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A Decade of Salt Marsh Elevation Change in New York City's Coastal Urban Parks

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Abstract
Coastal salt marshes of the eastern United States are particularly vulnerable to accelerated sea level rise, and urban marshes are at greater risk of erosion, inundation, and conversion to mudflat if left unmanaged. To guide New York City (NYC) salt marsh restoration strategies, NYC Parks collected up to 10 years of salt marsh elevation change data through 2020 at six salt marsh sites using the Surface Elevation Table-Marker Horizon (SET-MH) method, conducted a salt marsh trends analysis to determine shoreline change from 1974 to 2012, and conducted a salt marsh conditions assessment. We found that the city-wide average surface elevation trend of 3.31 mm yr^{-1} was not significantly different from the 30-year (1990–2020) Relative Sea Level Rise of 4.23 mm yr^{-1} at The Battery, NY, tide station, probably due to high variability across and within sites. We also found that accretion rates differed across sites and watersheds, and sites situated lower in the tidal zone had higher accretion rates. Notably, Jamaica Bay's Idlewild salt marsh, long suspected of being sediment-starved and ranking lowest in our conditions assessment, had the highest accretion rate at 9.5 mm yr^{-1}. Our salt marsh trends analysis also showed marsh loss at the shoreline edge, bare ground cover, and other indicators of marsh degradation. In mitigating marsh loss, the design grades for our recent wetland restoration projects enlarge the upper elevation ranges of the low- and high-marsh zones and incorporate wider and more gradual slopes in upland transition zones to enable inland marsh migration.

Keywords Salt marsh elevation change · Relative sea level rise (RSLR) · Surface elevation table-marker horizon (SET-MH) · Urban wetlands · Vertical accretion

Introduction

Coastal wetlands worldwide are vulnerable to climate change, and this risk is particularly high in the mid-Atlantic region of the United States (U.S.), where sea level rise risks are exacerbated by glacial isostatic adjustment (peripheral bulge collapse) following the last ice age (Sallenger et al. 2012). Centuries of alterations have filled and dammed tributaries for development, dredged and armored shorelines for shipping and industry, and crisscrossed marshes with ditches for agriculture and mosquito control (Black 1981; Adamowicz and Roman 2005; Adamowicz et al. 2020). In New York City (NYC), numerous present-day stressors further increase the vulnerability of existing salt marshes to deterioration. Stressors include increases in nutrient loading in coastal waterways, especially nitrogen effluent inputs from wastewater treatment plants (WWTPs) (Anisfeld and Hill 2011; Peteet et al. 2018; Rosenzweig et al. 2018; Watson et al. 2018). By the late 1990s, the rapid decline of NYC salt marshes was discernible from aerial imagery (Hartig et al. 2002; Mushacke and Picard 2002). Between 1974 and 1999, the marsh islands of the Jamaica Bay Wildlife Refuge lost 304 hectares (1.5% per year) (Hartig et al. 2002). Swanson and Wilson (2008) tracked how a century of dredge and fill practices altered the

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bathymetry by deepening the bay. The resulting wider and deeper channels increased the tidal range and effectively increased inundation at the marsh surface. Once the marsh surface can no longer drain sufficiently, hydrogen sulfide (H_2S) toxicity can trigger plant dieback and subsequent conversion to mudflat (Kolker 2005; Wigand et al. 2014; Alldred et al. 2020; Krause et al. 2020). Despite existing regulations intended to protect wetlands and clean water, NYC continues to lose salt marshes to erosion and drowning (Basso et al. 2015; Campbell et al. 2017; Haight et al. 2019). This trend is expected to worsen with sea level rise.

In the highly urbanized NYC setting, the loss of salt marsh is extremely concerning. Salt marshes filter contaminants and thus reduce pollutant loads in receiving waters, sequester carbon through mineral and organic sediment accretion (Pace et al. 2021), protect urban infrastructure from wave damage due to coastal storms (Gornitz et al. 2001), offer recreational opportunities for visitors and coastal communities, and support nursery habitat for fish and wildlife (Mitsch and Gosselink 2000; Gedan et al. 2009). NYC's salt marshes and their associated coastal habitats provide foraging, roosting, and nesting habitat to more than 330 species of birds (Fowle and Kerlinger 2001), including rare and imperiled species such as the Saltmarsh Sparrow and the Seaside Sparrow (Kocek et al. 2022). While much of NYC's 837 km of shoreline, including over 85% of tidal wetlands, has been filled and hardened (e.g., bound by bulkheads and/or riprap), over 30% of the shoreline remains relatively natural (NYCDCP 2021; Swadek et al. 2021), and over 1600 hectares of tidal wetlands remain in NYC (NYCDCP 2011, 2021; U.S. Fish and Wildlife Service 2023). In Jamaica Bay, a series of successful sediment placement projects to raise elevations and reconstruct the eroding marshes have supplemented marsh extent (U.S. ACE 2015; Cahoon et al. 2019), showing how management can play an important role in protecting and potentially increasing salt marsh extent in NYC.

This study seeks to discern the physical processes by which marsh loss is occurring, specifically through a lens of measured elevation change in NYC tidal wetlands. We evaluate naturally occurring salt marshes located in the Long Island Sound, Arthur Kill, and Jamaica Bay watersheds (Fig. 1), with the intent of informing long-term management to preserve, enhance, and restore these salt marshes for future generations.

