



# Sea level rise and marsh surface elevation change in the Meadowlands of New Jersey

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Received: 13 February 2020 / Accepted: 15 December 2020

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**Abstract** The marshlands of the Meadowlands of New Jersey are valuable wetland ecosystems in a highly developed urban area and provide a natural habitat to more than 285 species of birds, a great variety of fishes, and many other living organisms. It is not clear if these ecosystems and their associated ecological services will persist under conditions of accelerated sea level rise (SLR), in geography where space for a landward retreat of marshlands is limited. In this study, we used the deep rod surface elevation table method and feldspar marker horizons to measure surface elevation change and vertical accretion rate in five marshland sites over 11 years. The controlling parameters of the accretion rate were explored. The results showed that sediments were not limited for vertical accretion. About 16% of the total suspended solids reaching the marsh via the tide was trapped by the marsh surface. Hydraulic duty alone cannot explain differences in deposition rates between low and high marsh. Precipitation, snow accumulation, and sea surge from storms were the main drivers influencing subsidence. The overall subsidence rate was  $1.5 \pm 1.3$  mm/year. All sites combined showed increases in surface elevation of  $4.0 \pm 0.7$  mm/year. This rate of increase is not enough to keep up with the

8 mm/year SLR prediction. There is a 50% chance that in 80 years, 7% of current marshlands will be underwater or will convert to unvegetated mudflats, and most high marsh habitats will disappear.

**Keywords** Surface elevation table · Coastal wetlands · Sea level rise · Accretion · Subsidence

## Introduction

Coastal marshes are valuable ecosystems that provide important ecological services (Costanza et al. 1997). Future increases in sea level rise (SLR) may drown important coastal wetlands and significantly diminish or eliminate these valued services. According to the New Jersey Climate Adaptation Alliance, estimates of SLR for the twentieth century based on semi-empirical models indicate a rise of  $\sim 14$  cm, which is faster than the previous 27 centuries (Kopp et al. 2016b). The Climate Adaptation Report predicts there is a 50% chance that the New Jersey sea level will increase  $\sim 8$  mm per year from 2000 to 2030 (Kopp et al. 2016a). Based on this number, it becomes critical to revise and quantify the overall surface elevation change occurring in coastal wetlands to accurately project the future condition of coastal marshlands under this new sea-level rise scenario.

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In estuaries where adjacent land with slightly higher elevation is available, a landward retreat of salt marshes from SLR is possible (Kiviat and Macdonald 2004; White and Kaplan 2017). After the retreat, they may continue to buffer inland areas from coastal storms, support high levels of biodiversity, and through long-term sequestration, continue to remove atmospheric carbon dioxide (Rogers et al. 2013). Contrary to other estuaries, there are no adjacent areas in the Meadowlands of New Jersey where salt marshes can retreat. The Hackensack River estuary covers a 3 km wide glacial valley with steep straight sides that rise more than 40 m from the valley bottom (Widmer 1964). Moreover, industrial parks, residential areas, bulkheads, tide gates, railroad lines, and highways that crisscross the meadows, further complicates any possibility for landwards marsh migration. Under these “bathtub” conditions, if marshes are to overcome rising water levels, they must be able to accrete at a rate where surface elevation gain is sufficient to offset the rate of water level rise (Cahoon et al. 1995).

The transport of material in coastal wetlands is governed by the interplay of the tides and storms (Allen 2000; French and Stoddart 1992). Wetland surface elevation change occurs mainly by the trapping of inorganic and organic sediments brought by the tides (Callaway et al. 1997; Chmura and Hung 2004; DeLaune et al. 1983; Orson et al. 1998). Studies show that the main source of sediments is from the tidal exchange with the Hackensack River (Berry’s Creek Study Area Cooperating Group 2016). Analysis of sediment fluxes based on 2 years of near-continuous monitoring, confirms that approximately 14% of inorganic sediments carried by the tide is trapped which results in the net deposition of sediments on the marsh surface (Berry’s Creek Study Area Cooperating Group 2016). Marsh elevation change is not even across marshland areas (Baumann et al. 1984). The mobilization of sediments is variable and highly dependent on the age of the marsh and its tidal networks, elevation, and the size and frequency of storms and floods (Day et al. 1999). Sediment deposition is not the only factor contributing to surface elevation change. Below-ground root and rhizome growth and the type and density of vegetation also play a role (Nyman et al. 2006; Temmerman et al. 2005; Wang et al. 2016). In this case, the dominant vegetations are *Spartina Patens* and *Spartina alterniflora* interspersed with the invasive species

*Phragmites australis* (Kiviat and Macdonald 2004). Finally, the compaction of sediments and shrink and swell process also contribute to surface elevation change (Kaye and Barghoorn 1964; Lovelock et al. 2011; Stagg et al. 2016).

