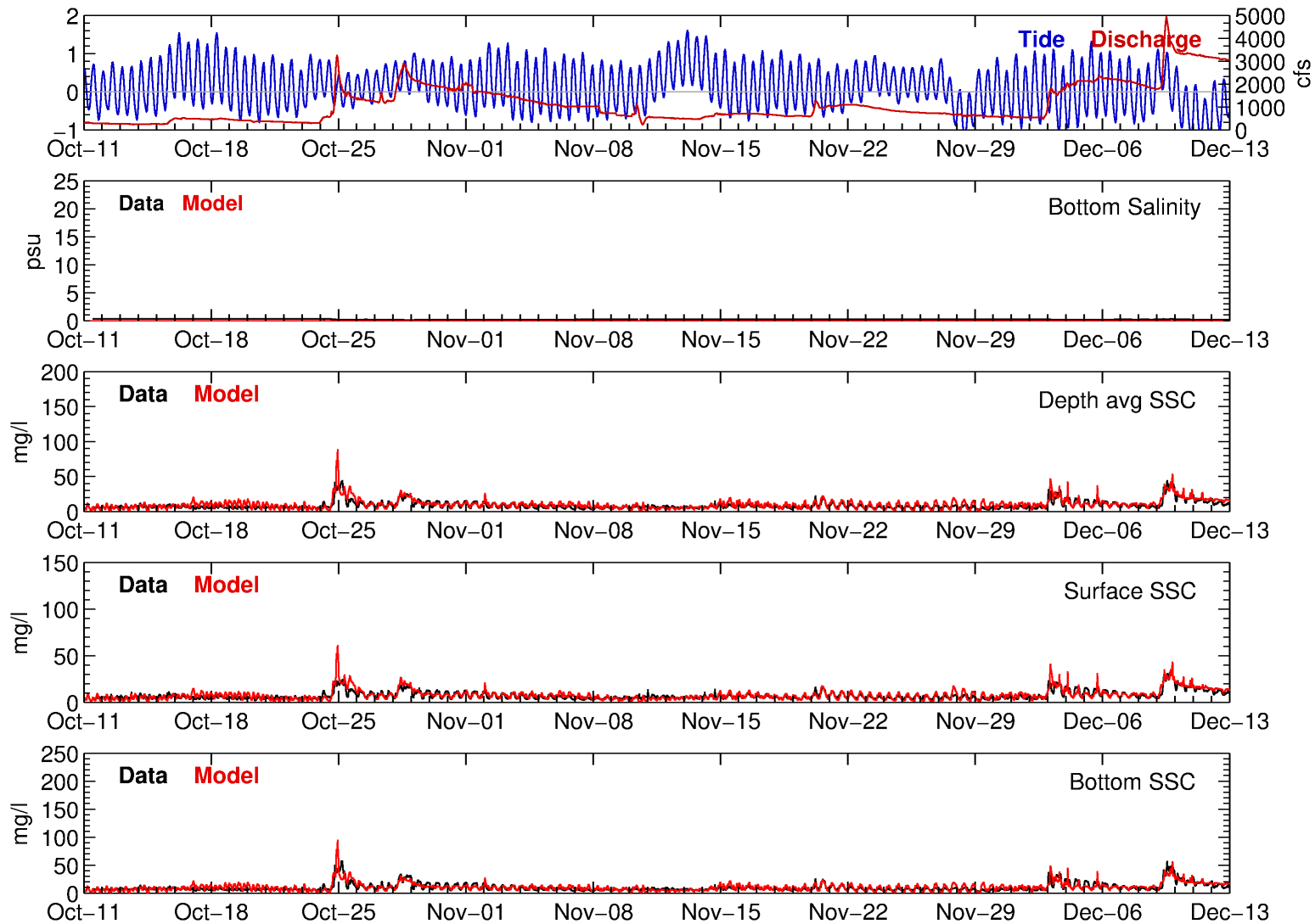


Figure 41. Time-series of model results and data during the Fall PWCM at RM 13.5

Sediment Transport Model of the Lower Passaic River

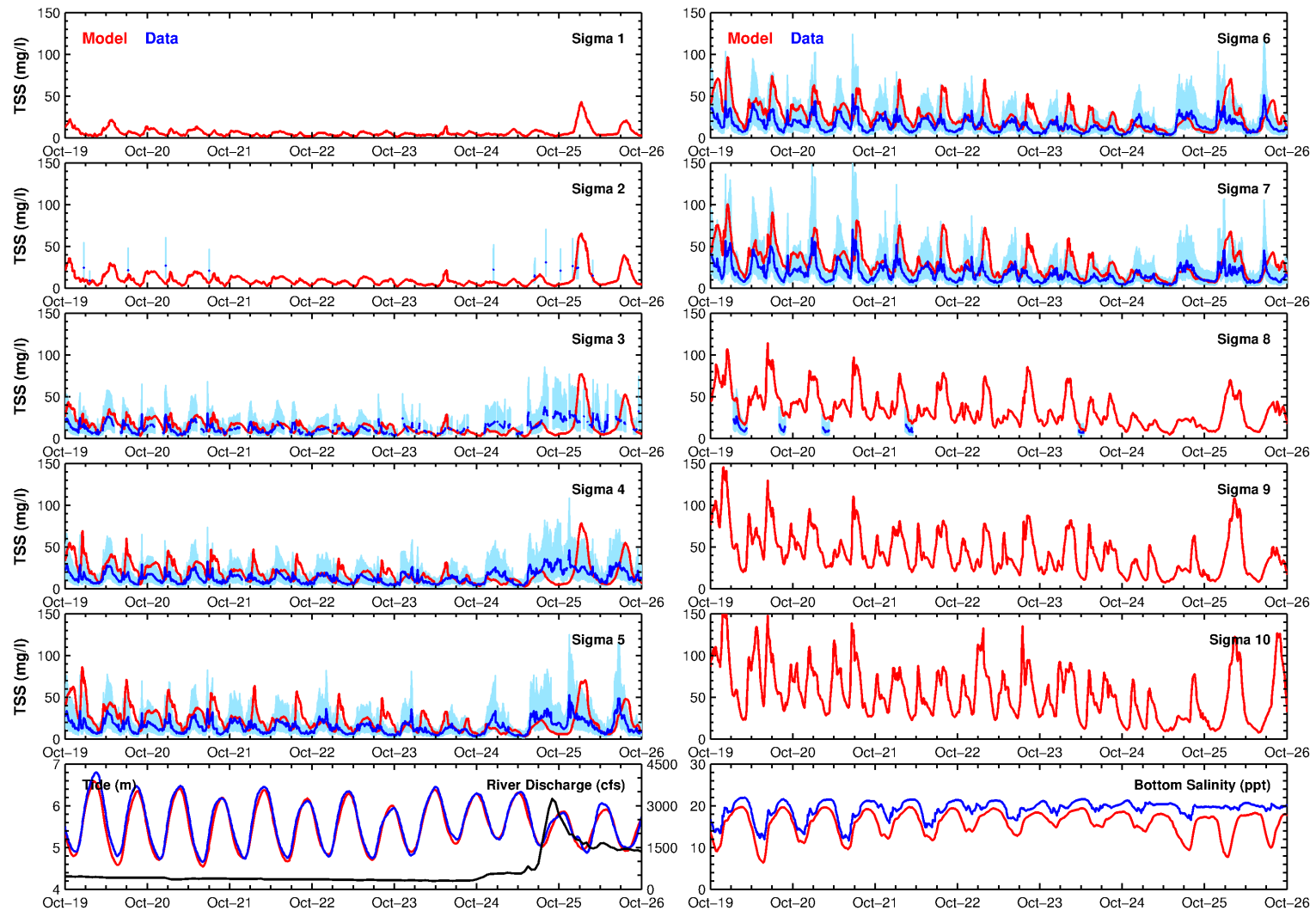


Figure 42. Time-series of model results and data (with prediction intervals) over the entire water column during the Fall 2009 PWCM at RM 1.4

Sediment Transport Model of the Lower Passaic River

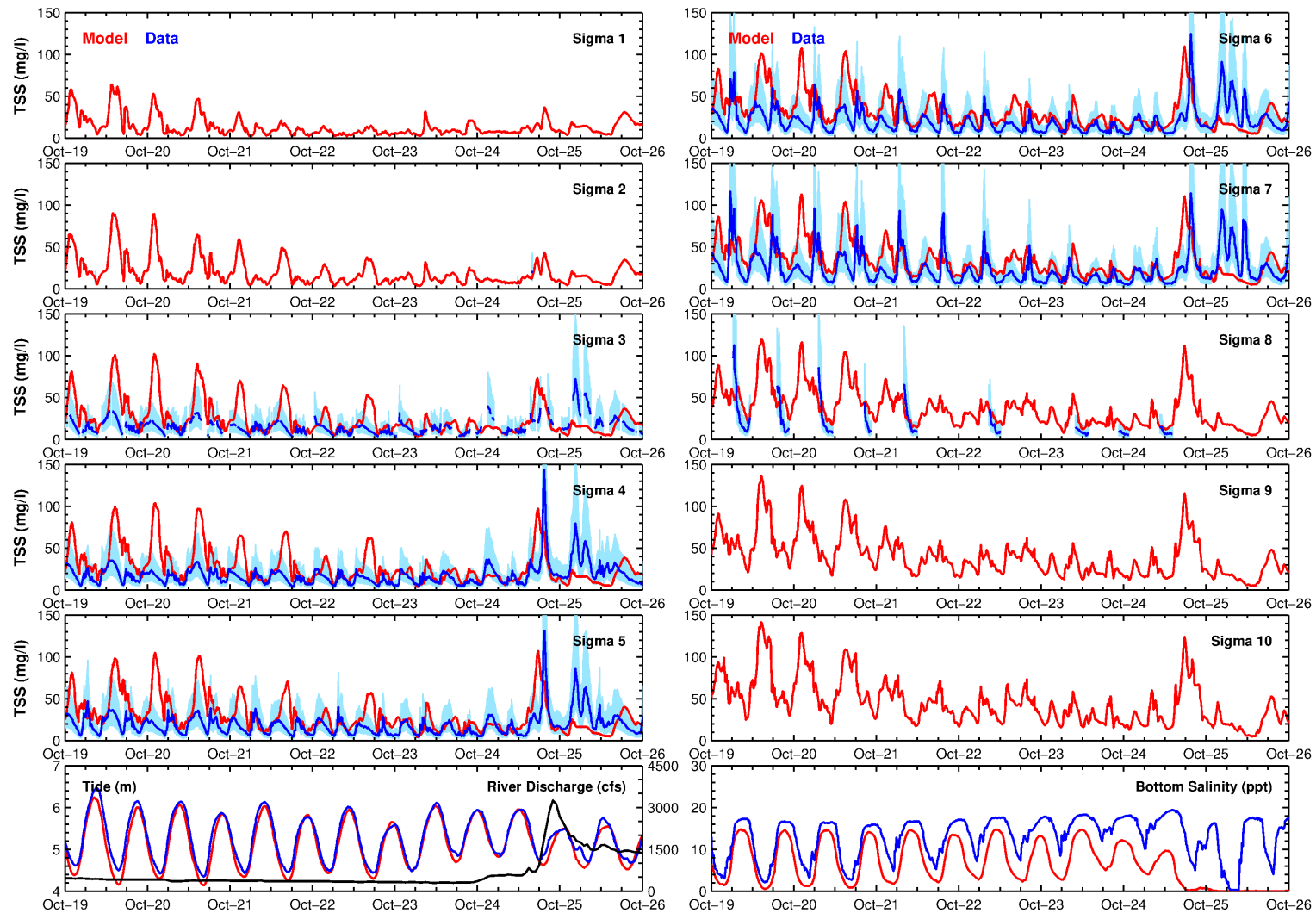


Figure 43. Time-series of model results and data (with prediction intervals) over the entire water column during the Fall 2009 PWCM at RM 4.2

Sediment Transport Model of the Lower Passaic River

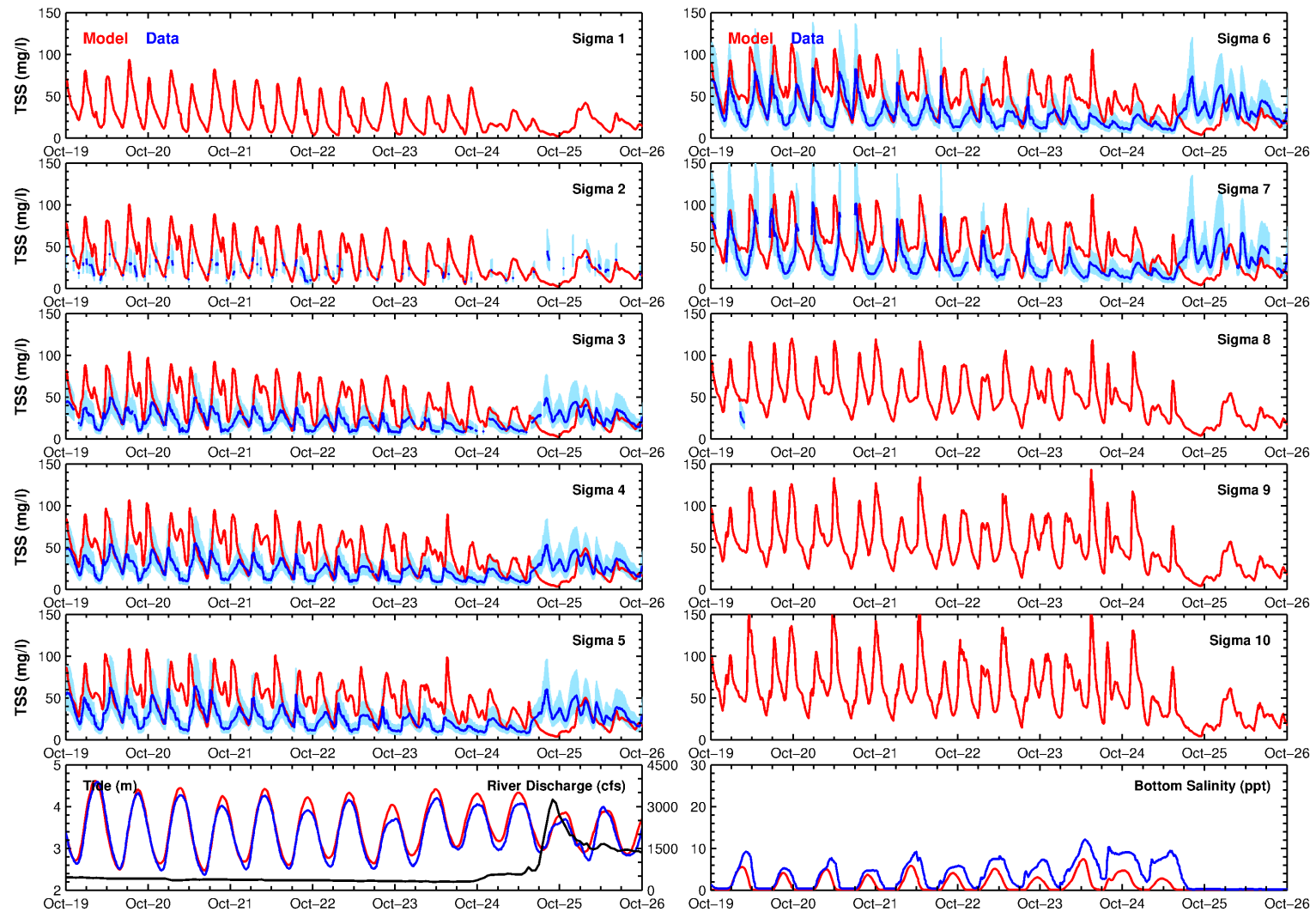


Figure 44. Time-series of model results and data (with prediction intervals) over the entire water column during the Fall 2009 PWCM at RM 6.7

Sediment Transport Model of the Lower Passaic River

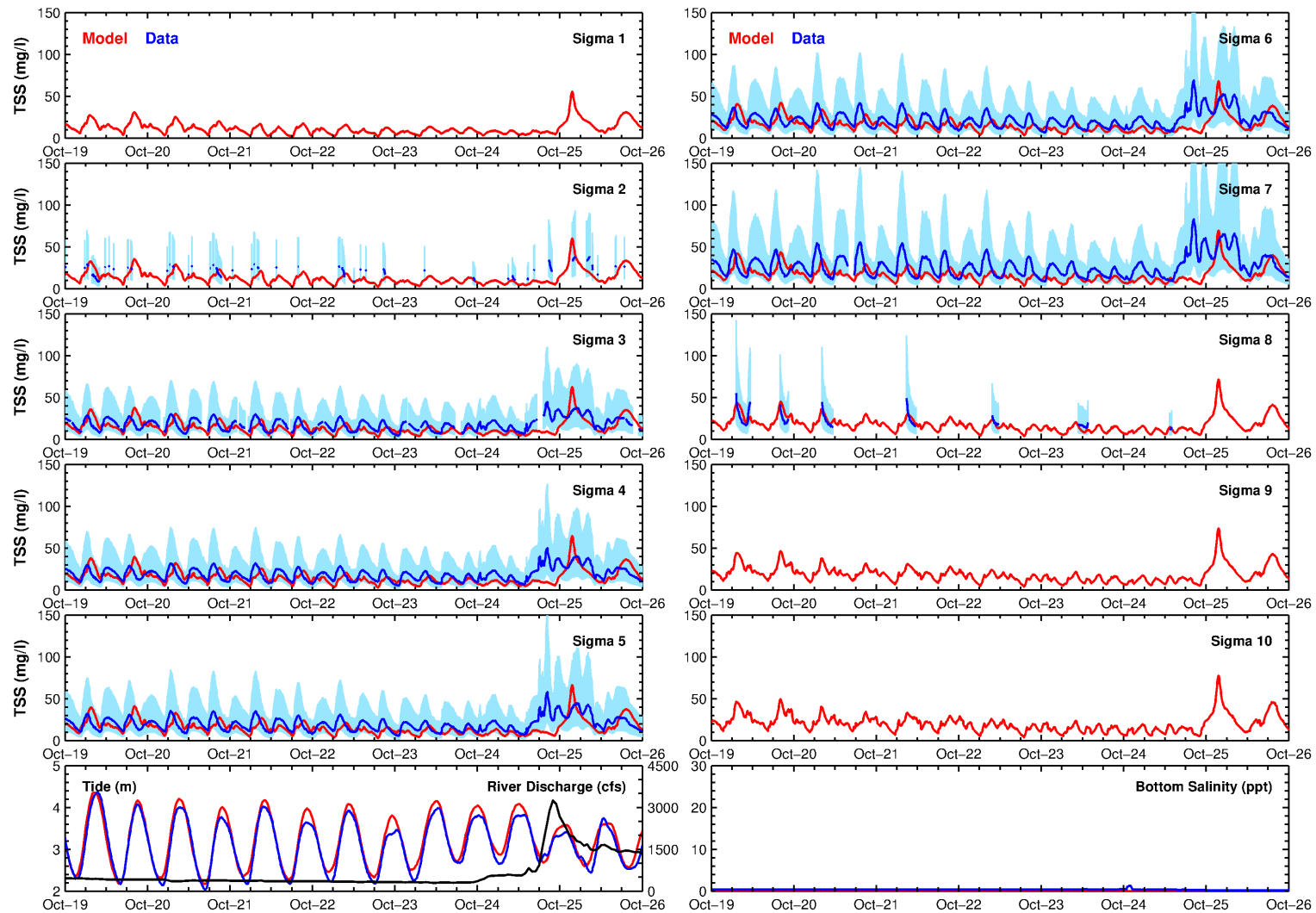


Figure 45. Time-series of model results and data (with prediction intervals) over the entire water column during the Fall 2009 PWCM at RM 10.2

