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Contrasting Hurricane Ike washover sedimentation and Hurricane Harvey flood sedimentation in a Southeastern Texas coastal marsh

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ABSTRACT

Category 4 Hurricane Harvey was an extraordinary rain-event. After landfall on the mid-Texas coast, the storm moved slowly to the east, dropping historic amounts of rainfall of more than 1.5 m over Southeastern Texas. A massive pulse of floodwater flowed down local canals and rivers, inundating coastal marshes on the McFaddin National Wildlife Refuge. The floodwaters left a muddy flood deposit over much of the marsh, averaging 2.8 cm in thickness along a north-south transect across the refuge. Hurricane Ike (2008) also left a sediment layer in marshes on the refuge, allowing a direct comparison of magnitude, pathways, distribution and character of the washover and flood deposits. Results suggest that Hurricane Harvey's flood sedimentation was the equivalent of seven years of "normal" sedimentation in the marsh. This is a significant contribution to marsh accretion, which counters elevation loss due to rising sea level. The pattern of flood sedimentation was weakly controlled by elevation, whereby lower elevations received more sediment, and more strongly controlled by proximity to flood sediment pathways, which included overbank flows from the Gulf Intracoastal Water Way and the delivery of sediment into the marsh via flows through interconnected lakes and ponds. In contrast, the magnitude of Hurricane Ike's washover sedimentation was controlled primarily by proximity to the Gulf shoreline. The study provides valuable new information on controls on the magnitude and distribution of flood sedimentation in coastal marshes and the role of terrestrial and marine sediment sources – a crucial and timely area of inquiry given the threat of submergence posed to coastal marshes by rising sea-levels.

1. Introduction

1.1. Coastal marshes and rising sea level

An improved understanding of sedimentation sources, pathways and rates in coastal marshes is vital and timely because marshes worldwide are threatened by global-warming-induced sea-level rise, regional subsidence caused by subsurface fluid withdrawal and reduction of sediment inputs caused by dams and levees. Sedimentation causes aggradation of marsh surfaces, countering elevation loss from relative sea-level rise and forestalling conversion of marshes to open water, with the consequent loss of valuable ecological and protective functions (Blum and Roberts, 2009; Fagherazzi, 2014; Gedan et al., 2011; McKee and Cherry, 2009; Möller et al., 2014; Shepard et al., 2011; Temmerman et al., 2013; Turner, 1997).

In recent years, studies have focused on two major sediment sources for coastal marshes: hurricane washover sedimentation (Bianchette et al., 2016; Hodge and Williams, 2016; Williams, 2009, 2010, 2012; Lane et al., 2011; Liu et al., 2011, 2014; Yao et al., 2018; Turner et al., 2006; Walters et al., 2014); and, organic sedimentation from in-situ plant growth (Cherry et al., 2008; Hill and Anisfeld, 2015; Ratliff et al., 2015; Walters and Kirwan, 2016). In contrast, relatively little attention has been paid to another major source of marsh sedimentation – inorganic sediment carried into marshes by terrestrial flood waters.

Bayhead delta marshes in coast-perpendicular incised river valleys, such as the Pearl River marsh on the Louisiana/Mississippi border, are characterized by high levels of fluvial flood and organic sedimentation (McCloskey et al., 2018). These marshes are proximal to riverine sources and the hydrologic head of river systems ensures sufficient soil moisture to allow vigorous plant growth despite increasing marsh elevation due to the deposition of thick clastic layers by floods and storm surges. Processes of marsh growth in these settings is, however, quite different to sedimentological and hydrological processes in coast-parallel fringing marshes, which may be remote from riverine sources.

In studies of sedimentation in Louisiana coastal marshes resulting from the historic 2011 Mississippi River floods, Falcini et al. (2012) and

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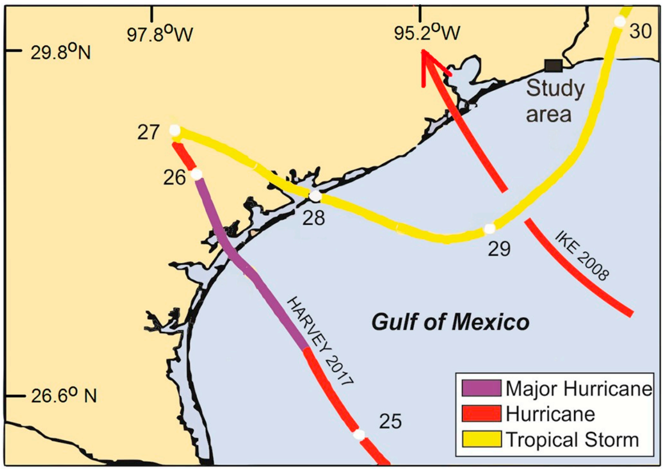

Fig. 1. Track of Hurricane Harvey August 25–30, 2017 (NOAA, 2018a). White circle is position at 0600 Central Time. Track of Hurricane Ike September 13, 2008.

Khan et al. (2013) found that Mississippi River floodwaters, diverted into the Atchafalaya River Basin, created a suspended sediment plume that carried inorganic sediment into coast-parallel fringing marshes more than 100 km from the Atchafalaya River. Although the Mississippi River carried a much greater flow and sediment load than the Atchafalaya River, its sediment plume was much more constrained, did not interact with coastal currents and carried its sediment load far offshore, with little to no input into surrounding marshes.

1.2. *The Hurricane Harvey flood event*

Hurricane Harvey was a powerful wind event and extraordinary rain event. The Category 4 storm made landfall on August 25, 2017 at San Jose Island on the mid-Texas coast, accompanied by 212 km/h sustained winds. The strong winds and a storm surge up to 3 m above ground level caused widespread destruction between Port Aransas and Matagorda, Texas; particularly hard hit was the City of Rockport, which was devastated by sustained hurricane-force winds. Over the next four days, the hurricane weakened to a tropical storm as it moved inland and then followed a meandering path to the east that took it back out over the Gulf of Mexico, before its final landfall in Southwestern Louisiana (Fig. 1). The storm's slow forward progress, return to the warm waters of the Gulf of Mexico and counter-clockwise cyclonic circulation, brought near constant onshore flow of outer rain bands to Southeastern Texas over a 5-day period. The resulting prolonged and intense rainfall caused major to catastrophic urban flash flooding and river flooding between Houston, Texas and Lake Charles, Louisiana. With peak rainfall totals exceeding 1.5 m, Hurricane Harvey produced the most rain on record for a tropical storm or other weather event in the contiguous United States (Blake and Zelinsky, 2018; NOAA, 2018a).

