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Key Points:

- Suspended sediment concentration (SSC) and accretion are not indicators of marsh stability
- Flood-ebb SSC differential is a suitable indicator of sediment transport direction
- Organic to inorganic SSC ratio is an indicator of relative marsh degradation

Supporting Information:

- Figures S1–S4 and Tables S1 and S2

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Sediment transport-based metrics of wetland stability

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Abstract Despite the importance of sediment availability on wetland stability, vulnerability assessments seldom consider spatiotemporal variability of sediment transport. Models predict that the maximum rate of sea level rise a marsh can survive is proportional to suspended sediment concentration (SSC) and accretion. In contrast, we find that SSC and accretion are higher in an unstable marsh than in an adjacent stable marsh, suggesting that these metrics cannot describe wetland vulnerability. Therefore, we propose the flood/ebb SSC differential and organic-inorganic suspended sediment ratio as better vulnerability metrics. The unstable marsh favors sediment export (18 mg L^{-1} higher on ebb tides), while the stable marsh imports sediment (12 mg L^{-1} higher on flood tides). The organic-inorganic SSC ratio is 84% higher in the unstable marsh, and stable isotopes indicate a source consistent with marsh-derived material. These simple metrics scale with sediment fluxes, integrate spatiotemporal variability, and indicate sediment sources.

1. Introduction

Coastal wetlands are vulnerable to sea level rise and anthropogenic disturbance [*Gedan et al.*, 2009; *Kirwan and Megonigal*, 2013; *Deegan et al.*, 2012; *Weston*, 2014]. Their vulnerability is related to mineral sediment availability because marshes build vertically in part due to deposition on the marsh surface [e.g., *Allen*, 2000; *Friedrichs and Perry*, 2001; *Day et al.*, 2011; *Thorne et al.*, 2014], but net sediment input is also critical to maintain the geomorphic planform of tidal channels, intertidal flats, and the marsh plain under conditions of sea level rise and lateral erosion [*Fagherazzi et al.*, 2012, 2013; *Mariotti and Fagherazzi*, 2013]. However, attempts to quantify these dependencies are challenging, and relationships between suspended sediment concentration (SSC) and wetland vulnerability are generally weak [*French*, 2006; *Ensign et al.*, 2014]. Vertical accretion decreases across a vegetated marsh with distance from the rivers and tidal channels supplying sediment [e.g., *Friedrichs and Perry*, 2001], but measurements of SSC exhibit large spatiotemporal variability [*Christiansen et al.*, 2000; *Temmerman et al.*, 2003]. *Reed* [1995] concluded that regional-scale predictions of wetland evolution are likely inaccurate due to the diverse sediment transport mechanisms in tidal and estuarine environments.

Numerical models and quantitative assessments of wetland geomorphology have long attempted to use SSC to quantify marsh vulnerability [e.g., *French*, 1993, 2006; *Allen*, 1994; *Kirwan et al.*, 2010; *Stralberg et al.*, 2011; *Fagherazzi et al.*, 2012]. Point-based (0-D) models simplify sediment dynamics by assuming that the evolution of marshes far from channels can be modeled using a single, spatially constant SSC [*Mudd et al.*, 2004, 2009; *Marani et al.*, 2007; *Kirwan et al.*, 2010]. Spatially explicit models coarsely model [*D'Alpaos et al.*, 2007] or impose [*Temmerman et al.*, 2003; *Kirwan and Murray*, 2007] a spatially variable SSC within the channel-marsh complex but do not attempt to treat variance in SSC through time. Neither approach allows for erosion to lead to local changes in SSC [*Mariotti and Fagherazzi*, 2010; *Mariotti and Carr*, 2014], and full conservation of mass requires computational effort that precludes long-term (decadal) spatial modeling of wetland evolution. These limitations are critical because each model predicts a strong dependence between the maximum rate of sea level rise that a marsh can survive and a specific time-averaged or spatially averaged SSC. Assessments that use such an approach cannot account for the spatiotemporal complexities of sediment transport nor feedbacks between marsh stability and SSC.

