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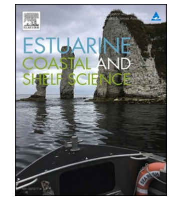

Changes in suspended sediment concentration along tidal rivers of the Chesapeake Bay: the tidal freshwater “sediment shadow”

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ABSTRACT

Transport of terrigenic sediment from nontidal watersheds into estuaries has important impacts on coastal habitat quality, pollutant transport, and resilience to sea-level rise. However, relatively little is known about changes in suspended sediment as nontidal rivers encounter tide, transition into tidal rivers through the tidal freshwater zone (TFZ), and enter saline portions of estuaries. The goal of this paper is to identify spatial and temporal patterns in suspended sediment concentration (SS) changes across tidal and salinity gradients over multiple tidal rivers, using a robust monitoring long-term dataset from the Chesapeake Bay. The multiple TFZs in the Chesapeake Bay consistently have a “sediment shadow” shown by a local spatial minimum in SS compared to upstream nontidal and downgradient oligohaline river reaches. Similarly, freshwater inputs from nontidal rivers have diminishing influence on tidal SS temporal dynamics with distance downstream from the head-of-tide. Therefore, little of the contemporary watershed sediment load is likely transported past the TFZ except during extreme floods when some sediment may be delivered to saline portions of the estuary. Tidal freshwater and brackish portions of the estuary have spatially variable trends in SS over time, both increases and decreases. However, the more saline downstream ends of tidal rivers and the mainstem of the Chesapeake Bay have had a consistent average 25% decline in SS over the past decades. In summary, the presence of “sediment shadows” suggests watershed loads of sediment are currently mostly not transported through the TFZ into the saline estuary, and likely generate sediment deficits for tidal freshwater wetlands.

1. Introduction

Sediment is an important regulator and stressor influencing ecosystem dynamics, impacting geomorphic change, pollutant transport, biota, and aquatic and wetland ecosystem health. Excess fine sediment decreases estuarine water clarity (Testa et al., 2019), degrades submerged aquatic vegetation habitat (Orth and Moore, 1984), and suffocates benthic fauna (Hinchey et al., 2006). Furthermore, sediment can accumulate toxic contaminants (Comeleo et al., 1996). However, sufficient sediment supply is also essential for tidal wetland resilience to sea-level rise (Kirwan et al., 2016). Thus, trade-offs in sediment supply drive tidal wetland and estuarine health and persistence.

Managing sediment sources and transport is often a focus of watershed management to restore downstream freshwater ecosystems and estuaries (Novotny and Chesters, 1989). Implementing soil conservation approaches, pasture fencing, stormwater management, stream restoration, and dam management, among other best management practices, are common techniques to reduce sediment erosion and downstream loading (Sekellick et al., 2019). In the Chesapeake Bay, decades of elevated nitrogen, phosphorus, and sediment loading from the watershed have impaired biota, dissolved oxygen, and water clarity in the estuary (Kemp et al., 2005). In response the U.S. Environmental Protection Agency (EPA) implemented a pollution diet, the total maximum daily loading (“TMDL”) plan, that mandates reducing export of sediment and nutrients from the nontidal watershed to the Chesapeake Bay (Linker et al., 2013).

However, watershed-estuary sediment connectivity, or the fate of sediment transported in nontidal rivers, is uncertain when it reaches the tidal zone. Most upland erosion that eventually is transported by nontidal rivers is trapped in nontidal floodplain wetlands (Phillips,

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1989; NOE and Hupp, 2009; Brakebill et al., 2010; Noe et al., 2022) or estuaries and tidal marshes and not delivered to the coastal ocean (Meade, 1982; Phillips, 1991). Sediment depositing short of coastal oceans is particularly important for lowland Coastal Plain rivers (Phillips, 1989;Phillips and Slattery, 2006). Accelerated rates of upland erosion following European colonization and widespread land use changes led to infilling of aquatic habitat near the most landward extension of tides (or head-of-tide), with creation of tidal freshwater wetlands and loss of navigability for ocean-going boats to many colonial ports (Gottschalk, 1945, Pasternack, 2007). For example, most sediment loaded from nontidal river inputs and shoreline erosion is trapped within the Choptank River with little sediment export to the mainstem of the Chesapeake Bay (Yarbro et al., 1983). In the Chesapeake Bay mainstem, long-term sedimentation rates have been minimal in the mid-Bay compared to locations receiving fluvial or oceanic sediment inputs (Biggs, 1970; Schubel and Carter, 1977; Donoghue et al., 1989; Donoghue, 1990). Under normal conditions, sediment is transported from the mainstem of the Bay upgradient into its tributary river estuaries (Schubel and Carter, 1977). Across the U.S., contemporary mineral fluvial sediment loading is insufficient to support accretion rates in tidal marshes to maintain desired resilience to sea-level rise (Ensign et al., 2023).

Relatively little is known about finer scale changes in suspended sediment as nontidal rivers encounter tide, transition into tidal rivers through the tidal freshwater zone (TFZ), and enter saline portions of the estuary. Many monitoring stations that measure sediment loading from nontidal watersheds are located distant upstream from head-of-tide. Extrapolating sediment loading from these locations to the tidal zone can often be inaccurate given the likelihood of sediment deposition in transit (Phillips, 1991; Noe et al., 2022). Sediment dynamics in the TFZ of tidal rivers is not well quantified for inclusion of estuarine sediment budgets, but tidal rivers can be extensive along coasts (Ensign and Noe, 2018; Jones et al., 2020). High sediment deposition rates in nontidal floodplain and tidal freshwater forested wetlands immediately downstream from the head-of-tide can lead to a decrease in river channel sediment load that generates a “sediment shadow” (Ensign et al., 2015) in the tidal freshwater zone's river channels and wetlands (Ensign et al., 2014; Hupp et al., 2015; Noe et al., 2016; Craft, 2012; Kroes et al., 2023). A recent synthesis of global sediment data collected from coastal wetlands identified that tidal freshwater forested wetlands have the greatest soil organic fraction and lowest bulk density (Holmquist et al., 2024), suggesting that tidal swamps have the least mineral sediment supply of any coastal wetland ecosystem. This accretion deficit makes tidal freshwater forested wetlands particularly sensitive to sea-level rise (Craft, 2012, Krauss et al., 2024).

The estuary turbidity maximum (ETM) further down gradient into the estuary in the oligohaline zone (Jay et al., 2015) is associated with greater suspended sediment concentrations (Meade, 1968; Sanford et al., 2001) and tidal wetland deposition rates (Darke and Megonigal, 2003; Loomis and Craft, 2010; Ensign et al. 2014, 2015), potentially restoring sediment availability below the sediment shadow in the TFZ. Water clarity in the estuary is influenced by watershed loads of sediment in the upper tributaries but not in higher salinity zones (Testa et al., 2019), where local shoreline erosion is a large source of inorganic sediment (Turner et al., 2021), suggesting that sediment delivered from the watersheds has limited extent. Despite the importance of suspended sediment to watershed-estuary dynamics, including landscape restoration efforts, relatively little is known about systematic patterns of sediment concentration along tidal rivers – critical information to understand and manage coastal ecosystems especially as coastal ecosystems respond to sea-level rise.

The goal of this paper is to identify spatial and temporal patterns in suspended sediment (SS) concentration changes across tidal and salinity gradients, from nontidal through tidal fresh into oligohaline and more saline zones of estuaries, over multiple tidal rivers of the Chesapeake Bay. Based on past findings of a “sediment shadow” in several tidal freshwater rivers and wetlands, we hypothesized that there is a general pattern of lowest SS concentrations in the TFZ compared to upriver nontidal fresh and downriver saline portions of estuaries. We also expected to find that spatial and temporal variability of SS concentrations along tidal rivers were less influenced by watershed river freshwater inputs and sediment loads with greater distance from the head-of-tide. The Chesapeake Bay offers a useful opportunity to summarize suspended sediment dynamics in the coastal zone. Multiple rivers discharge into the Chesapeake Bay from a heterogeneous nontidal watershed with large spatial variability in river SS concentrations. The Chesapeake Bay is the focus of management and restoration efforts that could benefit from a summary of sediment patterns (Noe et al., 2020). Finally, the Chesapeake Bay and its watersheds are relatively data rich with hundreds of tidal and nontidal monitoring stations that have regularly and frequently measured SS concentrations over the past decades. Other work has analyzed and summarized nitrogen, phosphorus, and other water quality parameters in the Chesapeake Bay's monitoring datasets (e.g., Testa et al., 2019; Murphy et al., 2022), but not SS concentration. Although sediment load, the product of sediment concentration and water discharge rate, is a meaningful metric for understanding sediment transport processes and implications for ecosystem processes, sediment loading rate is very difficult to measure in tidal waters and this paper relies on readily available SS concentration data to indicate patterns of sediment availability in space and time.