Record-breaking floods flowed down many local rivers, bayous and man-made channels into the Gulf of Mexico. The rapid input of massive amounts of floodwater caused heightened elevation of coastal waters and inundation of adjacent low-lying coastal marshes. Rapid response imagery captured some of this inundation and shows plumes of suspended sediment being carried into marshes by floodwaters (NOAA, 2017). The resulting flood deposits cover large tracks of marshland in Southeastern Texas and Southwestern Louisiana.

Hurricane Ike (Category 2; landfall at Galveston, Texas, September 13, 2008; Fig. 1) also left a widespread sediment deposit in marshes of the study area. This marine overwash event transported littoral sediments over Highway 87 and coastal foredunes, to build a tapering sediment wedge, extending over 1 km into the marsh and becoming finer and more organic-rich with distance inland. The magnitude, distribution and character of the washover deposit have been reported in other studies (Williams, 2009; Hodge and Williams, 2016).

Given the paucity of information on terrestrial flood sedimentation in coast-parallel fringing coastal marshes, more study is warranted. Important questions to be addressed include: How much sediment is deposited by terrestrial floods into coastal marshes? What are the controls on the spatial distribution of flood sedimentation? How does terrestrial flood sedimentation compare to hurricane washover sedimentation? What is the contribution of terrestrial flood sedimentation to long-term marsh accretion?

Hurricane Harvey's coastal flood event presents a rare opportunity to document the characteristics of fluvial flood sedimentation in coast-parallel fringing marshes. In this study, we present sedimentological and microfossil data from a series of sediment cores and monoliths collected from McFaddin National Wildlife Refuge (MNWR) in the southeastern corner of Texas, to document the flood deposition associated with Hurricane Harvey and to contrast Hurricane Harvey's flood sedimentation with Hurricane Ike's washover sedimentation.

2. Study area

McFaddin National Wildlife Refuge (MNWR) is a 238 km^2 tract of marshes and lakes located in Jefferson County in the far southeastern corner of Texas (Fig. 2). Hurricane overwash has been shown to make significant contributions of inorganic sediment to accretion of marshes on the refuge (Williams, 2010; Hodge and Williams, 2016). The refuge is separated from the Gulf of Mexico by Texas State Highway 87, low discontinuous foredunes and a wide sandy beach. Most of the marshes on the refuge are classified as irregularly flooded estuarine intertidal emergent wetlands (U.S. Fish and Wildlife Service, 2018). Much of the marsh surface ranges in elevation from 0 to 1 m above NAVD88. A narrow strip of palustrine emergent wetlands is located along the seaward edge of the refuge, adjacent to Highway 87. This area consists of washover fans formed by repeated hurricane overwash and elevations here range up to about 2 m NAVD88. The northern edge of the preserve borders the Gulf Intracoastal Water Way, a man-made canal that provides shelter for barge traffic serving petrochemical facilities located along the Gulf of Mexico coast. Numerous tidal creeks connect shallow lakes and ponds to Sabine Lake, located about 14 km to the east (Fig. 2b).

The maximum storm surge recorded in the vicinity of the study area (at Sabine Pass, Fig. 2b) during passage of Hurricane Harvey was about 1 m above mean sea level (approximates 0 m NAVD88) on August 28, 2017 (Fig. 3a). At this time, three days after landfall, Hurricane Harvey was moving closer to the study area and presumably tropical storm force winds generated by the storm caused this small storm surge (Fig. 1). There is no evidence that the hurricane's storm surge caused overwash in the study area: Highway 87 ranges from about 1.5–2 m NAVD88 in elevation and the adjacent foredunes are also considerably higher than 1 m; it is therefore unlikely that either the road or the foredunes were overtopped by the 1-m storm surge. Rapid response imagery acquired on August 29 and 30, 2017, shows no indication of washover sedimentation such as washover fans on the marsh or beach sand on Highway 87.

Precipitation at Port Arthur, about 17 km northeast of MNWR, in the 6-day period August 25–30, 2017, totaled 1.21 m (Fig. 3b). Record-breaking rainfall was recorded throughout Southeastern Texas and Southwestern Louisiana; the maximum total amount was about 1.54 m near Beaumont, Texas (National Weather Service, 2018; Figs. 2, 3b). The rainfall caused catastrophic flooding in Houston and other cities throughout the area. Many creeks and rivers experienced record discharges; the Neches River, one of the largest rivers in the region, recorded a peak average daily discharge of about 6500 cubic meters per second (cms) on September 1, 2017 (Fig. 3b). This is about three times higher than the 2nd highest average daily discharge recorded on this river in 2016 and about twenty-nine times higher than the median

Fig. 2. a. Regional setting of study area, showing cities of Houston, Beaumont and Port Arthur. b. Relationship of study area to Sabine Lake, Sabine Pass and the Gulf Intracoastal Water Way. c. Study area on the McFaddin National Wildlife Refuge showing core and monolith locations and location of topographic profile derived from LiDAR data. Star shows location of wrack line used to estimate maximum flood elevation. Google Earth images, 1/29/2017.

average daily discharge in the 15-year period 2004–2018 (USGS, 2018; Fig. 3c).