Numerous studies have quantified the role of sediment fluxes to wetland sustainability [e.g., *Settlemyre and Gardner*, 1977; *Stevenson et al.*, 1985, 1988; *Suk et al.*, 1999]. *Ganju et al.* [2013] documented the sediment budgets of two contrasting wetland systems adjacent to Chesapeake Bay, along the Blackwater and

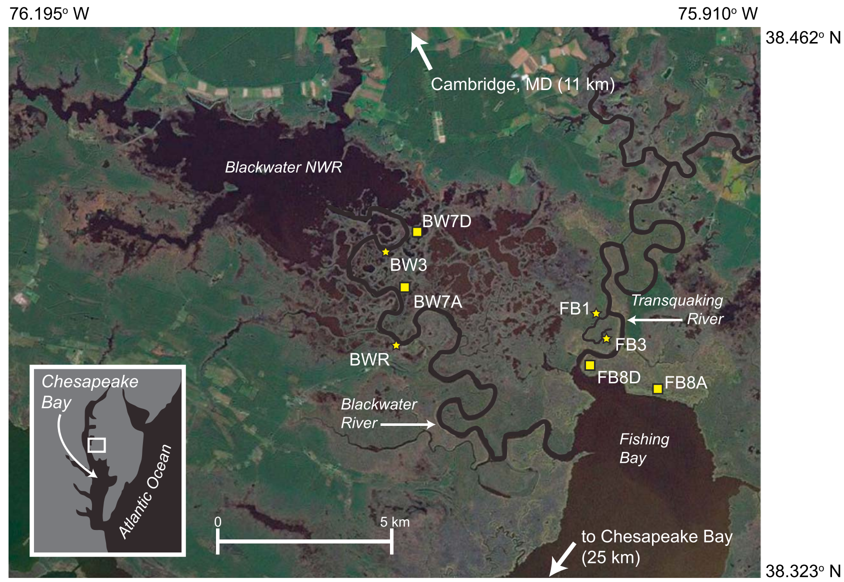

Figure 1. Study area, on the eastern side of Chesapeake Bay, USA. Sites with boxes are accretion measurement locations, sites with stars are SSC measurement locations.

Transquaking Rivers. Using continuous sediment flux measurements in tidal channels, they demonstrated the importance of tidal and subtidal sediment transport processes: northwest winds led to sediment resuspension and subtidal water export in the Blackwater system, while tidal transport led to sediment import in the Transquaking system. That study suggested that stability may be inferred by the sediment budget of a system: an unstable system may export sediment in response to numerous factors (e.g., marsh dieback, open water expansion, and destabilization of marsh edges), while a stable system must import sediment to maintain the geomorphic planform of channel, flat, and marsh plain under conditions of sea level rise. In this study we explore the measurements of SSC and accretion to determine if they are suitable stability indicators. We find that while mean SSC and accretion are higher in the rapidly deteriorating marsh system (Blackwater) than the adjacent stable system (Transquaking), other metrics suggest instability: the flood-ebb SSC gradient and the organic to inorganic suspended sediment ratio in the tidal channels. These findings demonstrate that linking sediment transport and wetland stability requires a more integrative approach that connects accretion rates, net elevation change, suspended sediment source and transport, and geomorphic adjustment of the wetland complex.

2. Methods

2.1. Site Description

We occupied sites in two wetland complexes on the eastern shore of Chesapeake Bay, centered on the Blackwater and Transquaking Rivers (Figure 1). Wetlands along the Blackwater River, mainly within the Blackwater National Wildlife Refuge (NWR) have undergone rapid disintegration over the last century, due to grazing by invasive rodents, subsidence, sea level rise, and shoreline erosion [*Stevenson et al*., 1985; *Kearney et al*., 1988; *Ganju et al*., 2013]. Conversely, wetlands along the Transquaking River have maintained stability during the same period, while importing sediment at a rate equivalent to sea level rise [*Kearney et al*., 2002; *Ganju et al*., 2013]. Vegetation and stratigraphic characteristics of the study sites are similar. Both sites consist of thin, organic-rich facies overlying terrestrial clastic sediment reflecting marshes formed by drowned uplands and are dominated by *Spartina patens* and *Schoenoplectus americanus* [*Stevenson et al*., 1985; *Hussein*, 2009; *Kirwan and Guntenspergen*, 2012]. Riverine sediment supply to both complexes is minor due to limited watershed yield and low river flows. Tidal range is approximately 1 m at our Transquaking River sites and less than 20 cm at our Blackwater River sites [*Ganju et al*., 2012; *Kirwan and Guntenspergen*, 2015]. The tide is attenuated as it propagates landward; the farther landward distance of the Blackwater sites leads to a reduced tide range. The historical rate of relative sea level rise in Cambridge, MD, on the Choptank River is 3.48 mm/yr over the years 1943–2006. (http://www.tidesandcurrents.noaa.gov/sltrends/sltrends.shtml).

