Estuaries and Coasts (2021) 44:1649–1657
https://doi.org/10.1007/s12237-021-00946-x

SPECIAL ISSUE: CONCEPTS AND CONTROVERSIES IN TIDAL MARSH ECOLOGY REVISITED

From Cedar Cemeteries to Marsh Lakes: a Case Study of Sea-Level Rise and Habitat Change in a Northeastern US Salt Marsh

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Received: 2 October 2020 / Revised: 26 April 2021 / Accepted: 3 May 2021 / Published online: 5 June 2021

Abstract
Evidence for relative sea-level rise in the Mullica River-Great Bay, a relatively undisturbed watershed in southern New Jersey, stretches over hundreds of years. The increase in global sea-level rise in the region is enhanced by subsidence and results in rates that are approximately double the global average. In recent decades, the occurrence of "ghost forests," standing dead forests, especially of the salt-intolerant Atlantic White Cedar, is becoming increasingly obvious as tidal inundation of salty waters increases further inland, especially in the upper portions of the Mullica River and its tributaries. Even older evidence of sea-level rise in the watershed is the subtidal and intertidal occurrence of "cedar cemeteries," i.e., buried accumulations of Atlantic white cedar stumps and timbers that have been radiocarbon-dated from the fifteenth to the sixteenth centuries to as old as the fifth century. Some of these are being exposed as rising water extends intertidal creeks into adjacent wetlands and uncovers this rot-resistant wood. Sea-level rise is perhaps the most significant threat to the persistence of salt marshes over the coming century. Sea-level rise decreases salt marsh area by erosion at the marsh edge, drowning of the marsh surface, and the expansion of marsh pools into larger marsh "lakes." In some instances, this loss of salt marshes is compensated for by expansion landward into ghost forests, but in this watershed and others, the expansion is by invasive plant species such as *Phragmites australis*, which is suboptimal habitat for fishes, crabs, and other invertebrates. The combination of a fast rate of sea-level rise in an area relatively free from recent human intervention makes the Mullica Valley watershed an ideal location to continue to evaluate the effects of sea-level rise on salt marsh ecosystems.

Keywords Sea-level rise · Marshes · Ghost forests · Cedar cemeteries · Habitat

Introduction

Sea-level rise is increasingly recognized as a profound influence on estuarine habitats ranging from maritime forests to marshes (Cahoon et al. 2006; Colombano et al. 2021; Gedan et al. 2009; Mariotti 2020). This is especially evident in the Mid-Atlantic Bight region of the USA because the rates of sea-level rise are among the highest in the world, approximately double the global average (Ezer and Atkinson 2014; Horton et al. 2013; Kemp et al. 2013; Miller et al. 2013; Sallenger Jr. et al. 2012; Walker et al. 2021). One of the most impacted estuarine habitats is salt marshes both generally (Crosby et al. 2016; Roman 2017; Schuerch et al. 2018; Stevenson and Kearny 2009), and including in specific areas such as Chesapeake Bay (Beckett et al. 2016), southern New England (Cahoon et al. 2019; Watson et al. 2017a, b), and especially those that are microtidal (< 2 m) (Kearney and Turner 2016). This is evident in several metrics, most often as changes in vegetation type, loss at the marsh edge, or loss in the marsh interior.

The changes in the vegetation are evident as alteration from high marsh (e.g., *Spartina patens*, *Distichlis spicata*) to low marsh (*Spartina alterniflora*) species (Carey et al. 2017; Donnelly and Bertness 2001; Morris et al. 2002; Raposa et al. 2017; Smith and Pellew 2021). Marsh loss is most frequently recognized at the marsh edge even though the eroded edge sediments may add vertical accretion of the remaining marsh (Hopkinson et al. 2018). Marsh accretion can occur through such processes as ice rafting, where ice and associated sediments are carried on to the marsh surface and encourage

Communicated by John C. Callaway

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growth of vegetation (Hardwick-Whitman 1985, 1986). In some systems there is dramatic loss of vegetated marsh in the interior as it is converted to new and/or larger ponds or "lakes" on the marsh platform (Delaune et al. 1994; Mariotti 2016). This is a very dynamic process that varies between ditched and unditched marshes (Smith and Pellew 2021). However, the loss in interior vegetation is consistently reported from Maine (Wilson et al. 2009, 2010), southern New England (Hartig et al. 2002; Van Huissteden and Van De Plassche 1998; Watson et al. 2017b), and Maryland (Schepers et al. 2016). In other instances, coastal marshes are expanding and/or migrating in response to sea-level rise (Raabe and Stumpf 2015; Scheider et al. 2018) if there are no upland barriers or human influences which deter the marsh migration (Kirwan and Megonigal 2013).