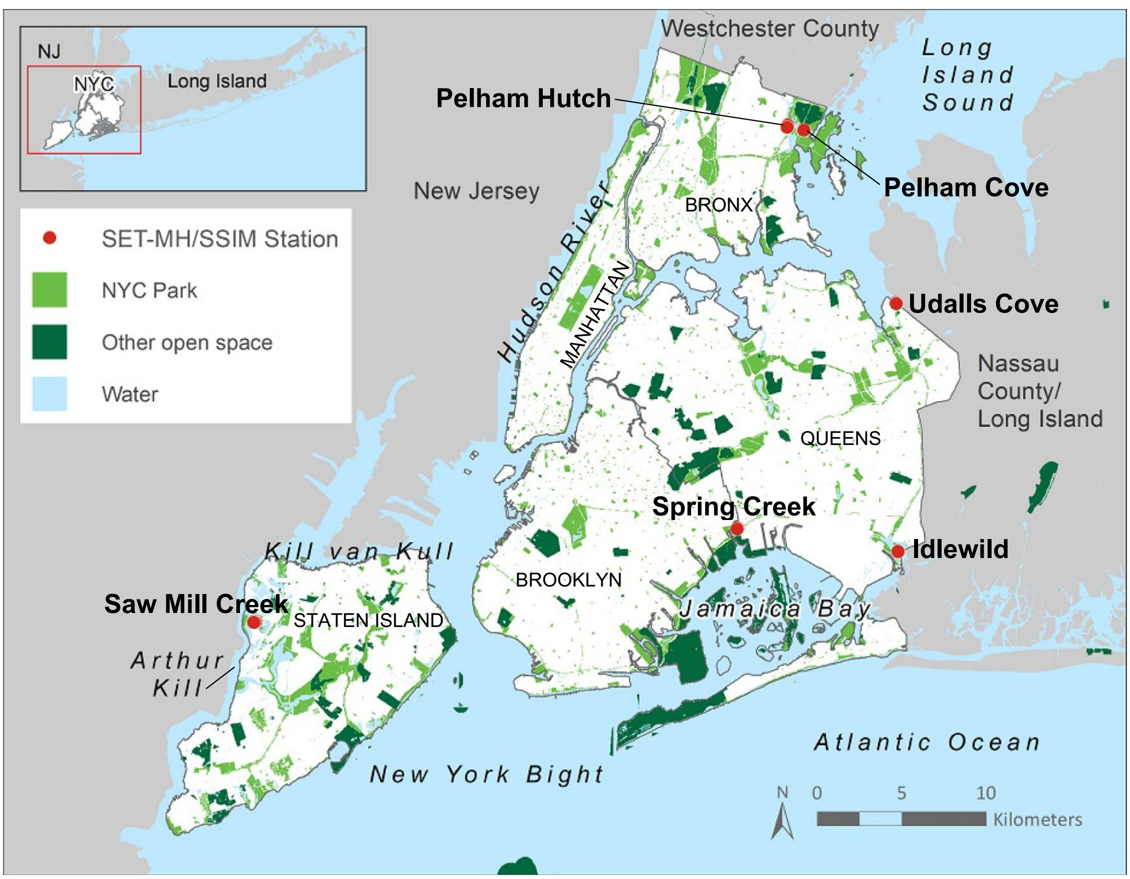


Fig. 1 Long-term SET-MH/SSIM monitoring locations including Pelham Hutch, Pelham Cove, and Udalls Cove along Long Island Sound, Saw Mill Creek along the Arthur Kill in northwest Staten Island, and Spring Creek and Idlewild in Jamaica Bay

While the Global Mean Sea Level Rise (GSLR) was about 1.8 mm yr^{-1} throughout most of the 20th century, GSLR has increased since 1993, averaging 3.1 ± 0.4 mm yr^{-1} (NOAA/STAR 2023). Locally, the long-term Relative Sea Level Rise (RSLR) recorded at the tide gauge station at The Battery, NY, in lower Manhattan has been approximately 2.92 mm yr^{-1} between 1856 and 2023 (Kemp et al. 2017; NOAA 2023). Projections currently used by NYC for planning purposes are based on the near-term local 30-year time series, 1980 to 2010, of 4.3 mm yr^{-1} for the New York (NY) metropolitan region (Horton et al. 2015; Gornitz et al. 2019).

Surface Elevation Tables and associated feldspar Marker Horizons (SET-MH) were used to measure changes in salt marsh elevation and sediment accretion (Cahoon et al. 2002b). SET-MH instruments were installed and monitored by NYC Parks at six sites throughout the city. The SET-MH method is also a component of NYC Parks long-term monitoring program based on the Mid-Atlantic Coastal Wetlands Assessment (MACWA) and Site-Specific Intensive Monitoring (SSIM) (MACWA SSIM QAPP 2010; PDE 2014). This study was conducted to determine (1) if the net elevation change was sufficient to keep pace with the near-term rate of RSLR, (2) if marshes are accreting sediment at a rate that is accompanied by a corresponding elevation change, (3) if a surplus in elevation capital necessarily indicated a stable marsh, and (4) if there was discernible variability within sites, across sites, and across watersheds.

Study Sites

Each of the six sites selected for this study is owned, managed by, and under the jurisdiction of NYC Parks (Fig. 1). These sites are all estuarine fringe marshes associated with upland slopes, except for Udalls Cove, an island marsh surrounded by creeks. While only areas within NYC Parks property boundaries were considered for this study, salt marsh extent often stretched onto private, state, or federal properties or outside NYC borders. Nevertheless, they all represent remnants of more extensive marshland, and most were used for harvesting salt hay and other agricultural crops, waterfowl hunting, and fishing into the 1890s and early 1900s (Teal and Teal 1969; Black 1981; Adamowicz et al. 2020). The marshes were subsequently heavily ditched in the last century in attempts to drain the marshes and rid them of mosquitos (Steinberg 2014). Shifts in vegetation since the 1970s are visible on aerial imagery but are also traceable in sediment cores (Kemp et al. 2017; Peteet et al. 2018). Recent rapid shifts in vegetated salt marsh extent have been documented from satellite imagery (Campbell et al. 2017). Basic marsh characteristics of each study site are given in Table 1. We refer to low marsh (regularly flooded and dominated by *Spartina alterniflora*), high marsh (irregularly flooded and dominated by *Spartina patens* and *Distichlis spicata*), or mixed high and low marsh within the same study site, giving further detail when these terms alone do not fully reflect current site conditions (Adamowicz et al. 2020).

Methods

Three main tools were used to document change and conditions at the six study sites: (1) investigations documenting vertical elevation change using the SET-MH method, (2) a salt marsh trends analysis using aerial imagery to evaluate shoreline change and marsh area change, and (3) a conditions assessment based on field and spatial data.