Sites in the Blackwater River complex included two locations for SSC (BWR and BW3) and two locations for accretion measurements (BW7A and BW7D). Site BWR was located adjacent to the marsh edge within the Blackwater River approximately 20 river km landward of Fishing Bay and the Transquaking River sites; site BW3 was located adjacent to the marsh edge in a small channel 150 river m from the Blackwater River. Sites BW7A and BW7D were situated on the marsh plain adjacent to the Blackwater River. Sites in the Transquaking River complex included two locations for SSC (FB1 and FB3) and two locations for accretion (FB8A and FB8D). Site FB1 was located adjacent to the marsh edge in a tidal creek 250 river m landward from the confluence with the Transquaking River and 4 river km landward of Fishing Bay; site FB3 was in a second-order tidal creek 2 river km farther landward of site FB1. Site FB8A was located 1 km from Fishing Bay in a small tidal creek, while site FB8D was located at the confluence of Fishing Bay and the Transquaking River.

2.2. SSC Measurement and Analysis

Point time series of turbidity at 10 min intervals were collected with a combination of YSI 6600 water quality sensors with optical turbidity probes (BWR and FB1) and Wet Labs Eco BBSB optical backscatter sensors (BW3 and FB3) between 22 March 2011 and 12 May 2011 and 20 September 2011 and 7 December 2011 [*Ganju et al*., 2012, 2013]. Site BWR was not occupied during the spring deployment. Sensors were mounted near channel edges, at 0.35 m above the bed in over 1 m of water at all sites. Bottle samples for suspended sediment concentration (SSC) [*American Public Health Association* (*APHA*), 1995] were collected on 14 occasions during the deployment for calibration [*Ganju et al*., 2013]. Comparison of samples between sites and tidal conditions showed no noticeable bias. Tidal velocities were measured with acoustic profilers during the fall deployment only [*Ganju et al*., 2012, 2013].

SSC spectral density was calculated using the WAFO toolbox for MATLAB [*Brodtkorb et al*., 2000]. The dominant M_2 tidal period is 12.42 h, which means that mechanisms corresponding to a single tidal direction (flood or ebb) or water level (high or low) will demonstrate coherence on this time scale. Coherence at 6.21 h indicates mechanisms that correspond to both flood and ebb directions and/or both high and low water. Wind data from Cambridge, MD, (NDBC site CAMM2, http://www.ndbc.noaa.gov) were retrieved to assess the influence of wind on SSC.

2.3. Suspended Sediment Composition

All SSC samples from each wetland complex were processed for organic content (via loss on ignition, LOI) [*APHA*, 1995] while a subset was processed for carbon and nitrogen isotopic analysis. Eight SSC samples from each site were analyzed for carbon and nitrogen content and stable isotope ratios at the Ecosystems Center Stable Isotope Laboratory. Isotope standards were calibrated against National Institute of Standards and Technology Standard Reference Materials; the long-term standard deviation is 0.2‰ for ^{13}C, and carbon results are expressed relative to Vienna Peedee belemnite.

2.4. Accretion Measurements

Vertical accretion (i.e., sediment deposition and erosion) was measured to the nearest millimeter from cryogenic cores [*Cahoon et al*., 1996] taken through a soil marker horizon (MH) laid on the marsh surface [*Cahoon and Turner*, 1989]. Eight MH plots (0.50 m × 0.50 m) were installed in the summer of 2005 at each site and measured seasonally through 2008 and once a year through 2011. Average vertical accretion rates were calculated using simple linear regressions using the pooled replicate MH plot data from each site for 6 years. Elevations relative to NAVD88 were determined using a Trimble R8 Global Navigation Satellite Systems model 3 Real Time Kinematic GPS at each site. The relationship between NAVD88 and mean sea level across this region was previously determined during a height modernization survey of these marsh complexes in 2005 by the National Geodetic Survey and was found to be close to zero, varying on the order of 13 cm. Accretion rates typically overestimate changes in salt marsh elevation since they do not incorporate the effects of shallow subsidence [*Cahoon et al*., 1995], though the two metrics are often similar [*Cahoon et al*., 2000; *Lovelock et al*., 2014]. For simplicity, we therefore report accretion rather than elevation change because our focus is specifically on sediment transport, and the link between SSC and wetland vulnerability.