Massive discharges draining down rivers, creeks and bayous into Sabine Lake and the Gulf Intracoastal Water Way caused elevated coastal water levels. Taylor-Alligator Bayou near Port Arthur, Texas, recorded a peak ocean surface elevation of about 2.3 m (NGVD 1929; approximates mean sea level) on August 31, 2017 (Fig. 3d). The elevated water levels flooded low-lying coastal marshes, including the marshes on MNWR. Rapid Response imagery acquired on August 31, 2017, shows plumes of suspended sediment being carried by flood waters into marshes on MNWR. The imagery indicates two main sediment pathways into the marshes: overbank flooding of the south shore of the Gulf Intracoastal Water Way; and, via the direct connection between Sabine Lake, the Port Arthur Ship Canal, Keith Lake and other interconnected lakes and tidal creeks on the refuge. A wrack line (line of vegetative debris caught on branches of trees and bushes) suggests a maximum flood elevation of about 1.35 m NAVD88 on the MNWR (Fig. 4).

3. Methods

Initial reconnaissance at the study area on November 26, 2017, indicated that Hurricane Harvey flood sedimentation was widespread at MNWR. A monolith obtained from near Clam Lake (site CL1 on Fig. 2c) contained a visually distinct 7-cm-thick layer of light-gray soft mud, with high moisture content and low organic content, sharply overlying a dark-brown, organic-rich, well-rooted marsh deposit, assumed to be the buried former marsh surface. The soft mud layer was identified as

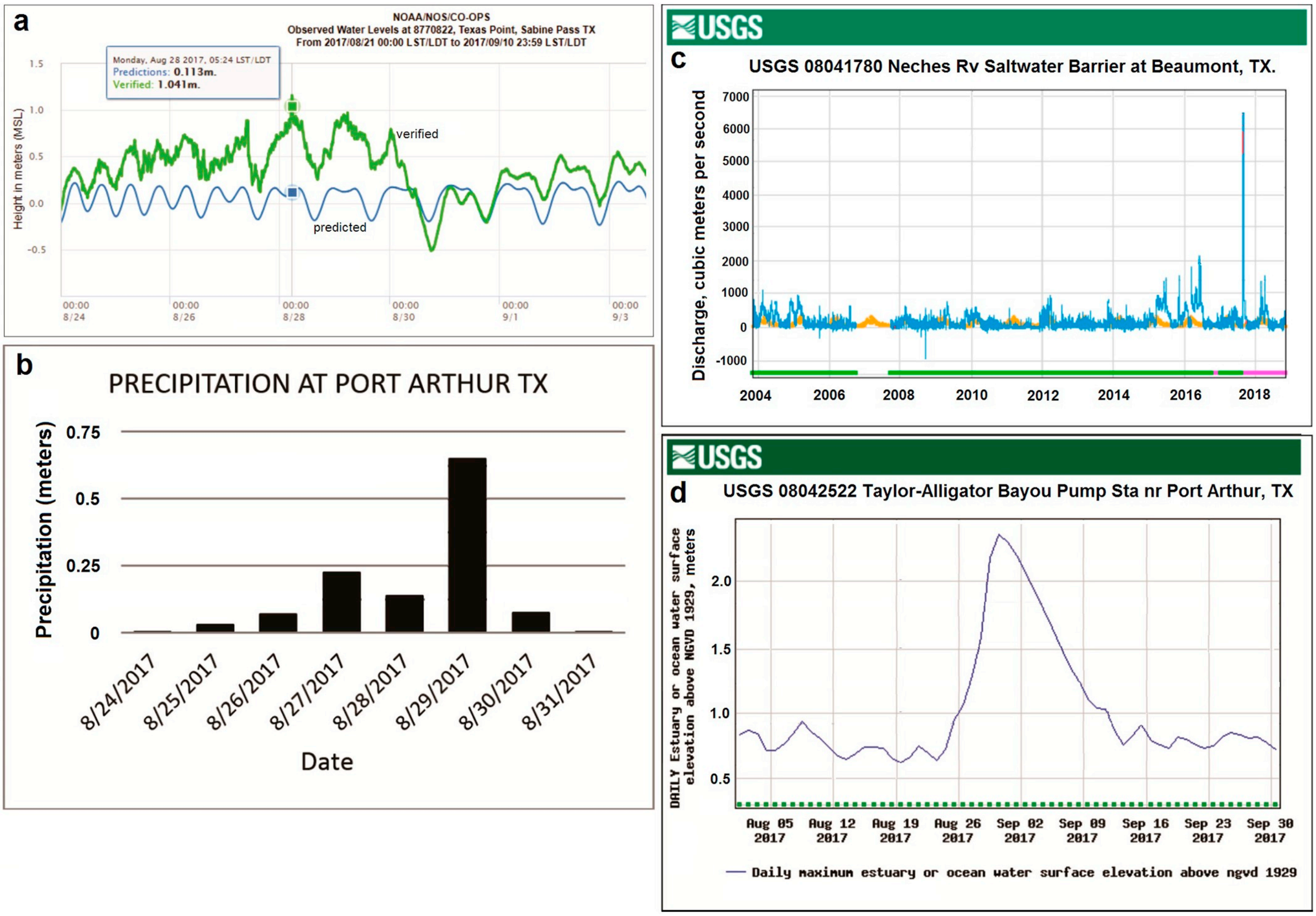

Fig. 3. a. Hurricane storm surge recorded at Sabine Pass, Texas (NOAA, 2018b).
b. Precipitation recorded at Port Arthur, Texas (NWS, 2018). c. Discharge of Neches River recorded at Beaumont, Texas (USGS, 2018). d. Ocean water level recorded at Taylor-Alligator Bayou near Port Arthur, Texas (USGS, 2018).

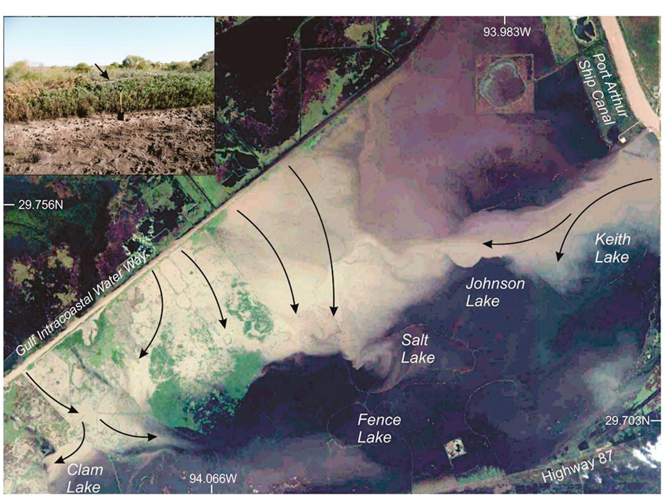

Fig. 4. Rapid response imagery acquired on August 31, 2017, showing plumes of suspended sediment being carried by flood waters into marshes on MNWR (NOAA, 2017; location shown on Fig. 2b). Inset photograph shows a wrack line (arrowed) with an estimated elevation of 1.35 m NAVD88 (surface elevation is about 0.45 m; length of spade handle is 0.9 m). Location of wrack line shown on Fig. 2c. Photograph acquired November 26, 2017.