Another habitat influenced by sea-level rise is maritime forests that are dying due to increasing exposure to salt water, i.e., "ghost forests" that are composed of standing dead trees that have been recently killed due to sea-level rise (Kirwan et al. 2007; Kirwan and Gedan 2019). Prior preliminary surveys in the Mullica River-Great Bay watershed have determined that the death of maritime forests is common based on the standing remains of many species of trees, including the salt-intolerant Atlantic white cedar bordering the estuary (Able et al. 2018a, b). Evidence of earlier sea-level rise effects are based on the occurrence of former ghost forests, now intertidal and subtidal Atlantic white cedar stumps and timbers, which are referred to as "cedar cemeteries," in now saline portions of the estuary (Able et al. 2018a, b; Able 2020).

Our ability to interpret the effects of sea-level rise on estuaries is often confounded by human impacts on these shorelines (Crotty et al. 2017; Gedan et al. 2009; Gilby et al. 2020). Sea-level rise is clearly occurring in the Mullica River-Great Bay watershed in southern New Jersey (Fig. 1) based on tide gauge data from the early 1900s at nearby Atlantic City (Miller et al. 2013). Fortunately, this watershed provides an exceptional baseline to evaluate these changes because the system is relatively unaltered (Good and Good 1984; Kennish 2004) and the shorelines of the estuary are surrounded by extensive *Spartina* marshes (Lathrop et al. 2000). The estuary has broad seasonal temperature range (− 2 to 28 °C) and a microtidal tidal range (1.1 m) (Kennish 2004). The Great Bay portion of the estuary is polyhaline, while salinity is somewhat reduced in the lower Mullica River. The freshwater-saltwater interface typically occurs further up the Mullica River near Lower Bank (Fig. 1). This watershed has low human population density, large areas protected by federal and state holdings, few dams to interfere with the hydrology, and a natural inlet to the ocean. As a result, there are several efforts to use a portion of this estuary (Sheepshead Meadows, Fig. 1, bottom) as a sentinel site for assessing climate change effects (Kennish et al. 2014a, b) including specific projects to determine changes in marsh vegetation, marsh accretion rates and surface elevation, and conversion of marsh to intertidal/subtidal habitat (Kennish et al. 2016; Meixler et al. 2017).

The purpose of this case study is to improve our understanding of sea-level rise effects on the marshes and maritime forests and evaluate the responses of these habitats over a time span from years to centuries in this relatively unaltered watershed. The study combines a review of the prior studies on sea-level rise in this system and original data on these topics in order to provide much-needed perspective from the past and for the future.

Perspectives

Sea-Level Rise

Evidence for sea-level rise in the Mullica River-Great Bay watershed is rapidly accumulating. In order to examine for change in the annual flooding regime on Great Bay Boulevard, and thus the surrounding marshes of the Sheepshead Meadows (Fig. 1), we evaluated US Geological Survey (USGS) tide gauge observations between 2001 and 2019 taken in the RUMFS boat basin and calibrated these against direct observations of flooding in the marshes along Great Bay Boulevard. Based on prior calculations, and numerous direct visual observations along the road, readings of 0.8 m and above were assigned marsh flooded status. An index to the total hours the road was flooded in each year was estimated using readings every 6 min from the USGS tide gauge. The total hours the road was flooded was estimated for each year by multiplying the total number of observations where the gauge reading was over 0.8 m by 6 (for 6-min intervals) and dividing that number by 60 (60 min in an hour). We then used linear regression to evaluate whether there was a trend in total hours flooded over time (Fig. 2). The trend observed was constant and increasing as was the tide gauge from nearby Atlantic City (Fig. 1), for the period 1912 to the turn of the century (Miller et al. 2013). The relationship between these tide gauges was closely correlated ($p < 0.0001$). At that site, there has been a consistent increase over time, with a rise in relative sea level of approximately 40 cm since 1912. This increase, coupled with subsidence, makes sea-level rise in Atlantic City about two times the global average (Miller et al. 2013). Thus, over the time period from 1912 to the present, these combined data show that relative sea-level rise in the region is occurring, in part because it is compounded by local (Miller et al. 2013) and regional (Crosby et al. 2016; Ezer and Atkinson 2014; Sallenger Jr. et al. 2012) subsidence. Thus, these observations in the study area account for some of the highest rates of sea-level rise in the world (Walker et al. 2021).