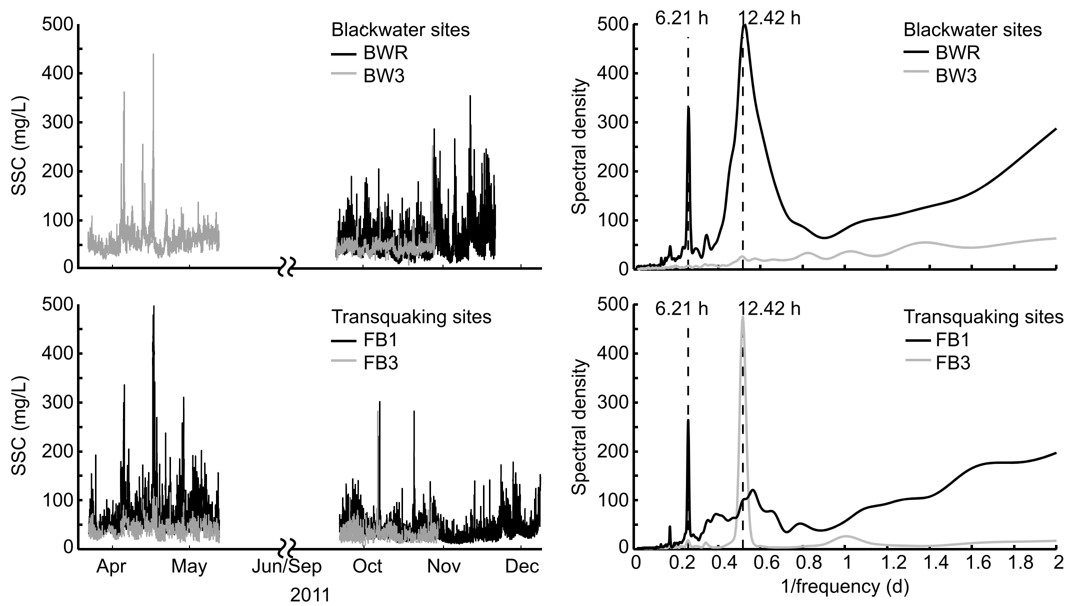

Figure 2. (left column) SSC time series and (right column) spectral density from (top row) Blackwater River sites and (bottom row) Transquaking River sites. Coherence at 6.21 h corresponds to flood and ebb tidal advection, coherence at 12.42 h indicates correspondence with either flood or ebb tidal advection. In this case, the large 12.42 h peak at BWR corresponds with ebb tide advection, while the large 12.42 h peak at FB3 corresponds to flood tide advection.

3. Results

3.1. SSC Statistics and Spectra

The highest peak and mean SSC were observed at site BWR on the Blackwater River, which drains the open water expanse of Blackwater NWR (Figure 2 and Table 1). The lowest peak and mean SSC were observed at site FB3, at the landward end of a second-order tidal creek off the Transquaking River. The flood-ebb differential in SSC was most noticeable at these sites, with ebb tide SSC 20% greater than flood tide at site BWR and flood tide SSC almost 100% greater than ebb tide at site FB3. Overall, the instantaneous SSC values measured in our study (5–400 mg L^{-1}) are similar to previous measurements near the BWR site (22–260 mg L^{-1}) [*Stevenson et al*., 1985]. Spectra between spring and fall deployments contained the highest energy at the same frequencies at all sites (except BWR which was not occupied during the spring deployment).