Hurricane Harvey's flood deposit, based on its lack of live root ingrowth (suggesting recent deposition), contrasting color to the underlying sediment and unconsolidated consistency (Khan et al., 2013). The flood deposit was overlain by about 1 cm of horizontally-layered plant debris, presumably settled out of suspension as flood levels declined (Fig. 5).

To further explore the distribution and magnitude of flood sedimentation on MNWR, a series of short cores and monoliths was obtained from along an approximate north-south transect across the refuge near Clam Lake Road (Transect 1; Fig. 2c). This area has been disturbed by road and ditch building, particularly in the vicinity of Clam Lake Oil Field and so another transect of monoliths was obtained from Sea Rim State Park, approximately 5 km to the east, where there is little artificial modification of the marsh (Transect 2; Fig. 2c). Monoliths CL1 and CL2 were collected November 26, 2017; cores M1 - M21 were collected on January 7, 2018; monoliths M22 – M27 were collected on May 3, 2018; monoliths SR1 - SR6 were collected on May 4, 2018 (core/monolith designations: M: McFaddin; CL: Clam Lake; SR: Sea Rim). Cores could not be collected from some targeted sites because of standing water (this is why core numbers are not continuous). The short cores, consisting of 0.3-m-long, 7.5-cm-diameter thin-walled aluminum tubes, and the monoliths, dug out by spade, caused negligible compaction of the marsh sediments (the tops of cores remained level with the marsh surface after the core tubes had been pushed into the marsh, suggesting negligible compaction).

Fig. 5. Monolith CL1, showing soft light-gray flood deposit overlying dark-brown well-rooted buried marsh surface. Dashed line shows approximate contact between the buried organic-rich marsh and overlying mud. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The location of each sample site was obtained by hand-held GPS. The elevation of each site was obtained from a DEM of the study area derived from bare-earth LIDAR data acquired in 2014 (NOAA, 2014). It is assumed that little elevation change would have occurred on the marsh in the three years between collection of the LIDAR data and landfall of Hurricane Harvey. Core tubes were sealed and monoliths were wrapped in aluminum foil. Samples were transported to the geomorphology laboratory at the University of North Texas, where the tubes were cut lengthwise and the sediment cores within were split into two halves longitudinally. Cores and monoliths were logged and photographed.

Selected cores and monoliths were sampled at 1-cm intervals for Loss-On-Ignition (LOI), textural and foraminiferal analysis. All samples were divided into two subsamples for analysis. One subsample was weighed and then oven-dried at 105 °C for 24 h to determine moisture content (% wet weight). The other subsample was weighed and then wet-sieved through a 63-μm sieve to retain the sand fraction. The sand fraction was air-dried and weighed. The measured moisture content was used to calculate the dry weight of the sieved sample, and the weight of the sand fraction was then used to calculate sand content (% dry weight). The dried subsample was weighed and then placed in a muffle furnace at 550 °C for 4 h to determine organic matter content (% dry weight). After re-weighing, the same sample was returned to the muffle furnace for 2 h at 950 °C to determine carbonate mineral content (% dry weight). LOI procedures follow the recommendation of Heiri et al. (2001) for consistency; all samples had uniform treatment in terms of sample size, furnace temperatures and furnace exposure times.

Sand fractions derived from wet sieving were examined under a dissecting microscope to identify and count foraminifers. If the sand fraction was less than 1 g, the entire sample was examined for foraminifers; if the sand fraction was more than 1 g, a dry splitter was used to obtain a subsample (typically 0.2–0.5 g) for analysis and foraminiferal counts were multiplied accordingly to estimate the number of specimens in the entire sample. Foraminifers were identified to the genus or species level and the percentage of calcareous and agglutinated species in each sample was calculated. The total number of foraminifers in the sample was used to calculate the number of foraminifers per gram of dry sediment.

4. Results

Of the twenty-nine cores and monoliths examined, five did not contain a flood deposit; the remaining twenty-four cores and monoliths contained a visually-distinct flood deposit, at the top of the sample, varying in thickness from 1 to 7 cm (Table 1). The five samples that did not contain a flood deposit (M18, M19, M20, M21 and SR6) are all located on the area of washover fans near Highway 87 (Fig. 2c). At these locations, a washover sand layer, deposited by Hurricane Ike in 2008, extends to the marsh surface. Hurricane Ike's washover deposit has been the subject of several previous studies and was examined at multiple sites in the study area in 2009, 2010, 2012, 2014 and 2016 (Williams, 2010, 2012, 2017; Hodge and Williams, 2016). The washover sand layer is still visually distinct; it is sand-rich, has a low organic content and a sharp contact with underlying marsh deposits.

Cores and monoliths were selected for detailed laboratory analyses to document characteristics of the flood deposit and to reveal contrasts in lithology and microfossil content between the Hurricane Harvey flood deposit, the Hurricane Ike washover deposit and enclosing marsh sediments. One set of samples was selected from Transect 1 and another set was selected from Transect 2. Samples were selected to illustrate the Hurricane Harvey flood deposit alone (M13, SR2), the Hurricane Harvey flood deposit and the Hurricane Ike washover deposit (both present at the same site) (M26, M16, SR5) and the Hurricane Ike washover deposit alone (SR6) (Fig. 6).

Table 1
Flood deposit thickness and site elevation.