Observations of the maritime forests in the watershed were made at large spatial scales with historic aerial imagery and, more recently, from helicopters and drones, to provide another metric of sea-level rise. Environmental Systems Research Institute (ESRI) aerial imagery was used to perform spatio-temporal analysis of marsh pools from 1930 to 2015 while HistoricAerials.com was used to observe change during intermediate years. Pools selected for comparison were on the relatively unaltered (not altered by any nearby Open Marsh Water Management [OMWM] or mosquito-ditched areas) southern portion of Sheepshead Meadows (Fig. 1, bottom). Photographs of individual pools were selected based on their occurrence, or their remnants, in aerial images from 1930 to 2015 based on a 1:1000 scale in the most recent images. Observations of marsh pools over time were based on the change in extent over time. Pool location and size were screen-digitized in ArcMap. We visited almost all pools that were identified from the 1930s and 2015 images by walking the marsh surface to verify their current status during fall 2017 and winter 2018.

Aerial images from a helicopter were collected by two observers with cameras and GPS locaters on four dates between 2015 and 2018 and filmed with a Go-Pro camera over the Mullica River Valley to identify the occurrence and location (Fig. 3) of "ghost forests" (Fig. S1). In addition, we used small drones to confirm the identity of individual ghost forests. In the fall of 2017, a DJI Phantom 3 Professional drone was flown at standardized elevations for most flights at 15 and 4 m. Other groundtruthing of marshes, ghost forests, and cedar cemetery occurrence and distribution was made during 2015–2019 from kayak (217 km) and motorboat (322 km) throughout the watershed (Fig. 3).

