Estuaries and Coasts (2025) 48:104
https://doi.org/10.1007/s12237-025-01524-1

Estuarine Sediment Dynamics and the Importance of Storms in Moving (and Removing) Mud

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Received: 5 March 2024 / Revised: 12 March 2025 / Accepted: 15 March 2025

Abstract
Studies of sedimentation in low-elevation coastal zones often focus on long-term average sediment accumulation rates. Although decadal and centennial sedimentation rates are key to understanding resilience to relative sea-level rise, they overlook short-term (often seasonal or shorter) fluctuations that complicate impacts on ecosystems. Using a combination of field observations and hydrodynamic model results, we examined event- to seasonal-scale sediment dynamics and deposition rates in the Coos estuary, Oregon, a small, strongly forced system representative of estuaries along the U.S. Pacific Northwest coast. During rainfall events, peaks in turbidity are followed by up to 3 cm of mud deposition on tidal flats in the middle and upper estuary. Meanwhile, little or no deposition (0–1 cm) occurs in the lower estuary. The spatial pattern of sedimentation on tidal flats is consistent across timescales (event to centennial) but is inconsistent with sedimentation patterns in higher-elevation marshes. Whereas deposition on tidal flats in the middle and upper estuary occurs 2–3 times faster than deposition in the lower estuary, deposition in marshes appears to be slowest in the middle estuary. After a storm, the sediment deposited on tidal flats in the middle and upper estuary is reworked on the scale of weeks to a month and thus is not preserved in the long-term record. Projected climate-driven increases in the frequency and intensity of rainstorms will likely increase event-driven peaks in turbidity, bed stress, and sediment deposition, heightening the importance of short-term events as drivers of long-term estuary change from both ecological and sedimentological perspectives.

Keywords Sediment accretion · Erosion · Estuary · Storm dynamics · Beryllium-7

Introduction

Globally, people rely on low-elevation coastal zones and their ecosystem services for economic, cultural, and ecological benefits (Barbier et al., 2011; Milcu et al., 2013; Zapata et al., 2018). Key estuarine habitats including eelgrass beds and oyster reefs serve as nursery habitat for juvenile fish and shellfish and a food source for migratory birds, while also dampening storm energy, trapping sediment, filtering water, and protecting against erosion (Grabowski & Peterson, 2007; Nordlund et al., 2016). While low-elevation coastal zones provide irreplaceable ecosystem services, they are also threatened by climate change and continued anthropogenic modification (FitzGerald & Hughes, 2019). Construction of infrastructure and maintenance of shipping channels often involves dredging, diking, and filling of coastal wetlands (Borde et al., 2003; Eidam et al., 2020). Depending on harvest method, the cultivation of commercial oysters and, to a

Communicated by Paul A. Montagna.

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lesser extent, recreational clamming can disturb eelgrass beds in the intertidal zone (Boese, 2002; Tallis et al., 2009). Climate change drives accelerated sea-level rise (Fox-Kemper et al., 2021), more frequent marine heat waves (Oliver et al., 2018), more extreme rainfall (Min et al., 2011), increased erosion (Zhang et al., 2004), and more frequent sedimentation events (Inman & Jenkins, 1999).

In many low-elevation coastal zones, sediment supply is a key driver of vertical accretion and directly impacts the ability of wetlands to keep pace with relative sea-level rise (RSLR; Mariotti et al., 2020; Peck et al., 2020). Many modern wetlands are vulnerable to submergence due to a combination of RSLR and low sediment supply (e.g., Blum & Roberts, 2009). Over short timescales, however, a sufficiently high sediment supply sometimes allows wetlands to accrete faster than accommodation space is created through RSLR (Gunnel et al. 2013; Peck et al., 2020). Periods of high short-term sedimentation occur naturally due to seasonal variation in depositional conditions (Woodruff et al., 2001) and events such as storms and tsunami (Cheng et al., 2013; Morales et al., 2008). Anthropogenic increases in sediment supply are commonly driven by activities such as logging and agriculture, and increases in estuarine turbidity are caused by dredging-induced resuspension (Gunnell et al., 2013; Rodriguez et al., 2020). Note that other anthropogenic activities such as damming and some watershed management strategies can reduce sediment supply (e.g., Verstraeten et al., 2003; Yang et al., 2005). Together, these anthropogenic activities alter natural processes of sediment redistribution (Van Maren et al., 2015) and produce sedimentation patterns different from those that occur under unmodified conditions (e.g., Avoine et al., 1981; Eidam et al., 2021; Nitsche et al., 2007).

U.S. Pacific Northwest estuaries are particularly sensitive to change because they typically have steep elevation gradients that leave little room for wetlands to migrate when faced with relative sea-level rise (Thorne et al., 2018). Coastal ecosystems are squeezed into narrow elevation zones bounded by competing marine, terrestrial, and human forces. Here, we focus on the Coos estuary (Fig. 1), an estuary on the U.S. Pacific Northwest coast that is strongly forced by river flow, tides, and wind, and is representative of the small systems typical of the region (Sutherland & O'Neill, 2016). Although small (54 km^2) in comparison to the Columbia River (330 km^2), Puget Sound (2600 km^2), and San Francisco Bay (4100 km^2) estuaries, the Coos estuary is one of the larger estuaries on the U.S. west coast and plays an outsized role in the economic, cultural, and ecological health of the region. It is home to diverse and sometimes competing interests including the largest deep-draft coastal port between San Francisco Bay and Puget Sound, one of Oregon's largest commercial fishing fleets, and the federally protected South Slough National Estuarine Research Reserve (SSNERR).

When evaluating the vulnerability of low-elevation coastal zones to relative sea-level rise and other stressors, studies of sedimentation often focus on decadal- to century-scale averages (e.g., Thorne et al., 2018; Törnqvist et al., 2021). Less is understood about the variability and impacts of short-term sediment dynamics, which operate over timescales relevant to many ecological processes (e.g., seasonal growth and reproduction). In this paper, we seek to fill this knowledge gap by investigating event- to seasonal-scale patterns of sediment movement in the Coos estuary. We propose the following three hypotheses: first, rainfall events in the Coos watershed correspond with peaks in turbidity and sediment deposition; second, in intertidal areas, storm-deposited sediment is largely re-eroded in the weeks following the storm; and third, short-term deposition exceeds both the long-term (century-scale) sedimentation rate and the local rate of RSLR. To address these hypotheses, we combine data from sediment cores collected approximately monthly for 13 months with long-term water quality monitoring data and hydrodynamic model output. Our work suggests that storms are an important driver of variable estuary sedimentation and erosion. While long-term mean sedimentation rates appear slow and steady, the magnitude of event and seasonal deposition and erosion can be substantial and may impact species abundance and distribution patterns in native ecosystems.

Methods

Study Area

The Coos estuary is located on the southern Oregon coast (Fig. 1), an area characterized by a mild climate with relatively dry summers and wet winters. Situated near an active continental margin undergoing tectonic uplift (Burgette et al., 2009), the estuary experiences a slower rate of relative sea-level rise (RSLR) than the global average. Based on tide gauge data from 1970 to 2022, the long-term rate of RSLR at Charleston, near the mouth of the estuary, is 0.1 ± 0.064 cm/year (NOAA, 2024). Due to spatial variability in uplift rate, RSLR ranges from ~0.06 cm/year at the coast to ~0.19 cm/year near the city of Coos Bay (Burgette et al., 2009; Eidam et al., 2024). The main source of freshwater and sediment is the Coos River (Fig. 1), which has highly seasonal discharge that ranges from an average of 3.2 m^3/s in the dry season (June through October) to an average of 32 m^3/s in the rainy season (November through May; Marin Jarrin et al., 2022), with peak discharge events reaching as high as 400 m^3/s (Coos Watershed Association, 2022). Semi-diurnal tides have a maximum range of 2.3 m