Sediment Transport Model of the Lower Passaic River

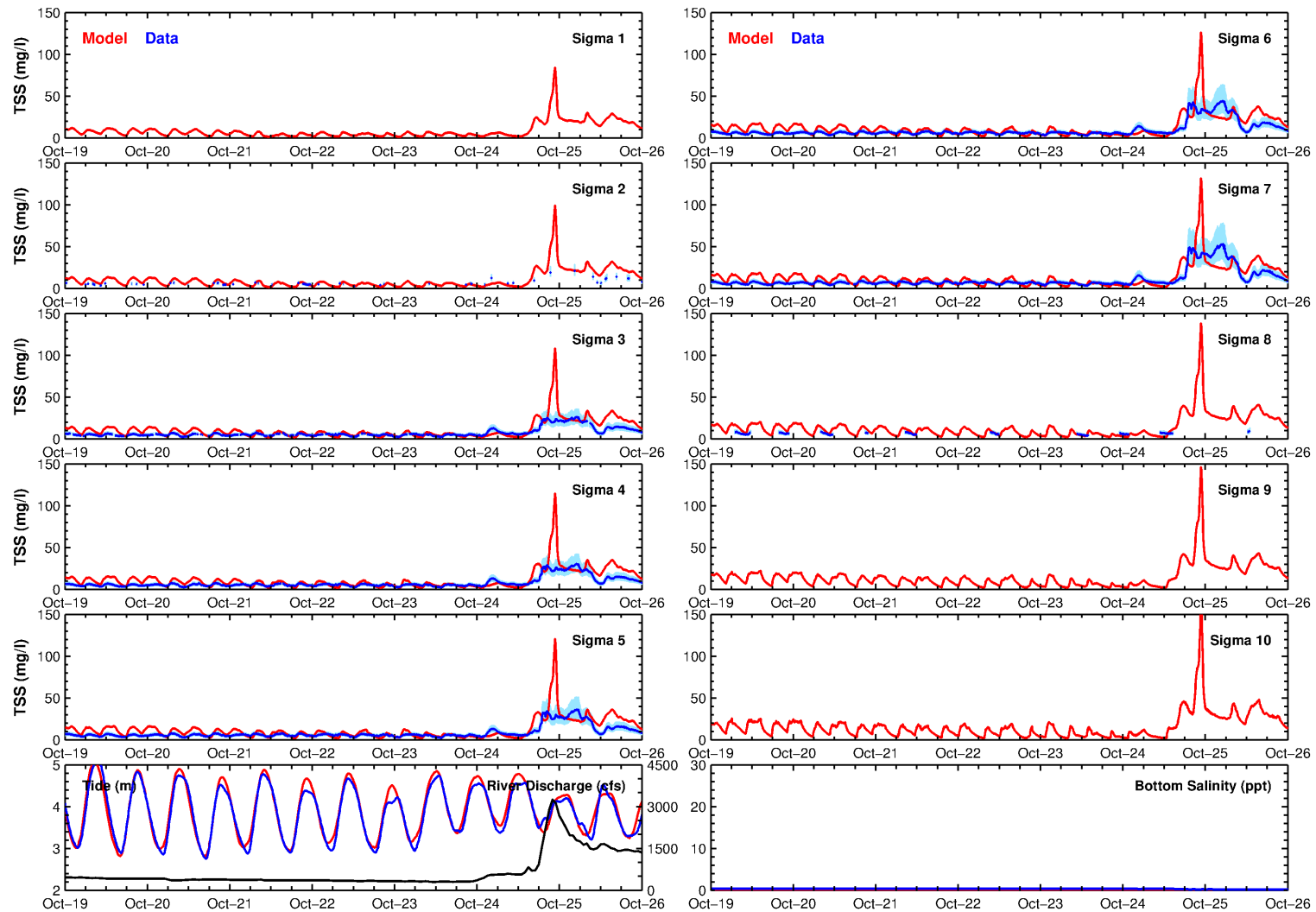


Figure 46. Time-series of model results and data (with prediction intervals) over the entire water column during the Fall 2009 PWCM at RM 13.5

Sediment Transport Model of the Lower Passaic River

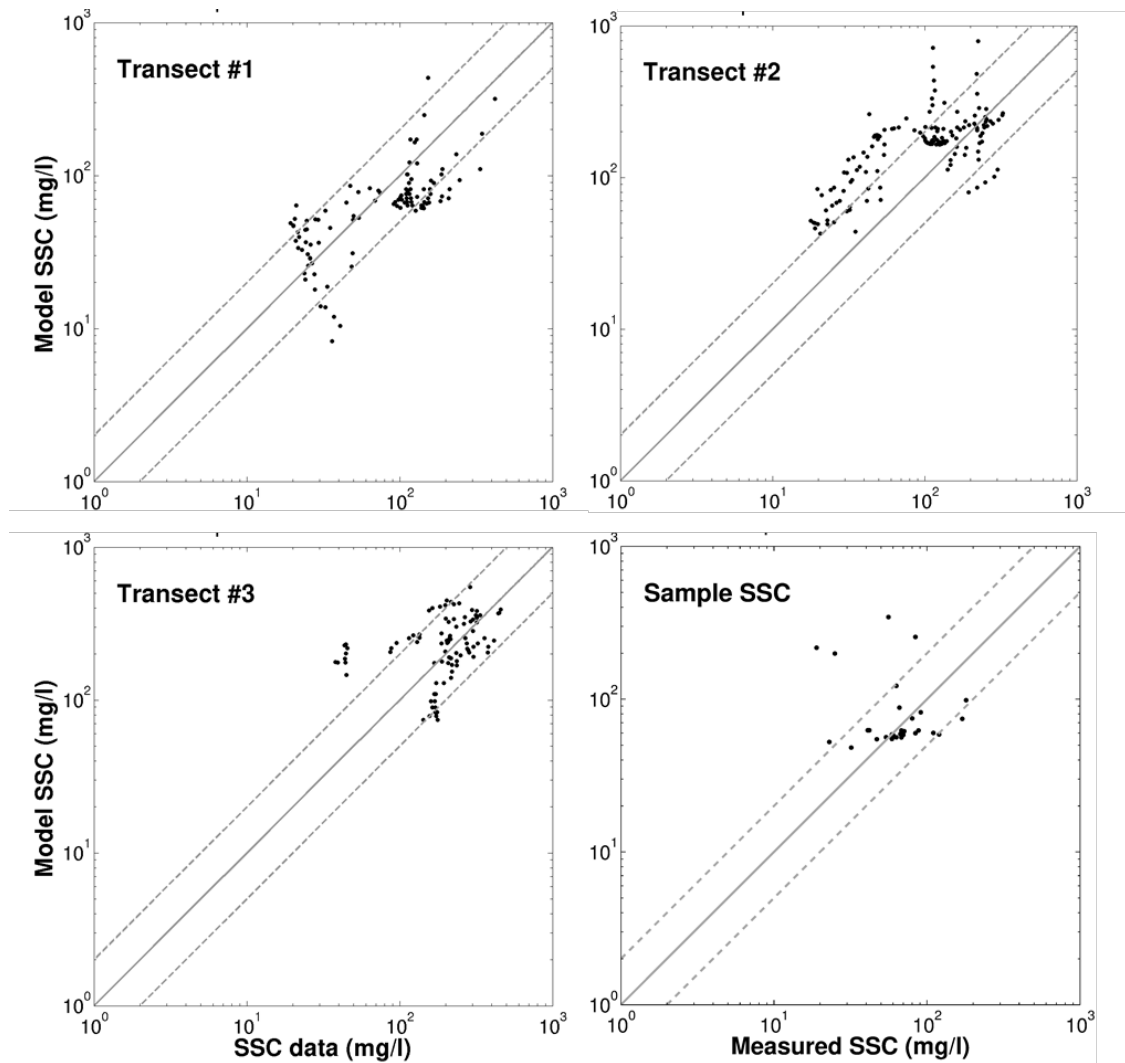


Figure 47. Model-data comparisons for high-flow event on March 16, 2010

Sediment Transport Model of the Lower Passaic River

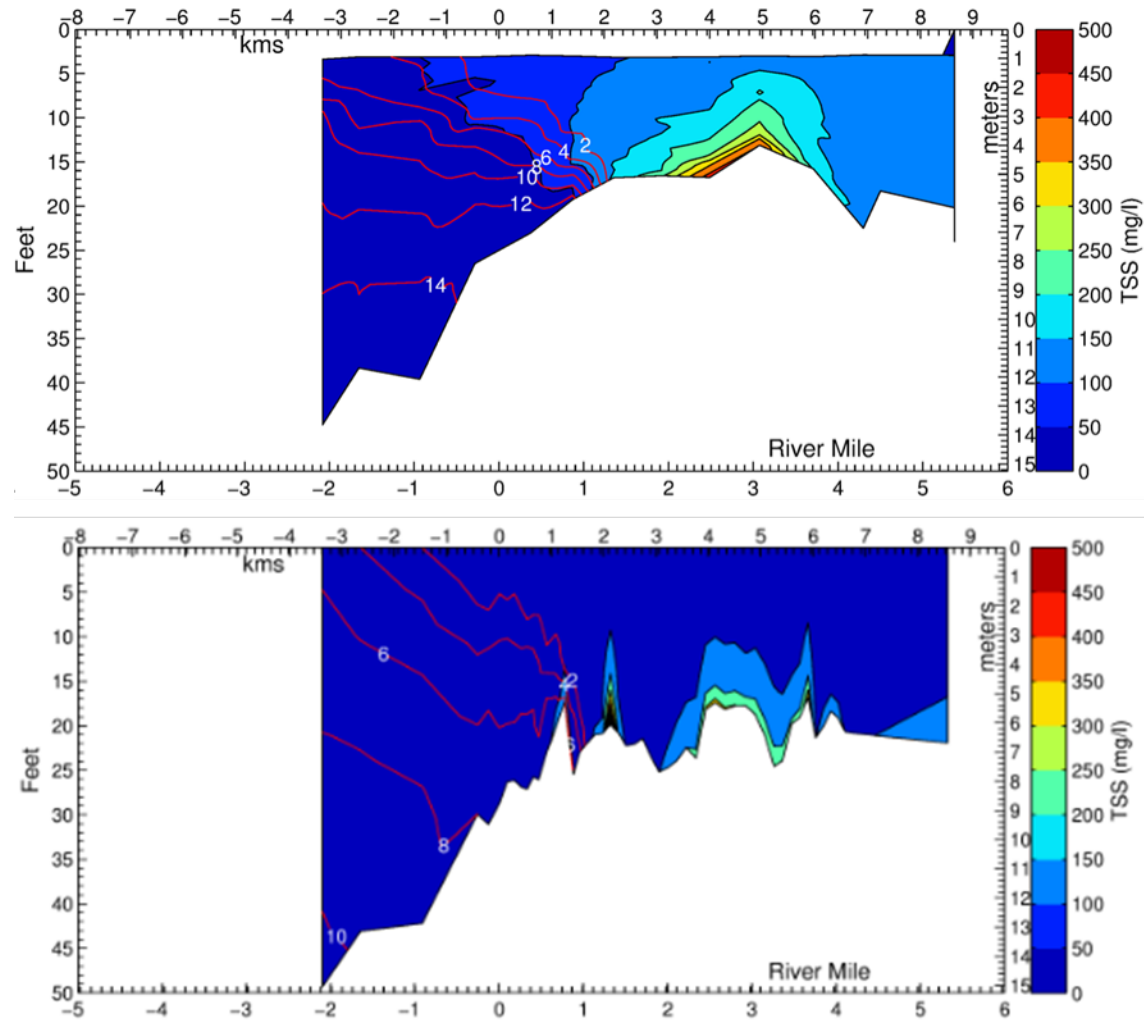


Figure 48. Transects of salinity and SSC along the longitudinal axis of the LPR and NB on March 16, 2010 (Transect #1); Data (upper panel) and model (lower panel). Salinity contours shown in red and SSC with background color.

Sediment Transport Model of the Lower Passaic River

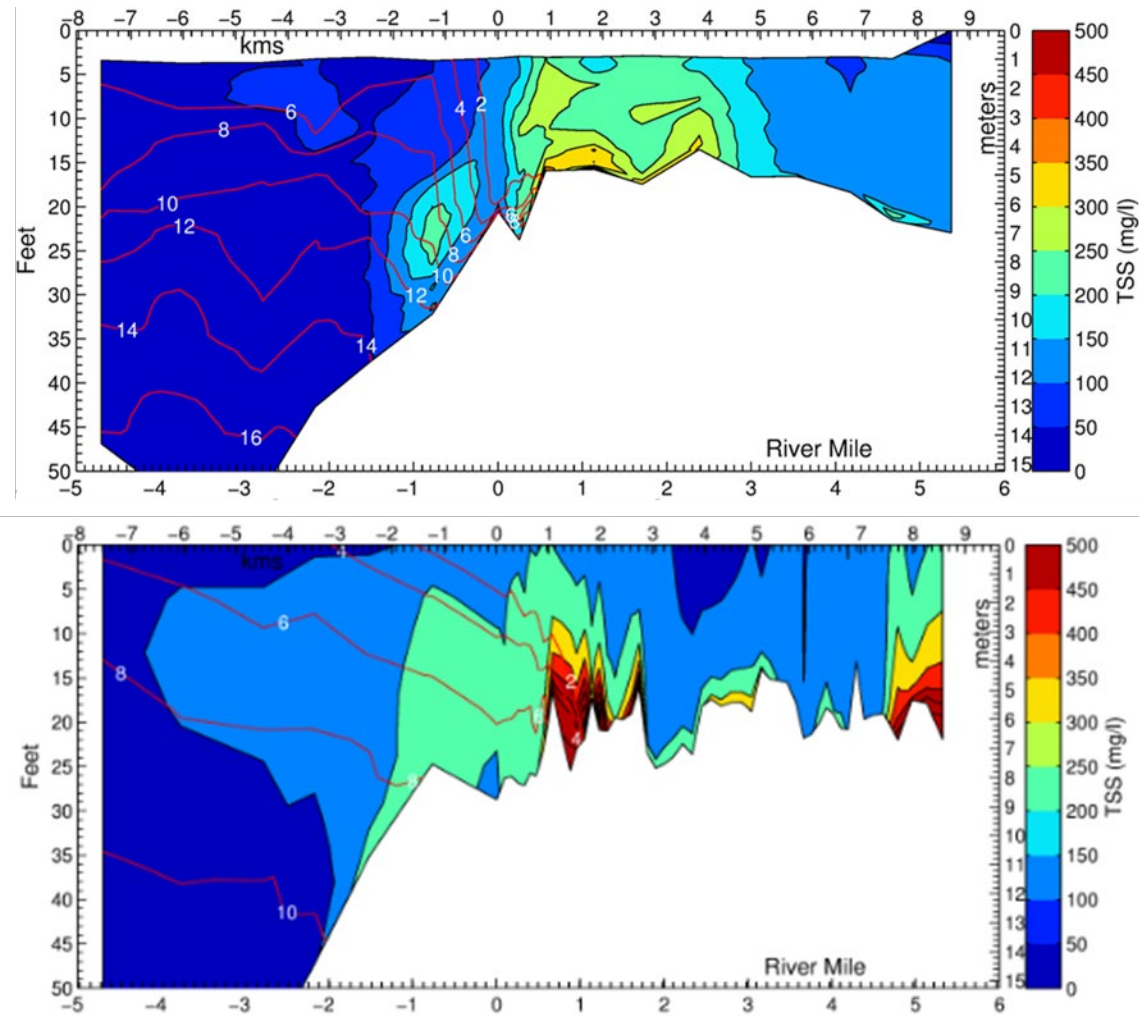


Figure 49. Transects of salinity and SSC along the longitudinal axis of the LPR and NB on March 16, 2010 (Transect #2); Data (upper panel) and model (lower panel). Salinity contours shown in red and SSC with background color.