Site	Flood deposit thickness (cm)	Elevation (m, NAVD88)
M1	1	0.88
M4	2	0.74
M5	2	0.48
M6	2	0.34
M7	2	0.55
M10	1	0.78
M22	3	0.51
M13	6	0.53
M23	5	0.54
M24	5	0.32
M25	3	0.50
M14	2	0.49
CL2	7	0.43
CL1	7	0.47
M26	4	0.42
M15	3	0.35
M27	2	0.38
M16	1	0.51
M17	1	0.58
M18	0	0.75
M19	0	0.77
M20	0	1.12
SR1	4	0.37
SR2	5	0.44
SR3	5	0.43
SR4	2	0.46
SR5	2	0.42
SR6	0	0.51
M21	0	0.47

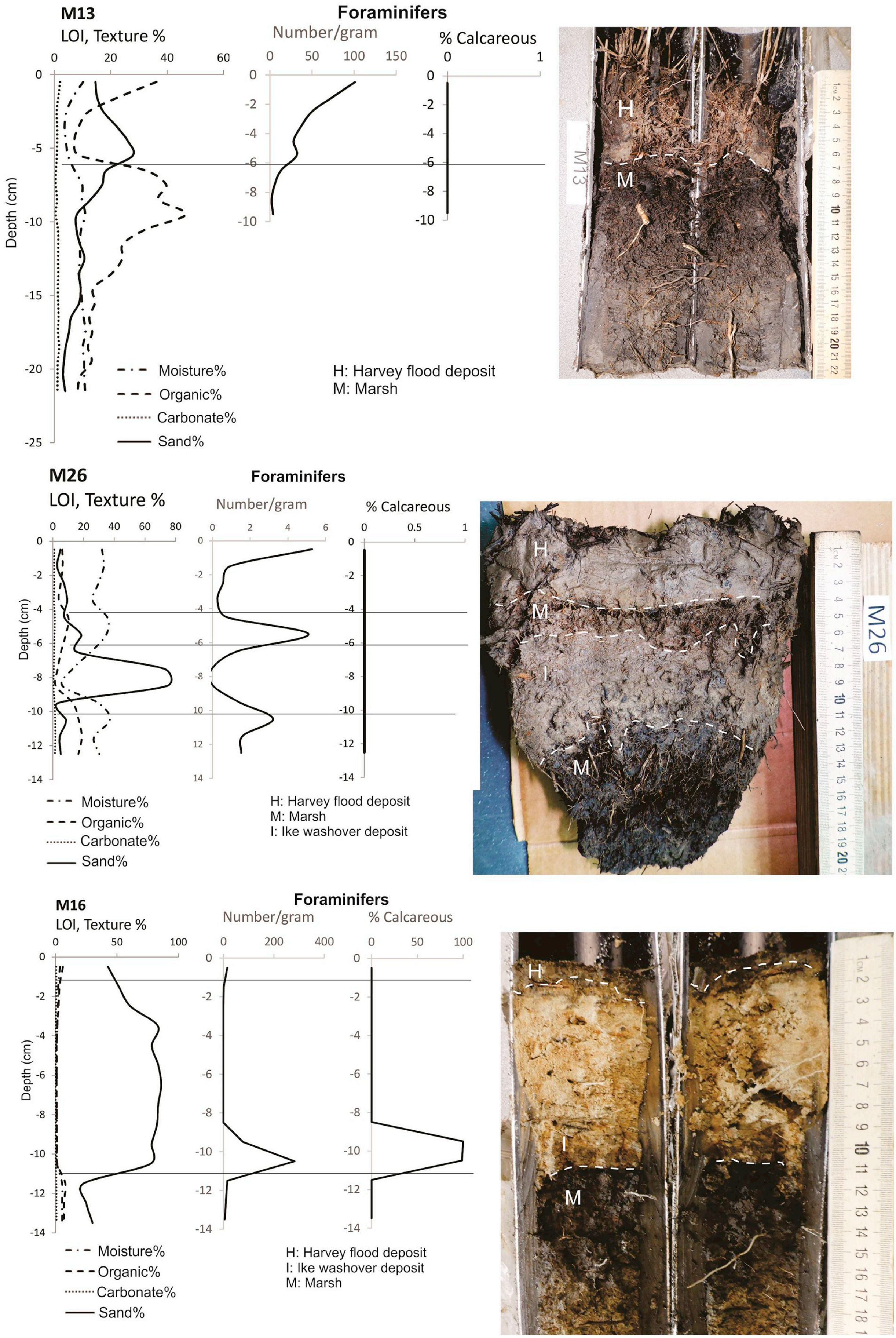

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Fig. 6. Loss-On-Ignition and foraminiferal analyses of selected cores and monoliths. Samples M13, M26 and M16 are from Transect 1; samples SR2, SR5 and SR6 are from Transect 2. Dashed lines show approximate contacts between deposits.

5. Discussion

5.1. Contrasting Hurricane Ike washover sedimentation and Hurricane Harvey flood sedimentation

Of the six samples subjected to detailed examination, Hurricane Ike's washover deposit has the most distinctive lithologic and foraminiferal characteristics. The washover deposit has the highest sand content, with peak values ranging from about 70–80%. There are also abrupt changes in sand, organic and moisture contents at the washover deposit's lower and upper contacts (see M26, M16, SR5 and SR6 in Fig. 6). Organic and moisture contents are typically lower within the washover deposit than in other parts of the sampled marsh deposits. Hurricane Ike's washover deposit is the only part of the sampled deposits that contains significant numbers of calcareous foraminifers. There is a peak of 282 individuals per gram of dried sediment in the base of the washover deposit in sample M16 and a peak of 465 individuals per gram of dried sediment in the lower half of the washover deposit in sample SR5 (Fig. 6). This characteristic is not consistent however; there are no calcareous foraminifers in the washover deposit in samples M26 and SR6. Previous studies have demonstrated that calcareous foraminifers are a good indicator of washover sedimentation, implying inland transportation of marine foraminifers from offshore into the marsh (Williams, 2010). It has also been found that foraminiferal contents can vary widely between sampling sites in the study area, possibly due to variation in hydrodynamics of storm surge deposition, dissolution of calcareous tests, or metazoan predation (Hodge and Williams, 2016).