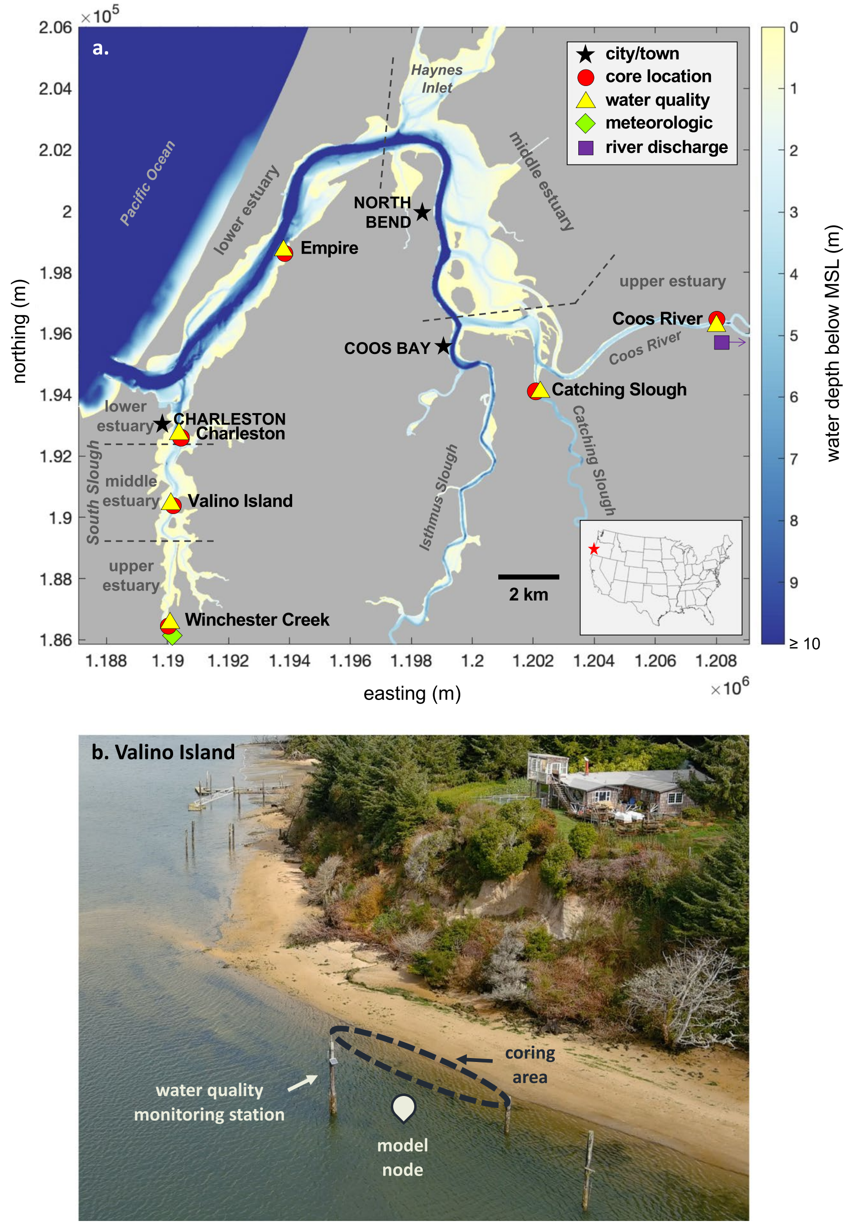

Fig. 1 **a** Location of the Coos estuary on the southern coast of Oregon, USA. Coring locations (red circles), water quality monitoring stations (yellow triangles), and the meteorology station (green diamond) are shown. River discharge (purple square) is measured on the South Fork Coos River 26.5 km upstream from the Coos River coring site. **b** Drone image of the Valino Island coring location. The ellipse (~ 11 m in length) indicates the extent of the sediment coring area. Note the proximity of both the Valino Island water quality monitoring station and the nearest hydrodynamic model node. Bathymetry data are from Conroy et al. (2020), with water depths below mean sea level (MSL). Drone image is from Dean Walton, University of Oregon Libraries

(NOAA, 2024). The main channel runs from the mouth of the estuary to the city of Coos Bay and is dredged to a depth of 14.3 m (USACE, 2023). In contrast to the heavily modified main channel, much of the southwestern branch of the Coos estuary has been protected since 1974 as the South Slough National Estuarine Research Reserve (SSNERR). South Slough is undredged except for the lowermost 2 km (Charleston to the estuary mouth, see Fig. 1), and is generally shallower (~ 5.5 m maximum depth in undredged areas near the mouth of the slough; Eidam et al., 2020). Freshwater enters South Slough through > 30 intermittent waterways and six perennial streams, the largest of which is Winchester Creek. Freshwater discharge through Winchester Creek is an order of magnitude less than through the Coos River: discharge ranges from < 0.2 m^3/s during the dry season to an average of ~ 1.1 m^3/s during the rainy season with peaks of > 2.8 m^3/s during storm events. The differences between the main estuary and South Slough in terms of geometry, sediment and freshwater input, and land use history set up an opportunity for comparison: these differences may drive variation in the magnitude and spatial pattern of sedimentation.

In the main estuary, sediment is primarily routed from the Coos River down the dredged navigation channel (Eidam et al., 2021). While the channel in the lower estuary is sandy and typically erosive (aside from the over-deepened navigation channel, which is a sediment sink and requires maintenance dredging), the upper channel (which also requires regular dredging) and shallow areas throughout the estuary are characterized by trapping of mud and muddy sand. Hydrodynamic modeling suggests that mud deposition primarily occurs during wintertime high discharge events, despite corresponding increases in bed stress, and occurs particularly in areas proximal to sediment sources (i.e., the Coos River and main tributaries in South Slough; Eidam et al., 2021). An estuarine turbidity maximum (ETM) is commonly present in the main channel between the northern bend of the estuary and the city of Coos Bay, and in South Slough surrounding Valino Island (see Fig. 1 for locations). Both ETMs are observable year-round but are notably stronger in the winter (Eidam et al., 2021).

South Slough and the Coos estuary are home to two key native species likely affected by short-term sedimentation. Both Olympia oysters (*Ostrea lurida*) and eelgrass (*Zostera marina*) have experienced complex histories of abundance, collapse, and restoration efforts with mixed results. Although shell deposits indicate the presence of a sizeable population of Olympia oysters in Coos Bay prior to European arrival, the species was not observed in the estuary at the time of European settlement in the 1850s (Groth & Rumrill, 2009). Leading hypotheses suggest that the oysters were decimated by a heavy sedimentation event resulting from either an 1846 wildfire in the Coos watershed (Dimick et al., 1941) or the 1700 subduction zone earthquake and tsunami (Nelson et al., 1996). Olympia oyster tolerance to burial depends on duration and grain size, with fine-grained sediment being more problematic than sand (Wasson et al., 2015). Accumulation of mud hinders oyster feeding and respiration (Thrush et al., 2004; Wasson et al., 2015). Beginning in the 1980s, a few living Olympia oysters were found in Coos Bay and small, localized populations became established by the 1990s. However, targeted attempts to reintroduce the oysters to South Slough have been unsuccessful (Kornbluth et al., 2022; Larsen et al., 2014; Office for Coastal Management, 2023).

Eelgrass, another foundation species in the Coos estuary, grows in marine intertidal and shallow subtidal environments throughout Pacific Northwest estuaries (Sherman & DeBruyckere, 2018), where it provides critical food and shelter to fish, invertebrates, and birds (Hughes et al., 2014; Phillips, 1984). Between 2014–2016, however, the eelgrass population in areas of South Slough collapsed (Marin Jarrin et al., 2022). Although this collapse and previous population declines have been linked to increases in water temperature (Marin Jarrin et al., 2022; Thom et al., 2003), eelgrass survival is also affected by short-term sediment dynamics through plant burial (Mills & Fonseca, 2003), bed scour and uprooting (Marion & Orth, 2012), turbidity (Magel et al., 2023), and the attenuation of light (Thom et al., 2008). However, eelgrass also benefits from some amount of sediment deposition. While Mills and Fonseca (2003) found that burial of eelgrass to only 25% of its shoot height (~ 4 cm) resulted in > 50% mortality, others have shown that burial of seeds to 2–3 cm prevents seeds from washing away (Marion & Orth, 2012), reduces seed predation (Fishman & Orth, 1996), and improves rates of seedling establishment (Marion & Orth, 2012).

Data Sources

To study short-term sediment dynamics in the Coos estuary, we combined data from newly collected sediment cores, long-term water quality and meteorologic data, and hydrodynamic model simulations. Field sites are shown in Fig. 1 and data sources are summarized in Table 1.