Tidal fluctuations and marsh surface elevation changes are independent and complimentary of each other (Cahoon et al. 2002). Because tide gauges are anchored to upland structures, they fail to capture the genuine relationship between wetland surface elevation and sea-level rise. Marshland surface elevation change can be measured with the deep rod surface elevation table method (SET) (Cahoon et al. 2002; Lynch et al. 2015). This method is widely used to capture changes in surface elevation between the sediment surface and the base of the benchmark (rod) (Cressman 2020). Also, vertical accretion is determined by using feldspar marker horizons (Cahoon and Turner 1989). Repeated measurement over time using these methods captures vertical accretion, erosion, and subsurface expansion and contraction occurring in the sediment profile.

Wetland elevation rate deficit or surplus relative to SLR provides the critical levels to estimate the effects of sea-level rise, where wetland retreat to higher areas is not possible. This approach allows identifying challenges and opportunities to manage the Meadowlands estuary under twentyfirst-century estimates of sea-level rise. Our research questions are: what is controlling accretion rates in the estuary? What are the subsidence rates from diagenetic processes, and are there sufficient sources of sediments for marshlands to keep up with sea-level rise? Our approach is to measure the sediments reaching the marsh surface, quantify surface elevation change, and determine the future surplus or deficit of marsh surface elevation relative to the latest local estimates of sea-level rise.