2. Methods

2.1. Location

The Chesapeake Bay is located in the Coastal Plain of the temperate mid-Atlantic Coast in the U.S. The large watershed area (166,000 km^2) relative to the water volume of the shallow estuary makes the Chesapeake Bay highly influenced by watershed inputs of water and material loads (Kemp et al., 2005). A large number of tributaries create distinct tidal river sub-estuaries before joining the mainstem of Chesapeake Bay. These tidal rivers include a few large rivers like the Susquehanna and Potomac Rivers, to several medium, and many small rivers and streams (Fig. 1). Sufficient freshwater discharge and low topographic gradients can lead to long tidal freshwater reaches with gradually increasing salinity as tidal rivers approach the mainstem of the Chesapeake Bay. Rivers along the Western Shore include the larger alluvial rivers that originate in the Piedmont or mountains and have higher sediment yield compared to smaller blackwater rivers that originate in the Coastal Plain of the Western and Eastern Shore and have smaller sediment yield (Hupp, 2000).

2.2. Source of data

The Chesapeake Bay Program (CBP) and U.S. Geological Survey (USGS) operate a large network of tidal and nontidal (NT) water quality stations, respectively. The CBP's Water Quality Monitoring Program began in 1984 with hundreds of tidal stations sampled through Maryland, Virginia, and Washington DC's monitoring programs. The USGS measures water quality and freshwater discharge at over a hundred nontidal stations throughout the watershed, including gages located near the outlets of the larger nontidal watersheds that are the focus of this analysis.

Data from the CBP Water Quality Monitoring Program were downloaded (http://datahub.chesapeakebay.net/WaterQuality; 2021.09.24) for all samples that included both total suspended solids (TSS, mg/L) and salinity measurements (psu) at tidal stations. Dates of sampling ranged from 23 January 1984 to 25 June 2021 and included 215,242 measurements of TSS. The state agencies collecting data with the CBP Water Quality Monitoring Program generally sample once each month during the colder late fall and winter months and twice each month in the warmer months. However, some stations are sampled less

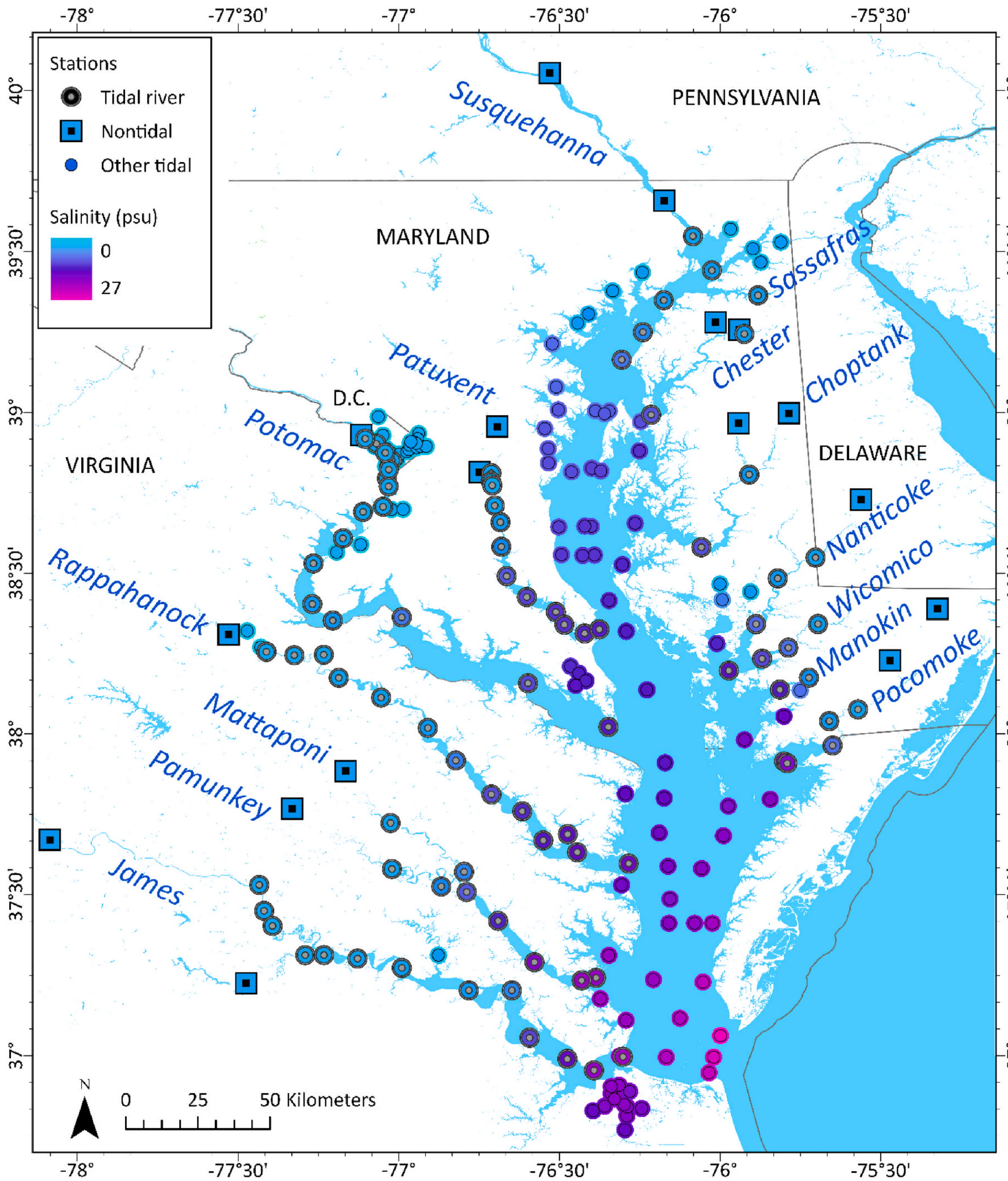

Fig. 1. Location of suspended sediment sampling stations in the Chesapeake Bay (circles) and in nontidal river stations closest to the head-of-tide along each river (squares). The tidal stations include a subset of those along the tidal rivers that are highlighted in this study (bullseye circles). Tidal station symbols' colors represent long-term average salinity. River names are shown in blue italics. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

frequently. The tidal sampling generally includes a hydrographic (physiochemical) profile at each station, and water samples for physico-chemical analysis are collected at the surface (surface is usually 0.5 or 1 m deep) and the bottom layers. For deeper stations, two additional mid-water depths are sampled depending on the existence and location of a pycnocline. Generally, samples have been collected via pumping system rather than a discrete sample collection device. TSS (mg/L) is measured by field filtering of a water sample of known volume using vacuum filtration with pre-weighed 0.7 μm glass fiber filters that were subsequently washed with deionized water, dried at 103-105 deg C, and weighed (Chesapeake Bay Program, 1993). Method-related changes in measured TSS values at some stations have been identified by the CBP (Chesapeake Bay Program, 2012, Murphy et al., 2019). As a result, temporal trends are restricted to the period after the method changes in 1999. Otherwise we have determined that the methods changes have no impact on our overall conclusions. The salinity value was either read directly using a Hydrolab Surveyor II (Maryland Department of the Environment and Old Dominion University) or computed later from conductivity and water temperature when using a water quality sonde (Virginia Institute of Marine Science). Duplicate samples were averaged for subsequent analysis. For this study, most analyses were conducted using data from the surface layer of the water column, except for a comparison of surface vs deeper layers at a subset of stations.

The CBP tidal stations were sorted into those located along the mainstems of the tidal rivers with multiple stations prior to joining the mainstem of the Chesapeake Bay. These tidal rivers include the James, Pamunkey and Mattaponi (both join and form the York in the oligohaline zone), Rappahannock, Potomac, Patuxent, Susquehanna, Sassafras, Chester, Choptank, Nanticoke, Wicomico, Manokin, and Pocomoke rivers, in clockwise order starting from the southwestern portion of the Chesapeake Bay watershed (Fig. 1). The downstream/downgradient end of each tidal river was generally considered to be the station nearest where the river joined the mainstem of the Chesapeake Bay. However, several northern tidal rivers had stations from the upper Chesapeake Bay mainstem included. Individual stations with small sample sizes (<100) were omitted.

The nearest USGS nontidal stations along each river, if available, also were included as the upstream end of the tidal rivers. Water samples at these Chesapeake Bay Nontidal Monitoring Network stations were collected using either the equal-width-increment or the equal-discharge-increment method to obtain a composite sample that is representative of the discharge-weighted suspended sediment concentration (SSC; Edwards and Glysson, 1999). Samples were generally collected monthly at baseflow conditions as well as multiple times each year at storm flows. Suspended sediment concentration data (mg/L, code P80154) were downloaded for each of these nontidal stations. In addition to the Susquehanna River at Conowingo that is located downstream of a series of dams and near the head-of-tide, data also were obtained from Susquehanna River at Marietta that is upstream of the reservoirs and represents typical free-flowing riverine conditions. Nontidal SSC and freshwater discharge was downloaded (U.S. Geological Survey, 2021). The year of the first SSC sample collection varied among river stations, ranging from 1972 to 2002. Samples collected prior to 1984 were omitted from further analyses so that nontidal and tidal station periods of records overlapped. Stations were generally omitted that had less than 100 samples, except the two Pocomoke watershed nontidal stations that each had fewer than 100 samples collected and Morgan Creek (99 samples).