Sediment Core Collection and Analysis

Short (10 cm) sediment cores were collected at six sites around the Coos estuary including three in South Slough (Winchester Creek, Valino Island, Charleston) and three in the main estuary (Coos River, Catching Slough, Empire). See Fig. 1 and Table 1 for site locations and characteristics. Coring sites were selected to capture geographic variability across the estuary, to target areas where the presence of mud facilitated the use of ^{7}Be as a radioisotopic tracer, and to be near established long-term water quality monitoring stations.

Over the course of 13 months (February 2021–March 2022), between 4 and 11 cores were collected at each site. During fall, winter, and spring, coring dates were generally spaced ~ 1 month apart in time. No cores were collected during the dry season (July–Oct) when little rainfall, low river discharge, and lack of storms were expected to yield relatively stable sediment conditions. Cores were collected in the intertidal zone at low to mid-tide using a 15-cm length of aluminum irrigation pipe with a diameter of ~ 10 cm. The pipe was pushed by hand into the sediment and dug out with a trowel. Core sectioning occurred in the field or in the SSNERR Estuarine and Coastal Science (ECOS) lab within 24 h in the case of inclement weather. Sediment was extruded in 1 cm intervals, bagged, and sent to the Coastal and Fluvial Sediment Dynamics Lab at the University of North Carolina (UNC) at Chapel Hill for analysis.

In the UNC lab, sediment samples were freeze dried for > 48 h. Once dry, each sample was analyzed for grain size distribution and presence of newly deposited sediment. Grain size distribution was measured using a Bettersizer laser diffraction particle sizer, with two replicate analyses per core interval. Newly deposited sediment was defined as sediment with measurable ^{7}Be activity (e.g., Sommerfield et al., 1999), a naturally occurring radioisotope with a half-life of 53 days. To measure ^{7}Be activity, sediment samples were sieved into fine (≤ 63 μm) and coarse (> 63 μm) components. The fine fraction underwent gamma spectroscopy

Table 1 Site name, data type(s), location, and source for field data used in this analysis. Names in parentheses are the specific locations near Winchester Creek and Valino Island where sediment cores were collected. Elevations are given in m above mean sea level (MSL). CTCLUSI is the Confederated Tribes of Coos, Lower Umpqua, and Siuslaw Indians

Site name	Data type(s)	Number of cores	Mean elevation above MSL (m)	Eelgrass or oysters?	Latitude (°N)	Longitude (°E)	Monitoring data availability	Data source
Winchester Creek (Kunz Marsh)	^{7}Be depth (cm) grain size (µm)	9	+ 6.8	none	43.2824	− 124.3205		- This study
	turbidity	-	-		43.2824	− 124.3203	1995–present	SSNERR
Valino Island (Crown Point)	^{7}Be depth (cm) grain size (µm)	11	− 0.1	eelgrass	43.3172	− 124.3215		- This study
	turbidity	-	-		43.3172	− 124.3216	1999–present	SSNERR
Charleston	^{7}Be depth (cm) grain size (µm)	10	+ 0.3	eelgrass, oyster shells	43.3373	− 124.3198		- This study
	turbidity	-	-		43.3377	− 124.3205	2002–present	SSNERR
Coos River	^{7}Be depth (cm) grain size (µm)	7	+ 1.4	none	43.3785	− 124.1048		- This study
	turbidity	-	-		43.3771	− 124.1033	2013–present	SSNERR
Catching Slough	^{7}Be depth (cm) grain size (µm)	7	+ 1.2	none	43.3550	− 124.1762		- This study
	turbidity	-	-		43.3528	− 124.1731	2013–present	SSNERR
Empire	^{7}Be depth (cm) grain size (µm)	4	− 0.1	eelgrass	43.3929	− 124.2806		- This study
	turbidity	-	-		43.3943	− 124.2805	2007–present	CTCLUSI
South Fork Coos River	River discharge	-	-	N/A	43.3763	− 123.9581	2003–present	Coos Watershed Association
Tom's Creek	Precipitation	-	-	N/A	43.2791	− 124.3184	2016–present*	SSNERR

*From 2001 to 2015, meteorological data were collected at a station in Charleston, 7.4 km north of Tom's Creek

for 24–48 h using a Canberra broad-energy germanium crystal well detector.

Monitoring Data Synthesis

We compiled publicly-accessible turbidity, precipitation, and river discharge data measured over the duration of our study period (January 1, 2021–March 30, 2022) at long-term monitoring stations around the Coos estuary (Fig. 1, Table 1). Note that our study period represents a small subset of the period of monitoring at these sites. Turbidity measurements were from water-quality sensors at six stations, each adjacent to one of our sediment coring locations. Precipitation data were collected at the Tom's Creek meteorological station in South Slough. River discharge data were from a gauge on the South Fork Coos River, which is the primary source of freshwater to the Coos estuary.

Turbidity data were filtered using a uniform cap of 250 formazin nephelometric units (FNU) to remove anomalously high values, resulting in removal of ≤ 0.6% of the raw data per site. As part of the National Estuarine Research Reserve System's quality control and quality assurance process, turbidity data are flagged for biofouling (when obvious); those flagged data have been excluded from this analysis (NOAA NERRS 2019). Under typical (non-event) discharge conditions, turbidity in the Coos estuary is generally < 30 FNU (< 50 mg/L) and may spike to ~ 60 FNU (~ 100 mg/L) during high discharge events (Eidam et al., 2021). After anomalous values were removed from the data, a Godin filter was applied to remove the influence of daily tides (Godin, 1972; Thompson, 1983). Note that the turbidity sensors used in this study are optical instruments and thus responsive to the way light is scattered in the water column but not to the specific grain size distribution of suspended sediment. In a study area with heterogeneous sediments (such as the Coos estuary), identical turbidity measurements may represent different suspended sediment concentrations (e.g., Bright et al., 2020).

Hydrodynamic Model Simulation

Output from an existing hydrodynamic model of the Coos estuary was used to explore spatial and temporal variability in sediment characteristics (see Conroy et al., 2020 and

Eidam et al., 2020 for model setup and parameters). The model was developed using the finite-volume community ocean model (FVCOM) and has a horizontal grid spacing of ~ 15 m in the estuary's main channels. For comparison, channel width ranges from 30 m at Winchester Creek (100 m including the intertidal area) to 570 m at Empire (900 m including the intertidal area). The model includes freshwater input from 14 rivers and creeks, has an open boundary at the ocean with tidal forcing, and allows wetting and drying of intertidal areas. Sediments were modeled using five size classes (fine mud to coarse sand) and five vertical layers in the bed. Fluvial sediments were modeled as mud and fine mud (to mimic flocculated and unflocculated muds, respectively). The model was previously evaluated using a combination of long-term monitoring data and targeted field measurements of water level, turbidity, bed grain size distribution, and salinity (Conroy et al., 2020; Eidam et al., 2020, 2021).

For the present analysis, two model scenarios with idealized forcing conditions were evaluated (Fig. 2; Eidam et al., 2021). The first run simulated winter conditions with a steady river discharge of 40 m^3/s (Fig. 2, blue lines). The second run included a simulated winter storm event, where river discharge increased over two days from 40 m^3/s to a peak of 400 m^3/s, and then gradually returned to background flow over seven days (Fig. 2, orange lines). Both scenarios were modeled to occur over a spring-neap tidal cycle with the spring tide coinciding with peak river discharge in the event case. Fine-grained sediments were introduced based on a rating curve of turbidity versus river discharge (Eidam et al., 2021). Bed stress and sediment characteristics including bed level, median grain size, and sand fraction were assessed at the model nodes closest to each coring location and within the intertidal zone (see Fig. 1 for an example node location) over 30 model days surrounding the modeled storm event.