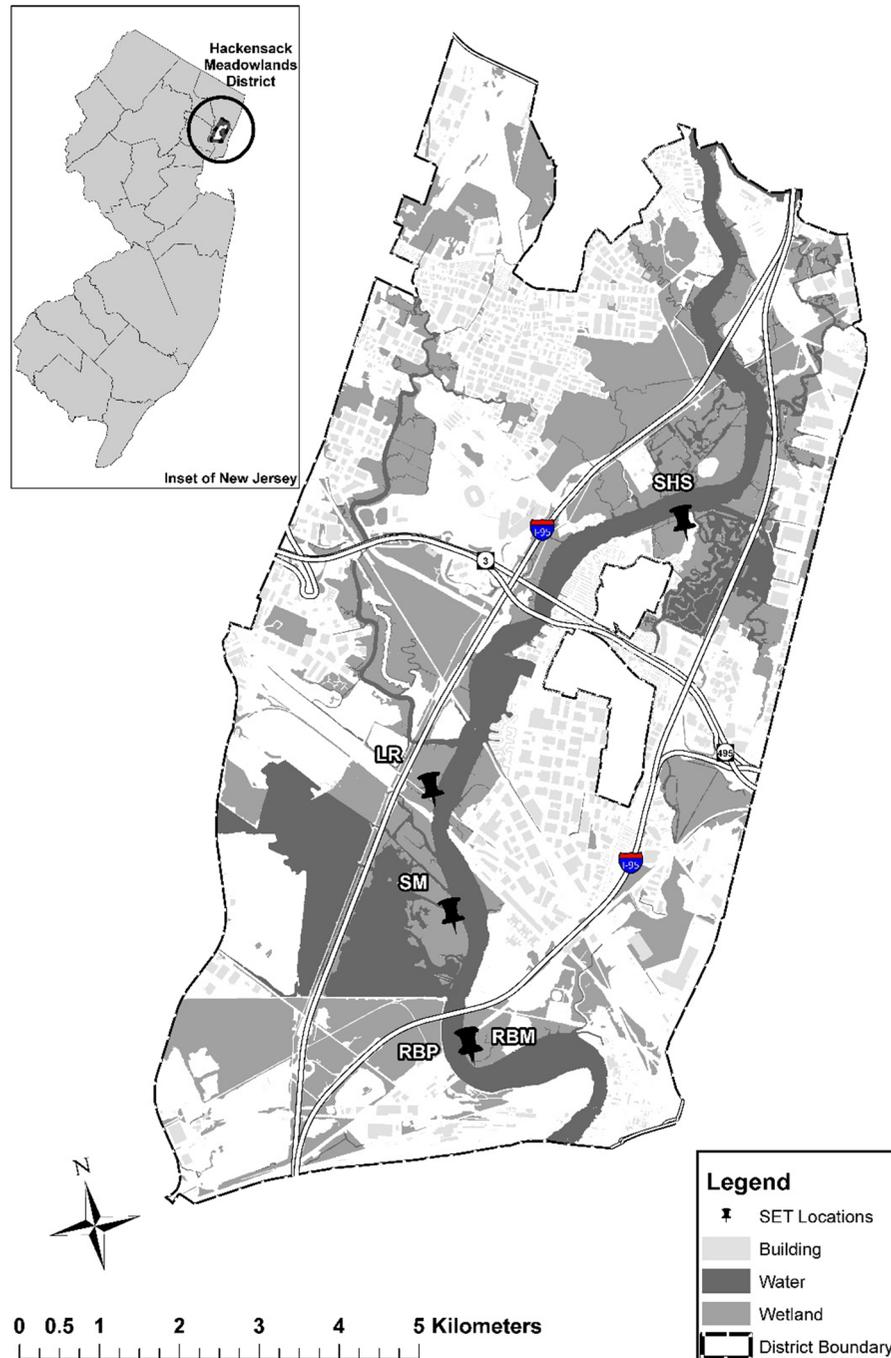
## Materials and methods

### Study area

Five locations in the Hackensack Meadowlands estuary were selected for a long-term study in wetland surface elevation change and vertical accretion. The sites represent different vegetation cover types along a salinity gradient of tidally influenced coastal wetlands (Fig. 1). Marsh surface elevation was measured by

LIDAR (Light Detection and Ranging) using a Leica ALS50 phase II system mounted in a Cessna Caravan (Artigas et al. 2016). The error estimate on the LIDAR values is 10–15 cm for bare surfaces and 20–30 cm for

vegetated surfaces. The two low marsh sites, SawMill marshland (SM) and Secaucus High School marshland (SHS), have surface elevations ranging from 0.62 to 0.67 m above sea level (NAVD88). The other three



**Fig. 1** Five long-term SET monitoring locations in the Hackensack Meadowlands estuary. *LR* Lyndhurst Riverside, *RBP* Riverbend Patens, *RBM* Riverbend Mixed, *SM* SawMill, *SHS* Secaucus HS

sites, Lyndhurst Riverside marshland (LR), Riverbend Patens marshland (RBP), and Riverbend Mixed marshland (RBM), have surface elevations that range from 0.85 to 0.90 m above sea level (Table 1). High marsh sites are mainly monocultures of *Spartina patens* or mixtures of *Phragmites australis* and *Spartina patens*. The low marsh plant cover is dominated by *Spartina alterniflora* mixed with *Phragmites*. The SHS site is further inland and exposed to the lowest average salinity of  $6.1 \pm 2.5$  PSU (Practical Salinity Unit, ‰). LR and SM sites have intermediate salinities ( $8.3 \pm 3.1$  PSU and  $10.4 \pm 3.1$  PSU, respectively) and RBP and RBM, which are closer to the bay, are exposed to the highest salinities ( $12.0 \pm 3.6$  PSU) (Table 1).

Amount of sediments reaching wetland surfaces through the tidal exchange

Turbidity is used as a surrogate variable to estimate Total Suspended Solids (TSS) entering and leaving tidal creeks in the proximity to the sites (Hannouche et al. 2011; Heyvaert et al. 2015). Twenty-one water column samples at different stages of the tidal cycle were collected and analyzed in the laboratory for total suspended solids (TSS) with Standard Method 2540-D (Baird et al. 2005). Turbidity was measured with a YSI Model 6820 multi-parameter probe. An empirical relationship was established between turbidity and TSS (N = 26) represented in Eq. (1). In this case, turbidity explained 93% of the variation in TSS.

$$\begin{aligned} \text{TSS} &= 1.7431 \times \text{Turbidity} - 16.108; R^2 \\ &= 0.9284. \end{aligned} \quad (1)$$

The average combined amount of inorganic and organic sediment retained by the marsh floor via tidal exchange was estimated from tidal creeks connecting two representative sites (SHS and LR) and using turbidity as a surrogate for TSS. A three-sensor cluster measured turbidity (NTU), water velocity (cm/s), and water elevation (m) for a combined total of 44 tidal cycles in two different deployments. A YSI Model 6820 multi-parameter probe measured turbidity and water depth every 5 min, and water velocity was simultaneously measured with a SonTek Argonaut ADV (San Diego, USA).

Surface elevation change and vertical accretion

Wetland surface elevation was measured by using the rod surface elevation table (RSET) method (Cahoon et al. 2002). This method provides a constant plane in space from which the distance to the marsh surface can be measured by lowering pins to the surface from a known plane. This method captures the change in surface elevation between the base of the benchmark, buried to refusal between 6 and 11 m deep (Table 1) and surface sediments, and thus quantifies the net elevation change of the marsh surface. Three benchmark plots with a constant plane were established at each of the five sites. All sites had benchmarks depths of 8.5–9.8 m except for SHS, which had benchmark depths of 6.1–7.3 m. During measurements, nine pins

**Table 1** Characteristics of the study sites in terms of surface elevation, marsh type, vegetation type, average salinity, and SET benchmark depth