Table 1 SET-MH study site characteristics

Characteristics	**Pelham Cove**	**Pelham Hutch**	**Udalls Cove**	**Saw Mill Creek**	**Spring Creek**	**Idlewild**
Watershed	**LIS**[a]	**LIS**[a]	**LIS**[a]	**Arthur Kill**	**Jamaica Bay**	**Jamaica Bay**
Latitude °N, longitude °W	40.8710; –73.8089	40.8732; –73.8207	40.7789; –73.7488	40.6098; –74.1939	40.6595; –73.8561	40.6471; –73.7436
Geomorphic position	Fringe	Fringe	Island	Fringe	Fringe	Fringe
Salt marsh study area (hectares)	11	20	3.6	26.3	8.1	33.2
Salt marsh type	High	Mixed	Mixed	High	Low	Low
Dominant plant species[b]	SPAL, SPPA, DISP	SPAL, SPPA, DISP	SPAL, SPPA, DISP	SPPA, DISP	SPAL	SPAL
Start of sampling	Nov 2010	Dec 2011	Oct 2010	Oct 2013	Jan 2012	Apr 2013

[a]*LIS* Long Island Sound

[b]Dominant plant species refers to random plots within the larger Site-Specific Intensive Monitoring (SSIM) salt marsh study areas where SPAL = *Spartina alterniflora*, SPPA = *Spartina patens*, DISP = *Distichlis spicata*. Source—NYC Parks (2016)

SET-MH Field Investigations

SET-MHs were installed within the six salt marsh sites in NYC Parks. A deep Rod SET (RSET) benchmark was established by drilling 1.2-m stainless steel rods (one screwed onto the next) to the point of substantial resistance (> 60 s of drilling per 0.3 m) or 25 m deep, following USGS protocols (Cahoon et al. 2002a, b; Lynch et al. 2015). While there may be minor impacts from traversing the marsh to reach stations, impacts from installation and measurement are minimized by reaching the SET-MH work area from an aluminum plank (~3 m long) elevated by milk crates (> 0.3 m high) at both ends. In the absence of a permanent sampling platform that would introduce a standing vulnerability to vandalism, we carried the planks to and from the study site for each site visit. Baseline measurements were taken at a minimum of 4 weeks after the SET-MH installation. This allowed the 15-cm diameter PVC collar, cement protecting the top rod, and the connected receiver to set in place properly. At each monitoring session, the nine-holed portable arm, collar and rods were carried in and attached to the permanent SET-MH benchmark (Cahoon 2002b). Nine 76-cm fiberglass rods were inserted through the holes of the leveled horizontal arm and adjusted to rest lightly on the marsh surface. We used the most common configuration: rotating the arm to each of four alternate positions for measuring rod height at a total of 36 points (Russell et al. 2022). The length of the rod above the arm at each point was measured and recorded. All else being fixed, the repeat measurements of nearly identical points on the marsh surface allowed the SET-MH operator to measure marsh elevation change between the surface and the bottom of the deep RSET. Cahoon (2014) refers to this as the vertical land motion of the wetland (VLM_w) which then can be compared to tide station RSLR to determine if there is a surplus or deficit in marsh elevation capital, i.e., to determine if the marsh is able to keep pace with RSLR.

At the time of the baseline SET-MH measurements, three 0.25-m^2 plots around each SET-MH benchmark (3×18 stations = 54 marker horizon plots) were filled in with an approximately 0.6-cm thick layer of feldspar to form an artificial soil Marker Horizon (MH). This marker allows new mineral or organic accretionary sediments settling over time to be distinguished from the original baseline surface. At each subsequent visit, we sliced cores and measured the thickness of the accreted sediment at up to four positions above the bright feldspar MH.

Site Selection

Sites within the marsh complex were considered for SET-MH installations if they met the following criteria:

1. Loss of marsh extent has been observed since 1974.
2. Tidal tributaries inundating the marsh were not severely restricted by culverts or other infrastructure.
3. It was a naturally occurring marsh (no restoration sites were considered).
4. Public use for fishing or boating was infrequent.
5. Future management actions were feasible (e.g., if a site was found to be highly vulnerable to collapse, there would be the potential for supplemental sediment placement).
6. The marsh extent was at least 10 hectares in size (the study area may be smaller).
7. There was no evidence of recent nearby dredge and fill activity.

Station Selection and Measurement

For station location at the oldest of four SET-MH sites, we used a random number table to select three stations from among ten mapped spots near the confluence of two tributaries and set back 3.7 m from the vegetated marsh edge. Each of the stations under consideration had to allow for reasonable access by the monitoring team during a single low-tide window of at least three hours. For the two newest sites, Idlewild and Saw Mill Creek, a random number table was used to select locations anywhere internal to the marsh, provided they were a minimum of 3.7 m from the vegetated shoreline edge.

Monitoring started between 2010 and 2013, depending on the site (Table 1, Fig. 2a–f), and is reported herein through 2020. Initially, measurements were conducted in spring, summer, and fall; this was subsequently reduced to spring and fall, and then, starting in 2019, measurements were conducted annually, in the fall season only, after it was determined that intra-annual differences did not change the overall trend. Monitoring was timed to take place within a 4-h period centered on slack low tide. The few exceptions when flooded conditions at a SET-MH plot prevented a reading despite monitoring being conducted during low tide were documented on the field data sheets.

When Hurricane Sandy made landfall in New Jersey and flooded low-lying areas of NYC on 29 October 2012 (Sobel 2014), four of the SET-MH sites had three or more readings in the one or more years since installation. We were thus able to compare pre- and post-Sandy elevation and accretion at Pelham Cove, Pelham Hutch, Udalls Cove, and Spring Creek. In addition, since we had just conducted measurements at Pelham Cove on 9 October 2012 and could gain access there in the weeks that followed, we returned on 6 November 2012, just ahead of a nor'easter, and again just after the nor'easter on 11 November 2012. These extra sampling opportunities allowed us to document patterns in close succession around the extreme weather patterns at Pelham Cove.