2.3. Data analyses

2.3.1. Sediment concentration vs. salinity of all tidal Chesapeake stations

For all tidal stations, the average and coefficient of variation of TSS and average salinity was calculated for each station's entire record (including those stations not located along tidal rivers). For all of the nontidal river stations nearby the tidal rivers, the average SSC was calculated for each station's entire record. The tidal river stations were classified as nontidal, tidal freshwater (<0.5 psu), oligohaline (0.5 – 5 psμ), mesohaline (5 – 18 psμ), or polyhaline (18 – 30 psμ) (Cowardin, 1979) based on average salinity at each station, which sometimes differed from CBP station classification of salinity regime. The relationship between mean TSS and mean salinity among tidal stations was examined using a spline smoother function (lambda = 0.001, trim = 0) with bootstrap confidence limit (JMP16, SAS Institute Inc., Cary, North Carolina, USA).

2.3.2. Sediment concentrations among tidal and salinity zones along tidal rivers

For each tidal river, the downriver distribution of mean and all observed TSS/SSC measurements at each station (nontidal and tidal) was evaluated. The average TSS/SSC of the means of stations within each salinity class was then calculated for each tidal river. Differences among tidal/salinity zones were tested using non-parametric Wilcoxon tests.

2.3.3. Correlations in sediment among tidal and salinity zones along tidal rivers

Pearson product-moment correlations were calculated on TSS among the tidal river salinity zones, as well as the average annual sediment load (log-transformed, kg/yr; Ator, 2019) at the mainstem nontidal station, with each river treated as an experimental unit.

2.3.4. Downriver changes in sediment concentration along individual tidal rivers

For each tidal river, changes in TSS/SSC were compared sequentially among stations along the downriver gradient from nontidal, to tidal freshwater, to oligohaline, to mesohaline, to polyhaline.

2.3.5. Distances between monitoring stations

River distances from the head-of-tide to the nearest nontidal mainstem station and nearest tidal station were determined using ArcGIS Pro 3.4 (ESRI, Redlands, California, USA).

2.3.6. Differences among sampling depths

For the most upstream tidal freshwater station that included repeated sampling of both surface and bottom layers, the long-term average SS concentration was compared between the two sampling depths.

2.3.7. Temporal variation in TSS

The effects of freshwater discharge on temporal variation in TSS/SSC at individual stations was evaluated using generalized additive models (GAMs) (tidal) and linear regression (nontidal). Freshwater discharge effects on sediment were categorized as strong increase, weak increase, neutral, weak decrease, or strong decrease. Log-log regression of river discharge effect on SSC was calculated for each nontidal station nearest the tidal rivers. Freshwater flow influence on SSC was classified based on the slope of the regression and SSC at the greatest river discharge rates.

Murphy et al. (2019) implemented GAMs that investigated the effects of time and freshwater discharge on trends of Chesapeake Bay water quality parameters at individual CBP tidal Water Quality Monitoring Program stations. Using that approach here, each station's GAM fit from 1999 to 2022 was chosen as the best predictive model using nearest river discharges averaged over different antecedent periods or instantaneous salinity measured at the same time as TSS. From the relationship of freshwater flow effects on TSS, we here evaluated the directionality and magnitude of freshwater influence on temporal variation in tidal TSS. Freshwater effects on TSS were categorized based on directionality and a threshold effect size of 1.0 in the partial effect plots, and the time-scale of the most explanatory time period also is reported. When salinity at a tidal station was most explanatory, the effect was inversed to represent freshwater availability. Finally, the correlation of stations' long-term percent change in TSS and mean salinity was tested using Pearson product-moment correlation.

2.4. Data availability

The summarized data (average, coefficient of variation, and sample size), salinity zone, GAM and regression results, and SPARROW sediment load estimates are available at the Noe and Murphy (2025) data release.

3. Results

3.1. Sediment concentration vs. salinity of all tidal Chesapeake stations

Long-term (1984 to 2021) average TSS concentrations in the surface layer of the water column ranged from 5 to 67 mg/L among all tidal stations (Fig. 2). These stations include those along tidal rivers, as well as the mainstem of the Chesapeake Bay and its smaller tidal tributaries. Long-term average salinity ranged from 0 to 27 psμ across these tidal stations. Many tidal rivers had long reaches with tidal freshwater to oligohaline (0.5 to 5 psμ) average salinities over the period of record (Fig. 1). Generally, mesohaline (5 to 18 psμ) average salinities occurred in lower reaches of the tidal rivers and in the upper mainstem of the Bay,

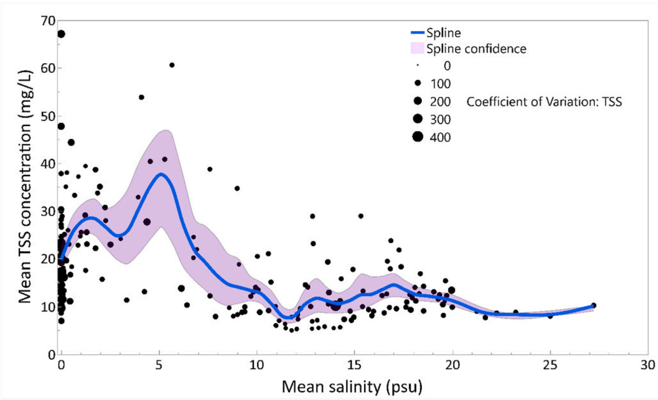

Fig. 2. Long-term average total suspended solids (TSS) concentration and average salinity in the surface layer of each tidal station in the tidal Chesapeake Bay Water Quality Monitoring Program (Chesapeake Bay Program). Size of the symbols represents the temporal variability (coefficient of variation ("CV") of TSS) at each station. The smooth spline curve of the TSS vs. salinity relationship is shown along with its bootstrap 95% confidence band.

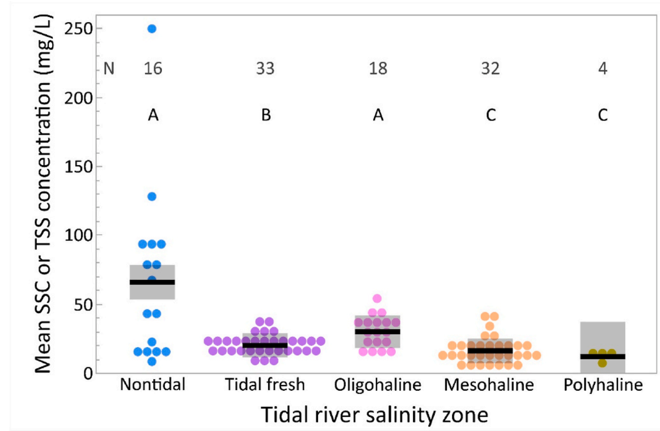

Fig. 3. Monitoring stations' long-term average suspended sediment concentrations (TSS = total suspended solids; SSC = suspended sediment concentration) measured at nearby nontidal (SSC) and tidal freshwater, oligohaline, mesohaline, and polyhaline stations (TSS) along tidal rivers of the Chesapeake Bay. Sample size (number of stations) is shown at the top of the plot. Different letters indicate significant differences among salinity zones. Mean and 95% confidence interval shown as black lines and gray boxes, respectively.

and polyhaline (18 to 30 psμ) stations occurred in the lower mainstem of the Bay closer to the Atlantic Ocean. Salinity was not measured at the freshwater nontidal river gages.

Long-term average SS concentrations among stations exhibited a complicated relationship to long-term average salinity in the surface layer of the Chesapeake Bay's tidal water column. A distinct peak in TSS of approximately 40 mg/L occurred near salinity of approximately 5 psμ at the boundary of the oligohaline and mesohaline zones (Fig. 2). The tidal freshwater zone had intermediate average TSS concentrations typically around 20 mg/L, but with the greatest spatial variability among stations of any salinity zone. Concentrations of TSS increased slightly from the tidal freshwater zone into the lowest salinities (1 to 3 psμ) of the oligohaline zone to typical values of about 30 mg/L. TSS decreased from its peak at 5 psμ up to 10 psμ in the middle of the mesohaline zone, and generally remained low above 10 psμ. TSS remained generally low as salinity increased from 10 to 20 psμ in the mesohaline and into the polyhaline zone. Temporal variability (coefficient of variation) of TSS at a station generally was highest in tidal freshwater zone, and moderate to low in oligohaline, mesohaline, and polyhaline zones.

3.2. *Sediment concentrations among tidal and salinity zones along tidal rivers*

Among the subset of tidal and nontidal monitoring stations that were located along tidal rivers (and excluding, for example, mainstem Bay stations), the stations were categorized into tidal/salinity zones: nearest nontidal stations upstream (NT), and tidal freshwater, oligohaline, mesohaline, and polyhaline zones based on each station's long-term average salinity. Mean SS concentrations (SSC in nontidal and TSS in tidal) differed among tidal/salinity zones (Wilcoxon test: $p < 0.0001$, Fig. 3). The NT stations differed from the TFZ (Wilcoxon pairs posthoc tests, $p = 0.014$), the TFZ differed from the oligohaline zone ($p = 0.0004$), and the oligohaline zone differed from the mesohaline zone ($p = 0.0016$), but the mesohaline and polyhaline zones were similar ($p = 0.633$). Oligohaline stations had similar mean SS as NT stations ($p = 0.15$).