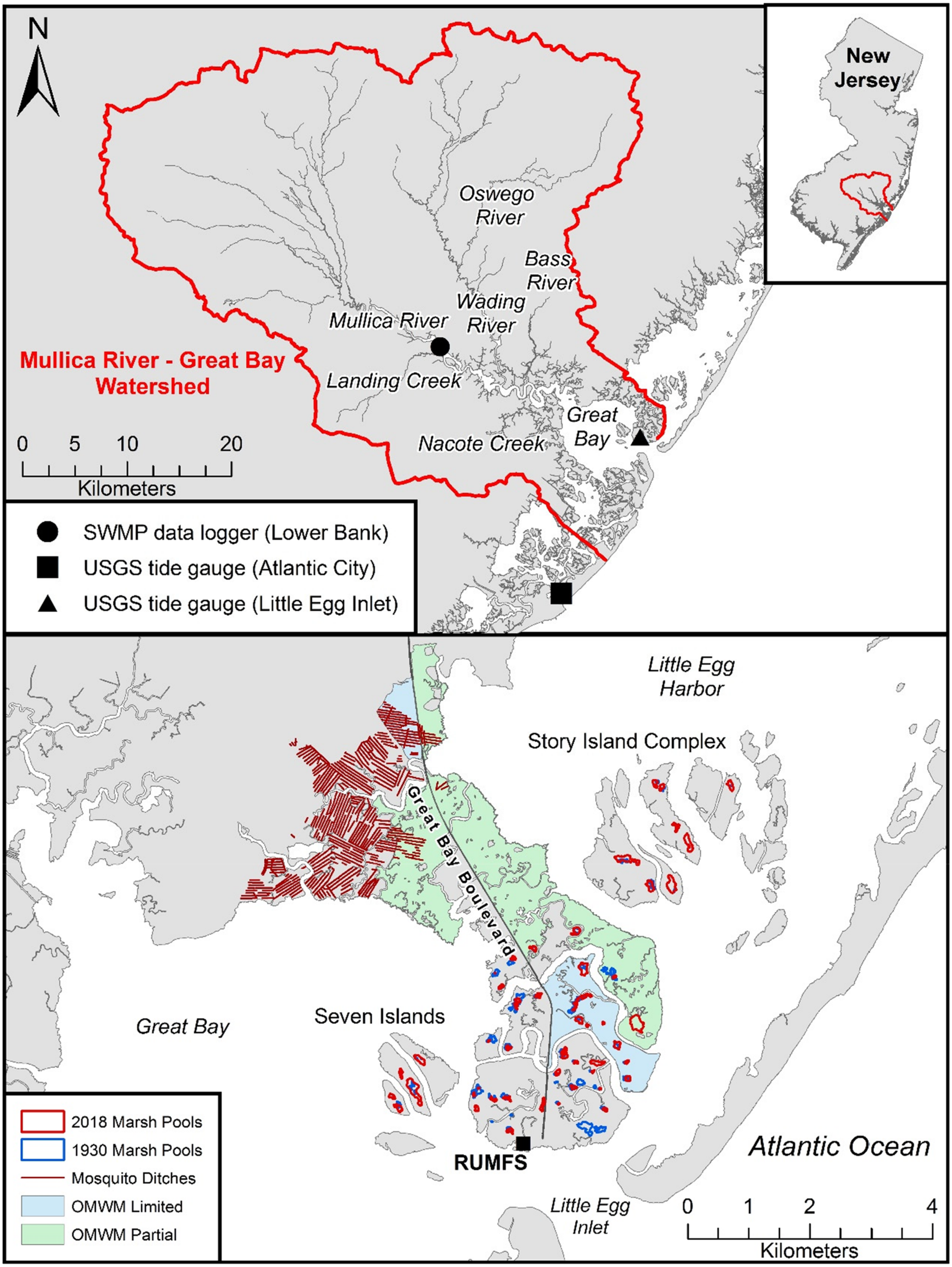
The record of the occurrence of modern "ghost forests" (Fig. S1) and ancient "cedar cemeteries" (Fig. S2) in the Mullica River-Great Bay watershed due to sea-level rise and subsidence over decades and centuries is evident from several sources. The distribution of ghost forests is centered in the upper portion of the watershed including the Mullica River and its tributaries including the Bass and Wading rivers and Nacote Creek. They are not present in the consistently freshwater portions of the upstream Mullica and Wading rivers. Ghost forests are absent from the lower, higher salinity portions of the Mullica, Wading, and Bass rivers as well as the entire perimeter of Great Bay (Fig. 3). This is particularly noteworthy because much of the mortality in these ghost forests is to Atlantic white cedar, which typically occurs in freshwaters of bogs and along streams (Able et al. 2018a, b; Able 2020; Sedia 2008). Another indication of sea-level rise is the frequent occurrence of ghost forests elsewhere along the east coast of the USA (Kirwan et al. 2007; Kirwan and Gedan 2019).

Former ghost forests, now cedar cemeteries, were also evident in intertidal creeks and just under the surface of the marshes (Fig. 3). As an example, an area in the upper, salty waters of Nacote Creek, where the marsh has been washed away based on comparisons of aerial photos from the 1930s and the present, there are large numbers of exposed Atlantic white cedar stumps and timbers (see Fig. 13.13 in Able 2020). Radiocarbon dating of this wood indicates it originated from the fourteenth to the fifteenth centuries (Able et al. 2018a, b). These types of features have been detected in the same general area as the ghost forests (Fig. 3) as observed abundantly in the upper intertidal edges of the Bass River (Fig. S2 and Fig. 13.9 in Able 2020). These cedar cemeteries also occur in deeper waters of the study area as detected with sidescan sonar in the subtidal waters of the Bass, Wading, and Mullica rivers (Fig. 13.14, 13.15 in Able 2020). In the Mullica River near Lower Bank (Fig. 1), radiocarbon dates from submerged Atlantic white cedar date to the fifteenth century (Able et al. 2018a, b).

Response of Marshes

The marsh edge in the Sheepshead Meadow is dynamic with regard to direction and rate of sedimentation. Sediments can be deposited, as overwash, on the marsh surface during storms. These typically sandy sediments, presumably of marine origin, are obvious from aerial photographs over the last 20 years (see Fig. S3). At the same time, significant erosion at the southern end of the Sheepshead Meadows peninsula is evident through the same imagery. As a result, the marsh edge at this location has retreated up to 57 m since 1995 (Fig. S3). At the same time, channel widening within the peninsula is frequently occurring as indicated by sloughing off of the channel edge (Able et al. 2018a, b).