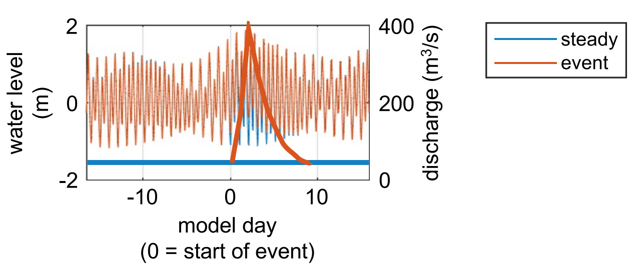

Fig. 2 Timeseries of modeled water level (thick lines) and Coos River discharge (thin lines) during typical winter conditions ("steady," blue) and high river discharge conditions ("event," orange) at the Coos River study site

Results

Observations of Event- to Seasonal-Scale Hydrodynamics and Sediment Movement

In the Coos estuary, river discharge responds quickly to precipitation in the watershed (Fig. 3a). Rainfall of at least 5–50 mm per day for multiple days commonly leads to discharge spikes wherein river flow increases by up to an order of magnitude over a few days before rapidly returning to background conditions (e.g., early January 2021, early January 2022). Sustained high-discharge rates lasting longer than a few days are rare and were not observed during our study period. Estuary turbidity is dominated by the daily tidal cycle, with the highest turbidities typically occurring during ebb and low tide. Tidally filtered turbidity (Figs. 3b and 4b) is largely controlled by the spring-neap tidal cycle, which drives higher turbidity during spring tides and lower turbidity during neap tides (for figure clarity, non-tidally filtered turbidity data are not shown). This pattern is particularly prominent at Coos Bay sites (Coos River, Catching Slough, Empire; Fig. 4b). River discharge events also increase turbidity by two to sevenfold over background levels, depending on location in the estuary (Figs. 3b and 4b). For example, high discharge in early January 2021 doubled turbidity at Winchester Creek (Fig. 3b) and Catching Slough (Fig. 4b). The discharge peak in January 2022 produced the highest turbidity observed during the study period at Coos River. Event-driven spikes in turbidity are more prominent in upper estuary sites (Winchester Creek, Coos River). Turbidity generally decreases with distance down-estuary. Note that some spikes in turbidity do not align with peaks in river discharge (e.g., Charleston in late June 2021) and may be caused by biofouling of the sensor, which occurs quickly during warm summer months, or by macrophytes blocking the sensor.

During the study, the delivery of new sediment to the estuary during the rainy season resulted in deposition of up to 3 cm of mud in a month (e.g., January 2022 at Valino Island, Fig. 3c; November 2021 at Coos River, Fig. 4c; January 2022 at Coos River, Fig. 4c; see Figs. S1–S6 for ^{7}Be profiles and interpretation). Upper and middle estuary sites in both South Slough and the main estuary tended to experience more sediment accretion. Deposition occurred during both high and low river discharge but was more substantial when discharge was high (e.g., February 2021 and January 2022 at Valino Island). Half (3 of 6) of the instances of ≥ 2 cm of new sediment deposition were associated with discharge peaks ≥ 100 m/s within the prior 10 days (February 2021 at Valino Island and January 2022 at Valino Island and

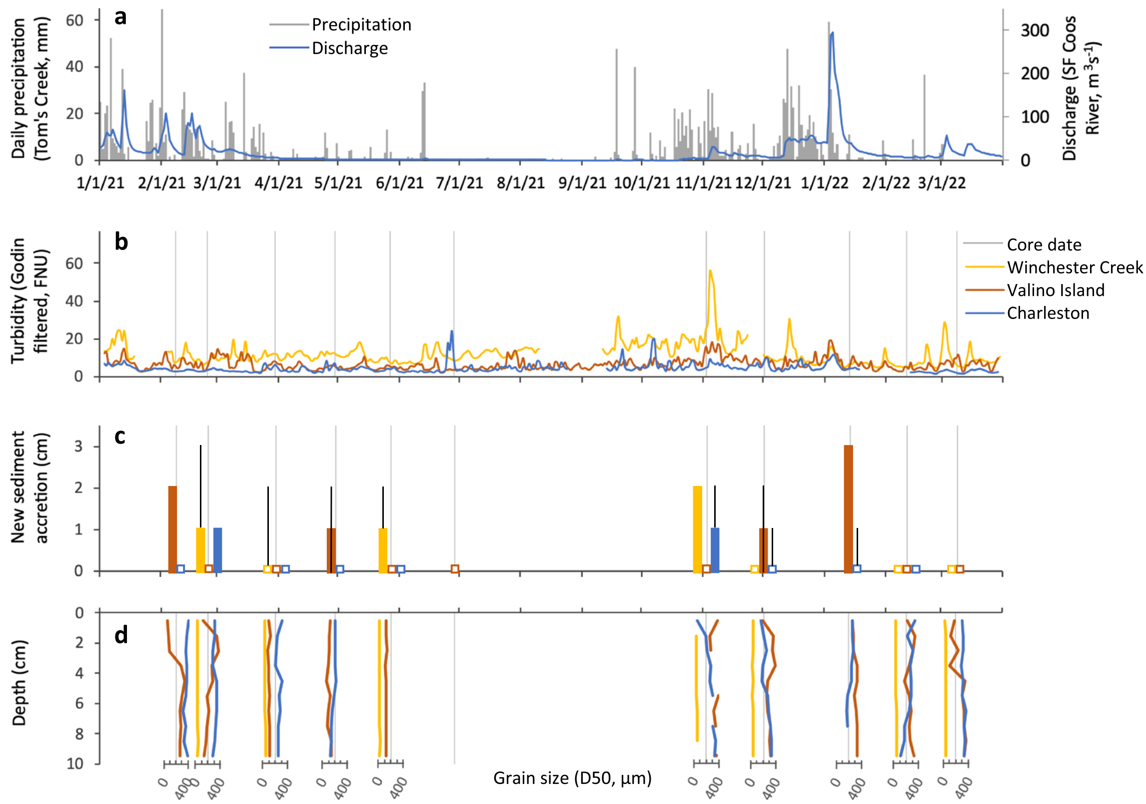

Fig. 3 Timeseries of hydrological and sediment observations in South Slough, including daily precipitation at the Tom's Creek meteorological station and South Fork Coos River discharge (**a**), turbidity (**b**), new sediment accretion (**c**), and median grain size profiles (**d**). In panels **b–d**, core collection dates are indicated by vertical grey lines. In panel c, open squares represent cores showing no new sediment accretion; absence of a marker indicates that either a core was collected but had insufficient fine-grained material for ^{7}Be analysis, or no core was collected. Also in panel c, vertical black bars represent uncertainty in the magnitude of new sediment accretion. See Figs. S1–S6 for ^{7}Be profiles and interpretation, and Fig. S7 for grain size profiles grouped by coring location

Catching Slough). The other half were associated with the first sustained period of rainfall in the fall following the dry summer season (November 2021 at Winchester Creek, Coos River, and Catching Slough).

Valino Island, Catching Slough, and Coos River, all of which are less than the distance of one tidal excursion below the mouths of major tributaries (5–14 + km, depending on tidal flow rate; Sutherland & O'Neill, 2016; Eidam et al., 2020), appeared to be hotspots for deposition. Although downward mixing of ^{7}Be could result in an overestimation of deposition, observation of high surficial ^{7}Be activity (~ 10 dpm/g) sandwiched between observations of little or no surficial ^{7}Be activity in the months before and after (Fig. 5) suggested limited time for bioturbation and other processes to induce mixing. Based on the range of plausible deposition thicknesses, our best estimates are generally conservative (Figs. S1–S6).

Lower-estuary sites (Charleston, Empire) experienced less deposition (up to 1 cm per month), and tended to be out of sync with deposition peaks observed at sites farther up-estuary (Figs. 3c and 4c). Note that two lower estuary cores (Empire, January 2022; Charleston, March 2022) had insufficient fine-grained material to allow analysis of ^{7}Be, our indicator of newly deposited sediment. It is possible that these two cores contained newly deposited coarse-grained sediment that was not observed because of the lack of analyzable material.

Beryllium-7 was commonly not observed in cores collected the month after an observed deposition event (Fig. 5), suggesting that newly deposited sediment was eroded within this timeframe. Erosion must have been particularly rapid in middle and upper estuary sites to regularly remove 2–3 cm of newly deposited sediment in less than one month. At each site, monthly cores were collected within a ~ 20 m reach of shoreline at approximately the same elevation, so differences in deposition and erosion were not likely due to spatial variation.