The NT stations had the greatest long-term average SS concentration (mean = 66 mg/L SSC), with the greatest variability among tidal/salinity zones with stations ranging from 250 to 12 mg/L (Fig. 3). The TFZ had a distinct local minimum of TSS (mean = 20 mg/L) compared to upstream NT and down-gradient oligohaline zones. The distribution of station means within the TFZ was skewed by a few relatively high SS concentration stations located near the freshwater-oligohaline transition (see next section), with most tidal freshwater station averages below 20 mg/L. The oligohaline zone had intermediate TSS (mean = 30 mg/L) with moderate variability among stations. Suspended sediment was low in the mesohaline zone (mean = 16 mg/L) with moderate variability among stations and low TSS in the few polyhaline stations along tidal rivers (mean = 12 mg/L).

3.3. *Correlations in sediment among tidal and salinity zones along tidal rivers*

Spatial patterns of long-term average SS concentrations and nontidal SS loads were assessed across rivers. Annual average SS loads (log transformed) and SS concentrations were not correlated (n = 11 rivers; $r = 0.165$, $p = 0.628$) among the 11 NT mainstem river stations. Because load is the product of concentration and discharge, this lack of correlation indicates that watershed freshwater discharge must dominate the spatial variation in sediment loads among NT rivers and not SS concentrations.

Mean TSS concentration in the TFZ of each river (mean of the multiple stations) was positively correlated with SSC at the mainstem NT station along the same river (n = 9 rivers; $r = 0.671$, $p = 0.048$), and not associated with NT river SS loads (log-transformed; $r = -0.214$, $p = 0.580$) (Fig. 4). At the individual station with the lowest average concentration within the TFZ of each river (where sediment availability is minimal), mean TSS was not correlated with average NT SSC along the same river (n = 9 rivers; $r = 0.176$, $p = 0.651$) or NT SS load (log-transformed; $r = -0451$, $p = 0.223$).

Mean TSS concentration in the oligohaline zone was negatively correlated with NT SS load along the same river (n = 11 rivers; log-transformed; $r = -0.623$, $p = 0.041$), but was not correlated with mainstem NT SSC concentration ($r = 0.145$, $p = 0.671$) (Fig. 4). And oligohaline mean TSS concentration was not correlated with the mean of tidal freshwater stations along the same river (n = 9 rivers; $r = 0.387$, $p = 0.304$), but was weakly positively correlated with the TSS concentration at tidal freshwater minimum station ($r = 0.616$, $p = 0.077$).

Mean TSS concentration for mesohaline stations along each river was uncorrelated with NT SS loads (log-transformation; n = 11 rivers; $r = -0.333$, $p = 0.317$), NT mainstem SSC ($r = -0.396$, $p = 0.228$), TFZ mean (n = 9 rivers; $r = -0.132$, $p = 0.736$) or TFZ minimum TSS ($r = 0.470$, $p = 0.202$). However, mean mesohaline TSS concentration was weakly positively correlated with mean oligohaline TSS concentration along the same river ($r = 0.580$, $p = 0.061$). Too few rivers

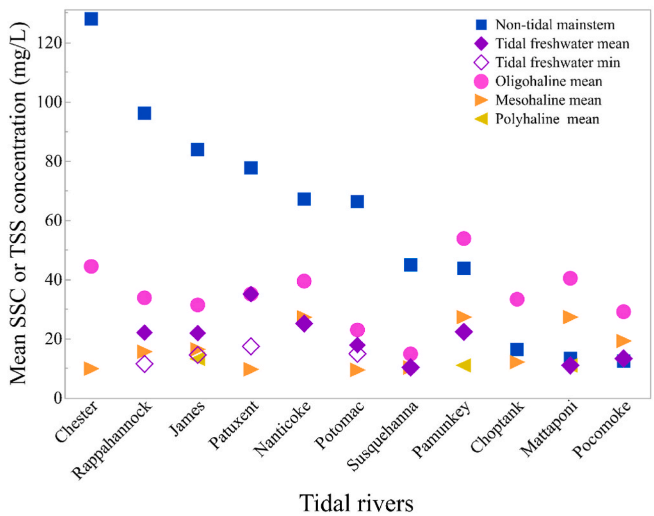

Fig. 4. Long-term average suspended sediment concentrations (TSS = total suspended solids; SSC = suspended sediment concentration) of stations in different tidal and salinity zones along individual tidal rivers, as the average of all stations within each zone as well as the minimum ("min") in the tidal freshwater zone. Rivers are ordered in rank decreasing order of mean nontidal concentrations.

(n = 2) had polyhaline stations to allow correlation analysis.

3.4. Downriver changes in sediment concentration along individual tidal rivers

Fourteen tidal rivers had sufficient monitoring stations to analyze downriver trends in SS concentration and salinity. Four categories of downriver trends were apparent. Seven tidal rivers had a local SS concentration minimum in tidal freshwater with an oligohaline peak, three tidal rivers had consistent SS concentration from nontidal downriver through TFZ followed by an oligohaline peak, three tidal rivers had consistent SS concentration everywhere, and one tidal river had decreasing SS concentrations downstream (Figs. 5 and 6).

3.4.1. Tidal freshwater local minimum and oligohaline peak

The category of tidal freshwater local minimum with oligohaline peak occurred along the five largest rivers (Susquehanna, Potomac, James, Rappahannock, and Patuxent) as well as two smaller rivers (Pamunkey and Nanticoke) (Fig. 5). Nontidal average SSC ranged from about 40 to 250 mg/L among these rivers, generally greater in this category compared to other categories of tidal river downriver trends. In particular, these NT stations had very large SSC measurements in the tails of their distribution, and typically low or intermediate SSC most of the time. The rivers in this category drain large watershed areas outside of the Coastal Plain, with the exception of the Nanticoke River.

The four longest tidal rivers (Potomac, James, Rappahannock, and Patuxent rivers) are the only tidal rivers with multiple tidal freshwater measurement stations. Each of these rivers had the lowest TSS at the tidal freshwater stations nearest the head-of-tide and gradually increasing TSS downriver through the TFZ towards the oligohaline transition (Fig. 5). All of the tidal rivers in this category had a large step decrease in SS concentration from the NT to the most upstream tidal freshwater station. For example, average SS concentration changed from 96 to 12 mg/L along the Rappahannock, 84 to 20 mg/L along James, 78-250 to 17 mg/L along Patuxent, 67 to 25 mg/L along Nanticoke, 66 to 19 mg/L along Potomac, 44 to 22 mg/L along Pamunkey, and 43 (at the outlet of the Conowingo Dam) to 10 mg/L along the Susquehanna River. Along the Susquehanna River, NT SS concentration at the Marietta station upstream of the three lower reservoirs also was much greater (88 mg/L) than the tidal freshwater station.

The greatest SS concentrations were observed at oligohaline stations in this category of tidal rivers (James, Pamunkey, Patuxent, Potomac, and Susquehanna rivers) or at mesohaline stations adjacent to the oligohaline zone (Nanticoke and Rappahannock rivers) (Fig. 5). All rivers in this category also had decreasing TSS concentrations downriver from the peak in or near the oligohaline zone to through the mesohaline and polyhaline zones towards the mainstem of the Chesapeake Bay.

3.4.2. Low and consistent from nontidal through tidal freshwater

Two rivers (Mattaponi and Pocomoke rivers) had consistent SS concentration from NT through the TFZ followed by an oligohaline peak (Fig. 6). Both had low SS concentrations (station averages between 11 and 14 mg/L) in NT and tidal freshwater stations. The Choptank River also had low NT SS concentration (16-21 mg/L), but lacked stations located in the TFZ (Fig. 6). All three rivers had an oligohaline peak (29-40 mg/L), that was followed by a downriver decrease of SS concentration (10-20 mg/L) in the mesohaline zone (Choptank and Pocomoke rivers) or in the polyhaline zone (Mattaponi) of the tidal rivers. All three river watersheds are located entirely or mostly (Mattaponi River) in the Coastal Plain.

3.4.3. Consistent everywhere

Three small Coastal Plain rivers on the Eastern Shore, the Manokin, Sassafras, and Wicomico rivers, had consistent and low average SS concentration across all tidal river stations. These rivers had relatively few stations to analyze downriver trends in sediment, with no NT stations, and these tidal stations encompassed only a portion of salinity gradients. All stations along all three rivers had average SS concentrations ranging from 19 to 26 mg/L.

3.4.4. Decreasing downstream

The Chester River had decreasing sediment concentrations from NT to oligohaline to mesohaline stations (Fig. 6). NT stations had very high average SS concentration (92 and 128 mg/L). No tidal freshwater stations were located along the Chester River, preventing an assessment of SS concentration in that zone.

3.5. Distances between monitoring stations

Both the nearest NT and most upriver tidal stations were located distant from the head-of-tide for some tidal rivers (NOE and Murphy, 2025). The James River nontidal station is the most distant from tide, roughly 70 river km upstream of the head-of-tide. The Mattaponi, Pamunkey, and Pocomoke mainstem nontidal stations all were roughly 30 km upstream of the head-of-tide. In contrast, several NT stations were within 6 km of the head-of-tide. Distances from head-of-tide to the most upriver tidal stations ranged from 0.3 km up to 29 km. The median distances from NT gage to head-of-tide was 7 km, and 10 km from the head-of-tide to the nearest downstream tidal station.