Marshes in the Mullica Valley have been able to keep pace with sea-level rise in previous centuries by trapping and retaining sediments (Suk et al. 1999) as occurs elsewhere (Hopkinson et al. 2018; Pennings and Bertness 2001). As an example in the study area, during winter 2017 through summer 2018, drone flights focused on the distribution and changes in ice-rafted sediments in the Sheepshead Meadows. A recent (January 2018) event, Winterstorm Grayson, contributed to marsh surface sedimentation in the study area. The event was prompted by near record cold temperatures which allowed the salt water to freeze to the bottom of creeks and in the process the muddy bottom sediments were incorporated into the ice in an area near RUMFS (Fig. 1, bottom). On January 4, 2018, the tides carried the ice, along with the bottom sediments, on to the marsh surface. Subsequently, we sampled the sediments at a number of locations and found 2.5–5.1 cm of sediment in a well-defined pattern on top of the previous year's dead vegetation (Fig. 5.8 & 5.9 in Able 2020). These sediments were visible until early May 2018 when the marsh vegetation began growing through the sediments. We verified that this ice-rafted sediment was a broader phenomenon when we identified the presence of similar muddy ice-rafted sediments at three other locations elsewhere in the Sheepshead Meadows during the same period. The


N
New Jersey
Oswego River
Bass River
Wading River
Mullica River
Landing Creek
Nacote Creek
Great Bay
Mullica River - Great Bay Watershed
0 5 10 20
Kilometers
SWMP data logger (Lower Bank)
USGS tide gauge (Atlantic City)
USGS tide gauge (Little Egg Inlet)
Little Egg Harbor
Story Island Complex
Great Bay Boulevard
Great Bay
Seven Islands
RUMFS
Atlantic Ocean
Little Egg Inlet
0 1 2 4
Kilometers
2018 Marsh Pools
1930 Marsh Pools
Mosquito Ditches
OMWM Limited
OMWM Partial

◀ **Fig. 1** Location of Mullica Valley study area in southern New Jersey (top right inset) with identification of major tributaries and variety of data loggers (top). The USGS tide gauge labeled Little Egg Inlet is located in the Rutgers University Marine Field Station boat basin. The location of natural marsh pools (n = 50) is indicated as closed circles in the Sheepshead Meadows and adjacent islands (Seven Island, Story Island Complex) largely outside the area of modifications (mosquito ditches, partial and limited Open Marsh Water Management [OMWM]) to these marshes (bottom)

occurrence of ice-rafted sediments occurs elsewhere (Hardwick-Whitman 1985, 1986), but might be becoming less frequent as the study watershed continues on a trend of warmer, ice-free winters (Able 2020; Able and Fahay 2010).

Another indication of marsh response to rising sea-levels is that the marsh platform vegetation in the Sheepshead Meadows was considered moderately stressed (McKenna et al. 2018). This was based on their findings that only 60% of *Spartina alterniflora* plants were situated in their optimal growth range. Furthermore, this finding was qualified by stating these plants "may not be unhealthy, potentially just in transition to a new community type such as upland or open water." Reference to the latter is relevant to our finding that extensive areas of the Sheepshead Meadow are transitioning to open water. This lower plant growth observed by McKenna et al. (2018) may be because *Spartina alterniflora* cannot tolerate continuous flooding or standing water (Adam 1990). The death of these plants eventually results in shallow pools or depressions with no vegetation (Fig. 13.23 in Able 2020). These new and expanded pools are typically located the furthest from the sources of sediment (Temmerman et al. 2005), i.e., the marsh creeks that flood the marsh surface.

Changes in marsh pool size and distribution are common in the high-salinity marshes of the Mullica River-Great Bay estuary based on the same aerial surveys for ghost forests. With the combination of sea-level rise and subsidence, individual marsh pools expand as the vegetation around the perimeter and in adjacent areas dies. These continue to grow in areal extent over time as pools enlarge and coalesce (Fig. S4). This results in individual pools that contain both shallow portions with stiff bottom peat substrates (Fig. 13.24 from Able 2020) and deeper portions with a soft substrate of digested peat and soft sediments (Fig. 13.26 from Able 2020).