Newly deposited sediment was generally silt-sized and, at coarser-grained sites, sometimes resulted in a fine-grained layer at the bed surface (e.g., February 2021 at Valino Island, Fig. 3d; November 2021 at Charleston,

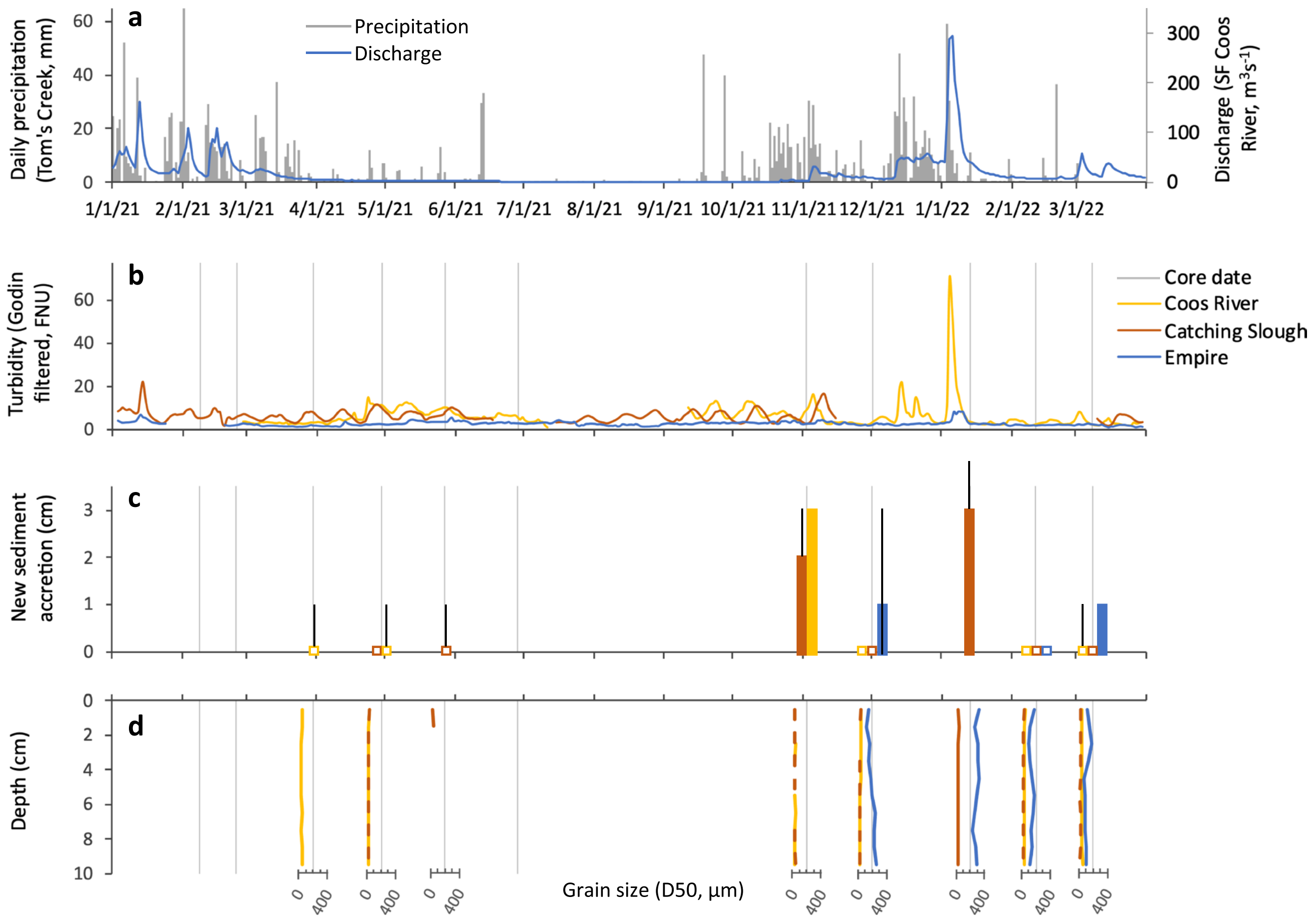

Fig. 4 Timeseries of hydrological and sediment observations in Coos Bay, including daily precipitation at the Tom's Creek meteorological station and South Fork Coos River discharge (**a**; duplicated from Fig. 3 for comparison), turbidity (**b**), new sediment accretion (**c**), and median grain size profiles (**d**). In panels **b–d**, core collection dates are indicated by vertical grey lines. In panel c, open squares represent cores showing no new sediment accretion; absence of a marker indicates that either a core was collected but had insufficient fine-grained material for ^{7}Be analysis, or no core was collected. Also in panel c, vertical black bars represent uncertainty in the magnitude of new sediment accretion. See Figs. S1–S6 for ^{7}Be profiles and interpretation, and Fig. S7 for grain size profiles grouped by coring location

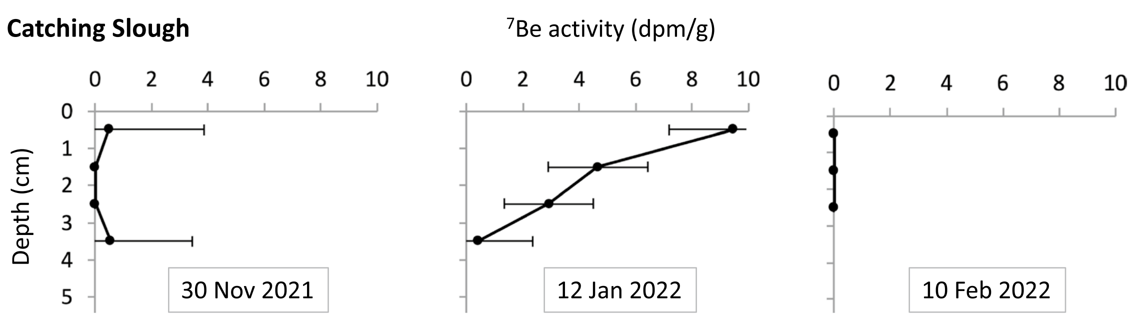

Fig. 5 Example ^{7}Be profiles at Catching Slough. In late November 2021 (left), the near-zero activity of ^{7}Be indicates no recent sediment deposition. In mid-January 2022 (middle), elevated ^{7}Be activity shows the deposition of 3 cm of new sediment. The following month (mid-February 2022, right), all the newly deposited sediment has eroded away, leaving surface sediments devoid of ^{7}Be activity. See Figs. S1–S6 for all ^{7}Be profiles

Fig. 4d). Upper estuary sites showed uniform grain size profiles because silt was deposited on top of existing silt. Median grain size generally increased down-estuary, with lower-estuary sites showing a wide range in observed grain size (silt to medium sand). See Fig. S7 for grain size profiles grouped by coring location.

Event-Driven Sediment Dynamics: Comparing Observations and Model Results

Hydrodynamic modeling allows us to expand estimates of sediment accretion across the estuary, with results evaluated through comparison with observations at coring locations. In general, model results agree with observational data. Modeling indicates that both deposition and erosion occur in response to wintertime high-discharge events (Fig. 6). Maximum deposition in the month following a discharge event (defined as maximum bed level minus starting bed level) is greatest in the dredged main channel upriver of North Bend, on the tidal flats of Haynes Inlet and the eastern bay, and in upper-estuary sloughs that are proximal to the source of most freshwater and sediment (Fig. 6a). In South Slough, maximum deposition is greatest in the middle estuary, particularly surrounding Valino Island. Maximum erosion (defined as starting bed level minus minimum bed level) primarily occurs in the lower estuary along the main channel. Note that the model grid is only one cell wide at Winchester Creek and in other narrow sloughs. Although model results are therefore not reliable for these areas, upper-estuary modeling is still useful for illuminating broad-scale patterns.