SSC spectra from site BW3 showed little coherence on tidal or subtidal time scales, likely due to a lack of channelization and integration of water masses from throughout the open water/marsh system (Figure 2). However, the more channelized site BWR demonstrated strong coherence on the 6.21 and 12.42 h time scales, corresponding to resuspension and subsequent flood and ebb tidal advection within the river, as it drained the majority of the complex. While coherence of SSC at site BWR is largely due to tidal advection, the relative magnitude of SSC is clearly a function of wind speed and direction (supporting information Figure S1). Northerly winds increase SSC over the open water area of Blackwater NWR through a combination of bed resuspension and erosion of marsh edges along creeks and interior ponds [*Ganju et al*., 2013]. Site FB1 showed coherence on both the 6.21 and 12.42 h time scales as well, while site FB3 contained the highest

Table 1. Suspended Sediment Concentration (mg/L) Statistics for the Fall 2011 Period (Mean Values From Combined Spring and Fall Deployments in Parentheses)[a]

Site	Mean SSC	Mean SSC Flood	Mean SSC Ebb	Flood/Ebb Differential
BWR	63	54	72	−18
BW3	41 (52)	42	41	+1
FB1	39 (55)	41	36	+5
FB3	28 (33)	34	22	+12

[a]Flood and ebb were separated using continuous velocity measurements at sites BWR and FB1.

energy on the 12.42 time scale, related to resuspension and subsequent flood tide advection of sediment from marine sources and an estuarine turbidity maximum in the main stem of the Transquaking River [*Ganju et al*., 2013]. The spring and fall deployments captured the passage of several frontal systems, spring-neap tidal cycles, and freshwater flow events from the Chesapeake Bay watershed (likely responsible for increased SSC in spring). In comparison, most prior work linking SSC and accretion in wetland systems has been limited to sporadic coverage of individual tidal cycles [*Reed et al*., 1999; *Davidson-Arnott et al*., 2002; *Darke and Megonigal*, 2003].

3.2. Suspended Sediment Composition

Organic matter content in suspended sediment and its carbon stable isotope ratio provide additional information regarding sediment sources in salt marsh systems [*Chen et al*., 2015]. Analysis of 37 samples from each complex indicated substantially higher organic mass per unit inorganic mass for samples within the Blackwater system, with a difference of nearly a factor of 2 between the sites (supporting information Figure S2). In a subset of those samples ($n = 8$ for each site), analysis of carbon and nitrogen content supports the LOI results, with average %C and %N 49% and 40% greater, respectively, in samples from the Blackwater sites (supporting information Table S2). *Stribling and Cornwell* [1997] documented stable isotopic composition for a range of primary producers in a nearby tidal creek system; carbon stable isotope ratio (δ^{13}C per mil) in samples from both of the sites suggests dominance of a C3 plant source ($-25.3 + 0.3$, Blackwater; $-24.9 + 0.8$, Transquaking). Given the relative lack of upland sediment and minimal contribution from marine phytoplankton in winter, we interpret the source as autochthonous particulate organic matter from eroded substrates dominated by C3 plants such as *Schoenoplectus americanus*, which is a prevalent species within both complexes [*Kirwan and Guntenspergen*, 2015]. It is important to note that decomposition of older material sourced from C4 plants (e.g., *Spartina patens*), phytoplankton contributions, and large spatial variability within marsh substrates may complicate this interpretation [*Chen et al*., 2015], but the similarity in isotopic ratios and therefore assumed organic matter source between sites allows for direct comparison of organic to inorganic mass ratios.

3.3. Accretion Rates

Total accretion over the 2005–2011 period averaged 0.04 m at the Blackwater sites and 0.03 m at the Transquaking sites. Mean accretion rates were higher at the Blackwater River sites than the Transquaking River sites, though variability between plots was higher at the Transquaking River sites (supporting information Table S1). Several factors, including higher SSC, may be responsible for this pattern. The Blackwater River sites are at a lower elevation relative to mean sea level than the Transquaking River sites (supporting information Table S1), closer to tidal creeks and inundated twice as frequently in the fall of 2011. Therefore, marshes in the degrading Blackwater River complex are more likely to trap suspended sediment from the tidal channel during high tides and are actually accreting faster than the more stable Transquaking River complex.

