A non-linear relationship between marsh size and sediment trapping capacity compromises salt marshes' stability

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Abstract:

Global assessments predict the impact of sea-level rise on salt marshes with present-day levels of sediment supply from rivers and the coastal ocean. However, these assessments do not consider that variations in marsh extent and the related reconfiguration of intertidal area affect local sediment dynamics, ultimately controlling the fate of the marshes themselves. Herein, we conduct a meta-analysis of six bays along the US East Coast to show that a reduction in the current salt marsh area decreases the sediment availability in estuarine systems through changes in regional scale hydrodynamics. This positive feedback between marsh disappearance and the ability of coastal bays to retain sediments reduces the trapping capacity of the whole tidal system and jeopardizes the survival of the remaining marshes. Here, we show that on marsh platforms the sediment deposition per unit area decreases exponentially with marsh loss. Marsh erosion enlarges tidal prism values and enhances the tendency towards ebb dominance thus decreasing the overall sediment availability of the system. Our findings highlight that marsh deterioration reduces the sediment stock in back-barrier basins and therefore compromises the resilience of salt marshes.

Keywords: salt marshes, coastal resilience, ecosystem services, COAWST, Delft3D.

Introduction

Salt marshes provide critical ecosystem services [Costanza et al., 1997]. In recent years salt marshes have been the focus of many restoration plans built on the concept of ‘nature-based solutions’ for flood defenses that aim to use vegetated surfaces to protect coastal communities from storms [Temmerman et al., 2013]. The economic value of salt marsh ecosystem services has been estimated to be up to 5 million USD per km^2 in the United States [Costanza et al., 2008], and 786 million GBP per year for all UK marshes [Foster et al., 2013; Leonardi et al., 2017]. Projections of salt marsh response to climate change are variable, with initial studies suggesting a 46% to 59% reduction of the present-day area by 2100 under moderate sea-level rise [Spencer et al., 2016], and more refined studies estimating “coastal squeezing” up to 30% when accounting for landward migration [Schuerch et al., 2018]. When allowed by the availability of accommodation space, the landward migration of fringing marshes supports the maintenance of marsh extent but erosion at the seaward side remains a serious threat to areal preservation [Schwimmer and Pizzuto, 2000].

Apart from hydrodynamics, salt marsh resilience has been linked to the sediment budget of the marsh complex as a whole, including not only the vegetated surfaces, but surrounding tidal flats, sea bed, and tidal channels [Ganju et al., 2013; Fagherazzi, 2014]. Ganju et al. [2017] synthesized sediment budgets of eight micro-tidal salt marsh complexes, and demonstrated the existence of a relationship between sediment budget and the unvegetated-vegetated marsh ratio (UVVR), indicating that sediment deficits are linked to conversion of vegetated marsh into open water. A positive sediment budget is indeed necessary to allow marshes and tidal flats to keep pace with sea-level rise [Mariotti and Fagherazzi, 2010].

Regional effects are crucial when evaluating coastal interventions under the management of multiple agencies. Though many studies have focused on local marsh dynamics, less attention has been paid to how changes in marsh areal extent might drive large-scale variations of hydrodynamic and sediment transport processes [Donatelli et al., 2018a; Zhang et al., 2018]. Donatelli et al. [2018b] studied the influence of salt marsh deterioration on the sediment budget in Barnegat Bay-Little Egg

Harbor estuary and showed the existence of a positive feedback between marsh erosion and the decrease in the trapping efficiency of the marsh and the whole tidal system.