Location	Surface elevation (m)	Marsh type	Dominant vegetation	Average salinity (‰)	Benchmark depth (m)
LR (Lyndhurst Riverside)	0.85	High Marsh	<i>Spartina patens/Phragmites australis</i>	$8.3 \pm 3.1$	8.5–9.8
RBR (Riverbend Patens)	0.90	High Marsh	<i>Spartina patens/Phragmites australis</i>	$12.0 \pm 3.6$	8.5–9.8
RBM (Riverbend Mixed)	0.90	High Marsh	<i>Phragmites australis/Spartina patens</i>	$12.0 \pm 3.6$	8.5–9.8
SM (SawMill)	0.62	Low Marsh	<i>Spartina alterniflora/Phragmites australis</i>	$10.4 \pm 3.1$	8.5–11.0
SHS (Secaucus HS)	0.67	Low Marsh	<i>Spartina alterniflora/Phragmites australis</i>	$6.1 \pm 2.5$	6.1–7.3

All surface elevations were referenced to NAVD88

were lowered to the sediment surface for each cardinal direction resulting in a total of 108 measurements per site per year (9 pins  $\times$  3 locations  $\times$  4 cardinal points). The average distance to the marsh surface from the constant plane becomes one data point for a site and represents the level of the marsh surface for that year. Also, feldspar horizons emplaced inside three corners of each benchmark plot are sampled every year to determine vertical accretion. Vertical accretion is measured by calculating the average sediment depth above the feldspar marker from nine readings at each site per year.

To obtain a yearly rate of surface elevation change and vertical accretion, the resulting values from each yearly measurement were divided by the number of days elapsed between each reading. Finally, shallow subsidence was calculated by Eq. (2).

$$\begin{aligned} \text{Shallow Subsidence} &= \text{Accretion} \\ &- \text{Surface Elevation Change} \end{aligned} \quad (2)$$

The measurements took place between 2008 and 2019. During this period, tropical storm Irene (2011) and Hurricane Sandy (2012) had measurable effects on marsh surface elevation, as did snow accumulation above 76 cm in the winter of 2017.

Surface elevation and accretion over time were tested against zero slopes. One factor ANOVA was used to test differences in surface elevation change as well as vertical accretion rates between sites. Furthermore, pairwise comparison by ANOVA was used to identify which sites were significantly similar to each other in terms of surface elevation change over time. The significance level for all tests was set to  $p < 0.05$ , and the corresponding confidence level was higher than 95%.

## Results

### Sediments deposition

According to Eq. 1, 92% of the variability in TSS can be explained by the variability in turbidity. For the tidal creeks leading to the high and low marsh (LY site and SHS site, respectively), the amount of TSS flowing in with the tide is always greater than TSS flowing out (Table 2). When combining both tidal

creeks for a total of 44 cycles, on average,  $\sim 16\%$  of the sediments flowing in with the tide were retained by the marsh surface (Table 2). On the other hand, hydraulic Duty [i.e. the height difference between the marsh platform and the high-water mark (Allen 1994)] is 3 times larger for the low marshes compared to the high marshes (Table 2). A greater water column depth at high tide over the low marsh surface creates conditions that favor greater deposition rates in low marsh areas.