Fig. 2 **a** Pelham Bay Park (Pelham Cove) with Long Island Sound tributary and forested trails (1 October 2014). **b** Pelham Bay Park at the Thomas Pell Sanctuary (Pelham Hutch) with Coop City's residential towers on the far side of the Hutchinson River (29 December 2011). **c** Udalls Cove Park Preserve (Udalls Cove) with Long Island Sound in the background. The right side is in adjacent Nassau County (31 October 2018). **d** Saw Mill Creek Park SET 1 with train tracks and H-towers in the background (11 June 2018). **e** Spring Creek Park SET 1 in the background. Shrubs on the opposite side of the creekbed hide the Belt Parkway (24 May 2017). **f** Hook Creek Park (Idlewild) salt marsh pin heights near the JFK International Airport landing lights in Jamaica Bay (8 June 2018)

To determine surface elevation relative to the North American Vertical Datum of 1988 (NAVD88) for each SET benchmark, Real-time Kinematic (RTK) Global Positioning System (GPS) survey equipment with centimeter-level spatial accuracy was employed during a single site visit. More than ten RTK GPS elevation points were taken while walking along the elevated aluminum plank nearest the SET benchmark. Data were processed using the *Online Positioning User Service* (OPUS) for precise ephemeral corrections to obtain orthometric heights (meters, NAVD88) (NGS 2023, James Lynch, pers. comm.) and then averaged to determine a mean elevation at each SET-MH station (Table S1).

Salt Marsh Trends Analysis and Conditions Assessment

A citywide trends analysis was conducted comparing 1974 imagery (Mushacke and Picard 2002; NYSDEC 2014) with 2012 post-Hurricane Sandy imagery (NOAA 2012). The available 1974 black-and-white infrared imagery included the tidal wetland boundaries outlined to convey regulated areas, while the wetland boundaries in the 2012 imagery were verified in the field (NYC Parks 2016).

A citywide salt marsh conditions assessment was conducted in 2013 and 2014 to inform management strategies using a combination of field investigations, aerial photo interpretation, and historical documents. This assessment resulted in a conditions index that was developed in collaboration with The Nature Conservancy. The index was composed of a variety of metrics including marsh area, native plant richness, vegetation cover, soil strength using the shear vane test (Turner 2011), presence of breeding bird species (based on data from historic field surveys and eBird (Fink et al. 2023)), bare ground cover, and more (see Supplementary Material, Table S2). Individual metrics were standardized by z-scores and summed to create an index of marsh-wide conditions to compare sites relative to one another (NYC Parks 2016; Haight et al. 2019). Z-scores, or "standard scores", center the values on zero by subtracting the mean from each value and standardizing the range of values by dividing those values by the standard deviation. Based on the conditions index, the six salt marshes in this study were ranked from 1 (highest condition) to 6 (lowest condition).

Statistical Methods

All statistical analyses were performed using R version 4.2.1 (R Core Team 2022). Functions in the *Stats* package were used for analysis of variance, post-hoc testing, and linear regressions. Figures were generated using packages *ggplot2* version 3.4.1 (Wickham 2016) and *ggbreak* version 0.1.1 (Xu et al. 2021).

Elevation and Accretion Trends

Simple linear regression through the origin was used to determine the rate of elevation change (mm yr^{-1}) at each individual SET pin. Pin measurements that did not rest on the marsh surface due to vegetation, debris, mussels, or fiddler crab holes were excluded from determining the pin's best-fit line (Delgado et al. 2013). Out of over 11,000 pin readings, fewer than 3% of measurements were rejected. Pin readings from hummock locations (with densely rooted small mounds from 5- to 10-cm in diameter) were all included. The slopes of the 36 pin regressions around each SET were averaged to calculate an average rate of surface elevation change and standard error at that station. Estimates of elevation change at each station were transformed using a square root transformation to meet the assumptions of an analysis of variance (ANOVA) and then compared using a nested ANOVA with sites nested within watersheds. An overall rate of elevation change across each site was calculated by averaging the mean elevation trend at each of the three stations within the site. The citywide rate of elevation change and standard error were calculated by averaging and taking the standard deviation of the six site means (Beckett et al. 2016).

For each sampling day, the total accreted sediment at each SET-MH station was calculated by first averaging the sediment readings at each individual feldspar MH plot and then averaging the three accretion plot estimates at each station. Simple linear regression through the origin was used to determine the rate of accretion over time for each station using these averaged measurements (mm yr^{-1}). Accretion rate estimates at each station were log-transformed to meet ANOVA assumptions and then compared across sites with a nested ANOVA, with sites nested within watersheds. Tukey's Honestly Significant Difference (Tukey's HSD) test was used to examine pairwise comparisons across watersheds and across sites. The average accretion rate across each site was estimated by averaging the accretion rates at each station. The citywide rate of accretion and standard error were estimated by averaging the overall accretion rate at each of the six sites and taking the standard deviation (Beckett et al. 2016). Linear regression was used to determine if the log-transformed accretion rate was a good predictor of square root–transformed elevation rate at individual SET stations.

Since VLM_w incorporates both accretion at the surface and subsurface processes, the extent of subsidence (VLM_s) could be calculated by subtracting VLM_w from vertical accretion (VA) as follows:

$$\text{Shallow subsidence } VLM_S = VA - VLM_W \tag{1}$$

(Cahoon 2014) where VA is the vertical accretion as measured above the feldspar marker horizon, VLM_w is the total elevation change, and VLM_s is the subsidence (positive value) or shallow expansion (negative value) between the bottom of the RSET and the marker horizon (Cahoon 2014).

A nested ANOVA was used to test for differences in RTK GPS elevation (NAVD88) across the six different sites and three watersheds, with sites nested within watersheds (Fig. 3). Residuals were checked to meet the assumptions of using an ANOVA. Tukey's HSD was used to perform pairwise comparisons across sites and across watersheds.

We used the VDatum transformation tool (NOS 2023) to derive Mean Tide Level (MTL), Mean High Water (MHW), and Mean Higher High Water (MHHW). To determine the inundation level within the tidal frame we subtracted MHW from the RTK GPS elevations. We performed a simple linear regression to examine surface elevation relative to mean high water (RTK-MHW) compared to the vertical accretion rate at each of the sites.

Relative Sea Level Trends

We estimated the relative sea level trend using monthly average sea level measurements recorded by the tide station at The Battery, NY (NOAA 2023). Simple linear regression was used to estimate the average rate of sea level rise over five different time-series windows (Table 2). Sea level measurements have been previously shown to exhibit significant serial autocorrelation, so we adjusted the standard error of our estimates using the autoregressive coefficient for The Battery and the following equation suggested in Zervas (2009):

$$\frac{s_{\mathrm{b\ (autoregression)}}}{s_{\mathrm{b\ (linear\ regression)}}} = \left(\frac{1 + p_1}{1 - p_1}\right)^{1/2}$$

where p_1 is the lag 1 autoregressive coefficient representing the part of the time series predictable from the previous month's residual, and s_b is the standard error of the trend. We used these adjusted standard errors to calculate 95% confidence intervals for RSLR. Although we calculated RSLR for the 10-year window covering the study period, the 95% confidence interval was too large for a meaningful comparison given the high interannual variability. Therefore, we used the 30-year period (1990 to 2020) for the near term and the full record for the long-term RSLR (Table 2).