Herein, we conduct a meta-analysis of high resolution numerical modeling results for the hydrodynamics and sediment transport of six back-barrier estuaries along the US Atlantic Coast, extending the results presented in Donatelli et al., [2018b] to other five systems. The sediment dynamics of these bays were simulated under different scenarios of salt marsh loss obtained by artificially changing the current bathymetries [Donatelli et al., 2018b; Zhou et al., 2016]. The erosion of salt marshes was simulated by removing vegetation from the eroded marsh cells, and by matching the corresponding bathymetry values with the elevation of the surrounding tidal flats. Lowering marsh platforms to the tidal flat depth represents how salt marshes erode under wind-wave attack [Leonardi and Fagherazzi, 2014; Priestas et al., 2015]. The Coupled-Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modelling system [Warner et al., 2010] and the computational fluid mechanics package Delft3D [Lesser et al., 2004] were used to carry out a set of exploratory models [Murray, 2007]. Our study demonstrates that marsh vulnerability can be underestimated when not accounting for the effect of marsh loss on potential sediment storage of the entire system. The study sites are listed in Table 1, while the present-day salt marsh area is highlighted in Figure 1. Details of the model setup can be found in the supplementary material.

Results

For each bay, five simulations were run with different marsh loss percentages: 0% (present-day salt marsh distribution), 25%, 50%, 75% and 100% (vegetated area completely eroded). Salt marsh erosion alters tidal prism values (SI Appendix, Figure S8), and consequently the inlet morphology [D'Alpaos et al., 2010]. The tidal signal also changes across different portions of the basins. A comparison of tidal amplitude and phase lag (timing delay of high tide across the bay) values between the pre- and post-erosion salt marsh configurations suggests that changes in tidal amplitude depend on the increased filling time of the back-barrier bay due to post-erosion increases in intertidal storage volume of the estuary. Indeed, tidal water levels in back-barrier basins are controlled by the ratio between inlet cross-sectional area and basin planform area [Keulegan, 1967]. High ratios mean that tidal water levels in the back-barrier basin adjust quickly to offshore water level fluctuations and therefore the phase lag between the ocean and the lagoon tidal wave is small.

For those systems where marshes mainly fringe the mainland and barrier island boundary (Plum Island Sound, Jamaica Bay, and Barnegat Bay-Little Egg Harbor in our study), the tidal phase lag between the ocean and the lagoon increases, leading to a reduction in tidal amplitude over the entire back-barrier bay. In contrast, in Great South Bay, Chincoteague Bay, and Virginia Coast Reserve, large marsh portions are detached from the mainland, and different parts of the domain experience different variations in tidal amplitude. When salt marshes are detached from the mainland, the deterioration of the marshes produces an increase in tidal amplitude behind the eroded patches, and a decrease in tidal amplitude between the eroded vegetated areas and the inlets. This suggests that locations near the mainland sheltered by marsh will be more affected by frictional reduction due to marsh disappearance than by the increase in filling time. The spatial distribution of tidal amplitude and phase lag before and after salt marsh removal for each bay are depicted in Figure 2a, b, e, f and in the SI Appendix (SI Appendix, Figure S5-6-7f, g and S5o, p).

We isolated the effect of salt marsh location from the effect of tidal wave interaction coming from multiple inlets by artificially transforming the estuaries into systems with a single entrance (SI Appendix, Figure S9-S11). For coastal bays with multiple inlets, water levels are controlled by overlapping waves propagating from each inlet, and changes in estuary morphology can alter their relative phase and amplitude. Additional simulations were conducted to verify that increases/decreases in tidal amplitude were caused by changes in salt marsh area rather than by the interference of multiple tidal constituents (SI Appendix, Figure S9-S11).