Contrasts in lithologic and foraminiferal characteristics between Hurricane Harvey's flood deposit and adjoining marsh or washover deposits are less pronounced. The most consistent feature of the flood deposit is a sharp contact with underlying marsh or washover deposits, consistent with an abrupt depositional “event”. In general, sand contents are higher in the flood deposit than adjoining marsh deposits, with the exceptions of M16 where the flood deposit adjoins Hurricane Ike's sandy washover deposit, and M26, where the flood deposit and underlying marsh deposit have similar LOI results and similar low sand contents (Fig. 6). Organic and moisture contents are generally lower within the flood deposit, but again samples M26 and M16 are exceptions. None of the sampled flood deposits contain any calcareous foraminifers, but all contain low to moderate numbers (up to 101 individuals per gram of dried sediment) of agglutinated marsh foraminifers. These foraminifers are present in tidally-influenced environments including coastal marshes, but are not present in supratidal terrestrial environments where the flood waters originated. This implies entrainment, transport and deposition of marsh foraminifers by flood waters. Foraminiferal contents are similar in underlying marsh deposits (low to moderate numbers of agglutinated marsh foraminifers), where marsh foraminifers are presumably in situ (Williams, 2010).

To explore controls on the magnitude of flood sedimentation, scatter graphs were created to show the relationship between flood deposit thickness and elevation along Transect 1 and along Transect 2 (Fig. 7a, b). Regression lines added to the graphs indicate a weak relationship between flood deposit thickness and elevation (R^2 values of 0.33 and 0.44, along Transects 1 and 2, respectively). Along Transect 1 there is a general trend of greater thicknesses of sedimentation at lower elevations and three of the five highest elevation sites (M18, M19 and M20) received no flood sedimentation. However, a number of sites at approximately the same elevation of 0.5 m received as much as 7 cm of sedimentation and as little as 1 cm of flood sedimentation. (Fig. 7a, Table 1). Along Transect 2 there is a somewhat stronger correlation, but there is a small range in elevation along this transect of only 0.14 m between the highest and lowest sites (Fig. 7b, Table 1). These findings suggest that elevation does play some role in determining the magnitude of flood sedimentation, but there are large unexplained variations.

Another factor that most likely plays a role in the magnitude of flood sedimentation is proximity to sediment sources. Fig. 4 clearly shows multiple distinctive sediment pathways into the marsh with two origins: overbank flooding through multiple breaches of the south shore of the Gulf Intracoastal Water Way; and, via Keith Lake and other interconnected lakes and tidal creeks on the refuge. Identifying sediment pathways for sites along Transect 1 is complicated by the multiple overbank flows and by the many elevated roads, which, to some extent, probably act as physical barriers to flood waters. Transect 2 does not have these complications; in this part of the refuge it is likely that sediment-laden flood waters flowed through Salt lake and Fence Lake and into the area of the transect (Fig. 2c). To test this possibility, a third scatter graph was created showing the relationship between the thickness of flood sedimentation along Transect 2 and the proximity of sites to Fence Lake. The regression line added to this graph indicates a stronger correlation between flood deposit thickness and proximity to Fence Lake (R^2 value of 0.83), with sites closer to the lake having greater thicknesses of flood sedimentation (Fig. 7c).

In addition to elevation and proximity to sediment sources, there are likely other factors that play a role in the magnitude of flood sedimentation. Elevation is presumably a factor because low spots on the marsh are the first to be covered by flood water and the last to be uncovered as flood waters drain away. Low spots on the marsh spend more time submerged which will presumably promote more settling of suspended sediment and greater thicknesses of flood sedimentation. Physical barriers, such as roads, may also play a role in the residence time of flood waters on different parts of the marsh, by slowing the drainage of flood waters and promoting more sedimentation.

It is also likely that vegetation filters out suspended sediment from flood waters, so that sites more proximal to sediment sources (e.g. lake margins, nearby the Gulf Intracoastal Water Way) receive flood water that is less filtered and can deliver greater quantities of suspended sediment to the marsh surface (Li and Yang, 2009; Stumpf, 1983). These factors may also help explain why some sites recorded zero flood sedimentation; these sites were higher and/or farther from sediment sources, so they were more briefly submerged and/or received flood waters with lower concentrations of suspended sediments.

Along Transect 1, flood sedimentation was recorded up to, but not over, 0.9 m (Table 1; Fig. 7a). The average flood sedimentation thickness for sites below 0.9 m is 2.8 cm. To estimate the overall magnitude of flood sedimentation on MNWR, a topographic profile was derived from the LiDAR-based DEM, running across the refuge approximately parallel to Transect 1 (Figs. 2c, 8).

The length of the profile below 0.9 m elevation is 6155 m (Fig. 8). Assuming the average sedimentation thickness of 2.8 cm occurred along this part of the profile results in a volume of flood sedimentation of 172 m^3/m of coastline. The volume of Hurricane Ike washover sedimentation in the study area, calculated in a previous study, is surprisingly similar at 170 m^3/m of coastline (Williams, 2012). Although the study results suggest that Hurricane Harvey's flood sedimentation and Hurricane Ike's washover sedimentation have similar magnitudes, the two deposits contrast sharply in terms of sediment sources, sediment pathways, lithology, microfossil content and morphology. Hurricane Ike's washover deposit was derived from littoral sources (shallow offshore, intertidal zone, beach and dunes). These sediments were washed over coastal foredunes and Highway 87 into the adjoining marsh to form a wedge of sediment, up to 0.64 m thick and tapering inland. The deposit is sand-rich and organic-poor near the coast, but becomes finer-grained and more organic-rich inland. Calcareous marine foraminifers were