We used *t*-tests to compare net elevation change at each station and each site together with both the long- and near-term record RSLR from the tide gauge station at The Battery, NY as follows:

Table 2 Potential time-series windows of relative sea level trends for The Battery, NY

Years	Month/year range	Relative sea level trend (mm year^{-1})[a]
10	Nov 2010 to Nov 2020	4.01 ± 4.92
30	Nov 1990 to Nov 2020	4.23 ± 0.99
50	Nov 1970 to Nov 2020	3.73 ± 0.48
100	Nov 1920 to Nov 2020	3.20 ± 0.16
164	1856 to Nov 2020	2.88 ± 0.08

[a]Sea level trend estimates reported together with their 95% confidence intervals, adjusted for a lag 1 autoregressive coefficient of 0.33 as calculated in Zervas (2009). Source of CSV data set from The Battery, NY (ID 8518750) (NOAA 2023)

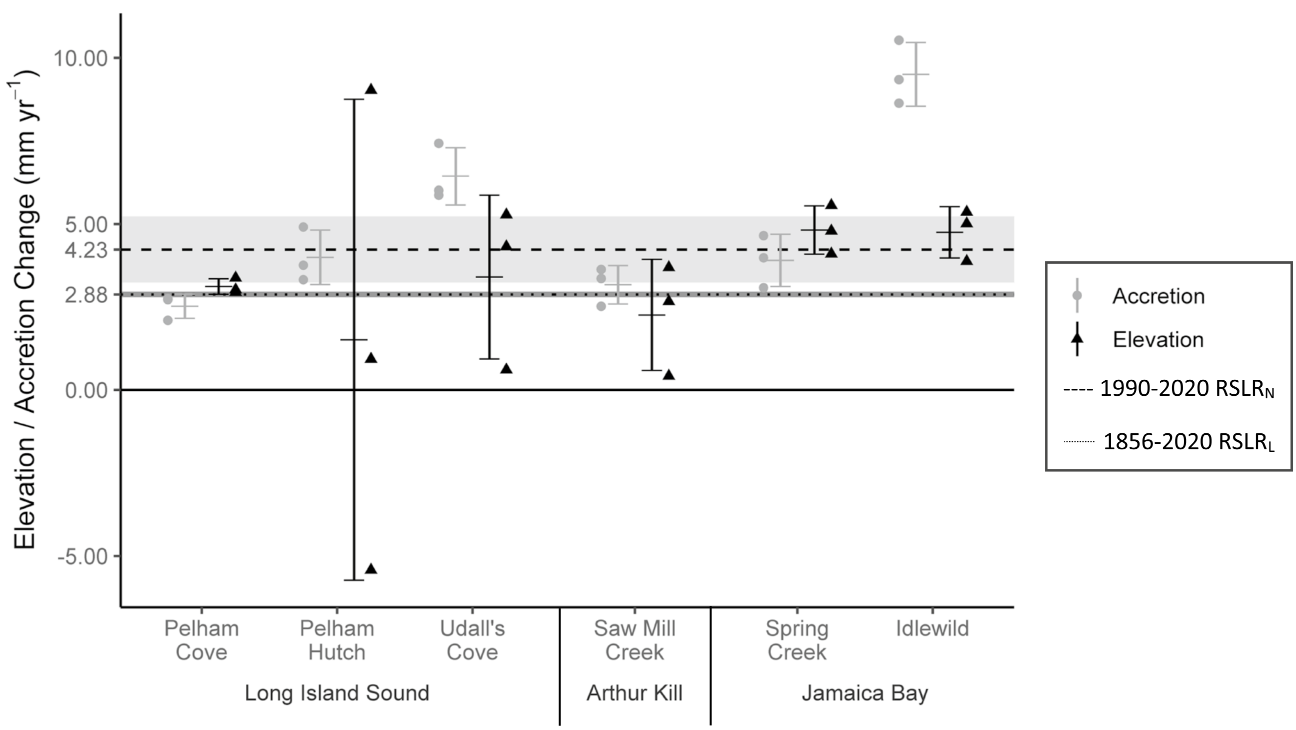


Fig. 3 Rate of surface elevation change and sediment accretion at the six SET-MH sites in relation to Relative Sea Level Rise for the near-term (RSLR$_N$) (30-year record) and the long-term (RSLR$_L$) (174-year record) based on monthly mean sea level trends at The Battery tide gauge, NYC (NOAA 2023). Error bars represent the mean for the three stations at each site ± 1 standard error. Shaded bars around the RSLR estimates show their 95% confidence intervals

$$\text{Long-term } RSLR_{wet} = RSLR_L - VLM_W \quad (2)$$

(Cahoon 2014)

$$\text{Near-term } RSLR_{wet} = RSLR_N - VLM_W \quad (3)$$

(Cahoon 2014) where $RSLR_{wet}$ is the wetland RSLR, $RSLR_L$ is the long-term RSLR, $RSLR_N$ is the shorter near-term RSLR, and VLM_w is the wetland Vertical Land Motion.

Results

SET-MH Monitoring Results

Elevation Change

Trends in surface elevation change at the six sites ranged from 1.51 ± 7.24 mm yr^{-1} at Pelham Hutch to 4.82 ± 0.73 mm yr^{-1} at Spring Creek (Table 3, Fig. 3). Individual SET-MH station information is given in the Supplementary Material, Table S1, Fig. S1a–f. The city-wide average rate of surface elevation change (VLM_w) was 3.31 ± 1.32 mm yr^{-1}. We did not find a significant difference among watersheds (ANOVA, $F_{2,3} = 0.620$, $p = 0.23$) or individual sites ($F_{3,12} = 0.228$, $p = 0.88$).