The occurrence and size of marsh pools in the Mullica Valley has varied over the period from 1930 to 2018 based on aerial photographs. Multiple surveys of the marsh pools on the undisturbed portion of the southeastern Sheepshead Meadows (Fig. 1, bottom) found one of the dominant types of change in these surveys is the birth and expansion of marsh pools and the resulting decrease in amount of vegetation (Table 1). These marsh pool processes are consistent between the peninsula and adjacent islands (Fig. 1, Table 1). Based on our analysis of marsh pools (n = 50), there was a net increase in pool area of 206,199 m^2, or 72% between 1930 and 2018 (Table 1). In some instances, pools had originated from previously completely vegetated marsh surfaces since the 1930 images. But during this time period, some pools became smaller and disappeared (76,817 m^2) because they become vegetated as they transitioned from isolated marsh pools to those connected to adjacent creeks, filled with sediment, and were colonized by *Spartina alterniflora*. This marsh pool "death" and revegetation is evident in Maine salt marshes (Wilson et al. 2009), southern New England (Watson et al. 2017a, b) as "paleopools" (Fig. 13.27 in Able 2020), and in southern New Jersey outside of this study area (Smith and Pellew 2021). In other marshes, these pools do not recover after connection to tidal creeks (Mariotti 2016). These changes, both increase and decrease in pool size, were most evident on the undisturbed portion of the Sheepshead Meadows (Table 1, Fig. 1, bottom). On the marsh islands, there were only positive increases of 165,730 m^2 in marsh pool area with no loss of them between 1930 and 2018 (Table 1). In addition to these changes, some pools were in transition, i.e., they were originally identified as marsh pools but in the most recent images were connected to an adjacent creek. As such, these were not isolated pools but neither were they vegetated. These pools were neither classified as marsh pool losses or gains because they were in a transitional state (Table 1).

As a result of this study, it is clear that the number of the pools and areal extent of the pools has become much larger, thus these are referred to as "lakes." As a result of these changes, the amount of vegetation on the marsh surface has become less. Based on closer inspection with drone imagery and groundtruthing individual pools, the number of pools was much greater than can be identified with aerial images. Thus, the transition to a wetter marsh surface occurred as more standing water accumulated on the lower elevations of the marsh

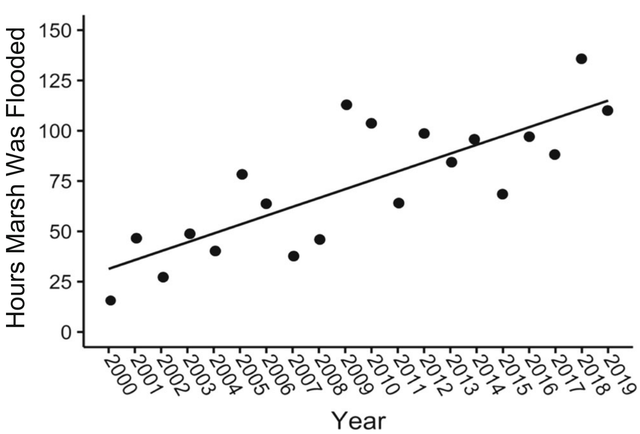


Fig. 2 Annual variation in flooding frequency in the marshes along Great Bay Boulevard in the Sheepshead Meadows study area from 2000 to 2019 based on comparison with a US Geological Survey tide gauge in the nearby Rutgers University Marine Field Station (RUMFS) boat basin as an indication of marsh flooding and local sea-level rise. See Fig. 1 for location