3.6. Differences among sampling depths

The analyses presented to this point were largely data from water samples collected from the surface layer only (typically 1 m deep below water surface) from tidal stations, that excluded samples collected from stratified bottom layers of the water column (collected at some tidal freshwater stations and all oligohaline, mesohaline, and polyhaline stations), but also included whole water column sampling of the generally well mixed water columns of the NT stations. For most rivers, the long-term average SS concentration was slightly greater in the bottom than the surface layer at the most upstream tidal freshwater station that included repeated sampling of both surface and bottom layers (Table 1). For most of these tidal freshwater stations, the bottom layer had 33% greater SS concentration than the surface layer. But at both the James and Potomac rivers the bottom layer had nearly twice the SS concentration in their bottom layer than surface layer. However,

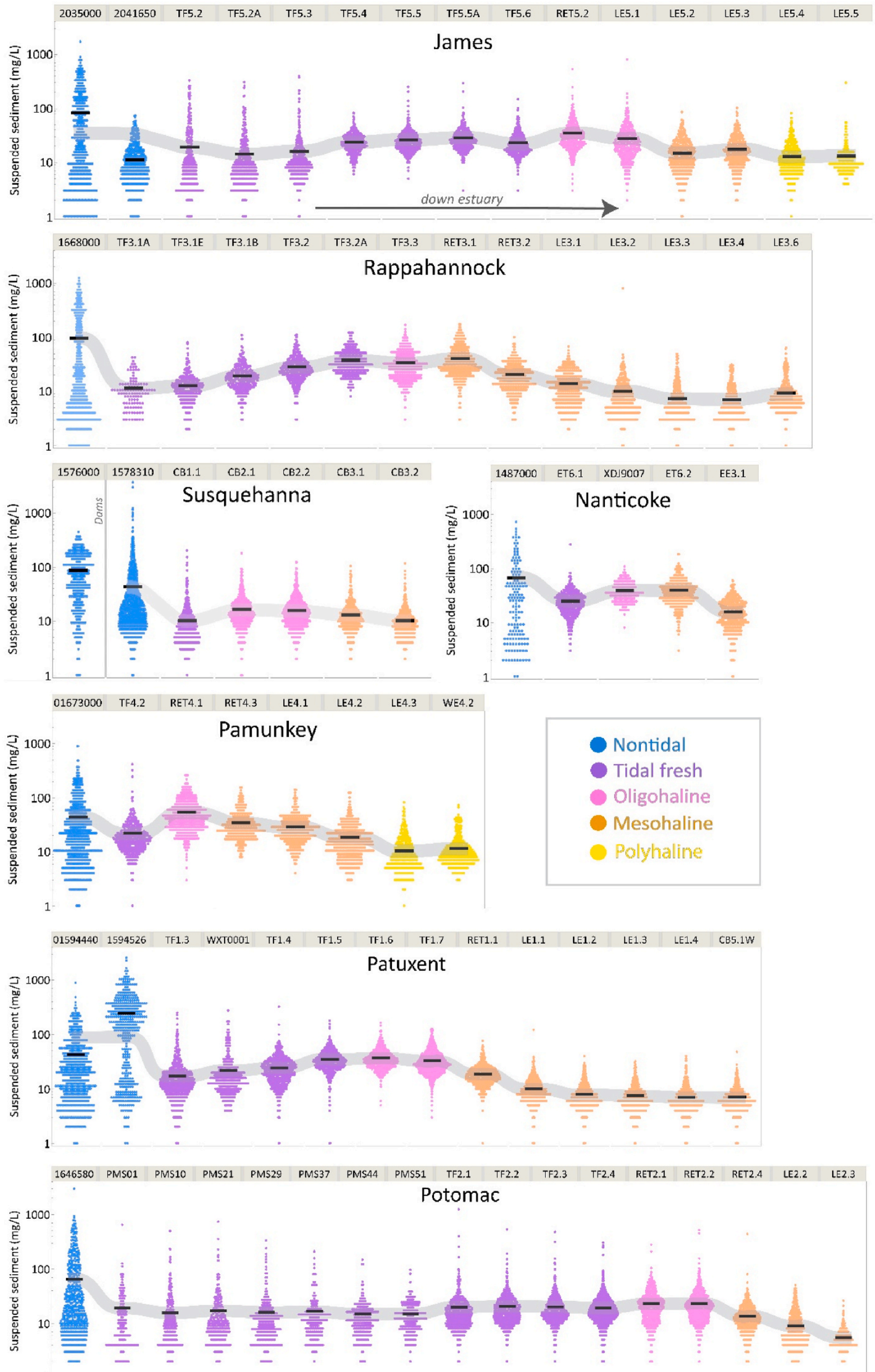

Fig. 5. Downriver changes in concentrations of suspended sediment (SS) samples (log scale) along Chesapeake tidal rivers. Stations along each tidal river are oriented in down-estuary order from nontidal (left; blue symbols), tidal freshwater (purple), oligohaline (pink), mesohaline (orange), and polyhaline (right; yellow), where each is present, based on long-term average salinity. Black lines are the mean of SS concentration at each station. The gray wide line is a visual cue of down estuary change in mean SS concentration. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

average bottom layer SS was still much lower than upstream NT SS concentrations along these two rivers as well at other rivers with greater NT SS concentration. Thus, the TFZ local minimum observations are unlikely an artifact of focusing on analysis of surface layer data only.

3.7. Temporal variation in TSS

The log-transformed distributions of SS concentration over time within each station shows positive skew at most stations, most strongly at NT stations and TFZ stations closer to the head-of-tide (Figs. 5 and 6). The rare occurrence of much greater SS concentrations in both the NT and TFZ suggests that major flood events do transport elevated sediment concentrations into the TFZ and some of those events also reach stations along the lower tidal rivers in the oligohaline and mesohaline zones. However, most measured SS concentrations are much lower than the mean in each station.

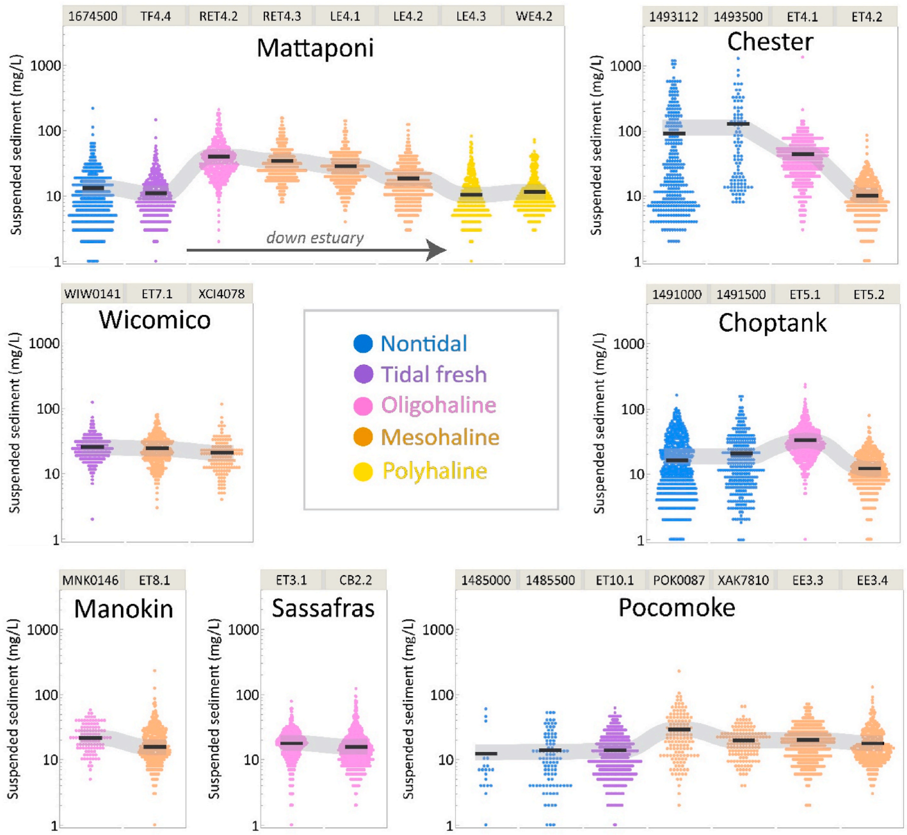

Fig. 6. Downriver changes in concentrations of suspended sediment (SS) samples (log scale) along Chesapeake tidal rivers. Stations along each tidal river are oriented in down-estuary order from nontidal (left; blue symbols), tidal freshwater (purple), oligohaline (pink), mesohaline (orange), and polyhaline (right; yellow), where each is present, based on long-term average salinity. Black lines are the mean of SS concentration at each station. The gray wide line is a visual cue of down estuary change in mean SS concentration. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Average suspended sediment concentrations in the surface and bottom layers of the water column at the most upstream tidal freshwater monitoring station with repeated stratified vertical sampling along Chesapeake tidal rivers, and whole water column suspended sediment concentration at the nearest paired nontidal station. SSC = suspended sediment concentration, TSS = total suspended solids.