4. Discussion

4.1. Instability, SSC, and Accretion

For more than 30 years, static measures of SSC and accretion have been used to identify threshold rates of sea level rise a marsh can survive in order to assess vulnerability [*DeLaune et al*., 1978; *Stevenson et al*., 1986; *French*, 2006; *Kirwan et al*., 2010; *Fagherazzi et al*., 2012]. However, our measurements of rapid accretion and high SSC along the Blackwater River do not match the historic degradation of these wetlands. Instead, elevated SSC at Blackwater River sites likely arise from wind wave resuspension over the submerged wetland plain and intertidal flats at the base of marsh edges, and wave attack on vertical marsh faces (e.g., interior marsh ponds) within Blackwater NWR [*Ganju et al*., 2013]. *Stevenson et al*. [1985] report high rates of marsh loss at Blackwater NWR between 1938 and 1979, suggesting that these wetlands are out of equilibrium with historical rates of sea level rise. The continued conversion of intertidal vegetated wetland to a subtidal non-vegetated sediment bed releases an internal sediment source that is creating the impression of stability as determined by high SSC and rapid surface accretion in portions that remain intertidal.

Comparisons of SSC and accretion would errantly imply that the Blackwater River complex is more stable than the Transquaking River complex. Correctly gauging the potential for sediment deposition and its effect on vulnerability requires accounting for the proximity of external sediment sources and the strength and frequency of transport mechanisms, because the sediment budget of salt marsh systems determines

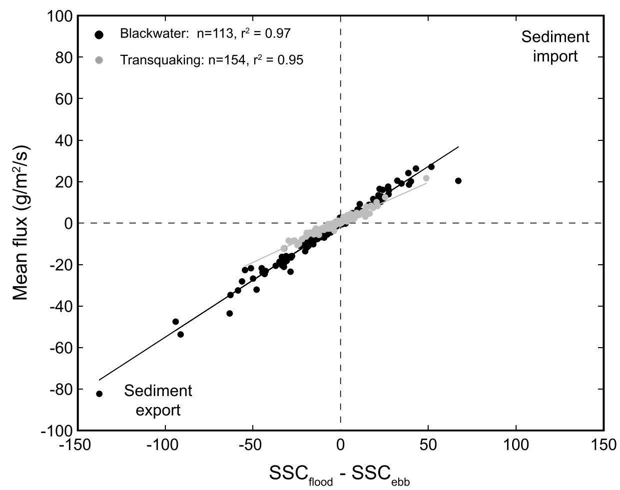

Figure 3. Mean sediment flux per unit channel area from *Ganju et al*. [2013] versus flood-ebb SSC differential. Fluxes and SSC from sites BWR and FB1 were averaged over 12 h windows; SSC measurements were time weighted to account for any differences in flood/ebb duration.

their fate even in the absence of sea level rise [*Fagherazzi et al*., 2013]. Numerical models, for example, would be improved by distinguishing internal from external sediment sources [*Ganju et al*., 2013]. Our results also suggest that SSC are likely now higher at the Blackwater River complex than they were before widespread erosion began. Thus, it is possible that existing models can predict vulnerability before the collapse/erosion begins. *Kirwan et al*. [2010] use various SSC values from several wetland systems to estimate threshold rates of sea level rise; this approach is susceptible to ignoring both spatiotemporal variability and the source of the sediment (i.e., external versus internal).

4.2. Toward Improved Sediment Transport-Based Metrics

Despite the difficulty of collecting continuous time series of SSC, it is imperative to properly parameterize sediment supply [*Suk et al*., 1999]. Resampling of our time series demonstrates that periodic measurements or short-term intensive sampling can lead to substantial error. For example, if SSC at site BWR was sampled once daily over our study period, the error in mean SSC approaches 20% and gives no information on tidal variability. Short-term intensive sampling (e.g., a sample every 10 min for 24 h) is also problematic as the period chosen may not be representative of the mean condition: the standard deviation of 24 h mean SSC at site BWR is 30 mg/L, almost 50% of the mean value. Sediment mobilization and transport mechanisms largely control this variability, and knowledge of the mechanisms can aid in sampling strategy. This is difficult in a system such as Blackwater, where episodic events are the dominant forcing thereby requiring seasonal continuous monitoring. In systems like the Transquaking, where tidal processes dominate, sampling over multiple tidal, spring-neap, and seasonal cycles may be sufficient.