Sediment Transport Model of the Lower Passaic River

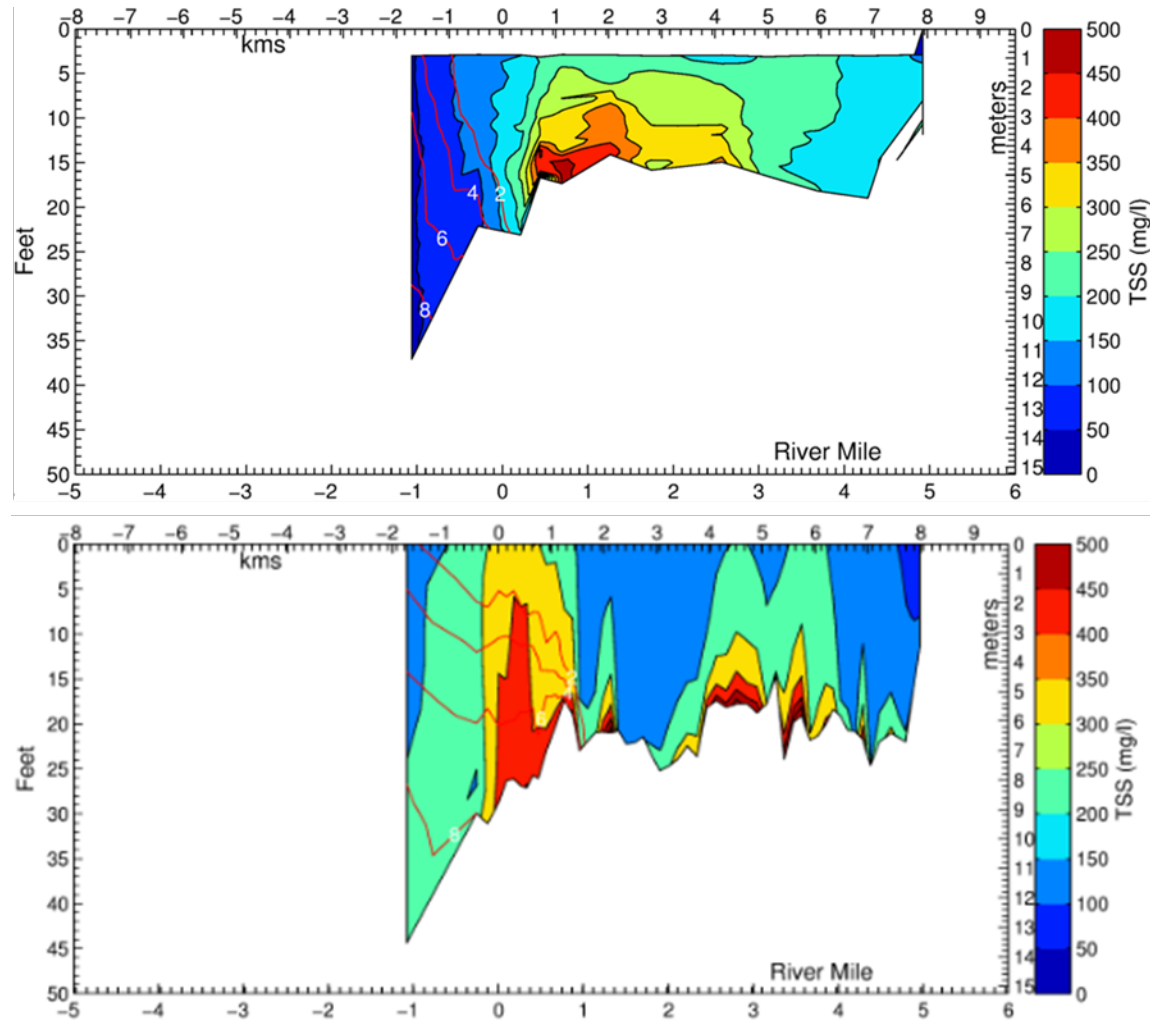


Figure 50. Transects of salinity and SSC along the longitudinal axis of the LPR and NB on March 16, 2010 (Transect #3); Data (upper panel) and model (lower panel). Salinity contours shown in red and SSC with background color.

Sediment Transport Model of the Lower Passaic River

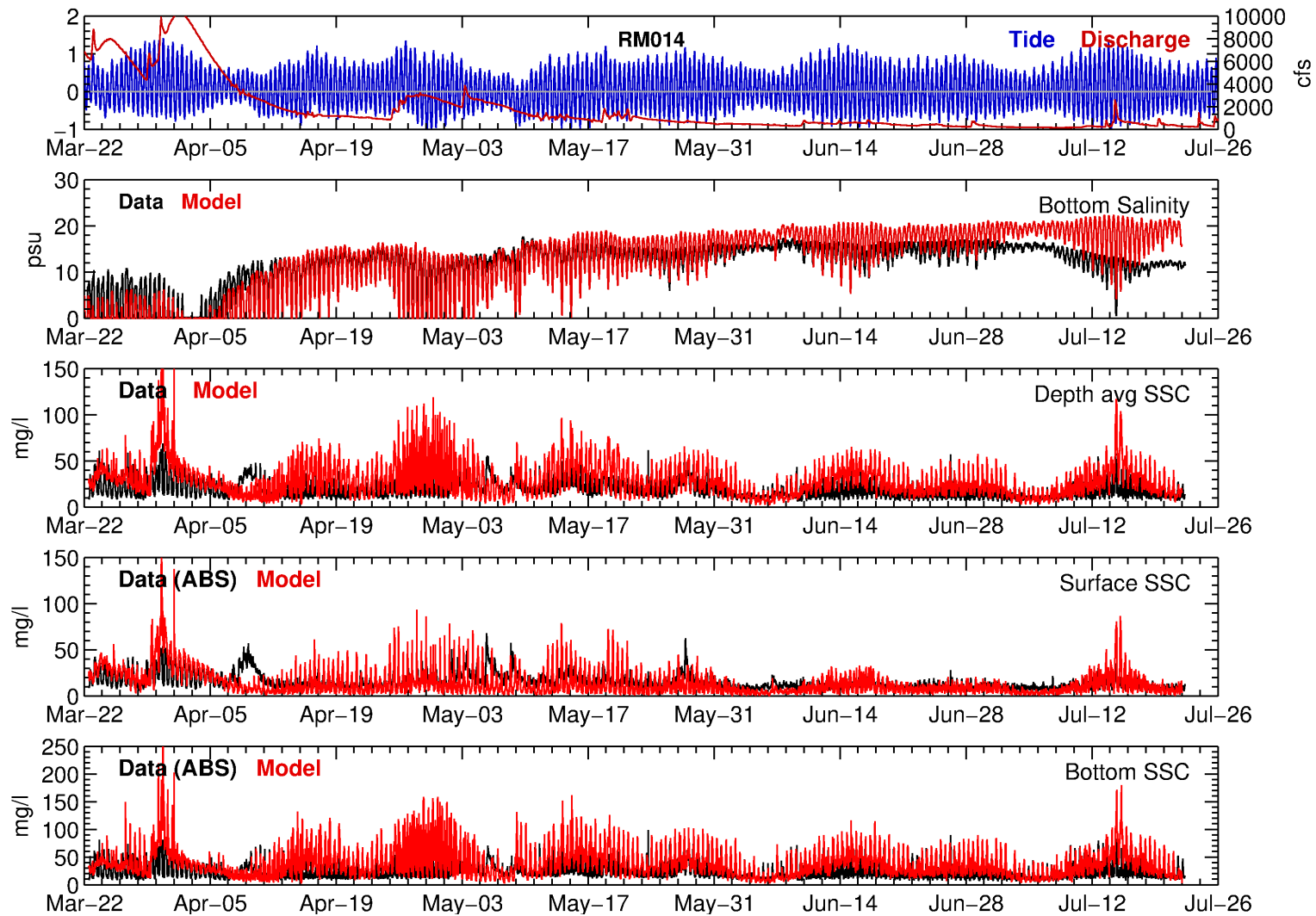


Figure 51. Time-series of model results and data during the Spring 2010 PWCM at RM 1.4 for bottom salinity, and the depth-average, surface, and bottom SSC.

Sediment Transport Model of the Lower Passaic River

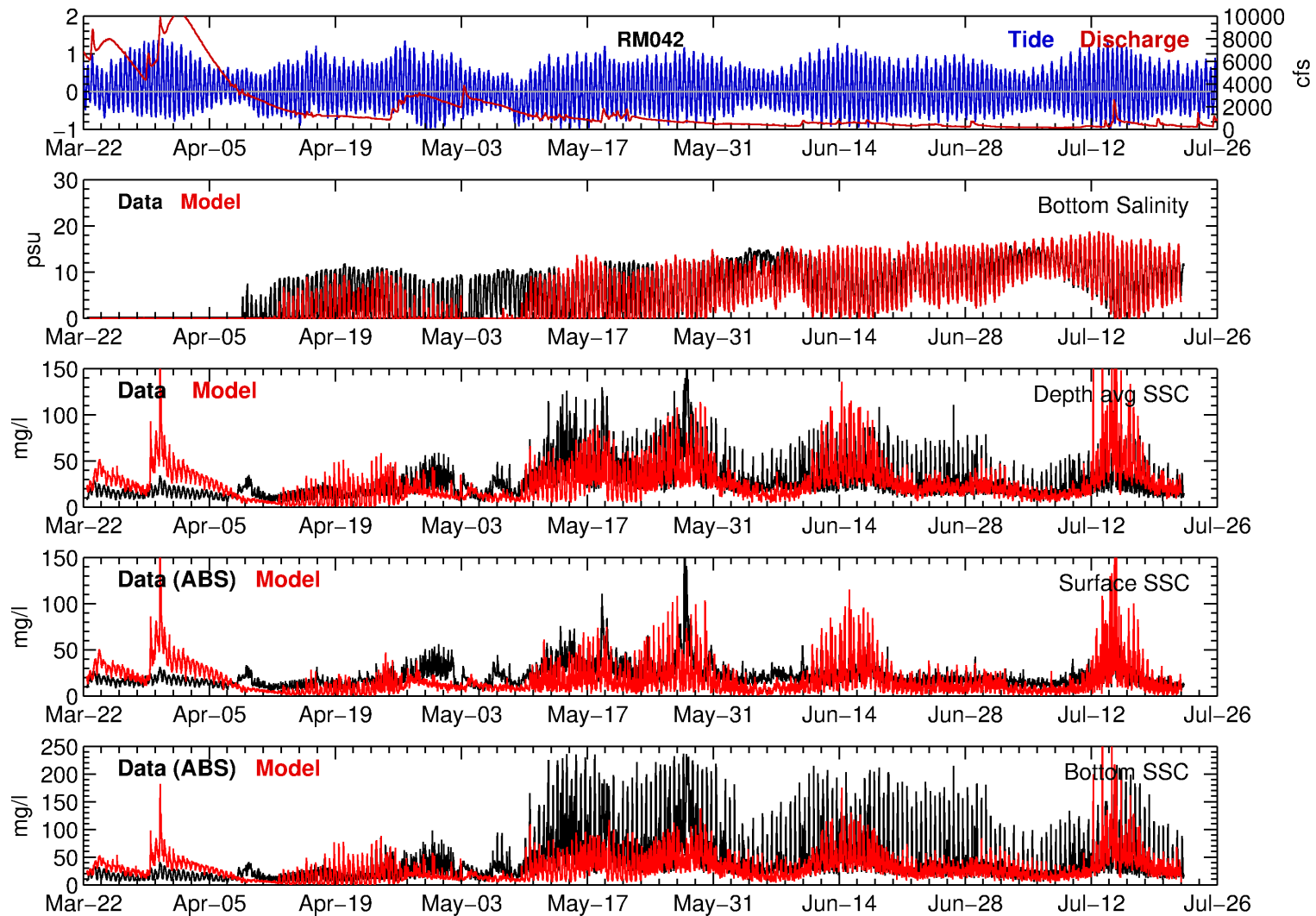


Figure 52. Time-series of model results and data during the Spring 2010 PWCM at RM 4.2 for bottom salinity, and the depth-average, surface, and bottom SSC.

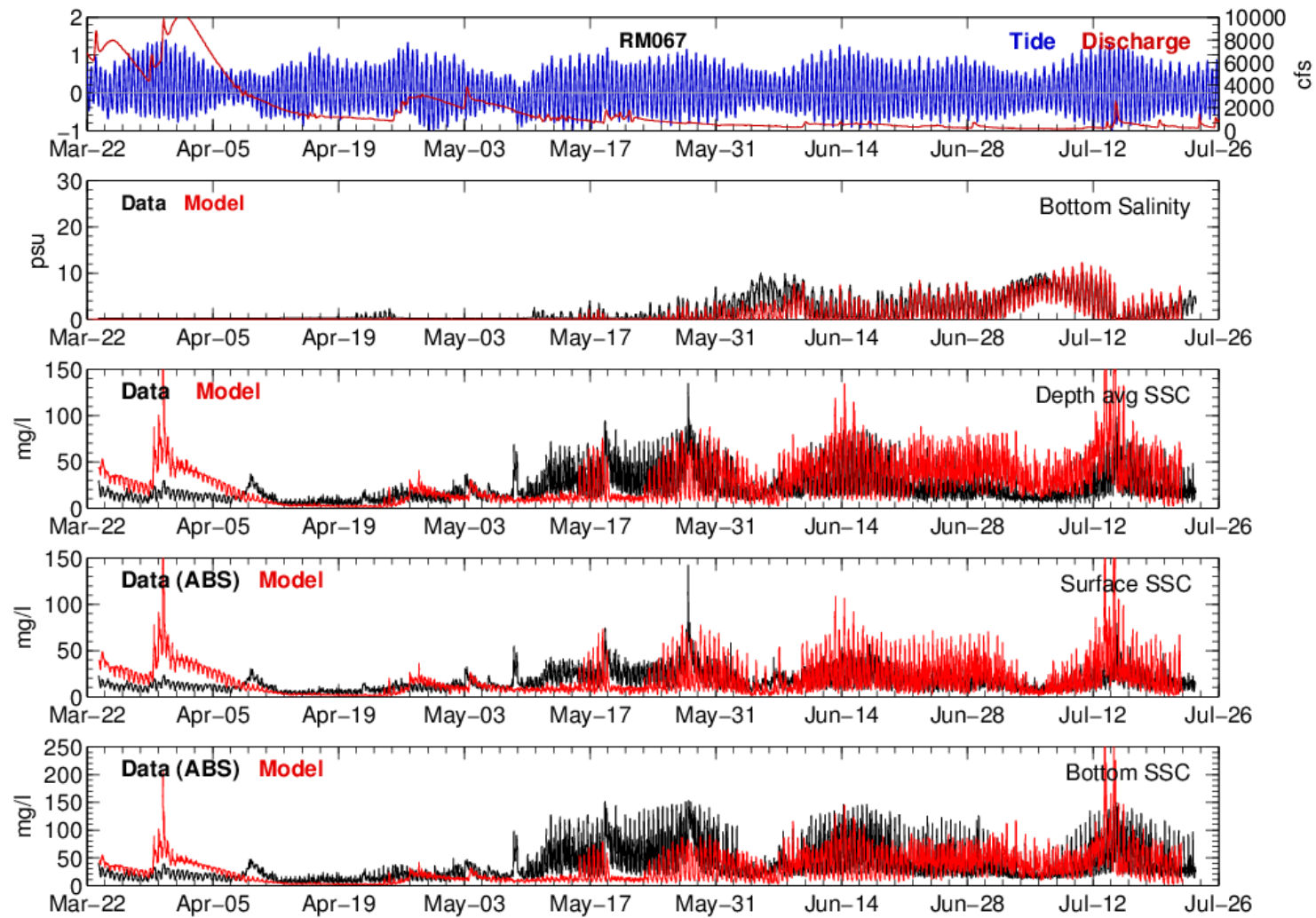


Figure 53. Time-series of model results and data during the Spring 2010 PWCM at RM 6.7 for bottom salinity, and the depth-average, surface, and bottom SSC.

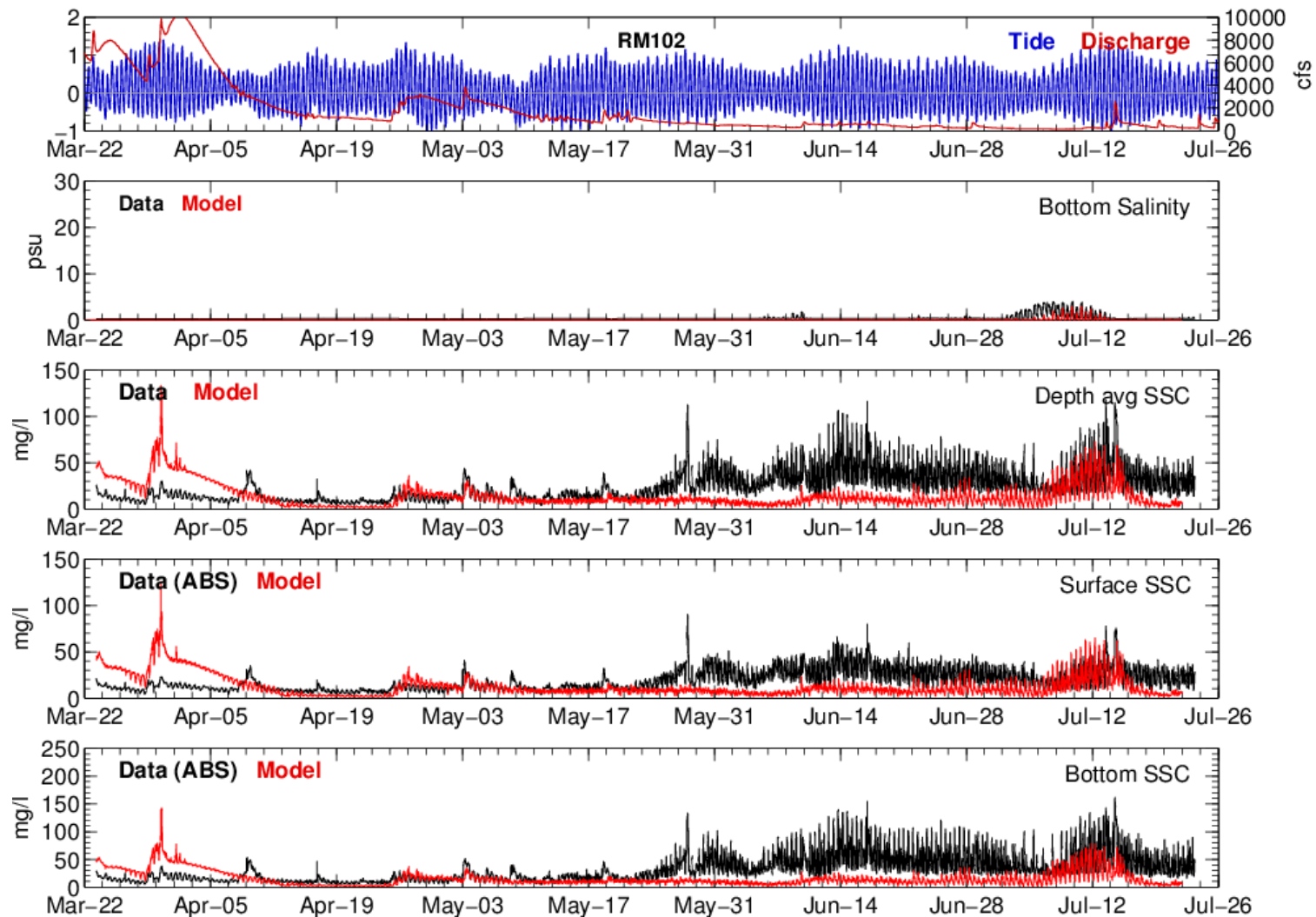


Figure 54. Time-series of model results and data during the Spring 2010 PWCM at RM 10.2 for bottom salinity, and the depth-average, surface, and bottom SSC.