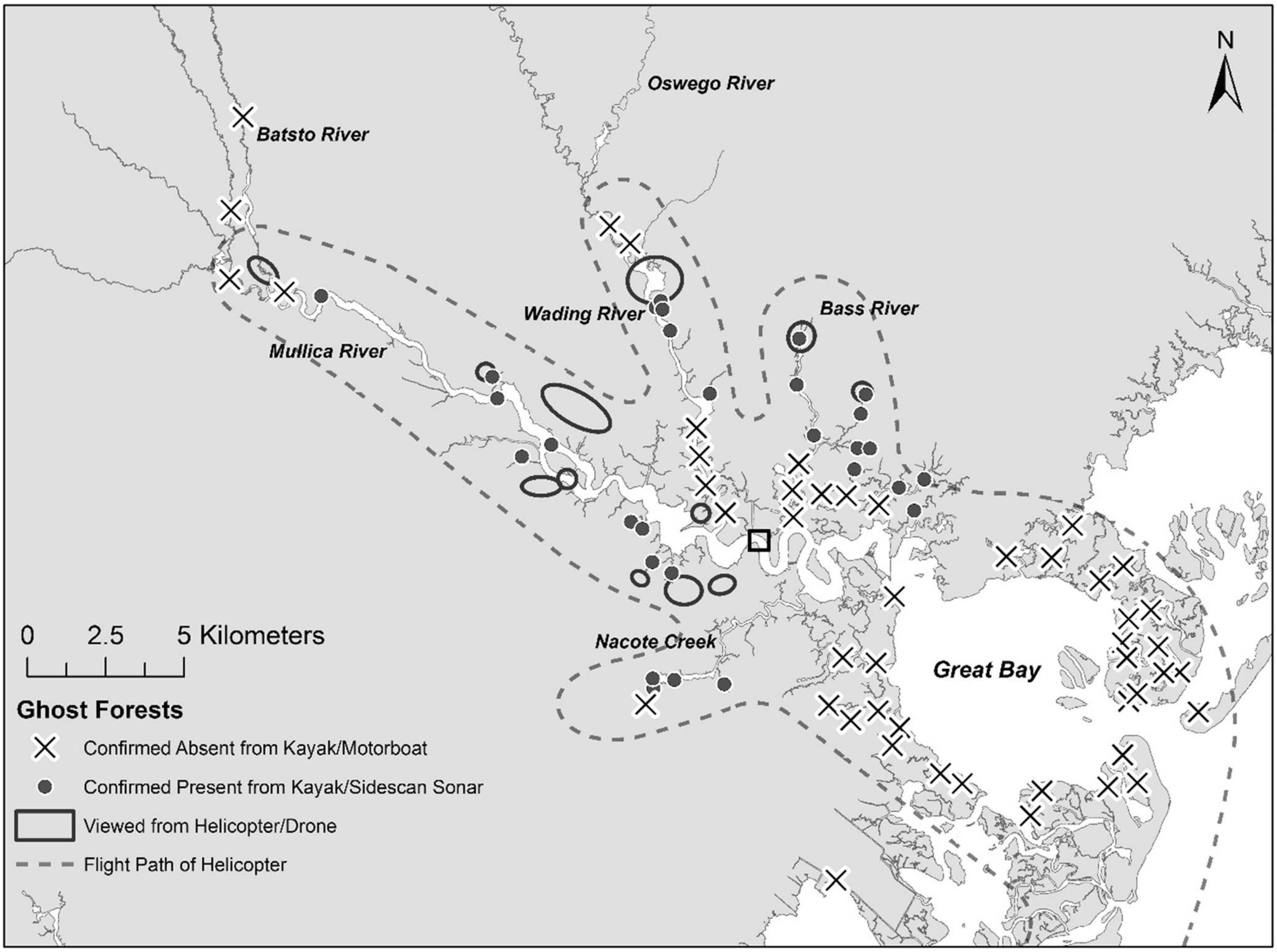


Fig. 3 Spatial distribution of recent standing ghost forests (open circles or ovals) in the Mullica Valley from aerial imagery (area enclosed within dashed line) from helicopter and drone flights and groundtruthing from kayak and sidescan sonar of cedar cemeteries (filled circles). "X" indicates no ghost forests or stumps observed. Square indicates location of cedar cemetery in deep marsh sediments

surface and reduced plant density and growth or eliminated them entirely.

These patterns of marsh pool gain, because of increase in number and size, are often referred to as "ponding" and have

Table 1 Summary of marsh pool loss (vegetation gain) and gain (vegetation loss) in the Sheepshead Meadows peninsula and adjacent islands (Seven Islands, Story Island Complex) study area from 1930 to 2018. Transitional pools include those that were previously marsh pools but are now connected to an adjacent creek. The majority of study marsh pools were located outside the major modifications to the marsh surface (mosquito ditches, Open Marsh Water Management [see Fig. 1, bottom])