River	Nearest nontidal station	Nontidal average SSC (mg/L)	Tidal station	Tidal surface layer (~1 m) average TSS (mg/L)	Tidal bottom layer average TSS (mg/L)	Tidal bottom layer depth (m)
James	02035000 James River at Cartersville, VA	83.8	TF5.2A	14.5	27.6	7.6
Mattaponi	01674500 Mattaponi River near Beulahville, VA	13.3	TF4.4	11.0	14.4	2.9
Nanticoke	01487000 Nanticoke River near Bridgeville, DE	67.1	ET6.1	25.1	32.7	4.1
Pamunkey	01673000 Pamunkey River near Hanover, VA	43.7	TF4.2	22.3	26.1	6.5
Pocomoke	01485500 Nassawango Creek near Snow Hill, MD	14.1	ET10.1	13.3	20.3	5.1
Potomac	01646580 Potomac River at Chain Bridge, at Washington, DC	66.3	TF2.1	20.1	49.4	18.0
Rappahannock	01668000 Rappahannock River near Fredericksburg, VA	96.1	TF3.1E	12.9	18.1	3.2
Susquehanna	01578310 Susquehanna River at Conowingo, MD	43.3	CB1.1	10.3	12.9	4.8

Concurrent (instantaneous) freshwater flow had a mixture of strong and weak positive effects on SSC at NT stations (Fig. 7). NT stations with strong positive effects had larger slopes of the log-log regression of discharge and SSC, as well as greater and increasing SSC at the highest discharges. For example, the Rappahannock River NT station (01668000) had a log-log slope greater than 1 and approximately 1000 mg/L measured SSC at the greatest discharges. In contrast, the Tuckahoe River (01491500; a large tributary to the Choptank River) had a log-log slope less than 0.5 and the greatest SSC measurements were approximately 150 mg/L.

The GAMs of drivers of temporal variation in SS concentration at each tidal station indicate strong downriver changes in the strength and duration of the watershed flow and freshwater effects on tidal station TSS. Watershed flow and freshwater effects on TSS were generally strong and rapid (acute) and positive in upper tidal rivers, particularly in the upriver TFZ, and flow and freshwater effects became weaker and slower

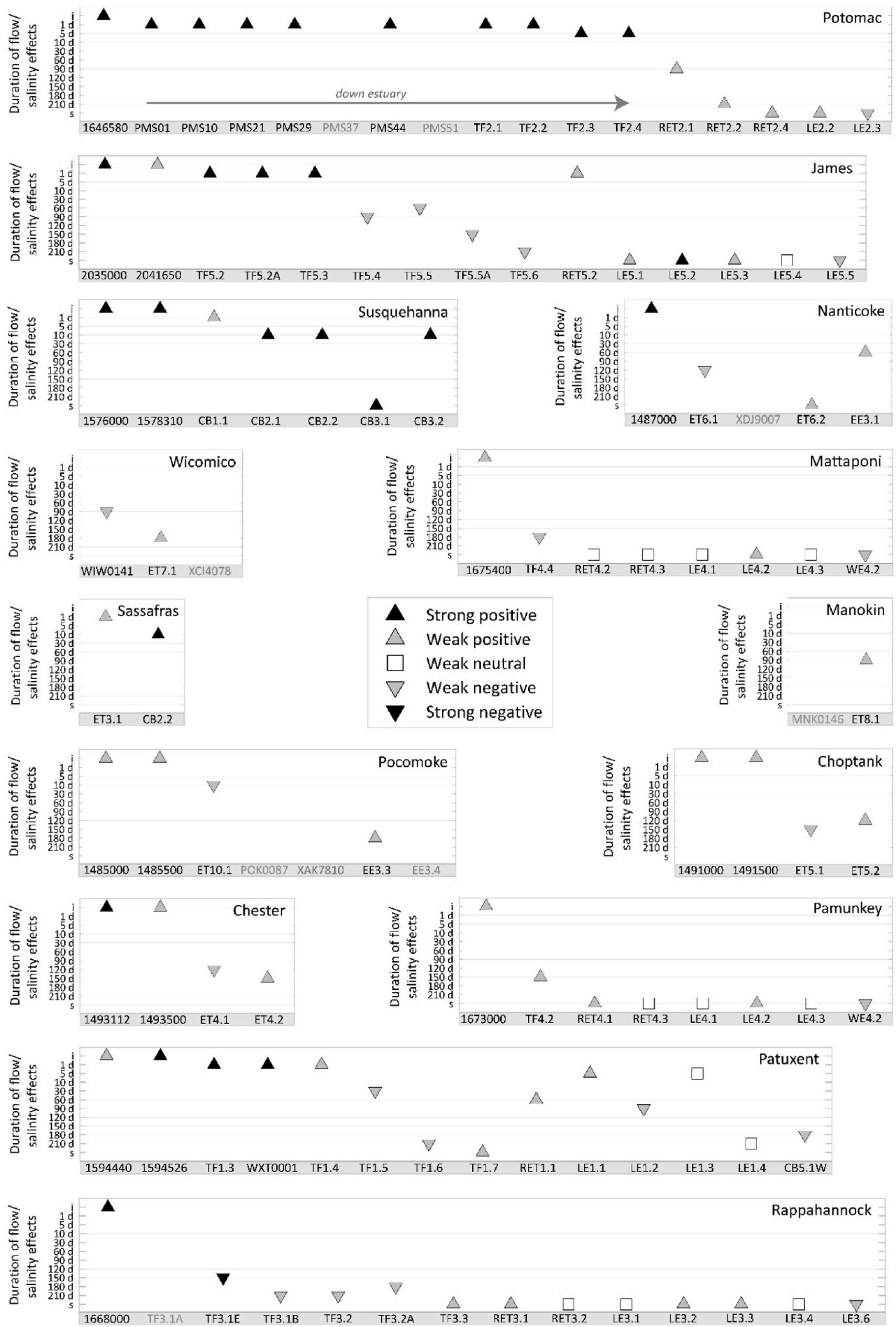

Fig. 7. Generalized additive model (GAM) fitted effects (strength and direction) of freshwater river discharge on total suspended solids (TSS) concentrations at each tidal station, and regression analysis effects of discharge on suspended sediment concentration (SSC) at the nontidal stations, along multiple Chesapeake tidal rivers. The time scale of freshwater effects on tidal stations are shown as the duration of averaged river discharge that led to the best GAM fit. i = instantaneous discharge. s = inverse of salinity. Stations along each tidal river are oriented in down-estuary order from nontidal (left) to the mainstem of the Chesapeake Bay (right) in each graph.

(chronic) and a mixture of positive and negative effects in lower tidal rivers (Fig. 7). For example, temporal variation in TSS at station TF5.2A, in the TFZ of the James River, was best explained by nontidal freshwater discharge averaged over the single day prior to sample collection (Noe and Murphy, 2025) and increased strongly with greater discharge (partial effect plot, Supplemental Fig. 1). Whereas nontidal freshwater discharge effects on TSS at the mouth of the Patuxent River (station CB5.1W) were weakly negative in relation to the average discharge over the prior 180 days.

The tidal freshwater stations nearest to the head-of-tide on the James, Patuxent, and Potomac rivers had TSS best explained by their average NT freshwater input over the past 1 day (Fig. 7). Farther downgradient into the lower tidal freshwater zone along most of the longer and well monitored tidal rivers (James, Patuxent, and Rappahannock rivers, but not the Potomac River), freshwater input effects were aggregated over a longer period of influence and often negatively influencing TSS. For some stations along lower tidal rivers, watershed flow effects were not as predictive of temporal changes in SS concentration as station salinity measured concurrently. Presented as the inverse of salinity in order to represent freshwater influence, these instantaneous effects were most often positive but weak with TSS increasing somewhat with freshwater influence and decreasing with salinity, or neutral for both freshwater influence and salinity. However, freshwater influence had a weak negative effect on temporal variability of TSS of some tidal rivers at the downstream end at the confluence with the mainstem of Chesapeake Bay.

The James River, for example, had strong positive and rapid effects of freshwater discharge at the NT gage (02035000) on SSC at that NT gage as well as TSS at the three tidal freshwater stations nearest to the head-of-tide (TF5.2, TF5.2A, and TF5.3) (Fig. 7). In the lower tidal freshwater James River, freshwater river inputs when averaged over the prior 60 to 210 days were associated with weak decreases in TSS (TF5.4, TF5.5, TF5.5A, TF5.6). The single oligohaline station (RET5.2) had rapid (1 day) but weak positive effects of river freshwater inputs on TSS. The mesohaline (LE5.1, LE5.2, LE5.3) and polyhaline (LE5.4, LE5.5) stations all had their best GAM TSS models utilize station salinity and not river freshwater inputs, and freshwater effects at these stations were a mixture of positive, neutral, and negative effects of strong and weak strength.

The average GAM estimate of change in tidal station TSS from 1999 to 2022 was −2.4 mg/L, or an average 15% decline. Seventy-five percent of tidal stations had a long-term decline in TSS. Long-term percent change in TSS at stations became more negative with increasing average salinity (Pearson product-moment correlation: $r = -0.35$, $p = 0.001$). Nearly all stations where mean long-term salinity exceeded 10 psμ had declining TSS, averaging a 25% reduction over the period of record (Fig. 8). Some stations with less than 10 psμ also had declining TSS trends, however, a large number of these stations instead had increasing TSS over time.