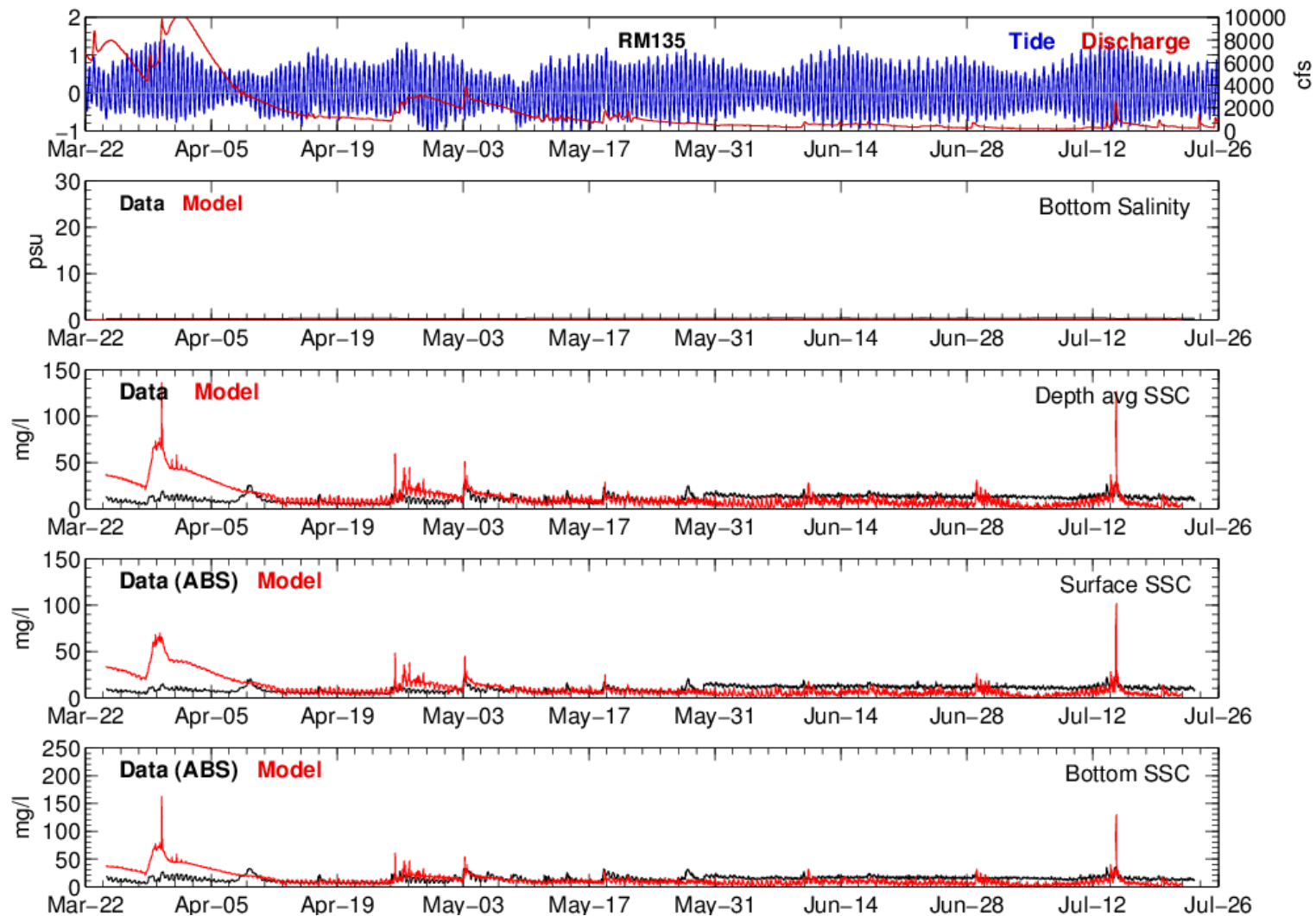


Figure 55. Time-series of model results and data during the Spring 2010 PWCM at RM 13.5 for bottom salinity, and the depth-average, surface, and bottom SSC.

Sediment Transport Model of the Lower Passaic River

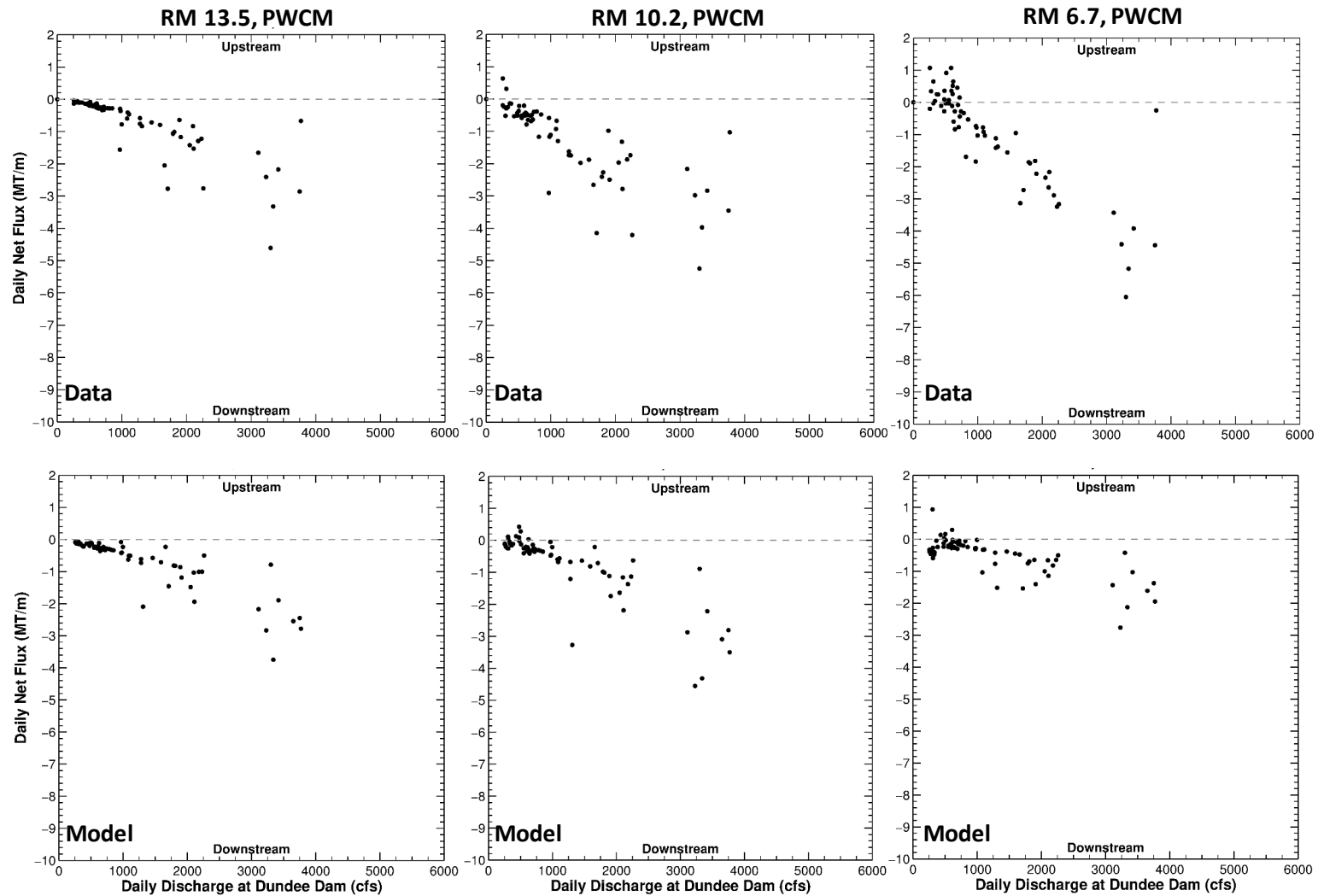


Figure 56. Net daily depth-integrated SS flux versus discharge for Fall 2009 PWCM data (upper) and model (lower) at RMs 13.5, 10.2, and 6.7

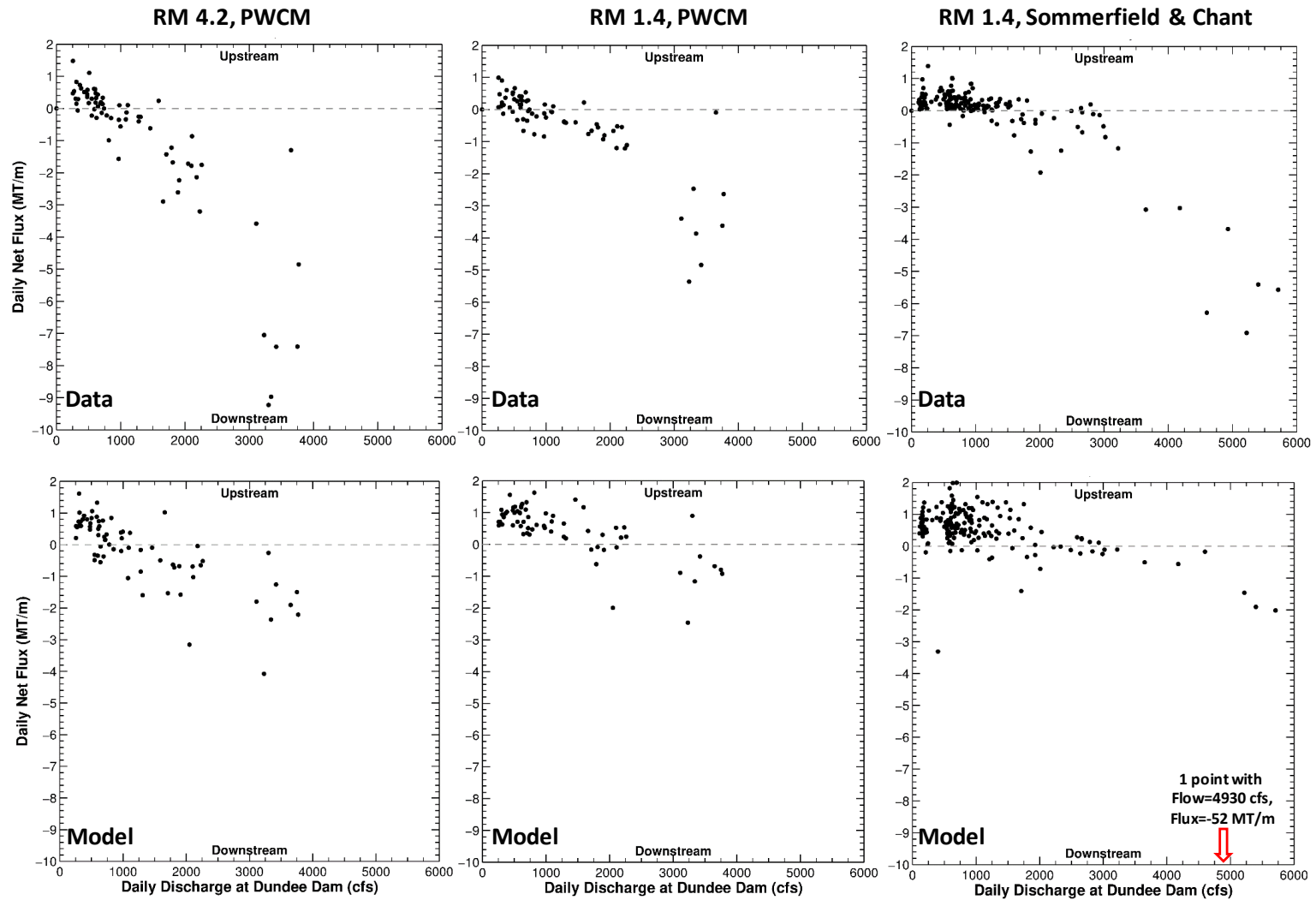


Figure 57. Net daily depth-integrated SS flux versus discharge for data (upper) and model (lower). For Fall 2009 PWCM at RMs 4.2 and 1.4 (left and middle columns), and RM 1.4 measured by Sommerfield and Chant (2010) in WY2008-WY2009

Sediment Transport Model of the Lower Passaic River

SSC (mg/L)

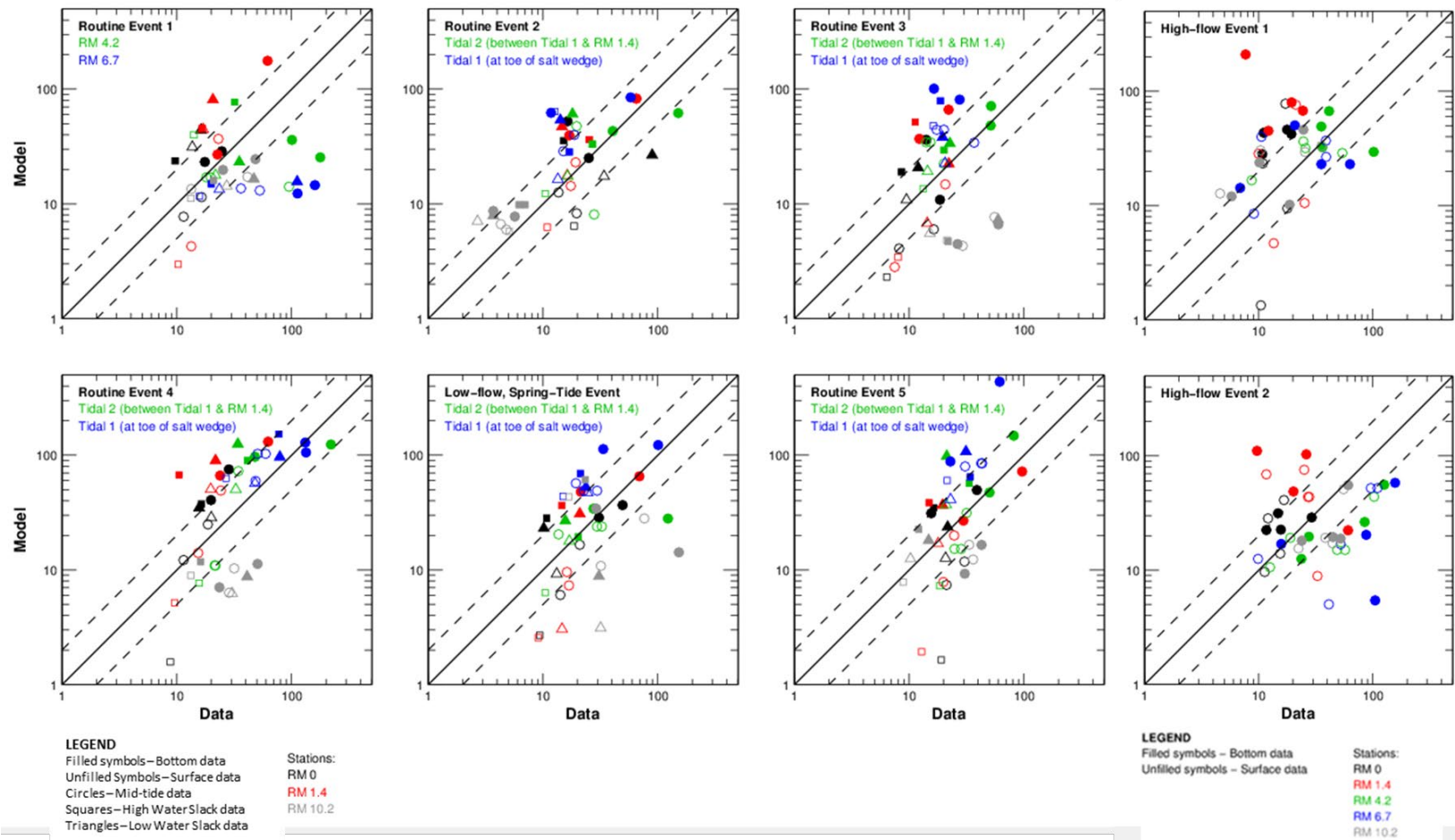


Figure 58. Model-data comparisons of SSC during CWCM events

Sediment Transport Model of the the Lower Passaic River

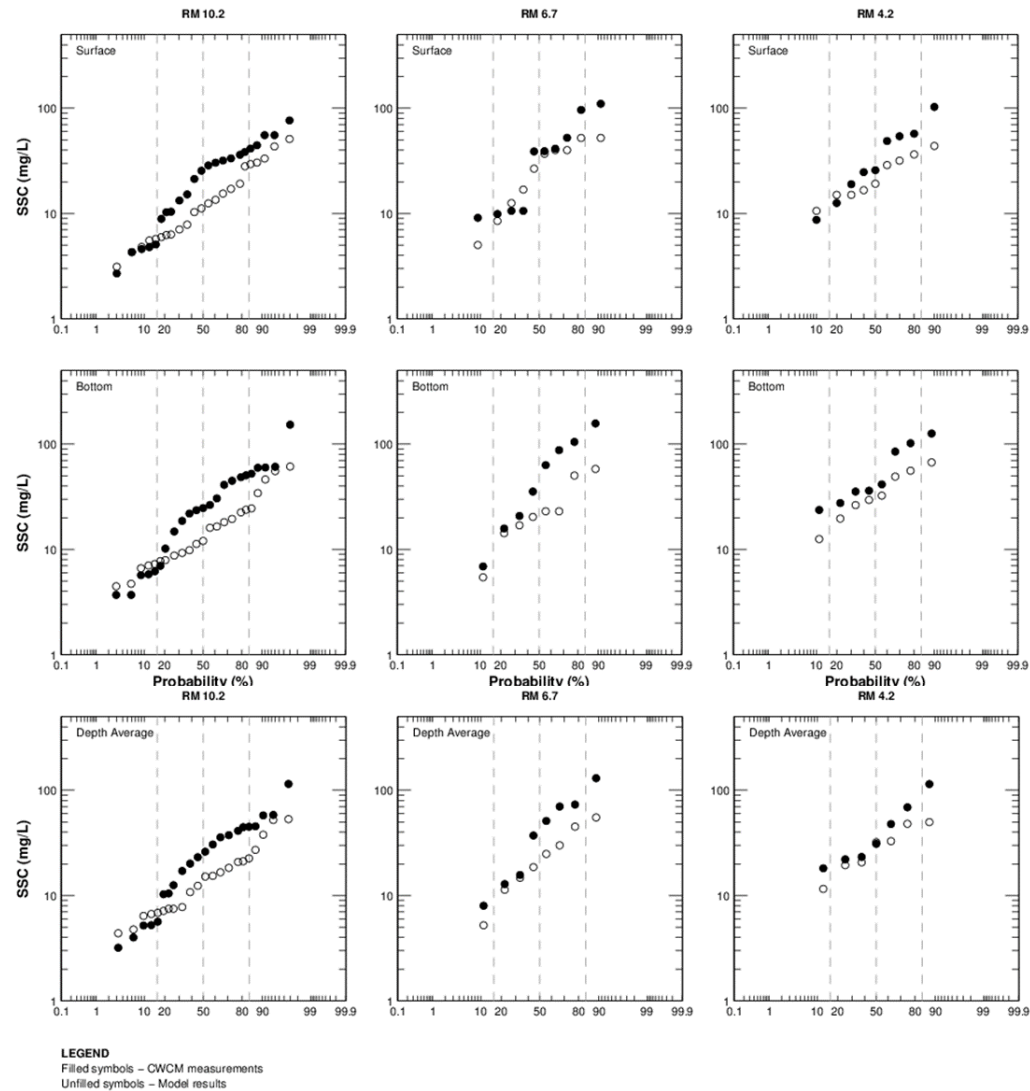


Figure 59. Probabilistic comparisons of model and data during the CWCM events at the freshwater stations