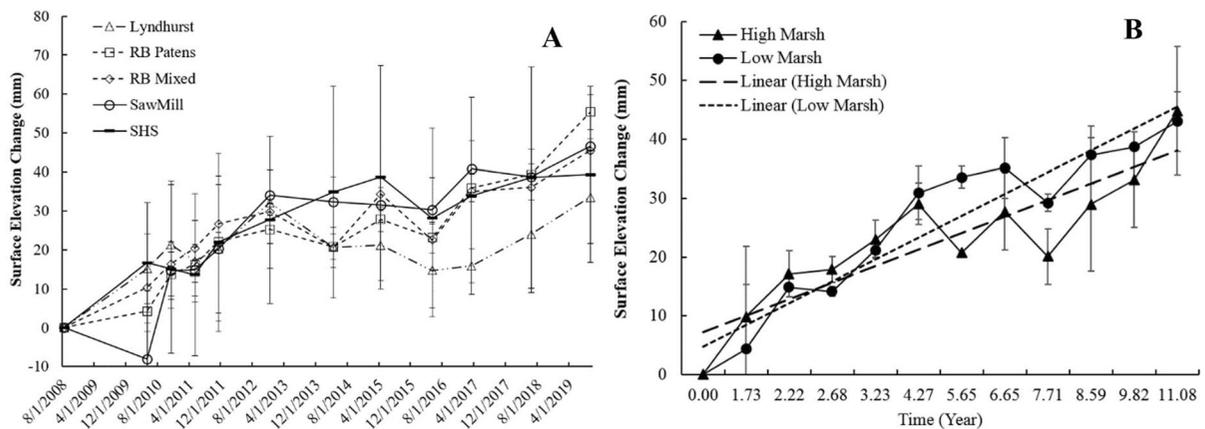
### Surface elevation change

Surface elevation change is the difference between the base of the buried benchmark (6–10 m) and surface sediments. All sites showed increases in surface elevation over time (Fig. 2a). The LR site (high marsh) with benchmark depths of 8.5 to 9.8 m and a surface elevation of 0.85 m showed the smallest increase in surface elevation rate ( $3.03 \pm 7.23$  mm/year). In comparison, the high marsh RBP, with similar benchmark depths (8.5 to 9.8 m) and surface elevation (0.90 m) but closer to the bay, showed the greatest increase in surface elevation ( $5.00 \pm 13.93$  mm/year). The average surface elevation changes from 2008 to 2019 for all sites are listed in Table 3. Between 2011 and 2012, all sites showed sharp increases in surface elevation. Between 2015 and 2016, all sites showed sharp decreases in surface elevation. This decrease coincided with the driest portion of the study period, which favors increase peat aeration and decomposition (Portnoy 1999) (Fig. 4). When all sites are considered, the average surface elevation change rate for the eleven-year study period was  $4.0 \pm 0.7$  mm/year.

Differences in surface elevation change rates between high and low marsh throughout the study period are presented in Fig. 2b. For this comparison, yearly high and low marsh values were grouped, and in each year, 216 measurements for the low marsh were compared to 324 measurements for the high marshes. The low marshes show a positive and steeper slope of surface elevation change rates compared to the high marshes; however, these differences were not significant at ( $p < 0.05$ ). Also, high marsh sites showed greater variability in surface elevation rate change over time compared to the low marsh sites.

**Table 2** Average sediment deposition per tidal cycle at Secaucus High School site and Lyndhurst site

Site	SHS (low marsh)	Lyndhurst (high marsh)
# Tide cycles	38	6
Average Ebb velocity, cm/s	9.54 ± 3.45	16.02 ± 12.12
Average flood velocity, cm/s	9.52 ± 2.97	16.19 ± 10.68
Ebb turbidity, NTU	25.46 ± 20.8	15.58 ± 3.92
Flood turbidity, NTU	30.19 ± 17.6	18.33 ± 5.67
Surface ELEVATION, m	0.67	0.85
High watermark, m	0.82	0.82
Hydraulic duty, m	0.15	- 0.03

**Fig. 2** **a** Surface elevation change (mm) at each marsh site between 2008 and 2019. **b** Average surface elevation of the high marsh (324 measurements a year) compared to low marsh (216

measurements a year) over an 11-year time-period. Differences in slope were not significant at  $p < 0.05$

**Table 3** Average accretion rate, subsidence rate, and elevation change rate based on measurements from 2008 to 2019

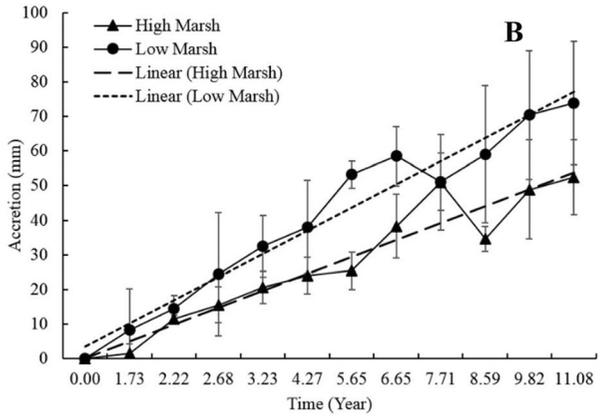
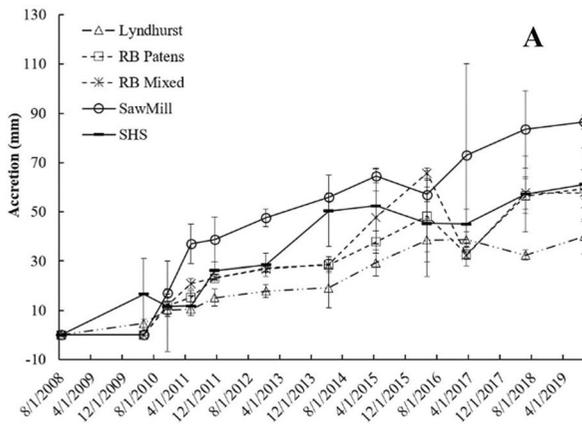
Location	Subsidence rate, mm/year	Accretion rate, mm/year	Elevation change rate, mm/year
LR (Lyndhurst Riverside)	0.58 ± 3.02	3.61 ± 1.39	3.03 ± 7.23
RBP (Riverbend Patens)	0.36 ± 1.52	5.36 ± 2.03	5.00 ± 13.93
RBM (Riverbend Mixed)	1.11 ± 2.95	5.21 ± 2.23	4.10 ± 13.47
SM (SawMill)	3.60 ± 2.34	7.80 ± 2.79	4.20 ± 16.31
SHS (Secaucus HS)	1.97 ± 1.35	5.52 ± 2.15	3.56 ± 10.92