Salt marsh erosion also influences tidal asymmetry. Asymmetric tides are important for the transport and deposition of sediment in shallow estuaries [Aubrey and Speer, 1985; Gerkema, 2019]. When asymmetry occurs, the associated distortion of the tidal wave is generally described by superposing a shorter period overtide (M_4) on the normal (M_2) tidal shape. Changes in the M_4 to M_2 water level amplitude ratio and the phase difference between M_4 and M_2 were calculated for each scenario. The relative phase shift is computed as $2\varphi_2 - \varphi_4$, where φ_2 is the M_2 phase and φ_4 is the M_4 phase as per Friedrichs and Aubrey [1988]. In this formulation a relative phase between 0° and 180º means that the tidal wave has a shorter flood duration (flood dominance, stronger flood currents), while for a relative phase between 180º and 360º the tidal wave has a shorter ebb duration (ebb dominance, stronger ebb currents). The maximum flood and ebb dominance occur for a relative phase of 90° and 270º. For all test cases the estuaries remain flood dominated, even though marsh loss raises the tendency towards ebb dominance in some systems (Figure 2c, d, g, h; SI Appendix, S13-S14c, d, g, h); the magnitude of the non-linear distortion increases with marsh removal (SI Appendix, Figure S12 and S13-14a, b, e, f). These results are consistent with previous 1D numerical investigations [Friedrichs and Aubrey, 1988]. Recent 2D numerical studies suggest that these findings might be also dependent on the choice of friction for small ratios of tidal amplitude to mean water depth [Zhou et al., 2018].

To quantitatively evaluate how changes in tidal dynamics impact the sediment budget of the systems, we quantified sediment trapping efficiency before and after the removal of the marsh. Sediment trapping was evaluated by releasing a fixed amount of sediment in the bay, and then computing the fraction stored in the marshes, tidal flats and channels. We stopped the simulations after 30 days because the deposited volume did not change significantly after this period. The sediment deposit was sampled in the last day of simulation. Results are presented as a function of the ratio between marsh extent and basin area (Figure 3). The fraction of sediment potentially stored in channels and tidal flats per unit area decreases exponentially as the ratio between marsh area becomes smaller (Figure 3a); similarly, the fraction of sediment per unit area trapped by salt marshes drops exponentially (Figure 3b). Excluding Jamaica Bay, the exponential decay in sediment trapping as a function of marsh loss is relatively similar in each bay and close to the overall trend.

Discussions and conclusions

Our findings in relation to the sediment budget are relevant for the long-term resilience of the systems, as the sediment budget is an integrated metric of ecosystem stability [Ganju et al., 2017]. More specifically, our model results demonstrate that variations in marsh extent affect the sediment storage capacity of back-barrier estuaries in both vegetated and un-vegetated areas. Herein, we extend the results of Donatelli et al., [2018b] for Barnegat Bay-Little Egg Harbor estuary to other five back-barrier bays and we demonstrate that the sediment trapping capacity of salt marshes in back-barrier estuaries depends on their size with respect to the basin area. This study shows that marsh resilience to negative stressors might be compromised even by small percentages of marsh lateral erosion, as the relationship between marsh areal extent and marsh sediment trapping capacity is strongly non-linear. Changes in marsh extent due to erosion or restoration projects will cause changes in the amount of sediments trapped within the entire estuarine system. This might in turn promote further establishment or erosion of salt marshes. A decrease in salt marsh area causes a decrease in sediment trapping of the system, which could in turn promote further marsh deterioration. Given the assumption that the net sediment budget is the driving factor for marsh stability, the non-linear relationship further suggests that any restoration project increasing salt marsh areas will trigger a positive feedback increasing sediment retention.

A shortcoming of this modeling framework is related to the choice to remove all of the sediments deriving from marsh erosion. In reality, the sediment generated by marsh deterioration could contribute to salt marsh survival [Mariotti and Carr, 2014], or might be distributed in the basin modifying the hydrodynamic field and mitigating the sediment loss. Furthermore, the sediment injected in each system to evaluate the sediment stock after 30 days represents a fictitious input, and therefore we neglect that sediments released in the basin by rivers might be trapped with a different efficiency with respect to sediments coming from offshore.