Sediment Transport Model of the Lower Passaic River

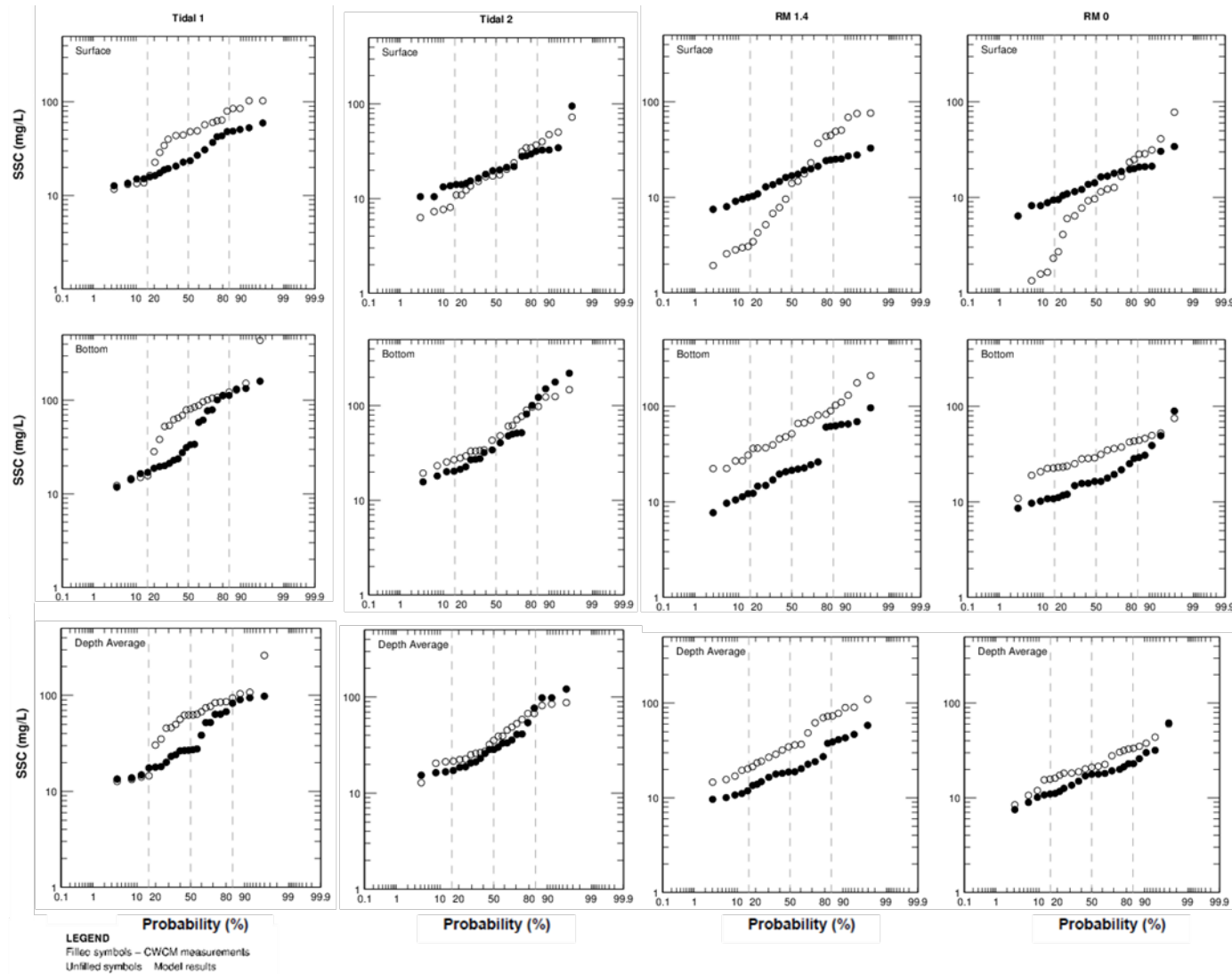


Figure 60. Probabilistic comparisons of model and data during the CWCM events at the estuarine stations

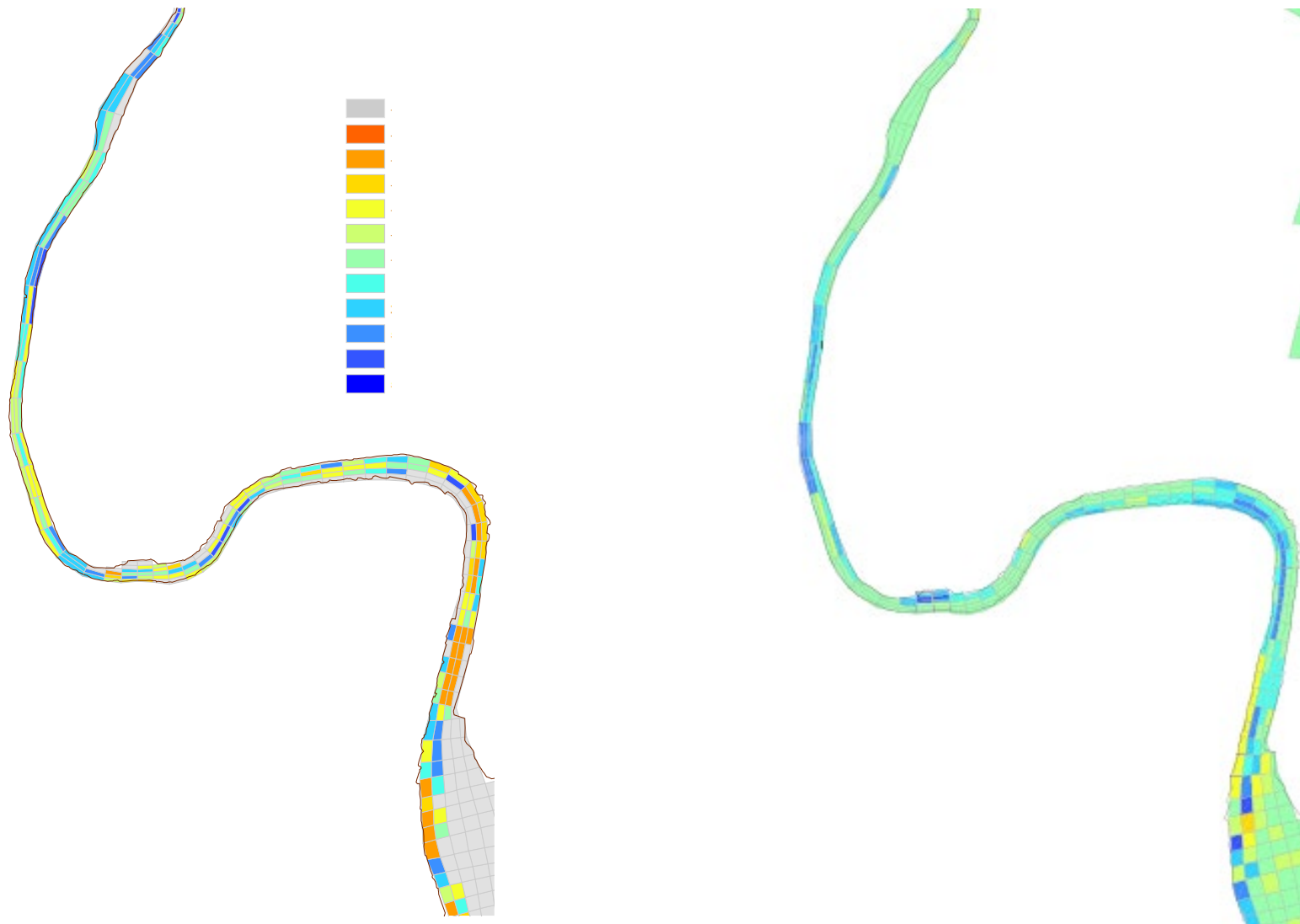


Figure 61. Bathymetric change between the 2007-2008 multi-beam surveys. Data (left panel) and model (right panel).

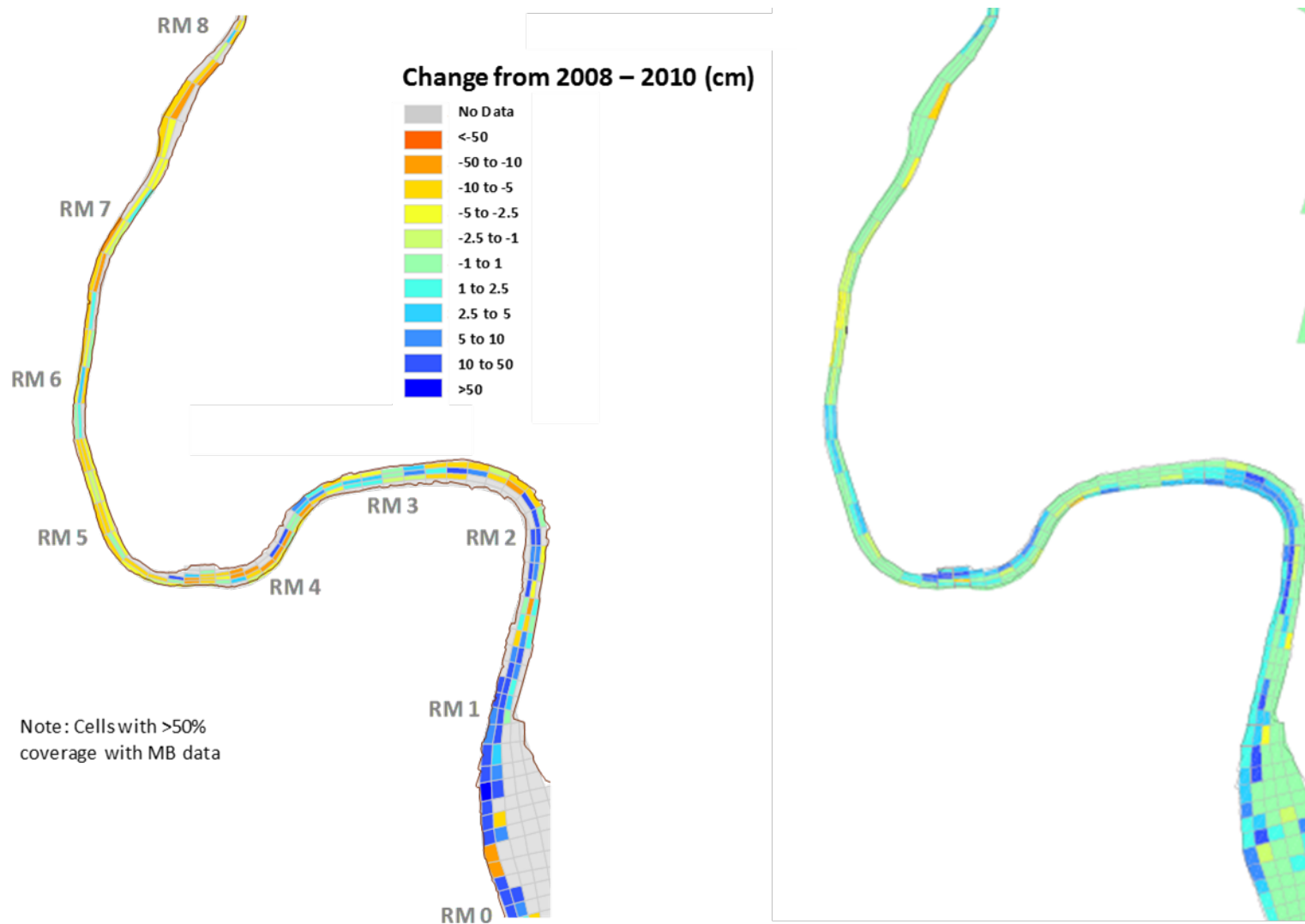


Figure 62. Bathymetric change between the 2008-2010 multi-beam surveys. Data (left panel) and model (right panel).

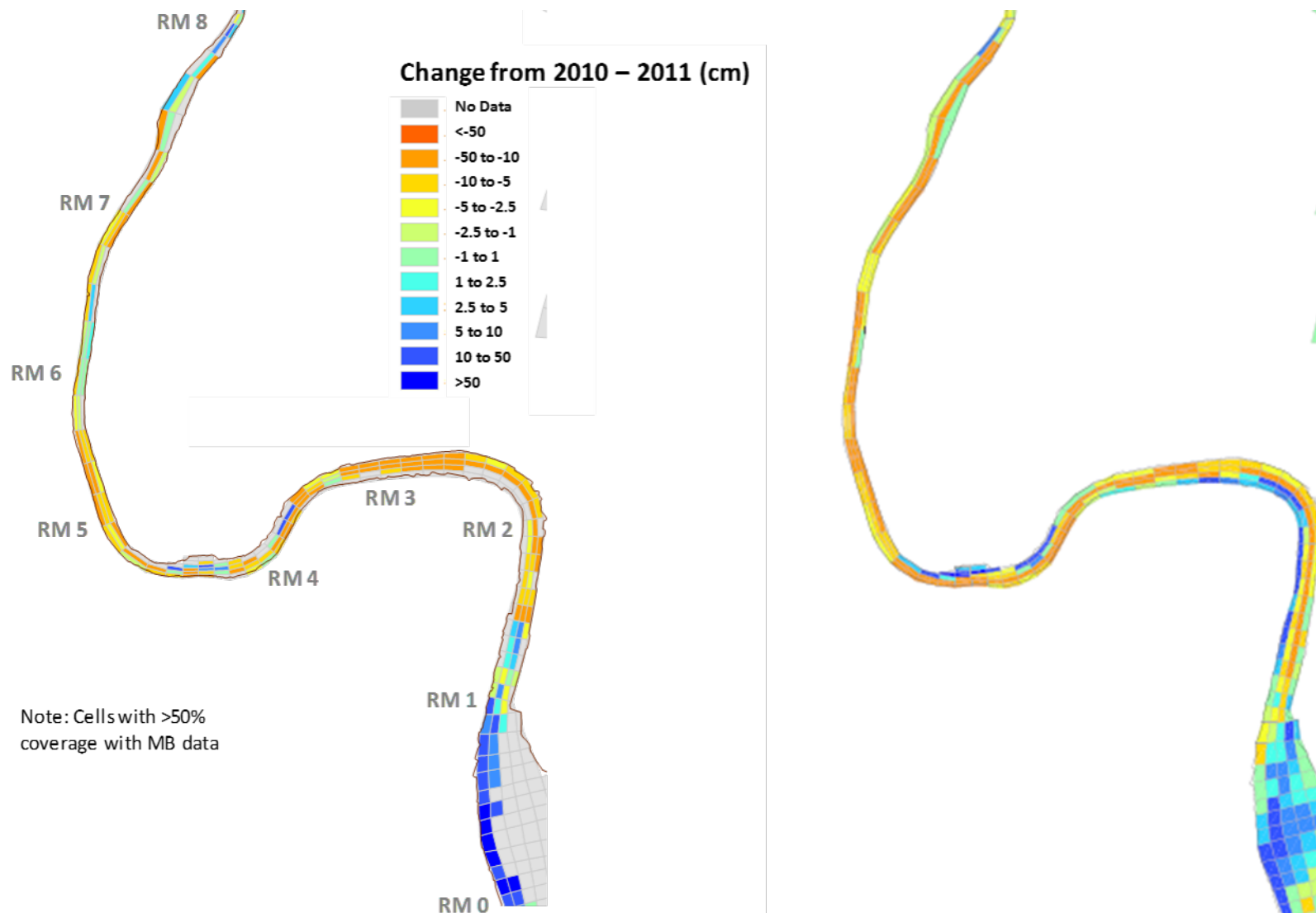


Figure 63. Bathymetric change between the 2010-2011 multi-beam surveys. Data (left panel) and model (right panel).