The average subsidence based on these five sites was  $1.5 \pm 1.3$  mm/year. The average accretion rate was  $5.5 \pm 1.5$  mm/year and the average elevation change was  $4.0 \pm 0.7$  mm/year

## Accretion

Accretion is the accumulation of mineral and organic matter on the marsh surface. All sites show an increase in vertical accretion over time (Fig. 3a). The overall average accretion rate when all sites are combined is  $5.5 \pm 1.5$  mm/year. From June 2016 to March 2017

the two Riverbend sites (RBP and RBM) show a decrease in vertical accretion, and LR and SHS show almost no vertical accretion in the same period. Between December 2016 and February 2017, the sites were buried with more than 76 cm of snow, and the observed decreases in accretion are most likely the result of surface compaction by the snow. The



**Fig. 3 a** Accretion change at each site over time from 2008 to 2019. **b** Average accretion rate of the high marsh (27 measurements per year) compared to low marsh (18

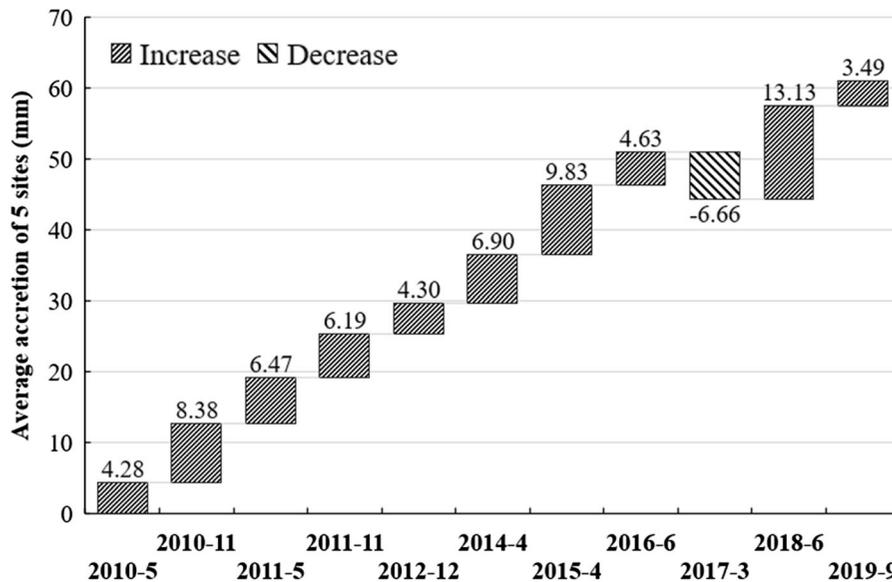
measurements per year) over an 11-year time-period. Differences in slope were not significant at  $p < 0.05$

remaining surface elevation measurements were scheduled in the fall (October–November) to avoid random snow effects.

In 2017, the average vertical accretion for all sites combined was  $-6.66 \pm 18.72$  mm. This coincided with the driest period of the study followed by the greatest amount of snowfall (Fig. 4). On the other hand, 2015 and 2018 show the greatest increase in average vertical accretion ( $9.83 \pm 6.14$  mm and

$13.13 \pm 12.75$  mm, respectively) and coincides with the very wet spring and summer months of 2015 and 2018. The year 2018 was one of the top five wettest years in New Jersey since 1895 (Office of the New Jersey State Climatologist and NCEI 2020).

The only significant differences in accretion rates were between three high and low marsh sites (LR-SM, LR-SHS, and RBP-SM) (Table 4). No clear pattern exists between accretion rates of low and high marshes



**Fig. 4** Average accretion from all sites combined. Each average was compared to the previous measurement. The starting point of each bar is the average accumulated accretion of last measurement. The end point of each bar is the final accumulated

accretion. The change of the average accretion of each measurement is labeled on the bar. The x-axis indicated the year and month of the measurement

**Table 4** Site accretion rate pairwise comparison by ANOVA

p-value (Accretion)	LR	RBP	RBM	SM
RBP	0.208			
RBM	0.104	0.642		
SM	<b>0.003</b>	<b>0.026</b>	0.064	
SHS	<b>0.008</b>	0.172	0.408	0.187

Confidence level less than 0.05 was in bold

since an equal number of high and low marsh site comparisons were not significant ( $p = 0.14$ ).