Among the oldest SET-MH sites, at Pelham Cove and Pelham Hutch, where pre-Hurricane Sandy data (pre-2012) could be compared with post-Hurricane Sandy data, there was high variability in how stations responded (if at all). Pelham Hutch presented the most extreme example of elevation (VLM_w) dropping at SET 3 (-5.42 ± 4.88 mm yr^{-1}), increasing at SET 1 (9.02 ± 4.66 mm yr^{-1}), and remaining relatively static at SET 2 (0.93 ± 2.04 mm yr^{-1}) (Table S1, Fig. S1b). By 2020, SET 3 never again reached its 2012 pre-storm elevation despite 8 years of vertical accretion, and Pelham Hutch had the highest standard error in surface elevation change compared to other sites (Table 3). In comparison, at the nearby Pelham Cove, station variability was low, and its standard error in surface elevation change was the lowest across all sites (Tables 3 and S1, Fig. S1a).

Only the two Jamaica Bay low marsh *Spartina alterniflora* dominated sites, Idlewild and Spring Creek showed an average surplus elevation trend in the marsh (near-term $RSLR_{wet}$), i.e., the difference between elevation change at the marsh site and $RSLR_N$ (i.e., 4.23 mm yr^{-1}). We observed that four of the six marsh averages kept pace if calculated against the $RSLR_L$ (2.88 mm yr-1) (Tables 3 and S1, Fig. 3) although these results were not statistically different. City-wide, NYC salt marshes have an average elevation deficit of 0.92 mm yr^{-1} using the near-term $RSLR_{wet}$.

Sediment Accretion Rates

All stations actively accreted sediment and were dry enough during most monitoring dates to obtain readable cores. Vertical accretion rates at the six sites ranged from 2.52 ± 0.37 mm yr^{-1} at Pelham Cove to 9.5 ± 0.96 mm yr^{-1} at Idlewild (Tables 3 and S1, Figs. 3 and S1a–f). The citywide average accretion rate was calculated to be 4.92 ± 2.61 mm yr^{-1}. No

Table 3 SET-MH monitoring results for six NYC Parks sites along three watersheds

Parameter	**Pelham Cove**	**Pelham Hutch**	**Udalls Cove**	**Saw Mill Creek**	**Spring Creek**	**Idlewild**	**Citywide**
Watershed	**LIS**	**LIS**	**LIS**	**Arthur Kill**	**Jamaica Bay**	**Jamaica Bay**	
Surface elevation trend (VLM_w) (mm yr^{-1})	3.12 ± 0.23	1.51 ± 7.24	3.40 ± 2.47	2.26 ± 1.67	4.82 ± 0.73	4.75 ± 0.78	3.31 ± 1.32
Vertical accretion rate (VA) (mm yr^{-1})	2.52 ± 0.37	4.00 ± 0.82	6.43 ± 0.86	3.17 ± 0.58	3.90 ± 0.79	9.50 ± 0.96	4.92 ± 2.61
Shallow subsidence VLM_s[a] (mm yr^{-1})	**−0.59**	2.49	3.03	0.91	**−0.91**	4.75	1.61
Long-term wetland relative sea level rise ($RSLR_{wet}$)[b]	**−0.24 (0.32)**	1.37 (0.85)	**−0.52 (0.83)**	0.62 (0.71)	**−1.94 (0.01)**	**−1.87 (0.02)**	**−0.43 (0.75)**
Near-term wetland relative sea level rise ($RSLR_{wet}$)[b]	1.11 (0.05)	2.72 (0.71)	0.83 (0.74)	1.97 (0.26)	**−0.59 (0.26)**	**−0.52 (0.58)**	0.92 (0.52)
Elevation capital ranking[c]	4	6	3	5	1	2	

Elevation and accretion rate estimates are shown with their standard error

Numbers in parentheses represent *p*-values derived from a *t*-test comparing marsh elevation trends with short- and long-term estimates of sea level rise (4.23 and 2.88 mm yr^{-1}, respectively)

[a]Shallow subsidence ($VLM_s = VA - VLM_w$) is a positive value when VA is greater than VLM_w; VLM_s is a negative value when VA is less than VLM_w indicating shallow expansion (in bold) (Cahoon 2014)

[b]$RSLR_{wet}$ is negative where there is a surplus elevation rate in the wetland compared to the local sea level (in bold) (Cahoon 2014)

[c]Sites were ranked from 1 (highest condition) to 6 (lowest condition)

Table 4 Tide levels from RTK GPS surveys and VDatum

Parameter Watershed	Pelham Cove LIS	Pelham Hutch LIS	Udalls Cove LIS	Saw Mill Creek Arthur Kill	Spring Creek Jamaica Bay	Idlewild Jamaica Bay
RTK GPS elevation (2013 and 2014)[a]	1.16	1.16	0.97	0.88	0.71	0.60
Mean tide level (MTL)[b]	−0.08	−0.07	−0.07	−0.11	−0.13	−0.10
Mean high water (MHW)[b]	1.03	1.04	1.02	0.68	0.71	0.76
Mean higher high water (MHHW)[b]	1.14	1.14	1.13	0.78	0.82	0.86
RTK-MHW	0.13	0.12	−0.05	0.20	0.00	−0.15

[a]All elevations are in meters, NAVD88

[b]VDatum transformation tool (NOS 2023)

significant correlation was observed between accretion and elevation rates ($R^2 = 0.064$, $p = 0.31$).

However, significant differences were found in average accretion rates across sites (ANOVA, $F_{3,12} = 29.8$, $p < 0.01$) and across watersheds ($F_{2,3} = 18.3$, $p < 0.01$). The sediment accretion rate at Idlewild (9.50 mm yr^{-1}) was significantly greater than at Pelham Cove, Pelham Hutch, and Saw Mill Creek (Tukey's HSD, $p < 0.01$) but not Udalls Cove (Tukey's HSD, $p = 0.39$). The next highest accretion was at Udalls Cove (6.43 mm yr^{-1}) where the sediment accretion rate was significantly greater than at Pelham Cove and Saw Mill Creek (Tukey's HSD, $p < 0.05$). We did not find significant differences in sediment accretion rates among the other sites (Tukey's HSD, $p > 0.06$). In pairwise comparisons across the three watersheds, the Jamaica Bay mean accretion rate was significantly higher than rates at both Long Island Sound (Tukey's HSD, $p < 0.01$) and the Arthur Kill (Tukey's HSD, $p < 0.01$); however, mean accretion rate was not significantly different between Long Island Sound and the Arthur Kill (Tukey's HSD, $p = 0.12$).