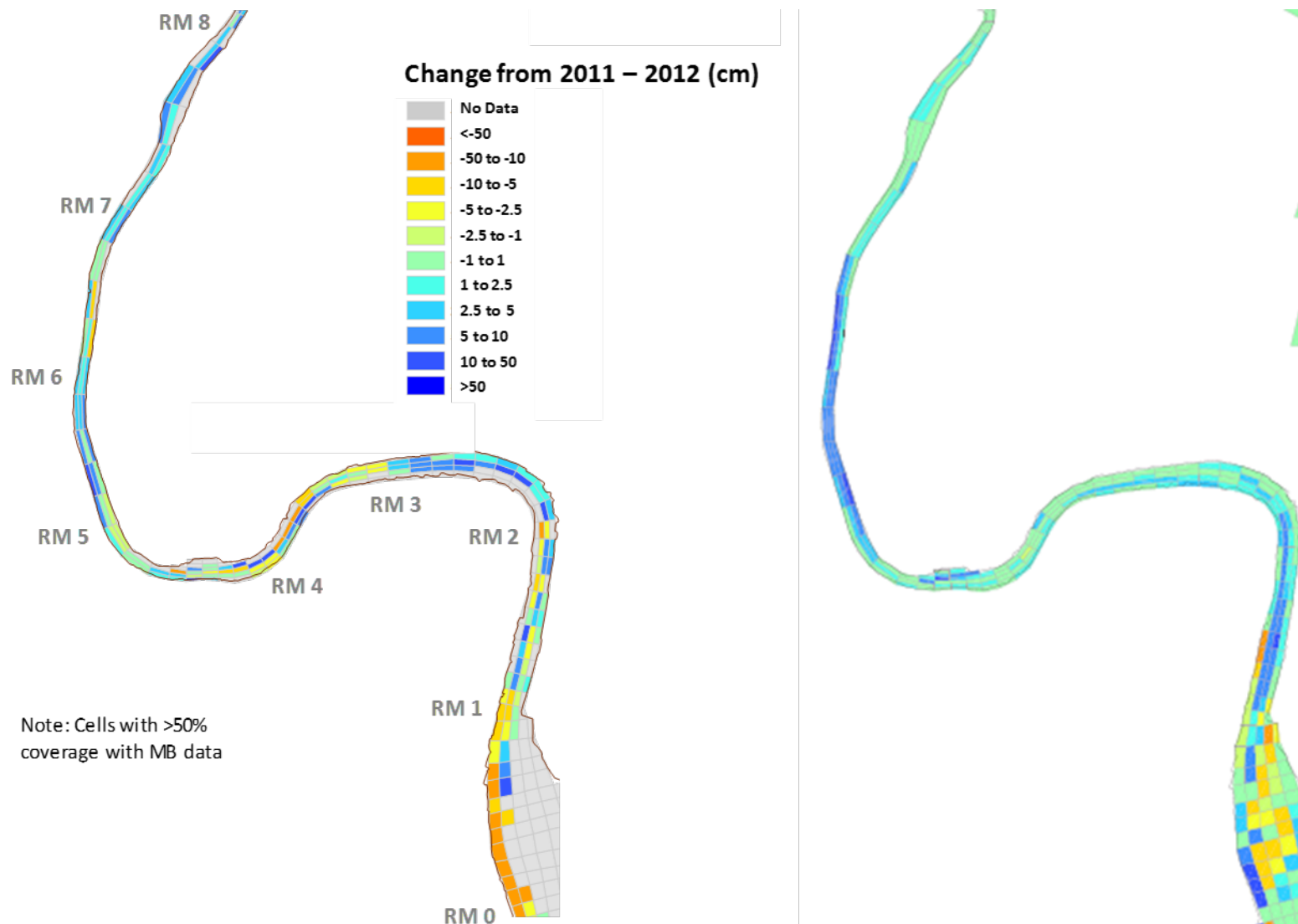


Figure 64. Bathymetric change between the 2011-2012 multi-beam surveys. Data (left panel) and model (right panel).

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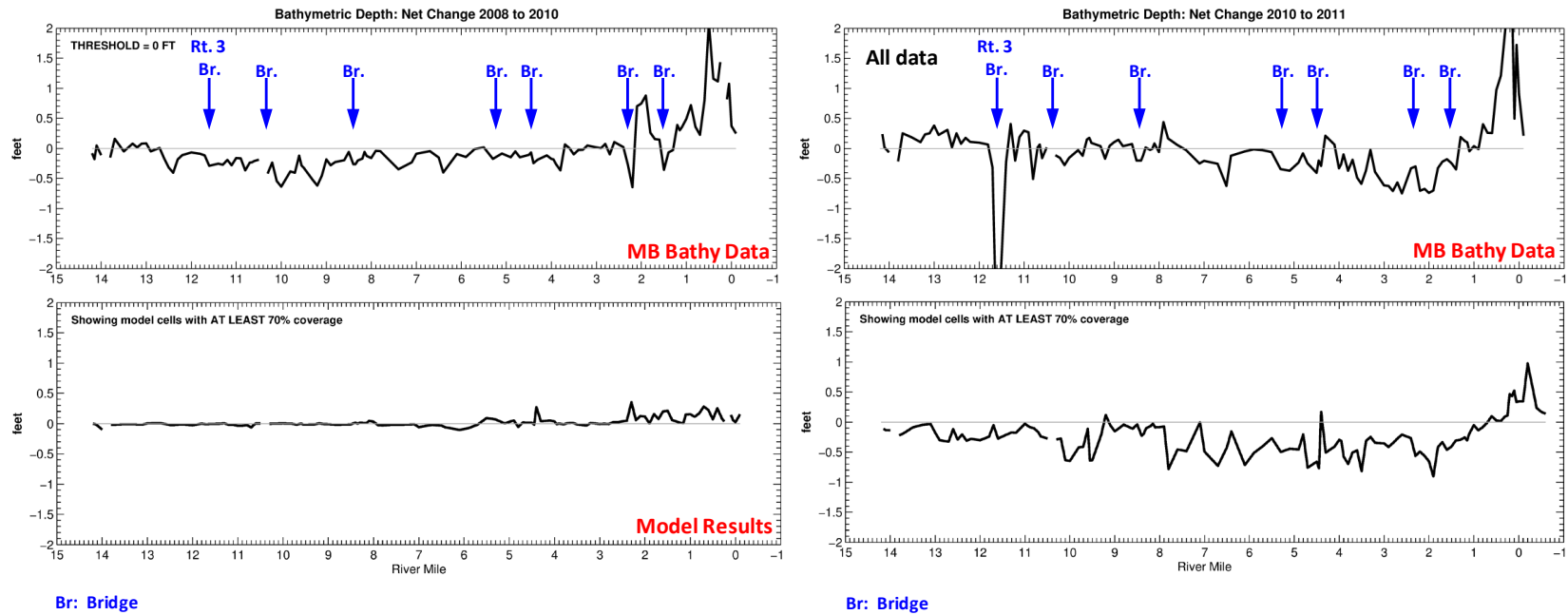


Figure 65. Cross-section average bathymetric change during 2008 to 2010 (left panels) and 2010 to 2011 (right panels) surveys.

Sediment Transport Model of the Lower Passaic River

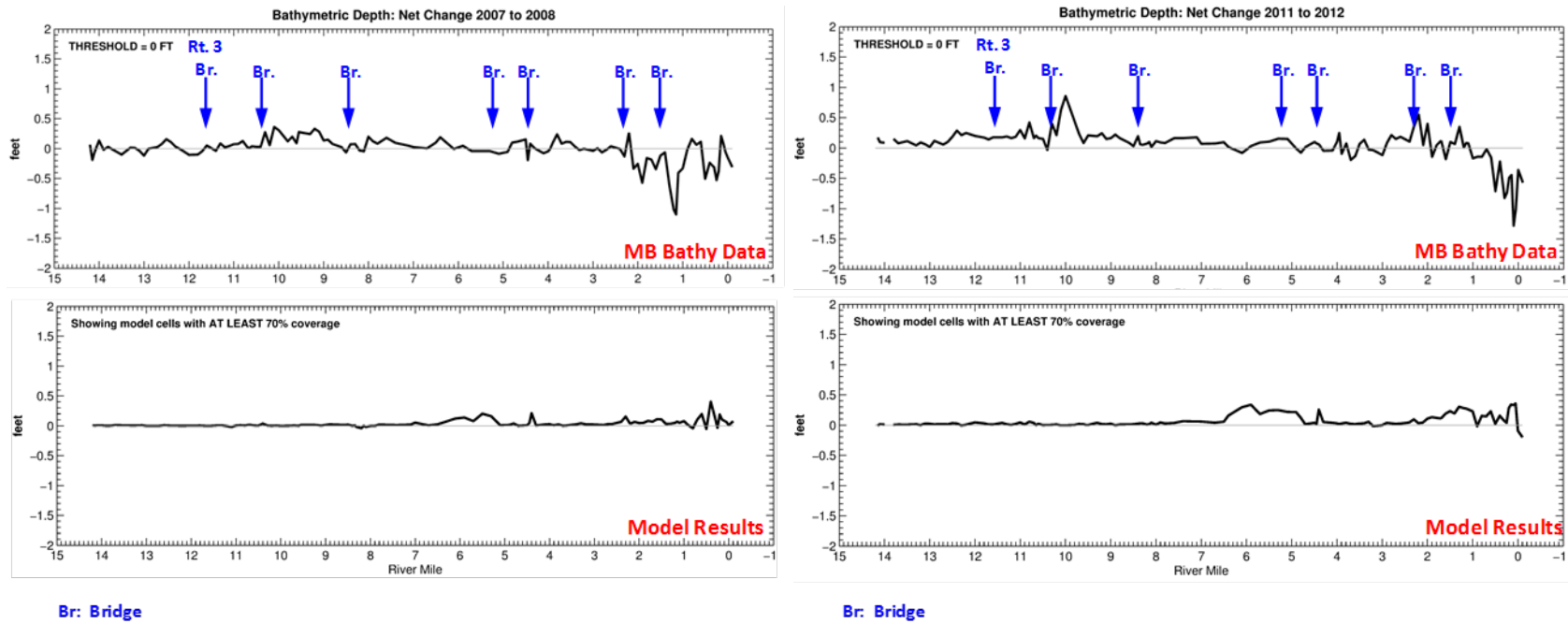


Figure 66. Cross-section average bathymetric change during 2007 to 2008 (left panels) and 2011 to 2012 (right panels) surveys.

Sediment Transport Model of the Lower Passaic River

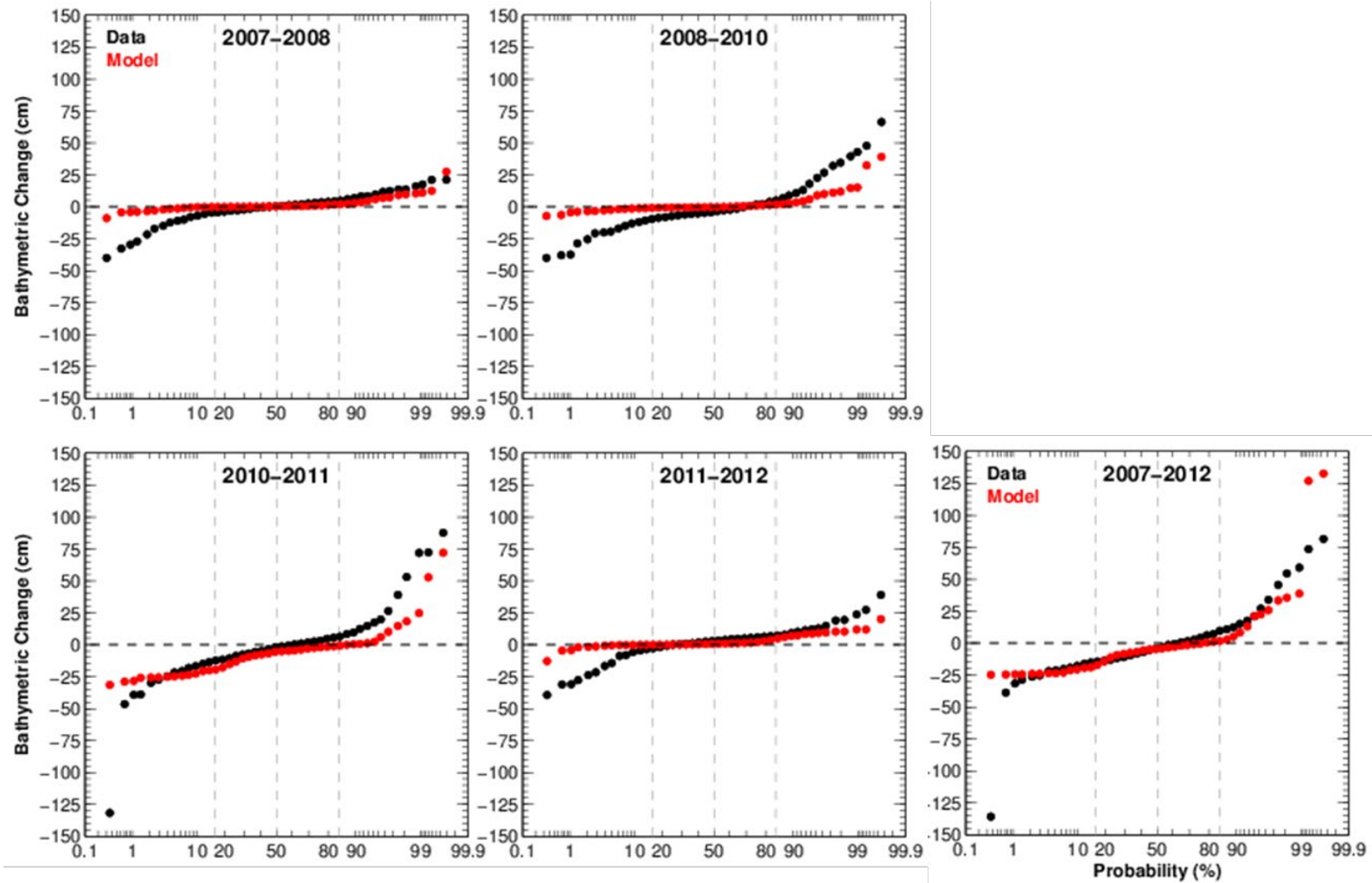


Figure 67. Probabilistic comparisons of the measured and model calculated bathymetric change over the duration of the various multi-beam bathymetric surveys. Negative values indicate erosion and positive values indicate deposition.

Sediment Transport Model of the Lower Passaic River

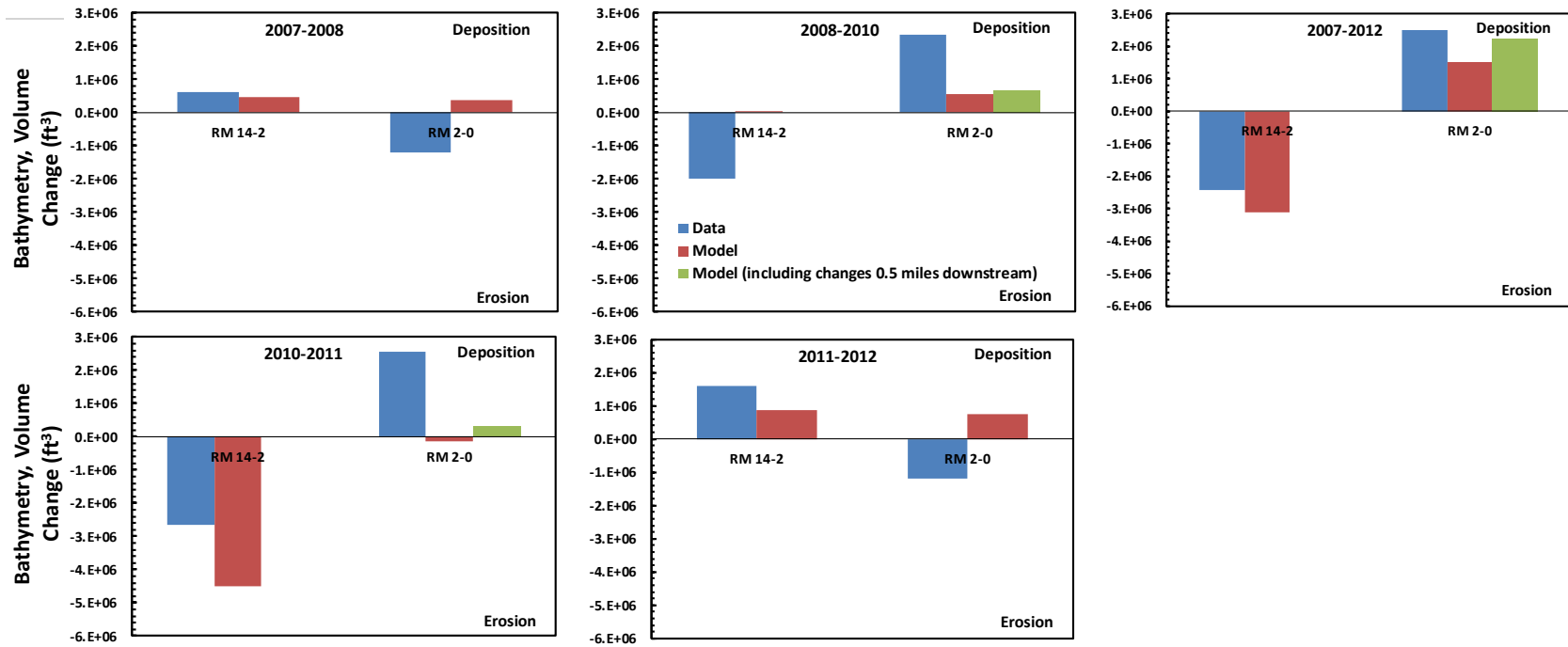


Figure 68. Large scale bathymetric changes during 2007-2012 (only including cells with at least 70% bathymetry data coverage).