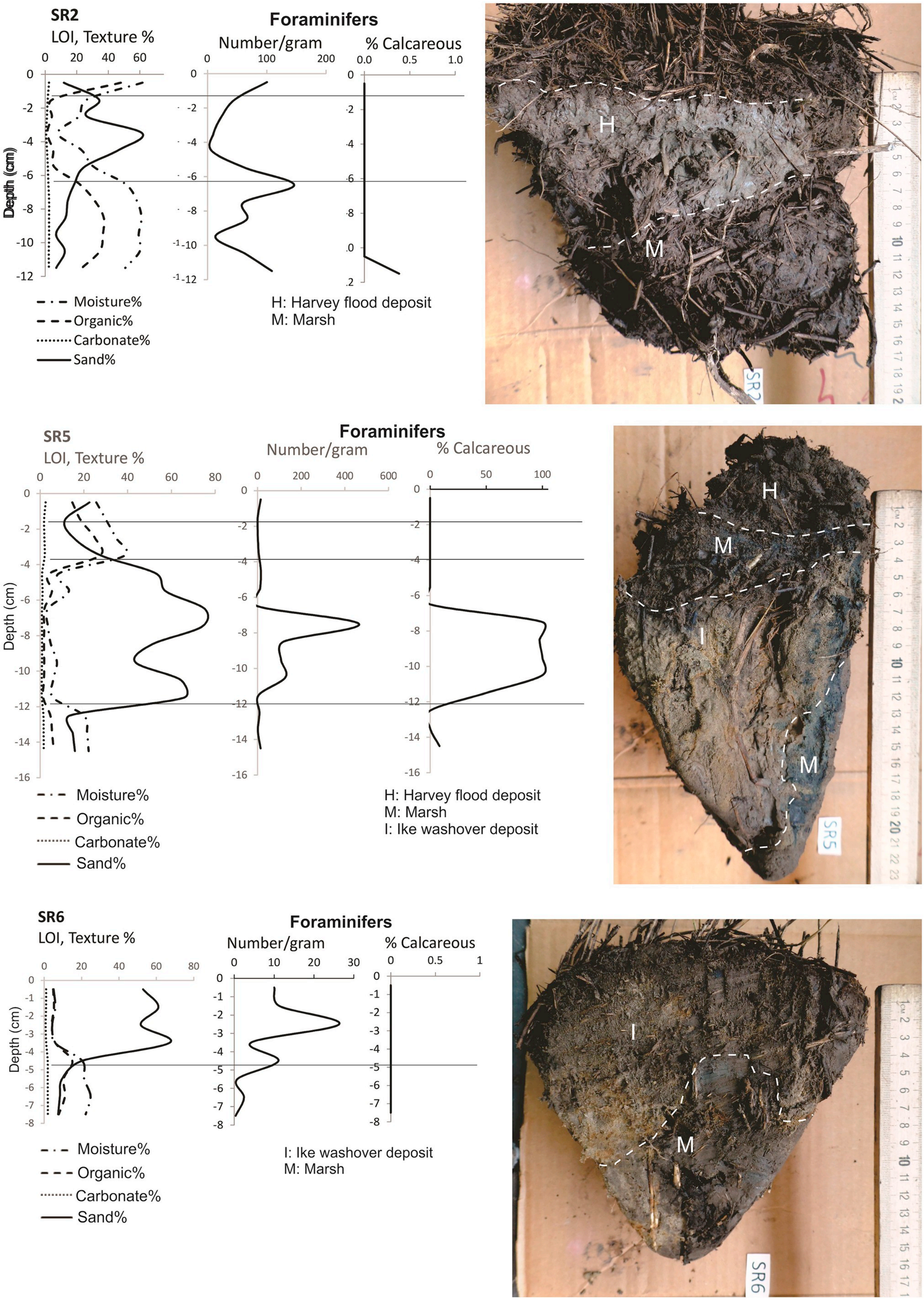

Fig. 6. (*continued*)

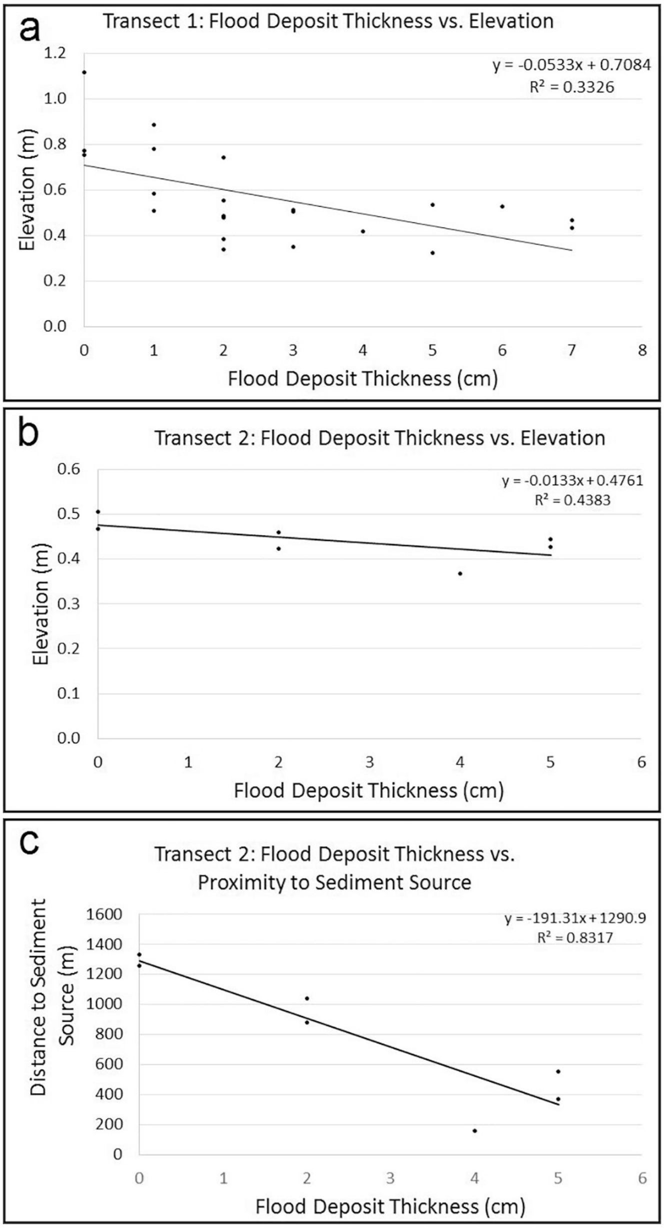

Fig. 7. a. Flood deposit thickness vs. elevation along Transect 1. b. Flood deposit thickness vs. elevation along Transect 2. c. Flood deposit thickness vs. proximity to sediment source along Transect 2.

common in the deposit immediately following landfall, but their numbers have apparently diminished over time, probably because of dissolution (Williams, 2010).