Subsurface Processes

As given in Table 3, shallow subsidence was evident at most sites though Pelham Cove and Spring Creek showed subsurface shallow expansion (a negative value). Stations with the greatest subsidence were Pelham Hutch SET 3 (at 8.74 mm yr^{-1}), Udalls Cove (at 5.27 mm yr^{-1}), and Idlewild SET 3 (at 6.65 mm yr^{-1}) (Table S1, Fig. S1b, c, f).

Marsh Vertical Elevation Range

The RTK GPS elevations (2013–2014) indicated that Idlewild marsh surface elevation was the lowest of all sites, followed by Spring Creek and Saw Mill Creek. Udalls Cove, Pelham Hutch, and Pelham Cove, the three Long Island Sound marshes, were all higher, with the two westernmost being higher in elevation than those at Udalls Cove (Table 4). Marsh elevations did not differ between the Pelham Hutch and Pelham Cove sites, which were both within Pelham Bay Park, but the pair were significantly different from all other Tukey pairwise comparisons (Tukey's HSD, $p < 0.001$). Elevation differed significantly across watersheds (ANOVA, $F_{2,3} = 4993$, $p < 0.001$) and across individual marshes ($F_{3,169} = 424$, $p < 0.001$). Idlewild, Spring Creek, and Udalls Cove elevations were within the regularly flooded zone (Mean Tide Level (MTL) to MHW) while Saw Mill Creek, Pelham Hutch, and Pelham Cove were within the irregularly flooded zone (MHW to Mean Higher High Water (MHHW)).

Figure 4 demonstrates the trend between accretion and surface elevation relative to MHW. There was a significant negative correlation in a linear regression between site-wide accretion rates and RTK-MHW ($p = 0.015$).

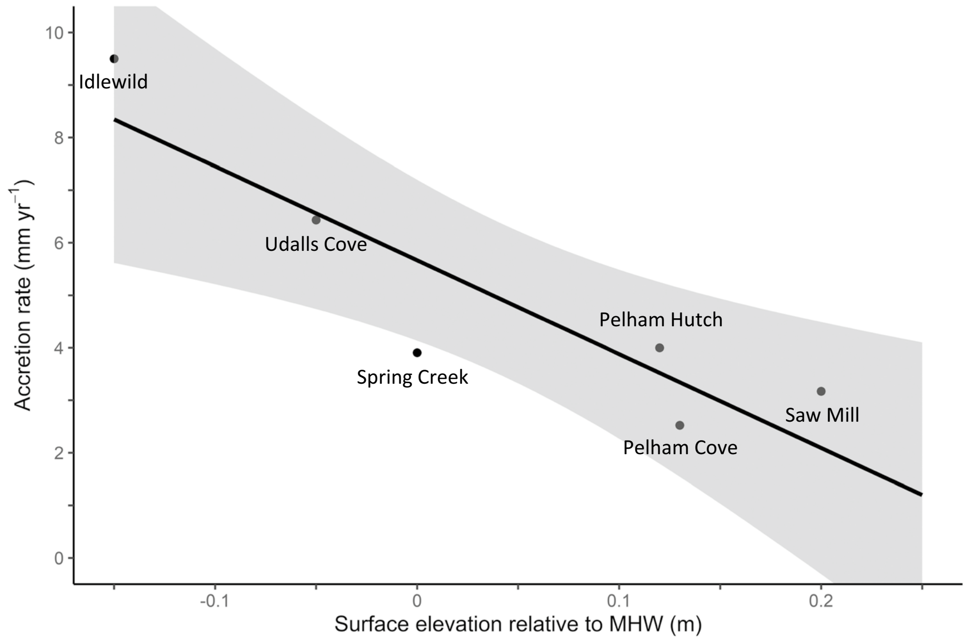
Salt Marsh Trends Analysis and Conditions Assessment

Shoreline loss within the 38-year period (1974 to 2012) is presented as percent loss per year in Table 5 (NYC Parks 2016). Of the six sites, the greatest percentage of wetland loss was at Udalls Cove with 1.30% per year while Saw Mill Creek had the lowest with 0.16% loss per year. According to the conditions assessment, Jamaica Bay marshes ranked lower for their overall condition compared to Arthur Kill and Long Island Sound (Table 3). The two Jamaica Bay sites, Spring Creek and Idlewild, are ranked fifth and sixth in terms of salt marsh condition, and they also had lower vegetation cover, higher bare ground cover, and lower soil shear vane strength compared to other sites. The salt marsh conditions index with the full set of metrics and z-scores for each site is given in the Supplementary Material, Table S2.

Discussion

This study does not provide a straightforward indication as to whether marsh surface elevation change is keeping pace with the near-term rate of RSLR. We found that elevation change and accretion rates were variable, and

Fig. 4 Relationship between vertical accretion rate (mm yr^{-1}) and the difference between RTK GPS elevation (NAVD88) and mean high water (RTK-MHW) in meters. Regression shading indicates the 95% confidence interval. Site names are given



accretion was not a useful predictor of surface elevation trend (VLM_w), which may be due to subsurface subsidence and other factors. Surplus elevation capital does not necessarily correspond to a more stable or healthy marsh, as only the Jamaica Bay sites showed a slight surplus in elevation capital compared to near-term RSLR but had the poorest rankings in the salt marsh conditions assessment. There were significant differences in accretion rates across sites and watersheds, with Idlewild in Jamaica Bay having the highest accretion rate even though Jamaica Bay is known to be a sediment-starved system (Swanson and Wilson 2008; Wigand et al. 2014; Peteet et al. 2018; Cahoon et al. 2019).

While results indicate some NYC marshes are keeping pace with RSLR when evaluated against the long-term rate of 2.88 mm yr^{-1}, more recent near-term rates (4.23 mm yr^{-1}) (1990–2020) revealed greater threats to all NYC marshes. Jamaica Bay sites appear to have an elevation surplus (negative values indicate surplus), ranking highest for $RSLR_{wet}$, but the effective elevation difference is small and not significantly different from near-term RSLR. We acknowledge that a longer measurement period may provide more accurate estimates of elevation change. Also, the limited number of SET-MH stations at each site may have led to an incomplete accounting of heterogeneity in elevation across the marsh plane. Nonetheless, our findings are consistent with other SET-MH studies of salt marshes in the New York region (e.g., Cahoon et al. 2019; Maher and Starke 2023).