Sediment Transport Model of the Lower Passaic River

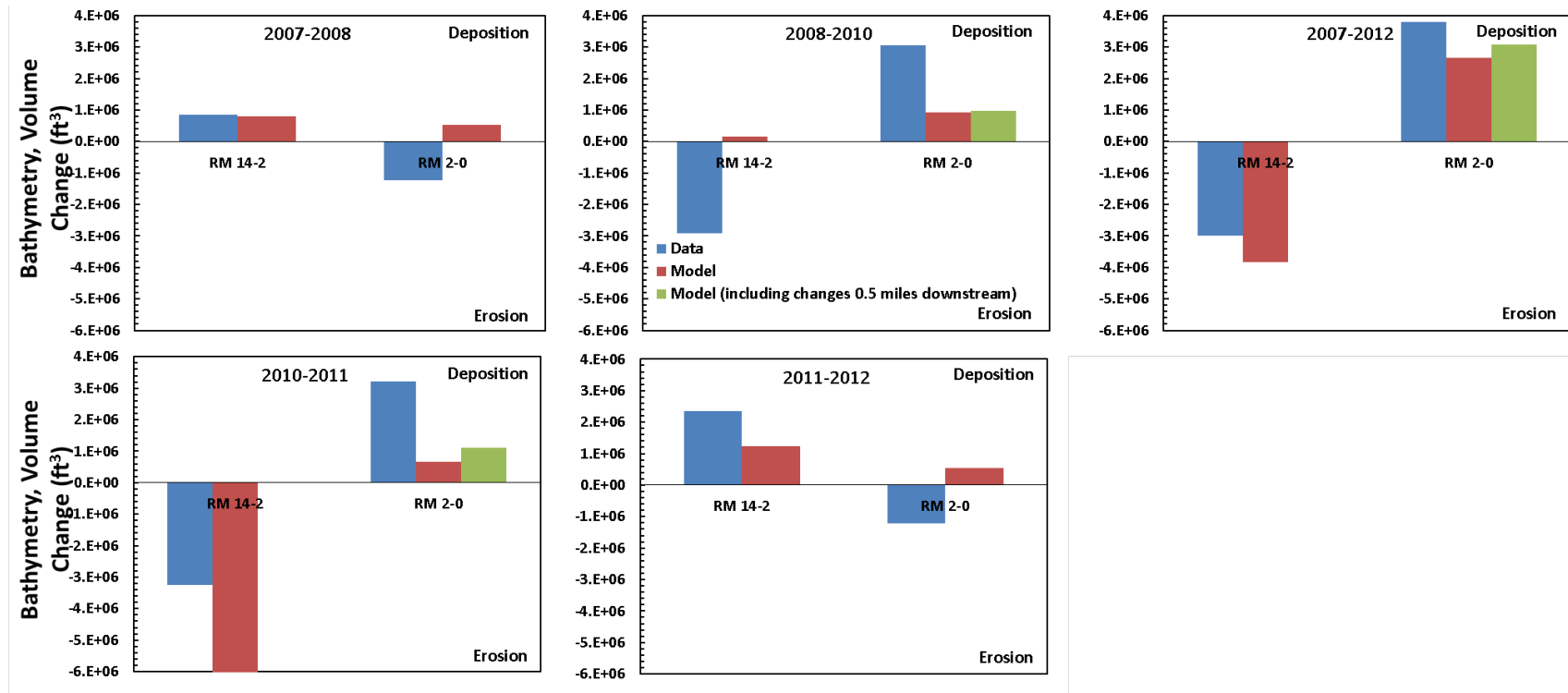


Figure 69. Large scale bathymetric changes during 2007-2012 (including any cells with bathymetry data coverage)

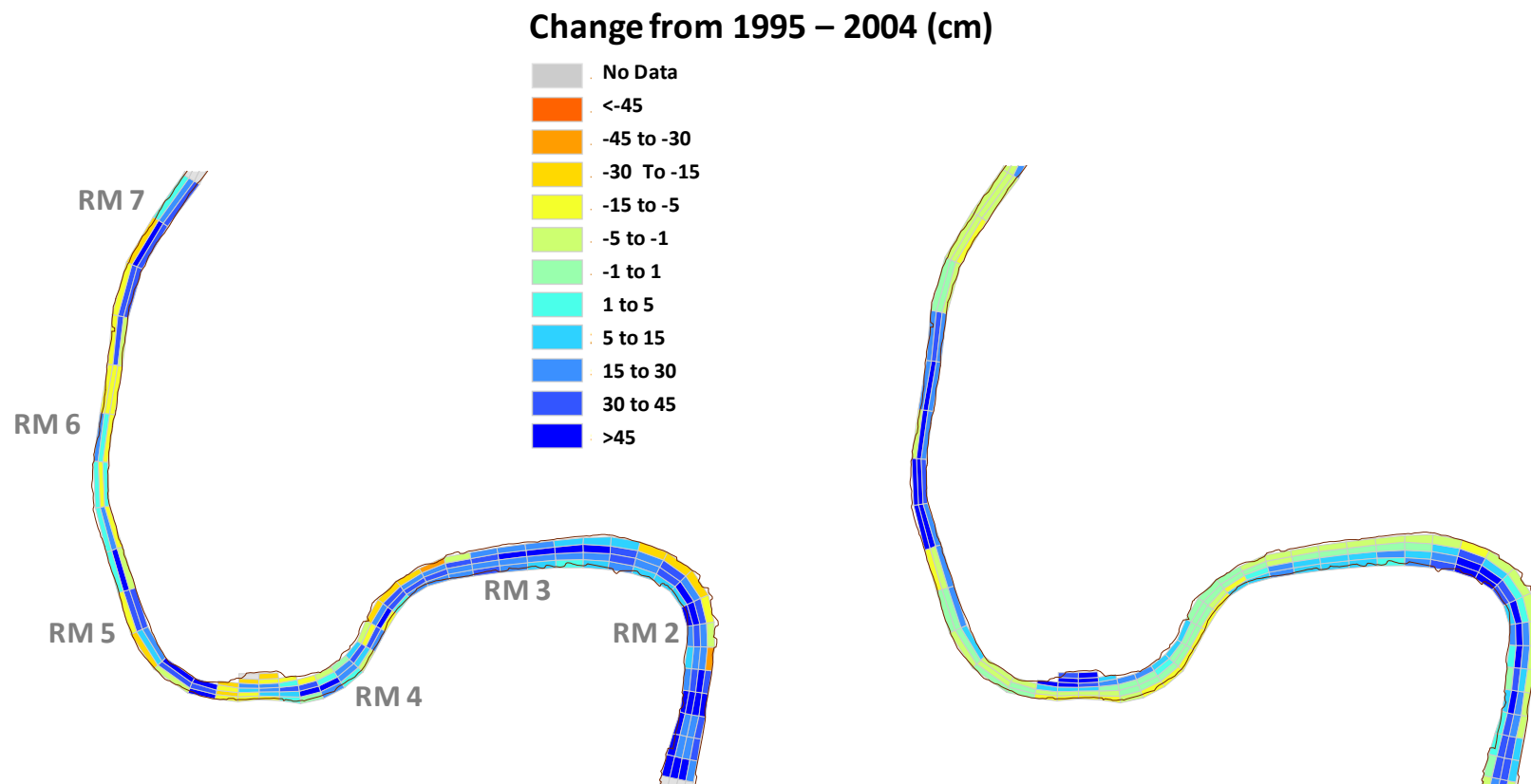


Figure 70. Bathymetric change between the 1995 and 2004 single-beam surveys. Data (left panel) and model (right panel).

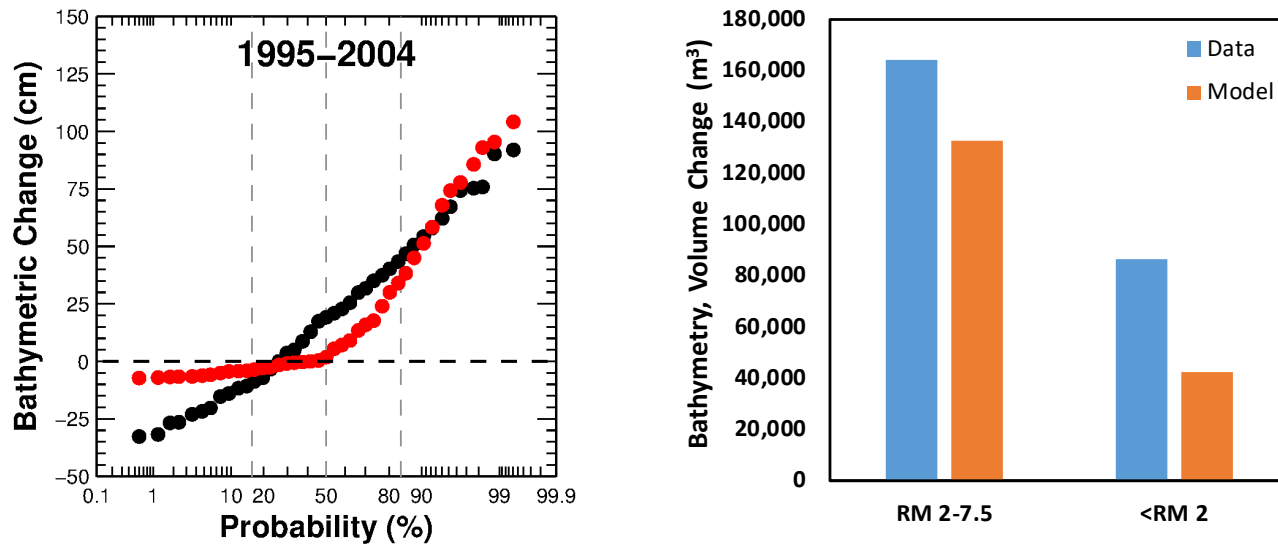


Figure 71. Left panel - probabilistic comparisons of the measured and model calculated bathymetric change over the duration of the 1995 and 2004 bathymetric surveys; negative values indicate erosion and positive values indicate deposition. Right panel – volumetric comparisons of the measured and model calculated bathymetric change between RM 1.5-2 and RM 2-7.5 over the duration of the 1995 and 2004 bathymetric surveys

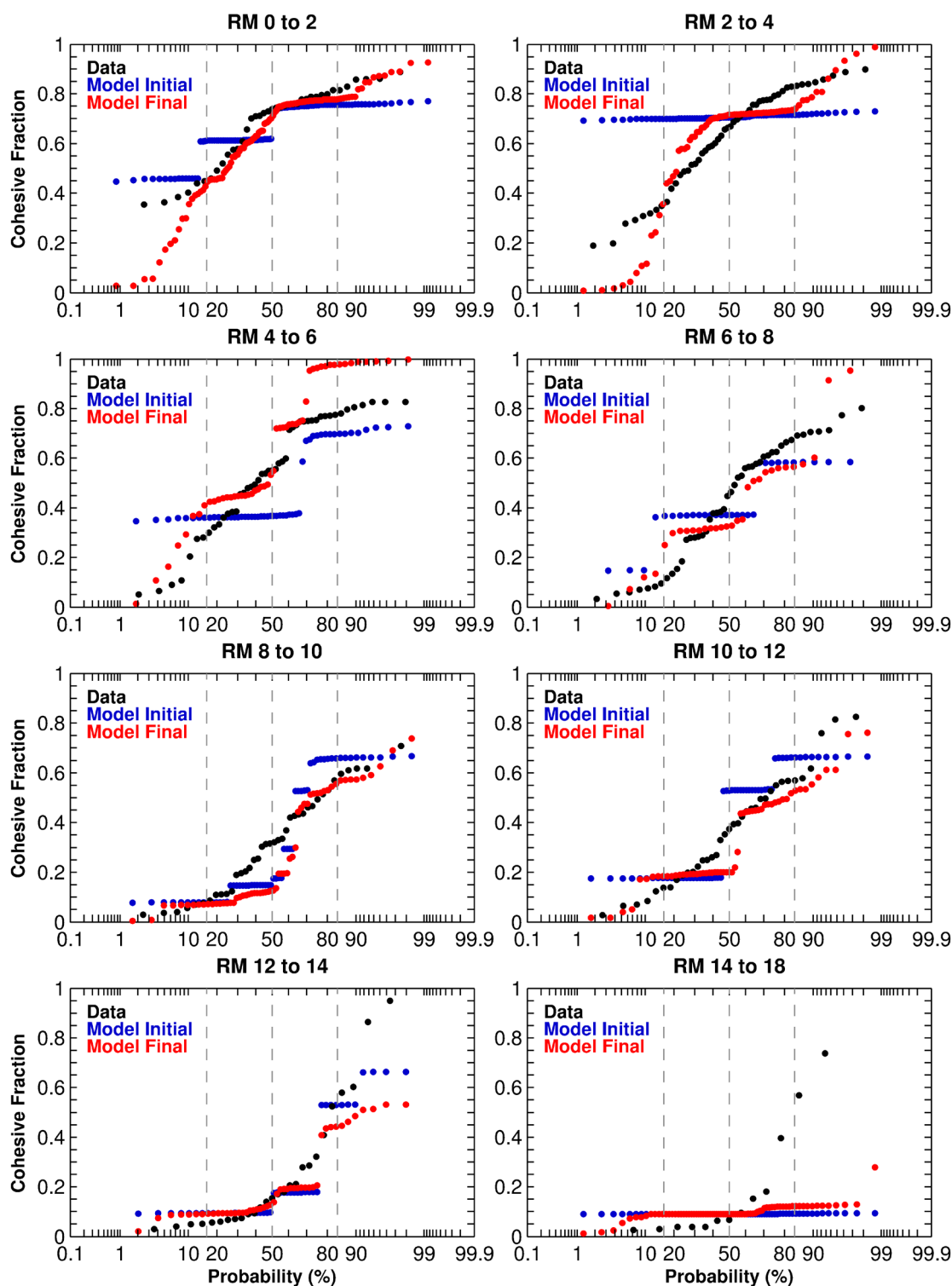


Figure 72. Cumulative probability distributions comparing the initial and final composition calculated by the model to LPRSA core data for top 15 cm of the sediment bed. Model results at the beginning and end of the WY1995-WY2013 simulation.

Sediment Transport Model of the Lower Passaic River

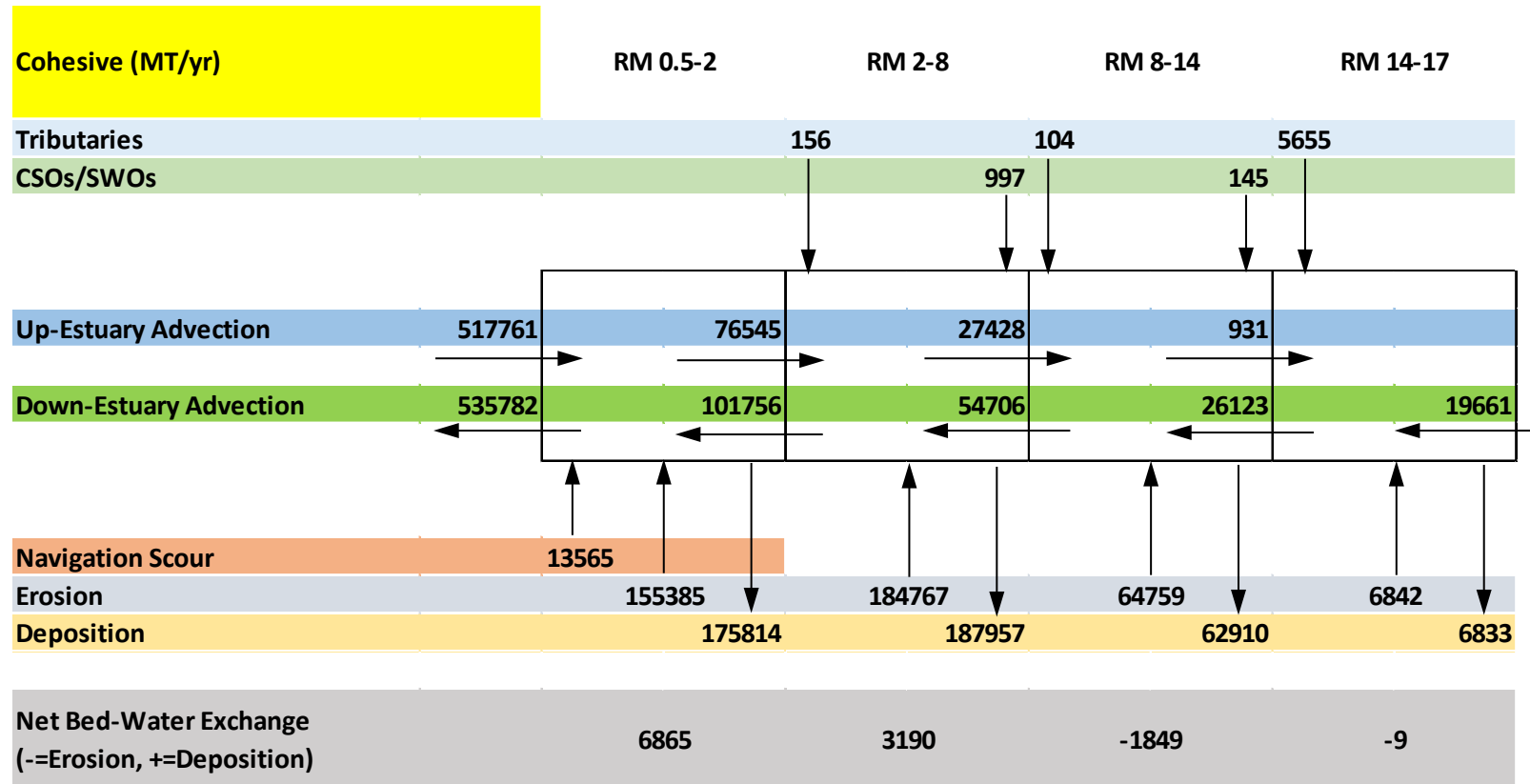


Figure 73. Mass flux summary for cohesive sediments in the LPRSA over WY1996-WY2013.