Continuous monitoring at multiple locations within a site offers useful diagnostic metrics for evaluating sediment supply without deployment of an entire sediment flux measurement system (Table 1 and Figure 3). The difference between mean SSC over flood tides versus ebb tides, differentiated by flow direction, over seasonal-to-annual time scales captures sediment transport variability without more intensive flux measurements. Exporting systems will demonstrate a large, negative flood-ebb differential in mean SSC (site BWR), while importing systems will demonstrate a large, positive differential (site FB1). These differentials scale linearly with prior sediment flux measurements which require substantially more effort to collect [*Ganju et al*., 2013]. The flood-ebb differential distils terms in the sediment flux decomposition [*Geyer et al*., 2001; *Ganju and Schoellhamer*, 2006] by accounting for correlations between velocity direction and sediment concentration. In lieu of continuous sediment flux measurements, we suggest that the flood-ebb differential in SSC may be useful as an initial proxy for wetland stability. It is imperative that this metric is quantified in systems with a relatively balanced water flux over spring-neap time scales (overall flow imbalance $<$4% at sites FB1 and BWR), because large imbalances may indicate alternate flow pathways. Nonetheless, the net sediment budgets presented by *Ganju et al*. [2013] were relatively insensitive to the flow imbalance. Of greater import is inherent tidal asymmetry: the predictive capability of the flood-ebb SSC gradient requires that mean SSC values for a given tidal phase are time weighted by the duration of the tidal phase (over 12 h averaging windows). Removal of time weighting (i.e., assuming flood and ebb were of identical duration) reduced correlations between the flux and SSC gradient significantly (from $r^2 = 0.97$ and 0.95 to 0.82 and 0.72 for BWR and FB1, respectively; supporting information Figures S2 and S3). Tidal asymmetry due to remote wind forcing leads to unbalanced flows over time scales $<$1 week [*Ganju et al*., 2013] and requires time weighting of the SSC metric, but over longer time periods (i.e., spring-neap cycle) ignoring time weighting is reasonable as flood and ebb tidal flows should be balanced.

An additional comparative metric is the slope of organic to inorganic suspended sediment relationship (supporting information Figure S4). For a given inorganic suspended sediment concentration, the Blackwater system has nearly twice as much organic mass in suspension (38% versus 23% of inorganic mass in the spring, 35% versus 19% in the fall). The slightly higher slope in the spring likely reflects increased introduction of decomposed marsh material when aboveground biomass and trapping are reduced, though marine contributions (i.e., phytoplankton) may also be responsible for the larger slope. In the systems studied here, the discrepancy in organic content likely represents differential erosion of marsh substrate, as the largest external source of inorganic mineral sediment is identical (i.e., Chesapeake Bay via Fishing Bay) [*Ganju et al.*, 2013]. Though prior studies have shown differential seasonal transport of the inorganic and organic fractions in tidal marsh channels [*Settlemyre and Gardner*, 1977; *Dankers et al.*, 1984], we observed no significant correlation between transport direction and organic-inorganic ratio; and therefore, the transport of the individual fractions followed the net transport direction. This ratio should be used in a relative sense, for comparing sites of similar vegetative type, productivity, and inorganic sediment source. These sites also benefit from a short tidal excursion: systems with longer tidal excursions and/or more exchange with far-field sources may have less clear relationships.

5. Conclusions

We found that suspended sediment concentrations and surface accretion rates are higher in a rapidly deteriorating wetland complex (Blackwater River) than an adjacent stable complex (Transquaking River), challenging the notion that SSC and accretion can be used in simple ways to predict wetland vulnerability. In the Blackwater River complex, large open water areas allow wind energy to increase SSC and enhance accretion, likely through internal scavenging of the submerged former marsh plain and exposed marsh edges; this process is manifested in a negative flood-ebb SSC differential. The adjacent Transquaking River complex displays lower SSC and accretion but benefits from external sediment supply from external sources demonstrated by a positive flood-ebb SSC differential. In both systems, the flood-ebb SSC differential scales linearly with mean sediment flux and is a suitable indicator for net sediment transport. We also find that organic content of suspended sediment is higher in the deteriorating complex and indicates a marsh-derived source. These results highlight that wetland vulnerability must be evaluated in the context of spatially complex interactions between physical and biological processes rather than on point-based measurements of sediment concentration or vertical accretion. There is a clear need for more long term, integrated, synchronous measurement of processes on the marsh plain (two-dimensional information on accretion and elevation change) and within the channels (flood-ebb differentials in sediment transport) to adequately assess current and future wetland vulnerability. These metrics are a step toward that direction.

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