Under future sea-level rise scenarios, further tidal prism enlargements and additional fragmentation of the barrier islands might be expected and these could potentially compromise the survival of entire lagoon ecosystems [FitzGerald and al., 2006]. Even if increasing hydraulic depth would reinforce existing tidal asymmetries [Friedrichs et al., 1990] and enlarge the mean tidal range of the estuary, with insufficient sediment supply the system will not be able to keep pace with sea-level rise. In the long-term, a reduced sediment trapping capacity might also control the lateral extension of salt marshes. A simple model proposed by Mariotti and Fagherazzi [2013] shows that the ratio between marsh to open water area in a bay is controlled by sediment availability (and sediment concentration). Similarly, the long-term modelling framework of Walters et al. [2014] indicates that marsh extension in back-barrier areas is a function of sediment supply; more sediment flushing and less trapping would therefore lead to a reduced marsh extension in these models.

Our study highlights the efficacy of coastal restoration interventions, which should target coastal erosion before the vegetated surface becomes too small compared to the basin area in order to maximize the large-scale efficiency of the interventions. Our findings further show the necessity to account for the nonlinearity of ecosystem response to changes in habitat size. A simplified approach that assumes ecosystem services provided by coastal habitats change linearly with their size would lead to a misrepresentation of the true economic value of salt marshes in terms of coastline resilience [Barbier, 2008].

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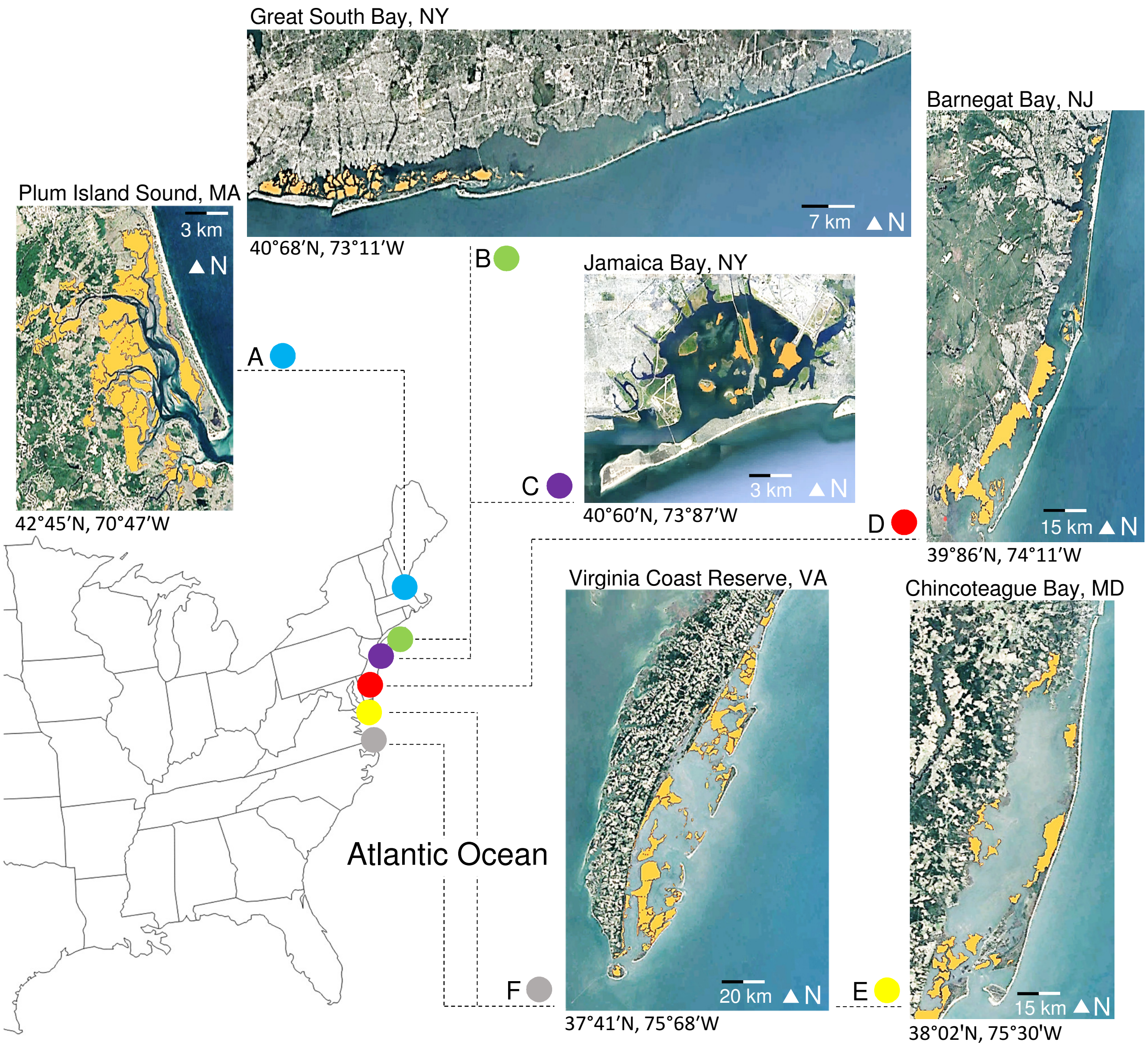
Figure captions