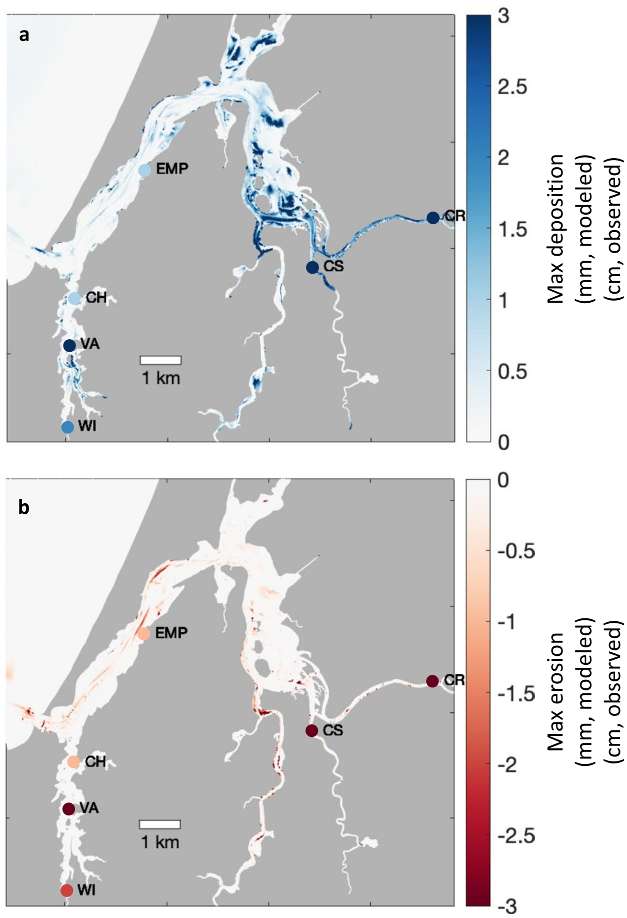

Fig. 6 Maximum deposition (max bed level minus starting bed level; **a**), and maximum erosion (starting bed level minus minimum bed level; **b**) that is modeled to occur in the month surrounding a high-discharge event, including 2 weeks before and 2 weeks after the event start. Darker colors indicate areas of greater change. For comparison, coring location symbols are colored according to maximum observed deposition (panel **a**) and erosion (panel **b**). Coring locations are labeled as WI (Winchester Creek), VA (Valino Island), CH (Charleston), CR (Coos River), CS (Catching Slough), and EMP (Empire)

Modeling suggests that over regular (non-event) tidal cycles, fluctuations in water level (Fig. S8a) correspond with changes in flow velocity (Eidam et al., 2021) and bed stress (Fig. S8b, Eidam et al., 2021), which in turn drive sub-mm bed level change (Fig. S8c). During a winter event (Fig. 7), increased bed level change is apparent in areas with direct river influence (Fig. 7; note the order-of-magnitude larger scale for bed level change at Coos River, Fig. 7d). Bed stress as much as doubles at Coos River (Fig. S8), amplifying changes in bed level and driving a complex multi-day timeseries of deposition and erosion. Over the same modeled time period, deposition is apparent at river-dominated middle and upper estuary sites across the estuary (Winchester Creek, Valino Island, Catching Slough; Fig. 7a, b, and e). At lower estuary sites (Charleston, Empire; Fig. 7c, and f), net bed level change is near zero.

Both observations and modeling indicate that Coos River is a particularly dynamic site that experiences extensive deposition and erosion (Figs. 4 and 7). Catching Slough, Valino Island, and Winchester Creek are also depositional hotspots. Observations and modeling differ on the degree to which deposition outpaces erosion. While the model produces reliable spatial patterns of deposition (Fig. 6; Eidam et al., 2021), it is not sufficiently tuned to represent accurate magnitudes of deposition. Thus, the real magnitudes of bed level change are likely larger than those shown in Fig. 7. At Charleston and Empire, observations and modeling agree that bed level change is minimal, although limited field data from Empire hampers the interpretability of observations.

Discussion

Sediment dynamics in the Coos estuary are highly seasonal. Steady-state (non-event) conditions are punctuated by storm-driven pulses of sediment deposition and subsequent redistribution (erosion) by tidal currents. During an event, heavy rain leads to peaks in river discharge. Fine-grained sediment washes into the estuary, driving turbidity spikes and deposition in the upper and middle estuary. In the Coos River, high discharge elevates bed stress, which drives channel scouring. Although not included in the parameters of the hydrodynamic model used here, wind and wave energy increase during storms

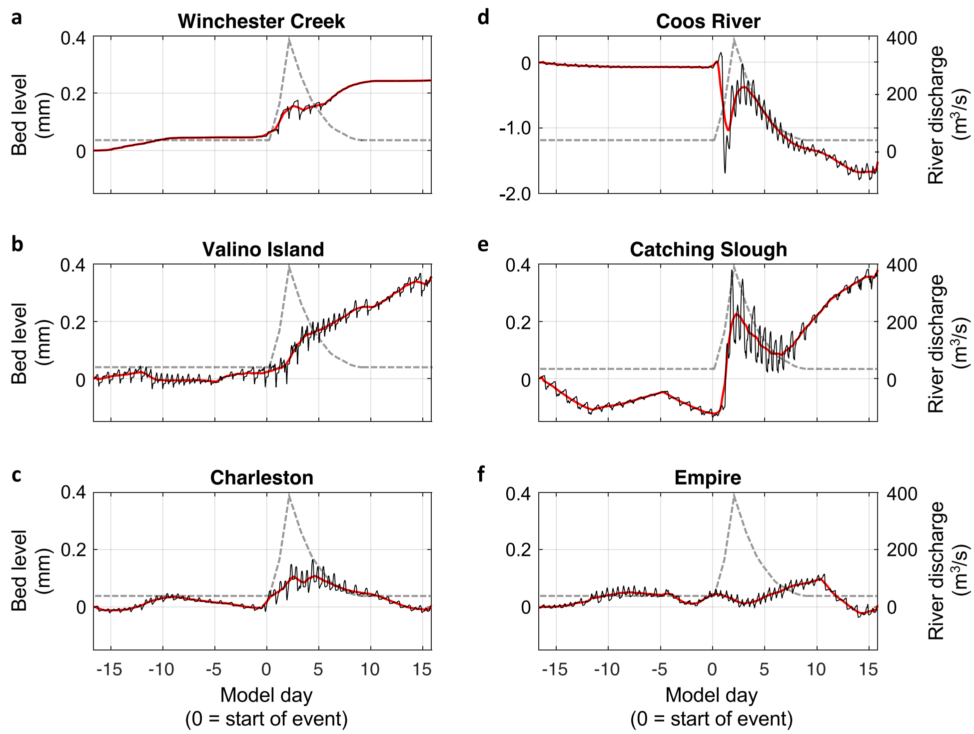

Fig. 7 Timeseries of modeled bed level during high river discharge conditions at the six coring locations: Winchester Creek (**a**), Valino Island (**b**), Charleston (**c**), Coos River (**d**), Catching Slough (**e**), and Empire (**f**). Bed level is modeled in 15-min increments (black line) and smoothed using a 25-h filter (red line). Dashed grey line shows the modeled river discharge

and likely also contribute to sediment redistribution (Green & Coco, 2014; Nowacki et al., 2024). Deposition of up to 3 cm is often ephemeral. After a storm, sediment is largely reworked by tidal forces within the following month. Storm-driven changes tend to be greater at the upper (riverine) end, above the ETM where the estuary becomes narrower and shallower. Regardless of estuary size, sites within ~ 1 tidal excursion above the ETM generally experience the most variation in turbidity and bed level, including during both storm and quiescent periods. Down-estuary from the ETM, sites show greater temporal variability in grain size but otherwise experience more stable turbidity and bed level conditions.

By combining observations at high temporal resolution with hydrodynamic model simulations, we produced a novel analysis of event- to seasonal-scale sediment dynamics in the Coos estuary. As a small, strongly forced system, the Coos estuary is representative of estuaries across the Pacific Northwest and estuaries globally with similar tide-dominated dynamics and strong seasonal precipitation. Here, we discuss the implications of three key results:

(1) Hydrodynamic conditions in middle estuary areas permit short-term sediment deposition.
(2) Although event-to-seasonal deposition rates exceed longer term average rates, the spatial pattern of deposition remains consistent across timescales.
(3) Dynamic patterns of deposition and erosion produce conditions that may be stressful to native species.

Middle Estuary as a Hot Spot for Sediment Accretion

Despite their differing geometries, fluvial inputs, and land-use histories, the middle reaches of both South Slough and Coos Bay experience high rates of short-term sediment deposition that exceed erosion, leading to net-depositional conditions over event to monthly timescales. Other studies have found similar sediment accretion patterns in estuaries globally, where deposition is commonly highest in wetlands that are mid-distance from both sediment sources and higher energy open tidal environments (e.g., Butzeck et al., 2015; Van Proosdij et al., 2006). Such zones have been shown to have a balance of sediment availability and flow velocity that is conducive to deposition (e.g., Keogh et al., 2019; Van Proosdij et al., 2006).