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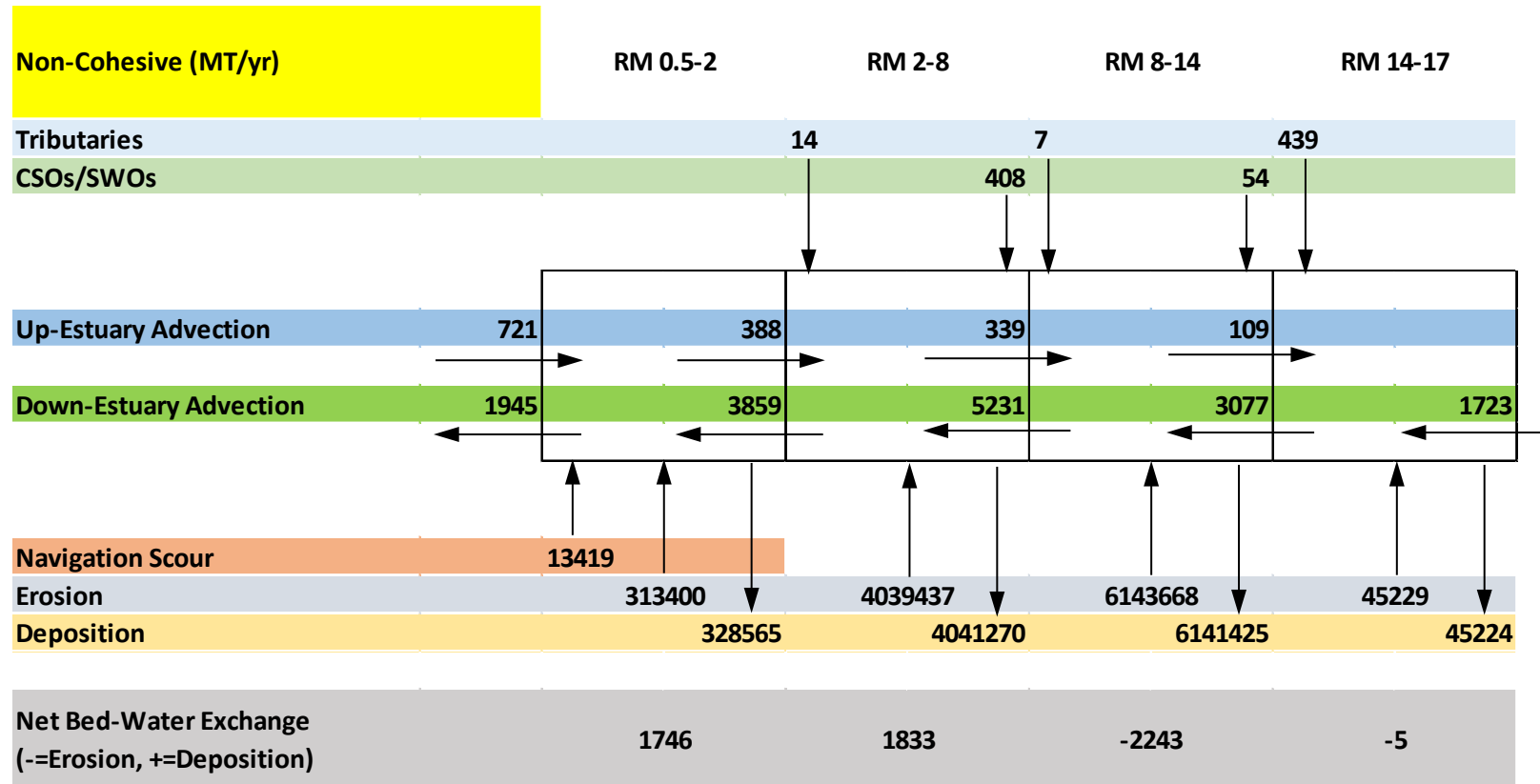


Figure 74. Mass flux summary for non-cohesive sediments in the LPRSA over WY1996-WY2013.

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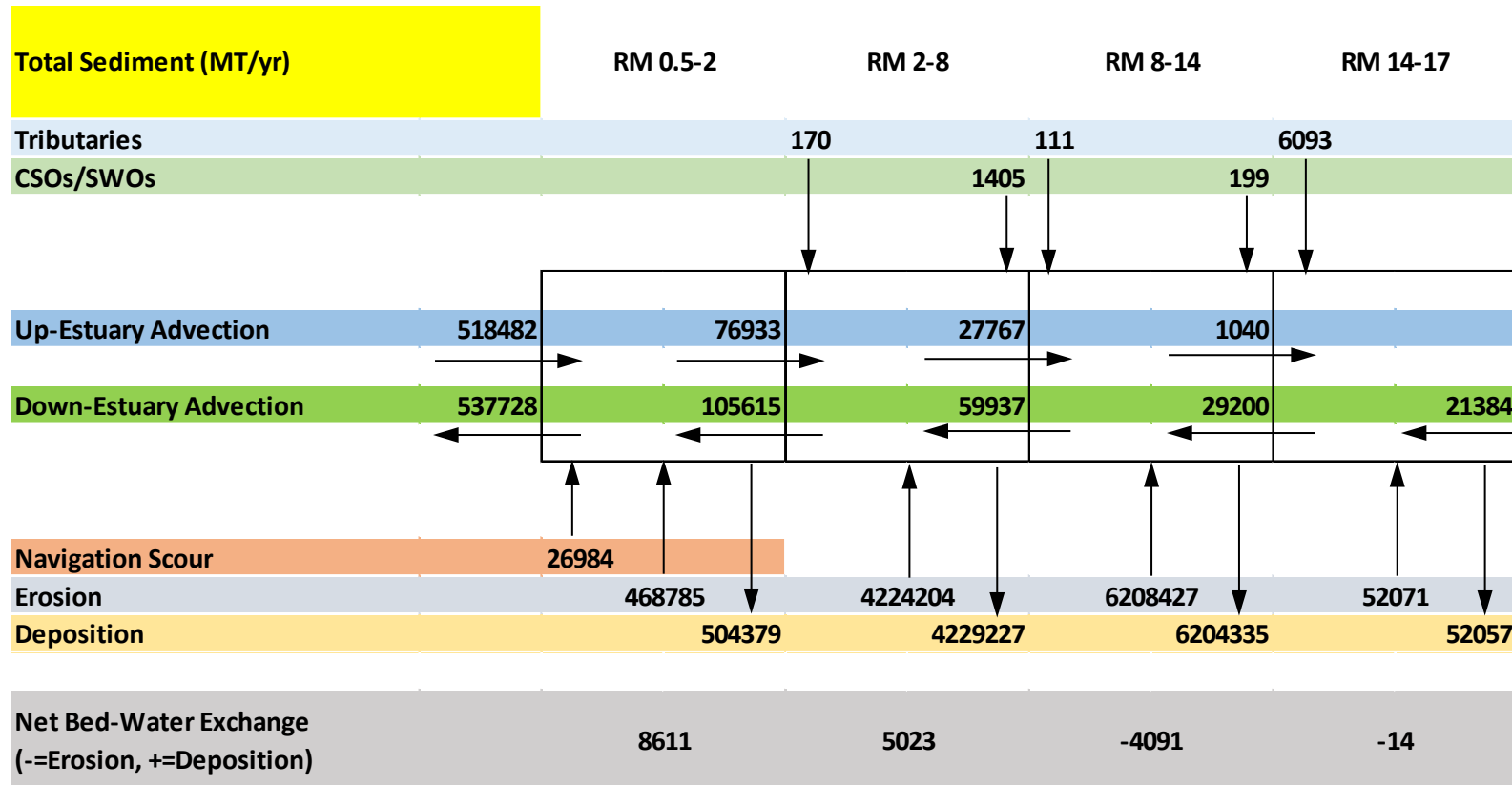


Figure 75. Mass flux summary for total (sum of cohesive and non-cohesive) sediments in the LPRSA over WY1996-WY2013.

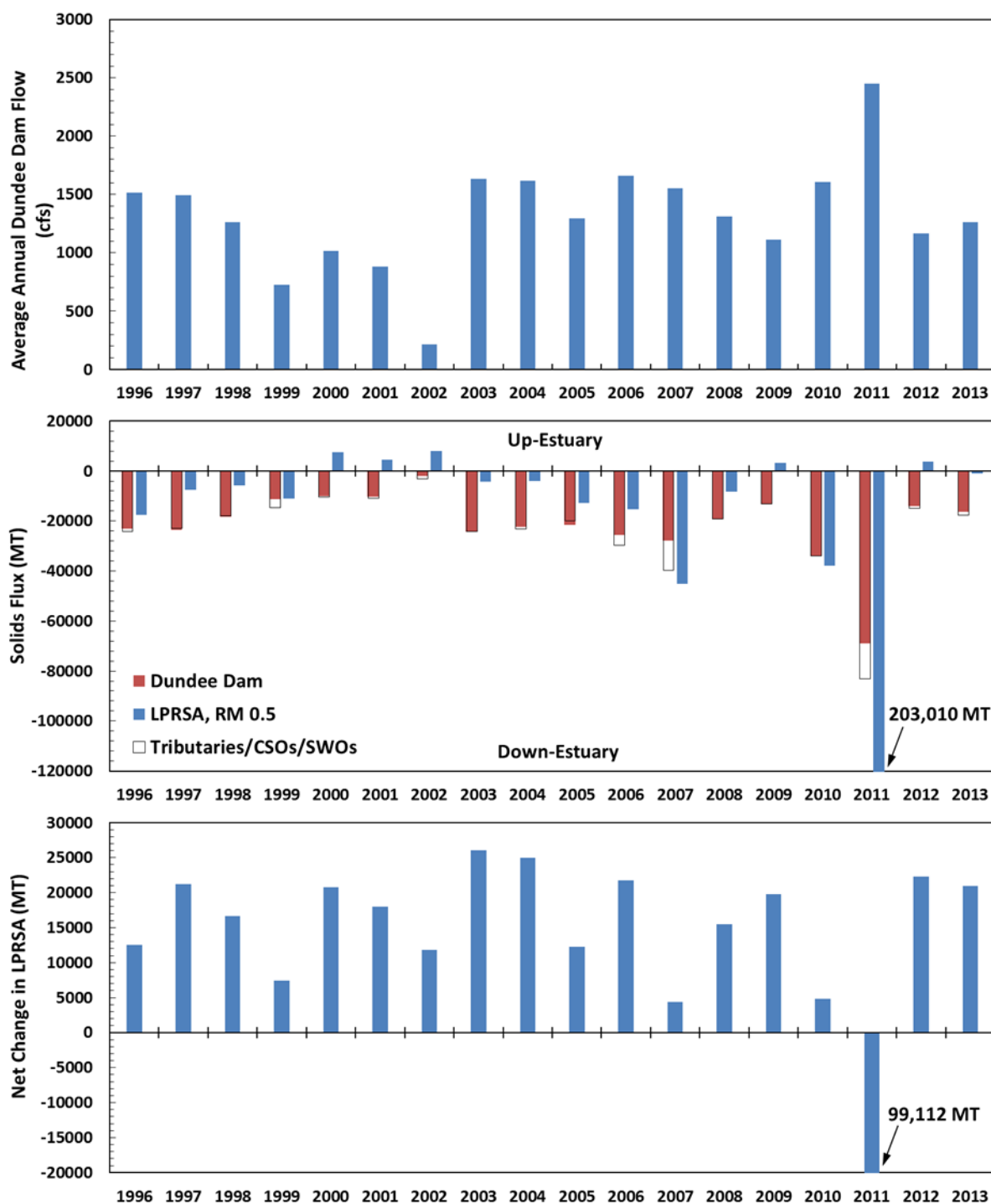


Figure 76. Annual mass balance summary for the LPRSA.

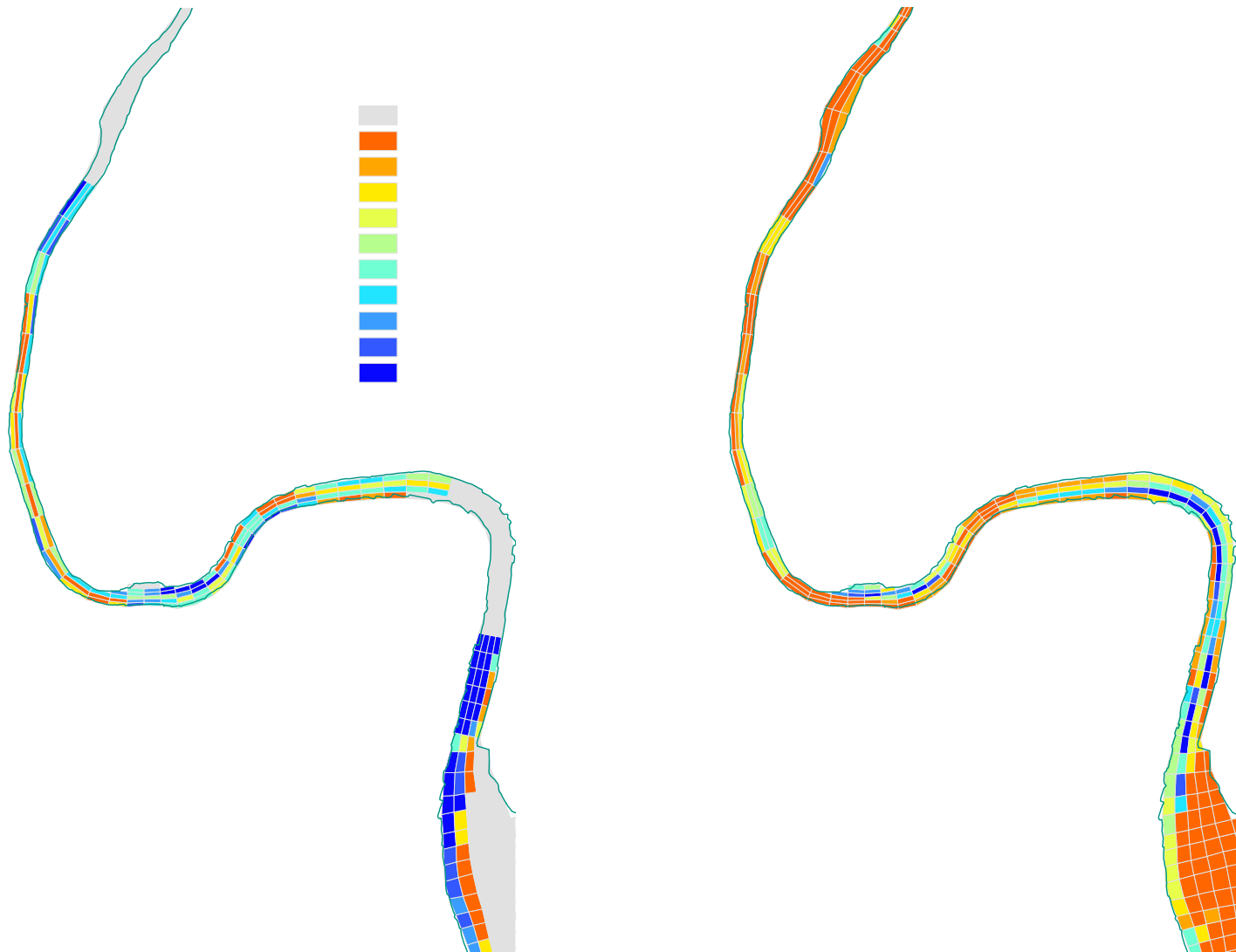


Figure 77. Measured (left panel) historical infill rates and model simulated (right panel).

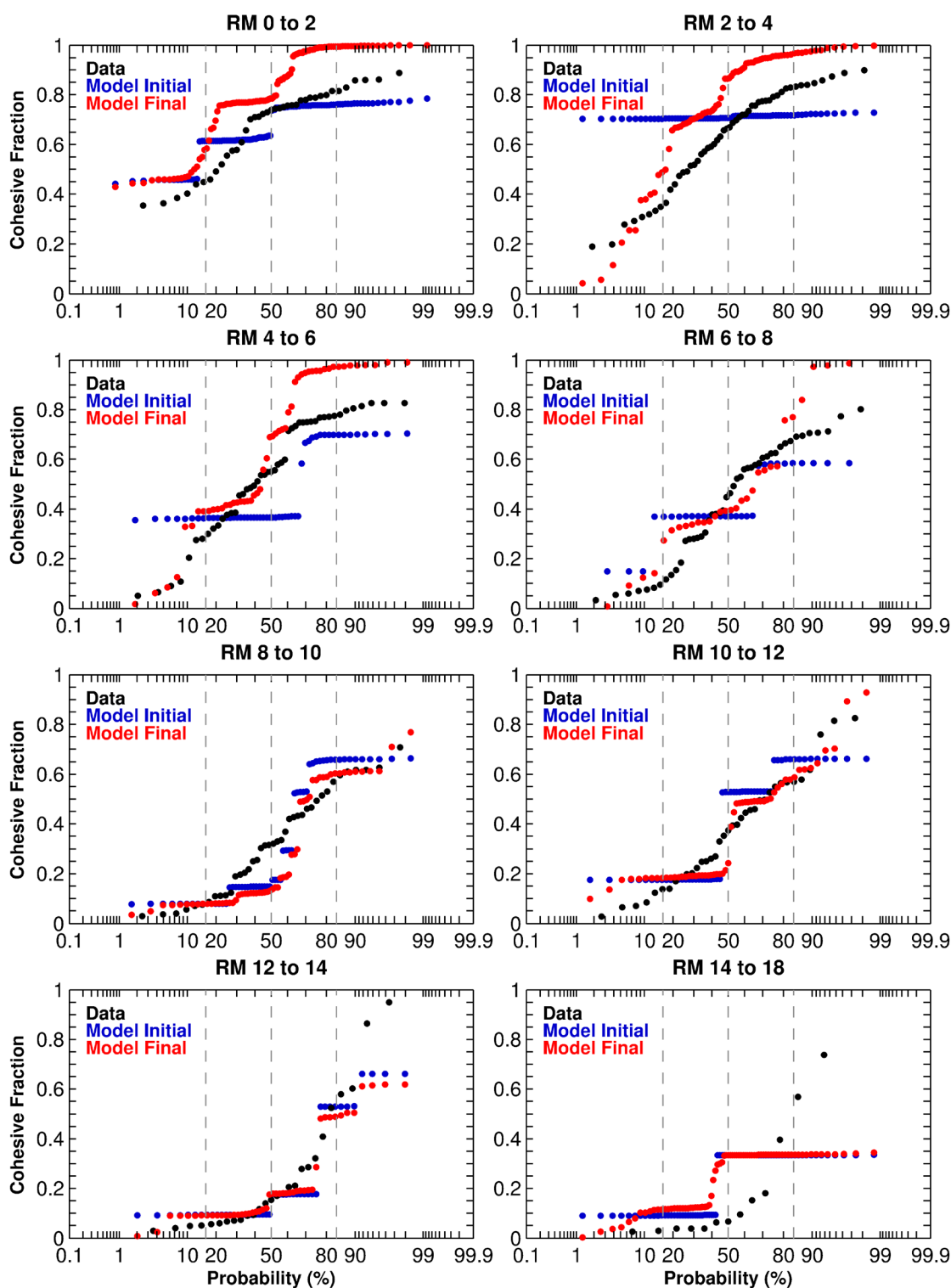


Figure 78. Cumulative probability distributions comparing the initial and final composition calculated by the model to LPRSA core data for top 15 cm of the sediment bed. Model results are from the historical infill simulation.