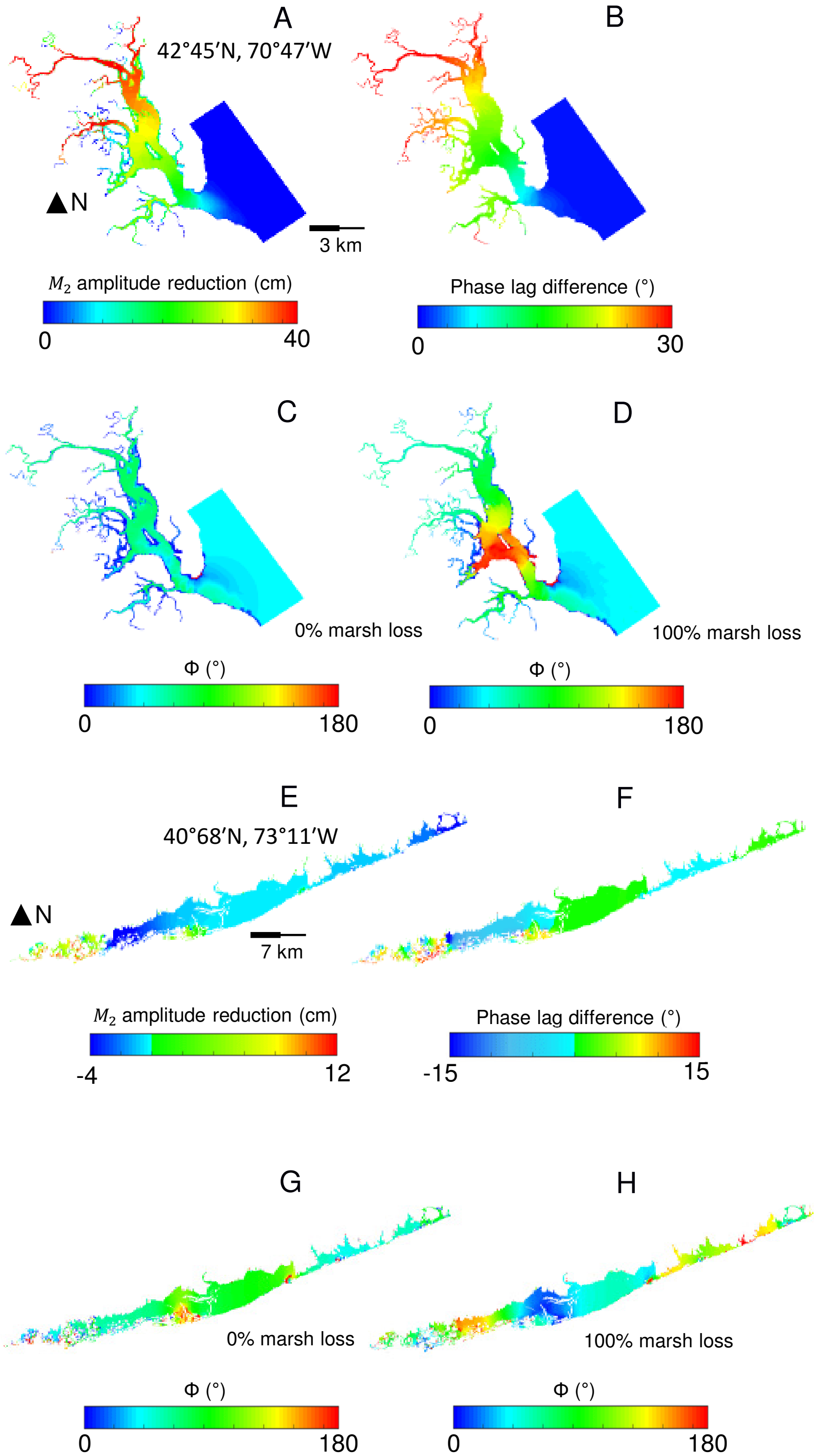
Figure 1: **Satellite images of the studied bays.** All the systems are located along the Atlantic coast of the USA: Plum Island Sound (a), Great South Bay (b), Jamaica Bay (c), Barnegat Bay-Little Egg Harbor (d), Chincoteague Bay (e) and Virginia Coast Reserve (f). The satellite images were acquired from Google Earth.