### Shallow subsidence

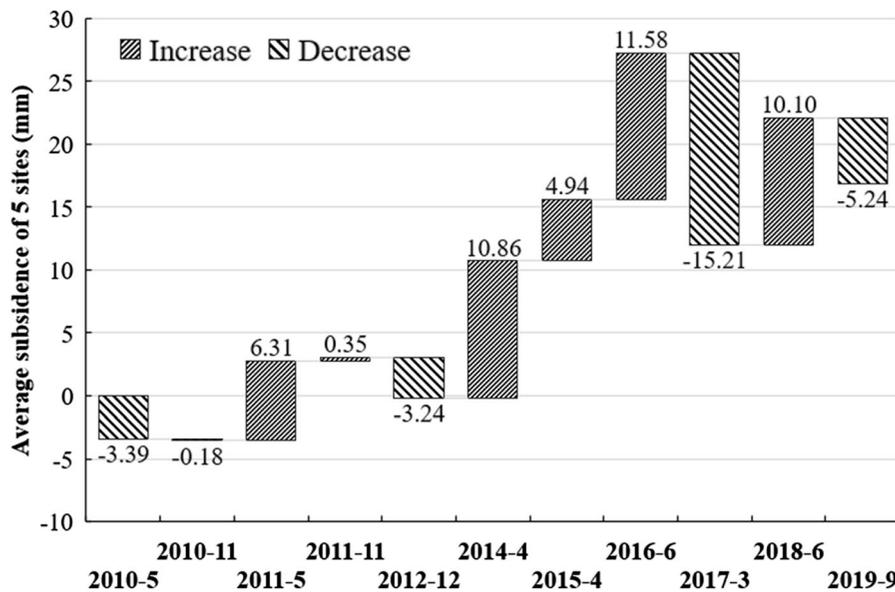
Shallow subsidence was defined here as the difference between accretion and elevation change (see Eq. 2). Positive shallow subsidence results in a sinking of the marsh surface while negative subsidence results in a net increase of the marsh surface elevation. The combined average shallow subsidence for all five sites over time is shown in Fig. 5.

The year 2017 was preceded by the driest year of the study period and snow accumulation reached more

than 76 cm. Sediment elevation measurements were conducted in March of 2017 right after the snow had melted. The re-filling of pore space by the melting snow and the rebound of the marsh surface from the removed weight of the snow most likely explain why that year had the most negative shallow subsidence change of  $-15.2 \pm 21.5$  mm. There were six years which had positive shallow subsidence with an average of  $7.3 \pm 4.3$  mm/year (downward movement). On the other hand, the years 2010, 2011, 2012, 2017, and 2019, showed negative shallow subsidence where the average upward movement was  $5.5 \pm 5.8$  mm/year. The overall resulting shallow subsidence from all sites during the study period averaged  $1.5 \pm 1.3$  mm/year (Table 3).

### Discussion

Three high marsh sites and two low marsh sites with different vegetation cover types, surface elevation, and salinity were monitored for changes in surface elevation and accretion over 11 years. The high marsh sites (LR, RBP, and RBM) have surface elevations of 0.85–0.90 m (NAVD88) and plant cover is dominated



**Fig. 5** The average subsidence from all sites combined. Each average was compared to the previous measurement. The starting point of each bar is the average accumulated subsidence of the last measurement. The end point of each bar is the final accumulated subsidence. The change of the average subsidence

of each measurement is labeled on the bar. Positive shallow subsidence results in the sinking of the marsh surface while negative subsidence results in a net increase of the marsh surface elevation. The x-axis was the year and month of the measurement

by stands of *Spartina patens* intermixed with *Phragmites australis*. In contrast, the low marsh sites (SM and SHS) have surface elevations of 0.62–0.67 m and plant cover of *Spartina alterniflora* intermixed with *Phragmites australis*. A range of surface and subsurface processes drive the elevation changes. Surface processes include sediment deposition and erosion, and subsurface processes include root growth, decomposition, pore water fluxes, and compaction (Lynch et al. 2015). Our measurements of sediment transport in tidal creeks indicate that most marshlands in the estuary were net depositional and that sediments were not limited. The measurement of 44 tidal cycles revealed that 16% of sediments moving in with the tide are trapped by the marsh surface. This is in agreement with sediment trapping levels of  $\sim 14\%$  measured in a two-year study in the nearby Berry's Creek (Berry's Creek Study Area Cooperating Group 2016). The sources of sediments are from resuspended sediments from the Hackensack River, erosion from the uplands, and sewage treatment plant effluents. A major component of the river's flow is in the form of effluents from sewage treatment plants. More than 100 million gallons of secondary-treated sewage are discharged daily into the estuary (USFWS 2005).

One would expect that the greater hydraulic duty and lower elevation of low marsh areas (Tables 1 and 2) would result in greater sediment deposition (Kirwan and Guntenspergen 2010; Morris et al. 2002). We observed that low marsh surfaces consistently had greater average accretion rates and steeper accretion rate slopes compared to high marsh surfaces (Fig. 3b). Nevertheless, differences were not statistically significant suggesting that other factors, such as distance from tidal creeks, length of marsh edge, and age of the marsh also play an important role (Temmerman et al. 2005).