We hypothesize that elevation change is not correlated with accretion due to a combination of factors, including subsurface subsidence. For example, at Pelham Hutch's SET 3 and Udalls Cove SET 2, the elevation change was flat despite measurable vertical accretion. Subsidence at these sites may be indicative of root decomposition, dewatering of sediment leading to compaction, and other subsurface

Table 5 Salt marsh trends analysis results to evaluate marsh condition

Parameter Watershed	Pelham Cove LIS	Pelham Hutch LIS	Udalls Cove LIS	Saw Mill Creek Arthur Kill	Spring Creek Jamaica Bay	Idlewild Jamaica Bay
% per year marsh loss (1974–2012)[a]	0.49	0.66	1.30	0.16	0.56	0.40
Salt marsh conditions index ranking[b]	1	4	3	2	5	6

[a]Shoreline marsh loss was analyzed using 1974 to 2012 post-Hurricane Sandy aerial imagery

[b]Sites were ranked from 1 (highest condition) to 6 (lowest condition). See Table S1 for additional parameters. Source—US EPA Wetland Program Development Grant (WPDG) report (NYC Parks 2016)

processes. It was beyond the scope of our study to measure rootzone growth specifically; however, Maher and Starke (2023) have done so nearby in Long Island, NY. Other studies describe changes from more mineral to more organic sediment flux, compaction from nor'easters and hurricanes, weight of winter ice, and compression from root decomposition or dewatering (Argow and Fitzgerald 2006; Deegan et al. 2012; Cahoon 2014; Wigand et al. 2014; Kemp et al. 2017; Hu et al. 2018; Peteet et al. 2018; Cahoon et al. 2019; Yeates et al. 2020; Wang et al. 2023).

We also found that accretion rates were negatively correlated with RTK GPS elevation (NAVD88) minus MHW (Table 4, Fig. 4): specifically, accretion rates were greater where the surface elevation was at or below MHW compared to where the surface elevation was above MHW. As described by Adamowicz et al. (2020), we found that particularly at Udalls Cove, there is a disconnect where the site already transitioned toward a regularly flooded marsh with high accretion, yet the vegetation continues to support a mix of high marsh *Spartina patens* and *Distichlis spicata* along with *Spartina alterniflora* (Table 1). Although NYC marshes are accreting, it is likely that a lack of mineral sediments flowing from upstream tributaries (Peteet et al. 2018), high nitrogen in the estuary (Watson et al. 2018) from effluent from WWTPs and Combined Sewer Overflow systems (CSOs) (Rosenzweig et al. 2018), and the historic deepening of the bay channels (Swanson and Wilson 2008) limits elevation capital of wetlands. As pointed out by Peteet et al. (2018), high nitrogen levels in Jamaica Bay may be contributing to the higher accretion rates found there though the benefits may be short-lived. The greater aboveground biomass production due to high nitrogen levels traps more sediment and in part compensates for the lack of mineral sediment supplies; however, improved tertiary treatment would lower nitrogen availability in the future.

High nitrogen content has also been correlated with sloughing, creek widening, and degradation of marsh peat (Deegan et al. 2012; Wigand et al. 2014; Peteet et al. 2018; Rosenzweig et al. 2018; Watson et al. 2018). These are all features exhibited by comparing Jamaica Bay historic aerial photo imagery since 1959 (Hartig et al. 2002), using a reconstruction of sediment fluxes since the 1800s (Peteet et al. 2018), and from Pelham Bay Park (Kemp et al. 2017). We also may be observing variable patterns described by McKee and Cherry (2009) and Turner (2006) for Louisiana salt marshes, where offshore sediments and eroded or scoured marsh might be supplying the sediment to enable a high accretion rate where observed.

Tidal wetland maps from 1974 and 1999 indicate larger areas of naturally occurring mixed marsh vegetation than what we see today in Jamaica Bay (Hartig et al. 2002; Mushacke and Picard 2002). As a result, we hypothesize that Jamaica Bay may serve as a sentinel environment for other NYC marshes, which sets it apart from the other watersheds in this study. The variation in results between marsh-wide conditions assessments and site-specific monitoring (SET-MH) also indicates that a broad range of metrics, scales, and monitoring approaches is needed for a more comprehensive evaluation.

While this study did not aim to evaluate changes in pre- and post-storm elevation, we documented highly variable responses at Pelham Cove and Pelham Hutch following Hurricane Sandy (Supplemental Material, Fig. S1a, b). At Pelham Hutch the overall trajectory of elevation and accretion differed dramatically across its three SET stations, with one losing elevation, one gaining elevation, and one being relatively stable. We suspect that because the station was situated nearest the confluence of two rivers, it was particularly vulnerable to severe compaction from the weight of excess water (more than 2 m higher than MHW water) during multiple tide cycles (Sobel 2014) or differential erosion depending on the relative differences in marsh stability. This aligns with McKee and Cherry's (2009) findings following Hurricane Katrina in the Gulf Coast where a hurricane can effectively "reset the clock" for elevation change. Ekberg et al. (2017) also describe how increased inundation can act as a force that either destabilizes sediments or acts to increase accretion rates through higher sediment availability.

Overall, these results aid in evaluating site vulnerability, capacity to accrete sediment, and opportunities for sustainable restoration, particularly with greater tidal inundation of nutrient-enriched waters under accelerated RSLR. Design grades for our newer wetland restoration projects have been planned for the upper elevation ranges of regularly flooded (low marsh) zones and irregularly flooded (high marsh) zones and also incorporate gradual slopes in upland transition zones to enable inland migration (NYC Parks 2018). The SET-MH network results offered a sense of urgency showing that while there were elevation surpluses and deficits, none indicated long-term stable condition. Looking forward, thin-layer placement restoration techniques that artificially add mineral soil and mimic natural sediment transport processes in estuaries may be very important management approaches to enable NYC's salt marshes to persist.

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