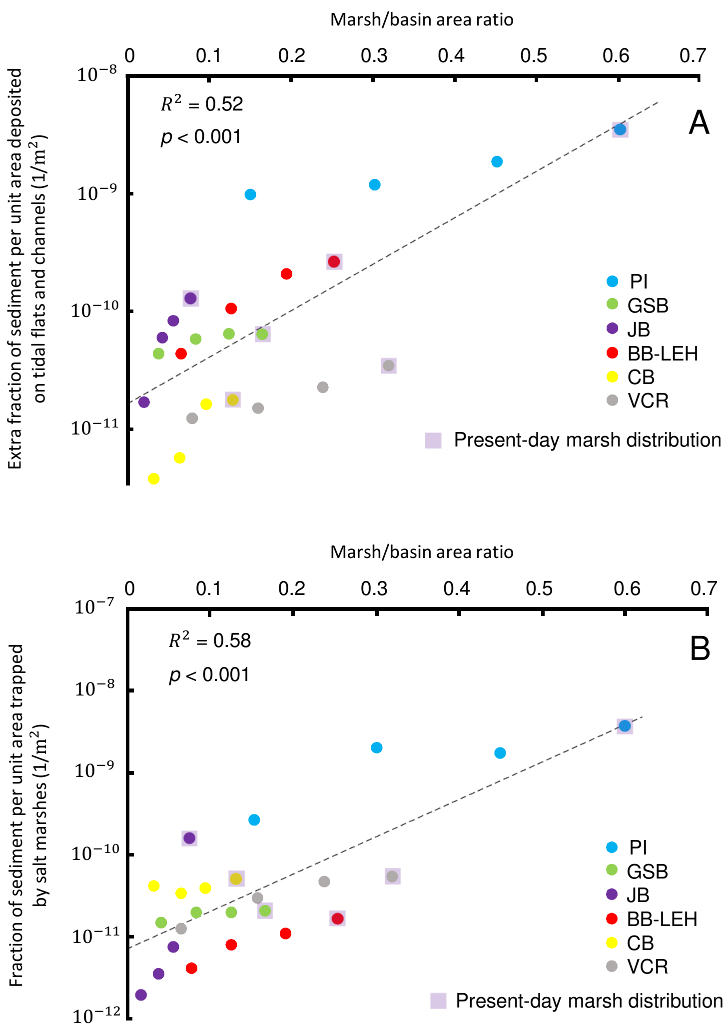
Figure 2: **Changes in tidal dynamics induced by marsh loss in Plum Island Sound and Great South Bay.** Reduction in M_2 amplitude (cm) and increase in phase lag (Φ) after the removal of the entire marsh surface (a-b, e-f); sea-surface phase of M_4 relative to M_2 for the current marsh distribution (c, g) and marsh completely eroded (d, h).