Location	Sample size	Area (m^2)	Percent vegetation loss
Peninsula			
Pool loss (in area)	13	76,817	
Pool gain	24	117,286	
Net pool change	37	+ 40,469	65.4%
Islands			
Pool loss (in area)	0	0	
Pool gain	13	165,730	
Net pool change	13	+ 165,730	100%
Peninsula/islands			
Pool loss (in area)		76,817	
Pool gain		283,016	
Net pool change	20	+ 206,199	72.8%
Transitional pools	6	41,527	-

been reported in Maine (Wilson et al. 2009, 2010), southern New England (Hartig et al. 2002), and elsewhere in New Jersey (Mariotti 2016) and the USA (Andres et al. 2019; Kearney et al. 1988; Mariotti 2016; Schepers et al. 2016). This is an area of particular concern since tidal range in the Mullica River-Great Bay watershed is microtidal, and thus, the volume of flood events, with associated sediments, is reduced. These general patterns of marsh loss due to marsh pools expanding and turning into marsh "lakes" are also observed in other Mid-Atlantic marshes including elsewhere in New Jersey (Mariotti 2016), Maryland (Kearney et al. 1988; Schepers et al. 2016), Virginia (Kirwan and Megonigal 2013; Kirwan et al. 2016), New York (Hartig et al. 2002), Maine (Wilson et al. 2009, 2010), and elsewhere in New England (Adamowicz and Roman 2005; Watson et al. 2017a, b; Wilson et al. 2010).

Together, the above responses to sea-level rise are resulting in overall marsh loss. This loss may be mitigated by marsh migration where human alterations do not occur (Crosby et al. 2016; Kirwan and Gedan 2019; Kirwan and Megonigal 2013; Scheider et al. 2018). As frequently happens, the migration of marsh grasses into upland forests, usually in ghost forests (Able et al. 2018a, b; Kirwan et al. 2007; Kirwan et al. 2016) is led by the invasive form of *Phragmites australis* in the study area (Fig. 13.7 in Able 2020; Windham 1999; Windham and Lathrop Jr. 1999), elsewhere in New Jersey (Smith 2013) and in North America (Chambers et al. 1999; Meyerson et al. 2000). Although *Phragmites australis* may provide some food web services (Weinstein et al. 2000) and an elevational buffer against sea-level rise (Weis and Weis 2003), the ecological services provided by it is limited relative to *Spartina alterniflora*. Our prior studies have shown that when *Phragmites* becomes established, i.e., the "late invasion" stage, its value as fish and invertebrate habitat declines (Able and Hagan 2003; Able et al. 2003, 2006; Angradi et al. 2001; Weinstein and Balletto 1999). This pattern is also evident in nearby southern (Able et al. 2003; Hagan et al. 2007) and northern (Raichel et al. 2003) New Jersey marshes and elsewhere along the east coast of the USA (Hunter et al. 2006).

In summary, the response to relative sea-level rise and subsidence in the Mullica River-Great Bay watershed is especially relevant to the understanding of the persistence of salt marshes in the future. This is because the study area is in a relatively undisturbed estuary where the effects of sea-level rise are less confounded by human alterations compared to many other estuaries and marshes elsewhere along the east coast of the USA. These observations, from multiple sources, indicate how change has occurred over centuries based on the distribution and abundance of cedar cemeteries. More recently, ghost forests and marsh loss, on the edge and interior, are further indications of the occurrence and rate of sea-level rise. The ability of marshes to migrate inland may compensate, to some degree, for these losses but these will be limited if they occur as the result of increases in the invasive *Phragmites australis* because of its reduced ecological contributions relative to *Spartina alterniflora*.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12237-021-00946-x.

Acknowledgements Numerous individuals helped to bring this review to fruition. Ron Baker and Matt Taylor organized and invited me to present the keynote address at the November 2019 CERF workshop on Concepts and Controversies in Tidal Marsh Ecology Revisited. Numerous RUMFS technicians and students assisted in bringing together the various parts of this study. Jason Morson developed the relationship between tide gauges and road/marsh flooding. Ryan Larum helped with interpreting changes in marsh pools over time. Other technicians assisted in various parts of data and image collection, especially Ryan Larum, Maggie Shaw, Roland Hagan, and T.J. Johnson. Pat Filardi lent his expertise with on-the-water observations from kayaks. Judy Redlawsk provided her skills and helicopter to observations from the air. This manuscript benefitted from several external reviews. The drone for aerial imagery was donated to RUMFS from the late Diane Adams of the Rutgers University Department of Marine and Coastal Sciences.

Funding Financial support for this project was provided from current studies by RUMFS.

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