In the Coos estuary, middle-estuary areas of maximum deposition are coincident with modeled ETMs, which are located around Valino Island in South Slough and in the dredged channels of upper Coos Bay (near the city of Coos Bay) and have the greatest suspended sediment concentrations during winter discharge events (Eidam et al., 2021). In monitoring data (Fig. 4b) and model results (Eidam et al., 2021), turbidity conditions at the Coos River and Catching Slough stations are generally comparable during normal river discharge. During winter discharge events, however, turbidity at Coos River can increase by four-fold or more, indicating increased sediment delivery to the estuary and resuspension of channel bed sediments (e.g., Sommerfield et al., 2017). Increases in turbidity are typically greatest at the riverine end. Despite proximity to the sediment source, Coos River is net erosive over monthly timescales. During winter events, however, Coos River experiences both high deposition and high erosion within the span of a few days (based on model results, Fig. 7) to a month (based on coring data, Figs. 3 and 4), likely because of scouring due to the elevated bed stress that commonly accompanies discharge events (e.g., Wengrove et al., 2015; Yan et al., 2021; Fig. S8). Meanwhile, modeling suggests net deposition at Catching Slough, likely because of its smaller watershed and limited freshwater discharge.

In South Slough, the monitoring station at Valino Island, which is proximal to the modeled ETM, measures turbidity that is generally lower than in the upper estuary (Winchester Creek). However, this order switches during high discharge events. During the largest discharge peak in our study period, which occurred in January 2022, turbidity at Valino Island exceeded that measured farther up-estuary. Storm-driven turbidity peaks at Valino Island are likely driven by a seaward shift of the ETM, which commonly occurs in estuaries during high river discharge (e.g., Chen et al., 2018; Eidam et al., 2021). Additionally, Valino Island is adjacent to the mouth of Day Creek, which has a channel that gradually migrates across the tidal flat. During the study period (2021–2022), active erosion of the channel edge was visible during ebb tides. Instruments at the nearby water quality monitoring station were cleaned regularly to remove sediment that collected on sensors or guards. This anecdotal evidence suggests that storm-elevated discharge from Day Creek may accelerate erosion and contribute to local turbidity peaks. Despite the typically high turbidity at Winchester Creek, the estuary is also shallow and narrow at this location, and thus susceptible to elevated bed stress and accompanying erosion driven by the increased river discharge during events (Traynum & Styles, 2007).

Consistency of Spatial Patterns Across Timescales but Not Elevation

In tidal flats, we find that monthly sedimentation rates are greatest in the middle to upper estuary. This spatial pattern matches that of centennial sediment accumulation rates measured in the same regions of South Slough (Eidam et al., 2024; Fig. 8). Additional data collected in future studies may help tease out whether there is an accretion peak in the middle estuary over either short (monthly) or long (centennial) timescales. Monthly sedimentation rates are an order of magnitude greater than centennial rates, which is expected due to the inclusion of more erosional periods and depositional hiatuses in longer-term records (i.e., the Sadler Effect, Eidam et al., 2024; Sadler, 1981).

Although the spatial pattern of tidal flat sedimentation is consistent across timescales, it differs from the spatial pattern of sedimentation in higher-elevation marshes (Fig. 8). SSNERR maintains a set of feldspar marker horizon plots to measure vertical accretion annually in high and low marshes (Schmitt & Helms, 2017; Tables S1 and S2). The feldspar plots show a spatial pattern of sediment accretion that is less clear but may be opposite of the pattern in tidal flats. While tidal flat sedimentation is greatest in the middle to upper estuary, sedimentation in marshes is variable but tends to be lower in the middle of the estuary (Fig. 8).

The rate of sediment accumulation in wetland environments, including tidal flats and marshes, is impacted by the magnitude of tidal inundation, vegetation cover, and exposure to waves and currents (Fig. 9). The presence of vegetation plays a confounding role in sedimentation, as plants both hinder water and suspended sediment from entering the wetland from the channel, but also reduce flow velocity

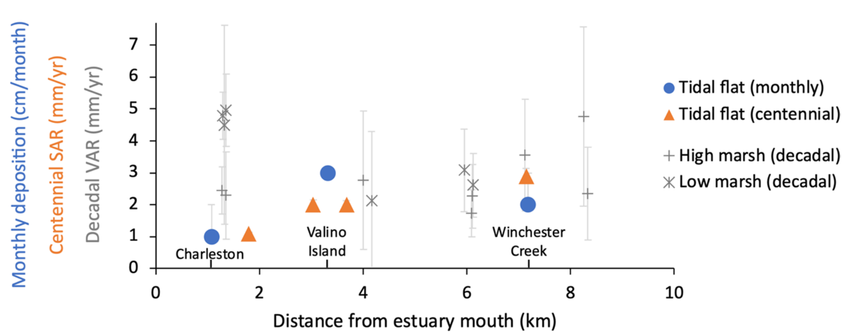

Fig. 8 Comparison of along-estuary patterns of sedimentation in South Slough over monthly and centennial timescales. Blue circles ($n=3$) show maximum monthly deposition observed at the South Slough tidal flat coring sites during the study period. Mean centennial sediment accumulation rates (SAR) from Eidam et al. (2024) are shown as orange triangles ($n=4$). For comparison, decadal vertical accretion rates (VAR) in high and low marshes (derived from feldspar marker horizon plots) are shown as plus signs ($n=8$) and asterisks ($n=6$), respectively, along with mean standard error

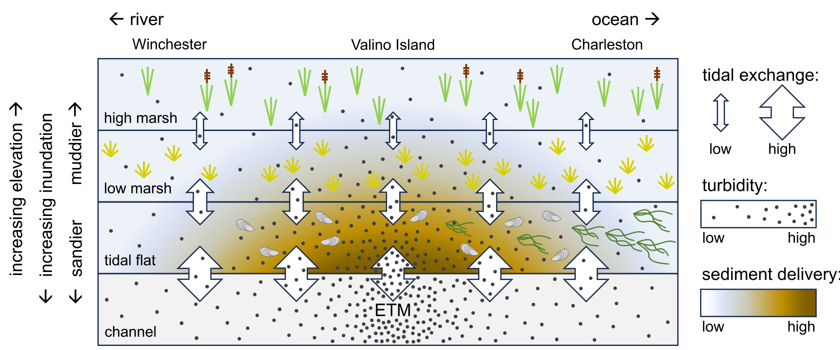

Fig. 9 Schematic depicting the interaction of turbid estuary water with various intertidal wetland environments. This figure is based on observations (tidal exchange, channel turbidity, and sediment delivery) and modeling (channel and tidal flat turbidity and sediment delivery) of Sough Slough, but the processes illustrated here are common to intertidal estuarine wetlands in general. Turbidity peaks at the middle-estuary ETM. Tidal exchange delivers sediment-laden water from the channel to the adjacent tidal flat, where direct connection with the channel leads to high water and sediment delivery, resulting in both high deposition and high erosion. In the tidal flat, eelgrass is depicted primarily down-estuary from the ETM (as is currently the case in South Slough) and Olympia oysters are shown in the middle estuary where hydrodynamic conditions are generally suitable (although substrate is not always available in South Slough). In low and high elevation marshes, emergent vegetation coupled with increasing elevation limits water and sediment delivery, resulting in less erosion and deposition. Note that the sediment delivery shown here represents conditions averaged over many tidal cycles, storms, and seasons

within the wetland and thus promote deposition (Beltrán-Burgos et al. 2023; Carrasco et al., 2023). Marshes in South Slough are typically densely vegetated and intermittently flooded (daily to fortnightly) by the tide for short periods of time. Tidal flats, in contrast, are deeply inundated on every tide and generally unbuffered by substantial vegetation.