4. Discussion

The extensive long-term monitoring of suspended sediment in the Chesapeake Bay estuary and adjacent nontidal rivers offers a robust opportunity to identify the spatial and temporal patterns of suspended sediment concentration as rivers cross the head-of-tide, through the tidal freshwater zone, and into lower estuaries. Analyses of decades of tidal and nontidal monitoring datasets provides multiple lines of evidence to support the general finding that all tidal rivers of the Chesapeake Bay that had monitoring of the tidal freshwater zone had either a long-term local minimum or low concentrations of suspended sediment concentration in the tidal freshwater zone compared to nontidal or oligohaline stations. The smallest SS concentrations were observed near the upriver head-of-tide along the rivers with multiple tidal freshwater zone stations. Freshwater river inputs had strong positive effects in tidal freshwater zone stations near the head-of-tide but delayed, weak, and often negative effects at tidal stations farther downstream toward the mainstem of the Chesapeake Bay. Low concentrations of SS also occurred at the highest salinities in and near the mainstem of the Chesapeake Bay. These observations suggest that contemporary watershed loads of sediment rarely transport past the tidal freshwater zone into the saline portions of the Chesapeake estuary. This phenomenon has previously been termed a “sediment shadow” (Ensign et al., 2015).

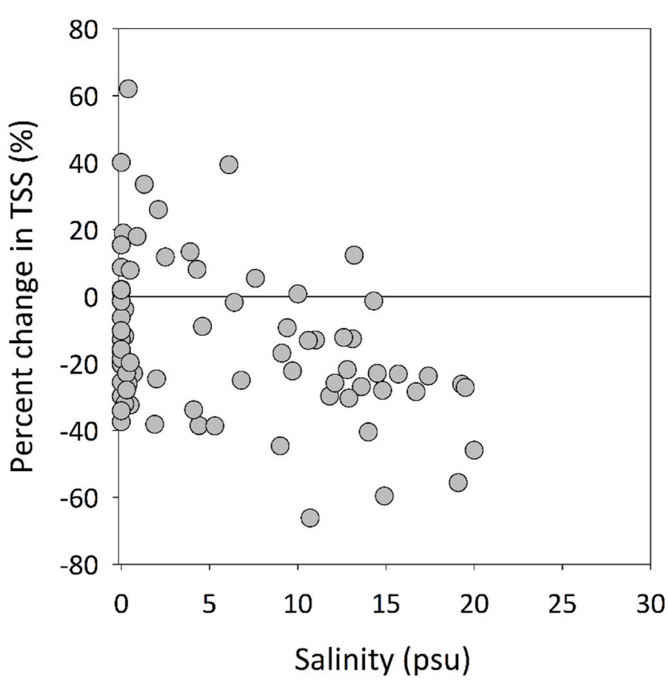

Fig. 8. Long-term trend of percent change in total suspended solids (TSS) concentrations at tidal stations in Chesapeake tidal rivers (as calculated from generalized additive model (GAM) results in relation to station average salinity.

4.1. Changes in suspended sediment along tidal and salinity zones of the estuary

Minimal sediment availability in the TFZ of upper estuaries has been observed elsewhere for both tidal river channel SS concentration as well as floodplain and wetland sediment deposition rates (Darke and Megonigal, 2003; Bukaveckas and Isenberg, 2013; Ensign et al., 2014; Ensign et al., 2015; Hupp et al., 2015; NOE et al., 2016; Ralston and Geyer, 2017; Craft, 2012; Kroes et al., 2023). Most documented examples were located on the U.S. Atlantic Coast Plain, although also in the Hudson River estuary. Dalrymple and Choi (2007) identify low suspended sediment concentrations as typical of river-dominated portions of estuaries. Multiple processes could lead to low sediment availability in the TFZ compared to other zones of the coast and estuaries. Five rivers included in this study also have had measurement of sedimentation rates in riverine wetlands along longitudinal tidal river gradients and had the smallest sedimentation rates occur in tidal freshwater forested wetlands near the head-of-tide (Mattaponi and Pamunkey rivers, Kroes et al., 2023) or in the downriver tidal freshwater zone (Choptank and Pocomoke rivers, Ensign et al., 2015) compared to down estuary oligohaline marshes. In contrast, tidal freshwater marsh had similar rates as oligohaline and salt marshes (Nanticoke River, (Beckett et al., 2016)). Tidal freshwater forested wetlands occur at higher intertidal elevations (Kroes et al., 2023) and likely have less sediment loading from the river channel into the wetland, and therefore less sediment accretion, than tidal freshwater marsh.

The local minimum in sediment availability in the TFZ could be due to hydraulic or geomorphic processes. Hydraulic damming or longer water residence times due to tidal influences near the head-of-tide could lead to high deposition rates. River loads of watershed sediment regularly meet higher tidally driven water level near and above the head-of-tide that can lead to deposition (Phillips, 2024). Tidal flow reversals increase water residence times also leading to deposition and the slowing of river currents in the upper estuary limit erosion (Dalrymple and Choi, 2007). Extensive tidal floodplain wetlands in the TFZ provide large areas for removal of channel loads through sediment deposition (Ensign et al., 2015; Kroes et al., 2023). Opportunity for tidal floodplain wetlands to trap river sediment are being augmented by rising relative sea-levels that increases sediment accommodation space (Rogers, 2021). Upgradient from the head-of-tide along many lowland rivers is extensive nontidal floodplain that can trap large proportions of watershed sediment loads as well (Hupp, 2000; NOE and Hupp, 2009; Craft, 2012; Noe et al., 2022). In addition, dilution could also reduce suspended sediment concentrations in the TFZ. Inputs of low sediment surface water from groundwater inputs or small local tributaries in the TFZ (e.g., Kroes et al., 2023) would decrease sediment concentration measurements. The larger water volume in the river channels of the tidal freshwater zone also could dilute the mass of sediment arriving from the nontidal river upstream and lead to lower sediment concentrations. Development of sediment mass balances using the watershed input sediment loads, wetland sedimentation rates, and areal extent could help confirm the role of river corridor deposition as an important mechanism that generates the sediment shadow.

Although SS concentration was generally low in the TFZ it did increase in response to river freshwater inputs from the watershed. Distributions of TSS concentrations at TFZ stations show positive skew with a few very large TSS measurements much like that of the nontidal stations. In addition, TFZ stations closer to the head-of-tide had quicker and larger increases in TSS with increasing nontidal river discharge. That signal of SS response was delayed and weaker with distance along tidal rivers from the head-of-tide. Similarly, Testa et al. (2019) found that TSS and sediment loading were correlated in low-salinity regions of the Chesapeake Bay, but not in mesohaline and polyhaline regions. Although the loading rate of SS is a useful metric of sediment transport and impact on ecosystems, unfortunately the complex hydrology of tidal waters and unavailability of water velocity and discharge estimates for the CBP long-term tidal monitoring stations preclude calculation of SS loads at the multiple tidal stations along each Chesapeake river.

These temporary increases in TSS are likely due to transport of terrigenic mineral sediment that was eroded from the watershed and transported into the TFZ during storms or eroded from river bed or bank of the tidal river during higher flows, followed quickly by deposition in the TFZ after cessation of the flow pulse. Most of the suspended sediment collected at the nontidal stations is mineral matter and with little organic content. The organic content of suspended sediment can vary spatially and temporally and influence interpretation. On average roughly 94% of SSC is mineral matter in the largest Chesapeake nontidal rivers (assuming 0.5 C/OM ratio; Zhang and Blomquist 2018). In contrast, in portions of the Chesapeake Bay at the highest salinities the TSS is increasingly organic matter derived from phytoplankton (Testa et al., 2019).

Finally, sample collection protocols could miss higher sediment concentrations. Low frequency sampling (such as used by the Chesapeake Bay Program) could miss episodic short events that transport greater sediment concentrations to and through the TFZ. Most of the annual sediment load in nontidal rivers is transported during the largest flood events (Meade, 1982) that may have been largely missed by the CBP's once or twice monthly sampling schedule in the tidal zone, but been apparent during sampling of the oligohaline zone where freshwater discharge effects on TSS are muted. In contrast, water quality sampling at Chesapeake nontidal river stations by the USGS includes multiple storm events annually. In addition, this study focused on the surface layer of tidal river channels. Bottom layers can have higher TSS concentration, as shown in this study at select tidal freshwater stations, as well as by Sanford et al. (2001) in the Chesapeake Bay mainstem. However, the only slightly greater SS concentrations in bottom waters compared to the surface layer of the tidal rivers in the Chesapeake Bay are still much lower than nontidal SS concentrations in most rivers, suggesting that SS was not meaningfully bypassing surface waters of the tidal freshwater zone. Finally, bedload could be an important process to transport sediment in tidal rivers, moving sediment both down and up estuary depending in part on location and flood vs ebb tide dominant transport (Ashley, 1980; Horne and Patton, 1989). Bedload transport has not been measured in the Chesapeake tidal rivers to our knowledge.