Shallow subsidence is the difference between accretion and elevation change and captures degradation, erosion, and compaction rates over time (Table 3). Previous studies showed that subsidence depends on the amount of precipitation, snow accumulation, sea surge from storms, and subsurface diagenetic processes (Montañez and Crossey 2018; Portnoy 1999). Tropical storm Irene (mainly rain) and Hurricane Sandy (mainly a sea surge) resulted in an upward movement, while snow accumulation in 2017 resulted in a downward movement (Fig. 5). During very dry

years (e.g. 2016), a downward movement of the marsh surface was observed.

Surface elevation change corresponded to the net surface elevation change after accretion and subsidence were considered. In our case, the average marshland elevation change was  $4.0 \pm 0.7$  mm/year. (Table 3). This is comparable to measurements of 4.9 mm/year reported in the Berry's Creek Study (Berry's Creek Study Area Cooperating Group 2016) and also in similar estuaries in the Mississippi River Delta (Lane et al. 2006) and the Ebro Delta Wetlands of Catalonia, Spain (Ibáñez et al. 2010). Surface elevation change using cores and geochronology methods showed an average of 1.6 mm/year elevation increase (Artigas et al. 2016). While there may be more uncertainties with the geochronology method, together, they provide upper and lower limits to the long and short-term variations in elevation change that are useful for comparisons to current sea-level rise.

The global mean SLR (1993–2020) measured with satellites is 3.3 mm/year (Beckley et al. 2016; Beckley et al. 2017). Sea level is rising at different rates in different places, and it is rising at a rapid rate in the North Atlantic and accelerating (Oppenheimer et al. 2019). According to the latest State of New Jersey report on the SLR (Kopp et al. 2019), there is a 95% chance that SLR in New Jersey by 2050 will exceed 21 cm relative to 2000, a two in three chance (50–75%) that SLR will exceed 43 cm, and a 95% chance it will not exceed 79 cm relative to the year 2000. Therefore, there is a 50% chance that the rate of SLR in New Jersey by 2050 will exceed 8 mm/year relative to 2000 levels, and there is a 95% chance that it will exceed 4 mm/year (Kopp et al. 2016a).

This study showed that marshlands in the Meadowlands were rising at a rate of  $4.0 \pm 0.7$  mm/year. This is not sufficient to keep up with the predicted 8 mm/year of sea-level rise. Rough predictions about future wetland losses can be made if it is assumed that 80 years out, the weather will not change, and sediments will not be limited. Under these assumptions and with the predicted rates of surface elevation and sea-level rise, 7% (2.2 km<sup>2</sup>) of the total 16.3 km<sup>2</sup> of today's vegetated wetlands in the Meadowlands will be mudflat or underwater by the year 2100. Finally, because there is nowhere for wetlands to retreat, areas that today support thriving high marsh communities will most likely completely disappear.

## Conclusion

Our measurements of sediment transport in tidal creeks showed that sediments in the Meadowlands estuary were not limited, and the main possible sources included resuspension from the Hackensack River, upland erosion, and treatment plant effluents. About 16% of the total suspended solids reaching the marsh via the tide was trapped by the marsh surface. Hydraulic duty alone cannot explain deposition rates between low and high marshes. Other factors such as distance from tidal creeks, length of marsh edge, and age of the marsh also play an important role in determining deposition rates. The drivers for subsidence are precipitation, snow accumulation, sea surge from storms, and the subsurface diagenetic process. These in turn control swelling, compaction, and decomposition rates. In this case, the overall subsidence rate was  $1.5 \pm 1.3$  mm/year. When drivers for subsidence were removed, all sites combined showed increases in surface elevation of  $4.0 \pm 0.7$  mm/year. Regardless of future CO<sub>2</sub> emissions, there is a 50% chance that by the year of 2050 the rate of SLR in New Jersey will be 8 mm/year. The existing rate of increase in surface elevation is not enough to keep up with the predicted SLR. If we assume no change in sediment supply or weather patterns, by 2100, 7% of current Meadowland marshlands will convert to unvegetated mudflats, and most high marsh habitats will disappear.

**Acknowledgements** This study was supported by the Meadowlands Environmental Research Institute and the New Jersey Sports and Exposition Authority. The authors thank the MERI Geographical Information System group for making the maps. Inputs from Michael Stepowij, Ildiko Pechmann, Yefim Levinsky, Sandy Speers, Miranda Meng, and Batu Cam are also appreciated.

**Author contributions** FJA supervised this study and wrote the manuscript. JG conducted the field measurement and data analysis. YY conducted the data analysis and wrote the manuscript.

**Funding** This study was supported by the Meadowlands Environmental Research Institute (MERI) and the New Jersey Sports and Exposition Authority (NJSEA).

**Data availability** The datasets generated during and/or analyzed during the current study are available from the corresponding author upon request.

**Code availability** No software applications and custom code is applicable to this MS.

## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no known conflict of interest that could have appeared to influence the work reported in this paper.

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