Sedimentation rates in both tidal flats and marshes vary by a factor of 2–3 across South Slough (Fig. 8). In contrast, tidal flats in other estuaries commonly experience high spatial variability in accretion while sedimentation in adjacent marshes is relatively consistent (e.g., Bouma et al., 2016; Poirier et al., 2017; Willemsen et al., 2018). In South Slough, the observed similarity in accretion rate variability across wetland elevations suggests that the timescale of our shortest observations (monthly) may be too long to capture the shortest-timescale deposition and erosion events, which may occur over a matter of days (as suggested by hydrodynamic modeling, Fig. 7). Whereas marshes receive water that has been filtered by dense vegetation, tidal flat accretion during high-discharge events may more closely reflect turbidity conditions in the adjacent channel and may be greatest near the middle-estuary ETM (Fig. 9). Alternatively, sedimentation may also be controlled by accommodation space, which is more limited in marshes at higher elevations in the tidal frame. The intertidal zone also experiences greater seasonal variability in deposition when compared to the adjacent marsh (e.g., Poirier et al., 2017; Willemsen et al., 2018). On tidal flats, increased exposure to waves and currents drives pulses of deposition and periods of erosion (e.g., Willemsen et al., 2018). Bed level changes increase with distance from the shoreline and increasing inundation depth (e.g., Bouma et al., 2016; Poirier et al., 2017; Willemsen et al., 2018). In marshes, dense vegetation and limited inundation appear to buffer these environments from more rapid changes.

Impacts of Sediment Dynamics on Key Native Species

In the Coos estuary, native eelgrass persists in the main estuary and some middle and lower regions of South Slough but is highly patchy and less abundant in upper South Slough despite suitable habitat (based on water depth and light requirements; Eidam et al., 2020; Thom et al., 2008) and previous high abundance (Fig. S9). Similarly, native Olympia oysters are absent from South Slough despite evidence of previous abundance throughout the polyhaline region of the estuary (18–30 parts per thousand; Groth & Rumrill, 2009) and current presence in the main estuary (Fig. S9). Attempts to restore both species in South Slough have had mixed results (Figs. S9 and S10; Larsen et al., 2014; Kornbluth et al., 2022; Office for Coastal Management, 2023; Ward & Beheshti, 2023). Although recent research suggests that elevated water temperature likely contributed to the initial eelgrass decline in South Slough (Marin Jarrin et al., 2022), excessive sedimentation may be a factor in preventing recovery of both eelgrass and Olympia oysters (Magel et al., 2022), particularly in middle-estuary locations. In South Slough, eelgrass and oyster restoration areas are situated on tidal flats in the highly dynamic middle reach of the estuary (Fig. S9). Once established oyster and eelgrass beds were wiped out, new individuals likely struggled to get a foothold without the shelter provided by neighboring mature individuals. Bouma et al. (2016) found that marsh grass (*Sporobolus anglicus*) seeds require bed level to be relatively stable over seasonal timescales to successfully sprout because excessive deposition prevents shoot emergence and erosion topples seedlings. Eelgrass seeds and seedlings are similarly sensitive to bed level change, although some amount of seed burial (2–3 cm) is important to prevent seeds from washing away prior to germination (Marion & Orth, 2012). Although this ideal depth of burial is similar to the event-scale deposition we observed in South Slough and Coos Bay (Figs. 3 and 4), erosion of the new sediment may occur faster than the rate at which seedlings can become established, particularly because storm-driven deposition events typically occur in the winter when eelgrass growth rates are slower (Orth & Moore, 1986). Oyster establishment is also hampered by active sediment dynamics. Fivash et al. (2021) found Pacific oysters (*Crassostrea gigas*) living in marshes at intertidal heights above where reefs typically develop. The survival of oysters in the marsh was attributed to the shelter provided by the vegetation and the corresponding reduction in hydrodynamic disturbance.

In the Coos estuary, regions where sediment conditions are more stable than in the dynamic middle estuary may be more conducive to restoration. In the lower reaches of South Slough, eelgrass either persisted through the marine heat wave (Barview, 1 km north of Charleston, Magel et al., 2022) or has since reestablished (Collver Point, Fig. S10). While some natural recovery of eelgrass has occurred in both the marine and riverine reaches of South Slough (Fig. S10), the middle estuary has not experienced natural recovery. In the middle reach of the main estuary, Olympia oysters are found living on hard substratum such as rip rap, gravel, wood, and Pacific oyster shells rather than directly on the muddy bed (Fig. S9; Groth & Rumrill, 2009). Such hard substrata are less available in South Slough due to limited human development in intertidal and subtidal areas.

Species native to the Coos estuary evolved under environmental conditions that are now changing with the climate. Although a variety of factors affect oyster and eelgrass health (e.g., water temperature, Marin Jarrin et al., 2022; bed scour, Marion & Orth, 2012; water clarity, Thom et al., 2008), sediment dynamics are commonly identified as a hinderance to restoration. A review of 82 eelgrass restoration projects on the US west coast found that sediment was the primary cause of failure in 13 cases (~16%; Ward & Beheshti, 2023). A study of eastern oysters (*Crassostrea virginica*) found sediment burial also hampered the survival of natural and restored oyster reefs (Colden & Lipcius, 2015). Although individual oysters could survive burial of up to 70% of their shell height, lower levels of burial hindered reef-building processes and the species' ability to persist. Although the middle reach of the Coos estuary has likely always experienced dynamic sediment conditions, even when eelgrass and oysters flourished in the area, climate change will likely drive more frequent and more intense storms (e.g., Espinoza et al., 2018; Gershunov et al., 2017; Payne et al., 2020; Sillmann et al., 2013) that deliver larger pulses of turbidity, deposition, and erosion. Sediment-related stressors compound other climate-driven stressors including warming water and air temperatures, decreasing water pH, and rising sea level. Combined, these changes may prevent some native species from persisting in their historic range.

Conclusions

Here, we present an analysis of event- to seasonal-scale sediment dynamics in the Coos estuary, Oregon (USA), and find that large-magnitude depositional events during the wet winter season are commonly followed by erosional periods, resulting in a bed that is highly dynamic over monthly timescales. We reach the following conclusions:

- On tidal flats, event-scale sediment deposition during the rainy season can occur at rates > 30 times the centennial rate and > 100 times the local rate of relative sea-level rise.
- Deposition is greater in the upper and middle estuary than in the lower estuary, matching the spatial pattern of measured turbidity, and reaches a peak near the modeled middle-estuary estuarine turbidity maximum.
- On tidal flats, the spatial pattern of monthly deposition matches that of centennial trends; over monthly timescales, tidal flat deposition exceeds the deposition that occurs in adjacent marshes, where sedimentation rates are close to RSLR.
- Rapidly deposited sediment is often eroded again within one month.

The results of this study demonstrate the importance of monitoring short-term (event to seasonal) sediment dynamics when assessing ecosystem change. Longer-term (decadal to century) average conditions can differ greatly from short-term rates. Large, event-driven pulses of deposition and erosion such as those observed in this study may stress ecosystems that are already under duress from other climate-related environmental changes.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12237-025-01524-1.

Acknowledgements Gamma spectroscopy analyses were conducted by lab technician Sherif Ghobrial and undergrad assistant Daniela Zarate. Thanks to the following volunteers for their assistance in the field: Chloe DaMommio, Luke Donaldson, Anne Farrell-Matthews, Peg Herring, Chase Kazzee, Matthew Lewis, Victoria McNeely, Kate (Wanrong) Qi, Deborah Rudd, Reagan Thomas, and Petra Zuñiga. Access to water quality monitoring data was provided by Adam DeMarzo (SSNERR) and John Schaefer (CTCLUSI).

Funding This work was sponsored by the National Estuarine Research Reserve System Science Collaborative, which supports collaborative research that addresses coastal management problems important to the reserves. The Science Collaborative is funded by the National Oceanic and Atmospheric Administration and managed by the University of Michigan Water Center (NA19NOS4190058).

Data Availability All sediment core data used in this analysis are included in the supplemental information. Precipitation and turbidity data from the Tom's Creek, Winchester Creek, Valino Island, and Charleston Bridge monitoring stations are also publicly available through the NERRS Centralized Data Management Office (https://cdmo.baruch.sc.edu). Turbidity data from the Coos River and Catching Slough monitoring stations are available upon request from SSNERR. Turbidity data from the Empire station are available upon request from the Confederated Tribes of Coos, Lower Umpqua, and Siuslaw Indians. River discharge data are available from the Coos Watershed Association (https://cooswatershed.org).

Declarations

Competing Interests The authors declare no competing interests.

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