Increasing SS concentration downstream through the TFZ was observed at all the tidal rivers with multiple tidal freshwater stations. Interestingly, rivers with substantial increases in TSS downstream through the TFZ have abundant tidal wetlands (James, Patuxent, Rappahannock) whereas the embayed Potomac River with less extensive tidal wetlands only had a slight increase in downstream TSS. A similar pattern occurs in very small Coastal Plain tributaries where embayed tidal channels have lower SS concentrations than wetland dominated planforms (Ensign et al., 2017). The processes that contribute to this pattern of increasing sediment concentrations in lower tidal rivers could include resuspension of subtidal shoals in the lower tidal freshwater zone (Kroes et al., 2023) or riverbank erosion of tidal floodplain wetlands associated with channel widening in response to sea-level rise (Ensign et al., 2017). In addition, proximity to the ETM further downstream could increase suspended sediment.

Peak tidal SS concentrations occurred at salinity of 5 psμ across all tidal Chesapeake monitoring stations, and TSS was greatest in the oligohaline zone, although maximum TSS occasionally occurred at adjacent mesohaline station on a few individual rivers. This ETM is a widespread estuarine phenomenon (Dalrymple and Choi, 2007; Jay et al., 2015). The ETM is often, but not universally, associated with the upstream limit of salt (Jay et al., 2015), including in the Chesapeake Bay (Sanford et al., 2001). The ETM also can move up and down the estuary in response to changes in fluvial sediment and freshwater inputs (Wang et al., 2022). In this study, ETMs in Chesapeake tidal rivers often had a long downriver range from the lower TFZ through the oligohaline and into the mesohaline zones. Average SS concentrations in the lower TFZ also were correlated with those in the oligohaline zone. The ETM forms from multiple processes (Jay et al., 2015), including convergent sediment fluxes as suspended fluvial loads transport downstream and estuarine channel bed fluxes transport upstream to the ETM (Sanford et al., 2001; Dalrymple and Choi, 2007). Benthic resuspension of sediment through higher bed shear stress at the convergence zone leads to greater suspended sediment concentrations (Sanford et al., 2001). Salinity driven flocculation also generates suspended sediment in the ETM (Dalrymple and Choi, 2007). In summary, the presence of the sediment shadow in the tidal freshwater zone does not preclude the presence of an ETM because estuarine sediment can be the source of suspended material in and near the oligohaline zone.

Suspended sediment concentrations in tidal rivers decreased from the oligohaline ETM to downstream into the mesohaline and polyhaline zones and into the mainstem of the Chesapeake Bay. Delivery of contemporary watershed sediment to the lower tidal rivers and mainstem Bay must be infrequent. Instead, erosion of bluffs along the Bay are thought to be the dominant mineral sediment source to most of the mainstem Bay that is downstream of the ETMs (Turner et al., 2021), along with marine sediment near the mouth of the Chesapeake Bay (Newell et al., 2004). Suspended matter is largely derived from phytoplankton biomass, and not mineral sediment, in the mesohaline and polyhaline regions of the Chesapeake Bay (Testa et al., 2019).

4.2. *Implications for Chesapeake Bay and estuarine management*

Like many degraded estuaries around the world, the management of the Chesapeake Bay has emphasized reducing pollutant loading from the watershed to restore the estuary. The Chesapeake Bay Program (CBP) partnership of Federal, State, and local governments and others is responsible for implementing watershed management actions that would reduce downstream sediment loading by 20% to meet the TMDL target (and reduce N by 25% and P by 24%; United States Environmental Protection Agency, 2010). Excessive fine sediment in the Chesapeake estuary is known to negatively impact habitat quality for submerged aquatic vegetation and macrofauna, particularly oyster (*Crassostrea virginica*) (Noe et al., 2020). However, the analyses presented in this paper indicate that under typical contemporary conditions, little upstream watershed sediment is delivered past the TFZs of the many Chesapeake tributaries.

There is little evidence of meaningful long-term delivery of nontidal watershed terrigenic sediment delivery through Chesapeake tidal rivers over past decades, in fact, the rivers with largest sediment loads have TSS local minimum nearest to head-of-tide. The local minimum of SS concentration in the TFZ indicates that little contemporary watershed sediment loading is contributing to the estuarine turbidity maximum, nor does much of the sediment in the ETM get transported further downstream to the lower tidal rivers or the mainstem of the Chesapeake Bay under typical conditions. Similarly, patterns of sediment deposition around the Chesapeake Bay indicate that the upper estuary traps nearly all watershed sediment delivered (Donoghue et al., 1989; Marcus and Kearney, 1991; Sanford et al., 2001). Watershed sediment delivery to estuaries could have been more important in the past. Nontidal river sediment loads were much higher in past centuries due to deforestation and intensification of agriculture after European colonization (James, 2018; Noe et al., 2022). These historically high rates of sediment delivery led to deposition in tidal rivers that formed extensive new wetlands near the heads-of-tide (Pasternack, 2007) and filled river channels around historic colonial port towns (Gottschalk, 1945). The source of elevated TSS in the ETM seems likely to be sediment delivered to the estuary long ago that is being reworked into suspension. Little watershed sediment is thought to be transported through estuaries and to the continental shelf (Meade, 1982).

Much of the nontidal river total phosphorus load is attached to suspended sediment (Zhang et al., 2015). The importance of suspended sediment transport to P dynamics in the Chesapeake estuary (Li et al., 2017) suggests that a similar spatial pattern of watershed P delivery exists. However, mineralization of particulate P leads to an important source of dissolved P that is likely more mobile within the estuary (Li et al., 2017). Relatively little of TN in the Chesapeake's rivers (Zhang et al., 2015) or estuary water column (Boynton et al., 1995) is particulate N attached to suspended sediment.

Some watershed sediment load clearly can be transported far into the estuary during major storms. The CBP tidal monitoring data show rare but very large TSS concentration measurements at most stations along the tidal rivers. Rare massive precipitation from tropical storms and other events is known to generate river floods that transport watershed-derived sediment into the tidal rivers, past the ETM, and into the mainstem of the Chesapeake Bay (Sanford et al., 2001). Hurricane Agnes (1972) and Tropical Storm Lee (1991) are the two most well-known of these storms. Hurricane Agnes generated the largest flood and sediment load of record in the Susquehanna River (Langland and Cronin, 2003) that led to large negative long-term impacts on Chesapeake Bay habitats. However, most of that watershed sediment was deposited (Zabawa and Schubel, 1974) and impacted submerged aquatic vegetation (Orth and Moore, 1984) in the upper Chesapeake Bay. Similarly, most sediment from Tropical Storm Lee was deposited in the upper Chesapeake Bay (Palinkas et al., 2014). Most of the sediment delivered from the Choptank River following the flood of record after Hurricane Irene (2014) was trapped in the upper tidal freshwater zone (Ensign et al., 2015).

For tidal wetlands to persist with sea-level rise, they need deposition of sediment onto the soil surface in addition to organic matter production ((Kirwan et al., 2016)). Ensign et al. (2023) found that contemporary river loads of sediment are generally insufficient for tidal marsh elevations to match relative sea-level rise rates across the U.S. The local minimum of water column sediment availability in the TFZ in this study suggests that tidal freshwater wetlands, in particular, are less resilient to sea-level rise than salt marshes. Low rates of long-term accretion (Craft, 2012) and surface elevation change (Stagg et al., 2016) in tidal freshwater forested wetlands were less than local rates of relative sea-level rise, particularly on the raised hummocks that are critical to woody vegetation and ecosystem services (Krauss et al. 2023). However, tidal freshwater marsh, occupying elevations lower in the tidal frame and further downstream and closer to the ETM than tidal freshwater forested wetlands (Kroes et al., 2023), can have substantial short-term accretion rates (Craft, 2007; Craft, 2012; Neubauer, 2008) and surface elevation change rates at or above relative sea-level rise rates (Cadol et al., 2014; Beckett et al., 2016).

4.3. Conclusions

Analysis of long-term monitoring data generated several insights into sediment transport from the watershed into the Chesapeake Bay, that are likely relevant in other lowland estuaries as well. The tidal freshwater zone consistently has a “sediment shadow” shown by a local minimum in suspended sediment concentrations in the river channel (this study) or sediment deposition in intertidal wetlands (other studies). Little contemporary watershed sediment load has apparently been transported past the TFZ over the past decades except during extreme floods when some sediment may be delivered to saline portions of the estuary. Similarly, freshwater inputs from nontidal rivers have diminishing influence on tidal suspended sediment with distance downstream from the head-of-tide. These findings have implications for efforts to reduce sediment delivery to the Chesapeake Bay by implementing management actions throughout the watershed. Few long-term declines in watershed sediment loads in rivers of the region have been observed (Noe et al., 2020), and here we found that tidal freshwater and brackish portions of the estuary have variable trends in TSS concentration over time. However, the more saline downstream ends of tidal rivers and the mainstem of the Chesapeake Bay have had a consistent 25% decline in total suspended solids over the past decades. The spatial pattern of the TSS trends also suggest that tidal marshes of the tidal freshwater, mesohaline, and polyhaline regions of the Bay likely have insufficient sediment availability to maintain elevation relative to sea-level rise.

CRediT authorship contribution statement

Gregory B. Noe: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Rebecca R. Murphy:** Formal analysis, Methodology, Writing – review & editing. **Ken W. Krauss:** Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecss.2026.109931.

Data availability

Data has been published on ScienceBase: https://doi.org/10.5066/P14AJH9J.

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