Figure 3: **Effect of marsh extent on the ability of tidal flats, channels and salt marshes to trap sediment inputs.** Fraction of sediment per unit area deposited on tidal flats and channels directly related to marsh presence as a function of normalized marsh area (a); fraction of sediment per unit area trapped on the marshes as a function of normalized marsh area (b). The four values for each location are the four quartiles tested (0, 25, 50 and 75%).

Table 1: Location (latitude and longitude) of each bay, initial marsh extent, average water depth (m), mean tidal range (m), marsh elevation above mean sea level (m), tidal prism (m^3) and numerical framework used for each estuary.


Great South Bay, NY
7 km
N
40°68′N, 73°11′W
Plum Island Sound, MA
3 km
N
42°45′N, 70°47′W
A
B
Jamaica Bay, NY
3 km
N
40°60′N, 73°87′W
C
Barnegat Bay, NJ
15 km
N
39°86′N, 74°11′W
D
Virginia Coast Reserve, VA
20 km
N
37°41′N, 75°68′W
F
Chincoteague Bay, MD
15 km
N
38°02′N, 75°30′W
E
Atlantic Ocean


A
42°45′N, 70°47′W
N
3 km
B
M_2 amplitude reduction (cm)
0
40
Phase lag difference (°)
0
30
C
D
0% marsh loss
100% marsh loss
Φ (°)
0
180
Φ (°)
0
180
E
40°68′N, 73°11′W
N
7 km
F
M_2 amplitude reduction (cm)
-4
12
Phase lag difference (°)
-15
15
G
H
0% marsh loss
100% marsh loss
Φ (°)
0
180
Φ (°)
0
180



Marsh/basin area ratio
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
10^{-8}
10^{-9}
10^{-10}
10^{-11}
R^2 = 0.52
p < 0.001
A
Extra fraction of sediment per unit area deposited on tidal flats and channels (1/m^2)
PI
GSB
JB
BB-LEH
CB
VCR
Present-day marsh distribution
Marsh/basin area ratio
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
R^2 = 0.58
p < 0.001
B
Fraction of sediment per unit area trapped by salt marshes (1/m^2)
PI
GSB
JB
BB-LEH
CB
VCR
Present-day marsh distribution

Table 1: Location (latitude and longitude), initial marsh extent, average water depth (m), mean tidal range (m), mean marsh elevation with respect MSL (m), tidal prism (m^3) and numerical framework used for each estuary.

System	**Location**		**Marsh/basin area ratio**	**Average water depth (m)**	**Mean tidal range (m)**	**Marsh elevation, MSL (m)**	**Tidal prism (m^3)**	**Numerical model**
Plum Island Sound (PI)	42°45'N	70°47'W	0.6	3	2.6	0.4	$6.4 \cdot 10^7$	Delft3D
Great South Bay (GSB)	40°68'N	73°11'W	0.16	1.2	0.25	0.45	$5 \cdot 10^8$	COAWST
Jamaica Bay (JB)	40°60'N	73°87'W	0.07	4	1.5	0.35	$1.4 \cdot 10^8$	COAWST
Barnegat Bay-Little Egg Harbor (BB-LEH)	39°86'N	74°11'W	0.25	1.5	0.4	0.55	$3.3 \cdot 10^8$	COAWST
Chincoteague Bay (CB)	38°02'N	75°30'W	0.13	1.4	0.25	0.25	$2.1 \cdot 10^8$	COAWST
Virginia Coast Reserve (VCR)	37°41'N	75°68'W	0.32	1.35	1.2	0.4	$7.8 \cdot 10^8$	Delft3D