In contrast, Hurricane Harvey's flood deposit originated from sediment-laden terrestrial flood waters that entered the marsh by multiple pathways, including overbank flows along the Gulf Intracoastal Water Way and via interconnected lakes and tidal creeks on the refuge. The flood deposit forms a relatively thin blanket of sediment covering much of the marsh below 0.9 m elevation. The deposit is relatively low in sand and organics throughout, but there is considerable variation. Low to moderate numbers of agglutinated marsh foraminifers are present throughout the deposit, but no calcareous marine foraminifers were found in the flood sediment. Contrasting features of the two types of deposit are summarized in Table 2.

5.2. Contribution of Hurricane Harvey flood sedimentation to marsh accretion

The long-term contribution of Hurricane Harvey's flood sedimentation to accretion of marshes on MNWR will depend on changes in the deposit as it is incorporated into the marsh. The similarity in textures of the flood deposit and underlying marsh sediment, suggests it is likely that bioturbation by plants and burrowing organisms will render the deposit visually unrecognizable relatively quickly. Williams (2011), for example, found that a thin, muddy, but visually recognizable washover sediment layer deposited by Hurricane Ike in coastal marshes in Southwestern Louisiana in 2008 was obscured by bioturbation and no longer visually recognizable by 18 months after landfall. Even if the flood deposit is mixed into the marsh and no longer forms a distinct layer, it will still contribute to marsh accretion. In addition, no evidence of erosion was observed on the marsh and there are no known mechanisms that could remove the flood deposit and consequently it represents a net gain of sediment to the marsh.

Given the unconsolidated consistency of the flood deposit it is likely that it will undergo some degree of autocompaction as it is incorporated into the marsh over the long-term. Compaction increased the bulk density of sediments at depth within nearby Trinity Bay marsh by an average of ~400% (Williams, 2003). If the flood sediment at MNWR is compacted, this will in effect decrease the contribution of the flood deposit to marsh accretion. However, the flood deposit may also contribute to marsh accretion by providing a medium for plant growth and nutrients to stimulate above-ground and below-ground biomass production (Walters and Kirwan, 2016). Increased above-ground biomass production may also increase inorganic sedimentation because of enhanced trapping of suspended sediment from flood waters (Cherry et al., 2008; Hill and Anisfeld, 2015; Ratliff et al., 2015).

Hodge and Williams (2016) used sandy washover marker beds deposited by Hurricane Carla (1961) and Hurricane Rita (2005) to

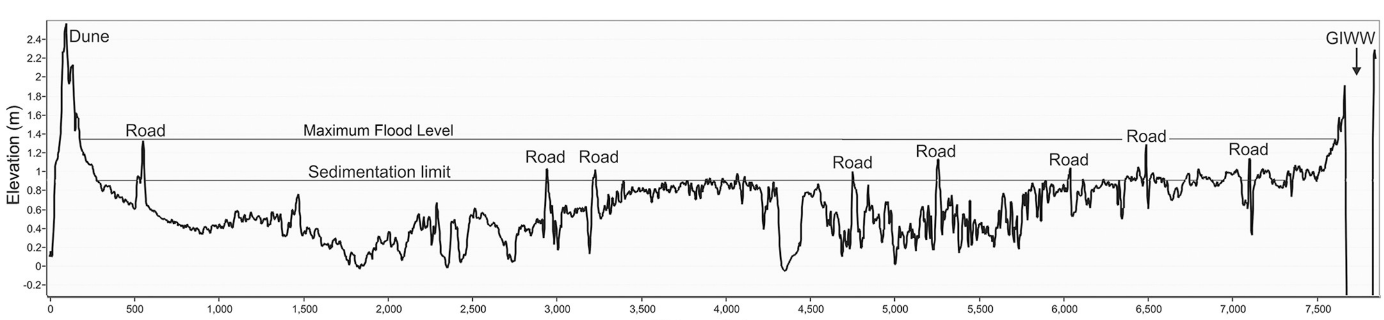

Fig. 8. Topographic profile along Transect 1. Flood sedimentation was not recorded above the sedimentation limit of 0.9 m. Maximum flood level was 1.35 m. Line of profile is shown on Fig. 2c. GIWW: Gulf Intracoastal Water Way.

Table 2
Contrasting characteristics of Hurricane Ike washover sedimentation and Hurricane Harvey flood sedimentation at McFaddin National Wildlife Refuge.

Deposit characteristic	Hurricane Ike washover sedimentation	Hurricane Harvey flood sedimentation
Morphology	Wedge-shaped, maximum thickness nearshore, tapering inland.	Extensive blanket of sediment below elevation limit (0.9 m NAVD88).
Maximum Thickness	0.64 m[a]	0.07 m
Texture	Coarser nearshore, fining inland[a]. Average maximum sand content 76%[b]	Spatially variable; probably dependent on proximity to sediment sources. Average maximum sand content 33%[c]
Organic content	Increases inland[a]. Average maximum organic content 5%[b]	Spatially variable. Average maximum organic content 14%[c]
Foraminiferal content	Calcareous foraminifers (indicating a marine origin) common throughout deposit soon after landfall, but may decrease and fall to zero over time[d].	Agglutinated foraminifers throughout the deposit, indicating entrainment of marsh foraminifers by flood waters[c].
Sediment sources and pathways	Littoral sources (shallow offshore, intertidal zone, beach and dunes). Storm surge and wave overwash of coastline. Sediment transported as both traction load and suspended load[a].	Terrestrial sources (rivers, creeks, canals). Suspended riverine sediment plumes, entering the marsh by overbank flows from Man-made channels and via interconnected lakes, ponds and tidal creeks.
Controls on magnitude of sedimentation	Proximity to Gulf shoreline.	Elevation, proximity to sediment pathways and, possibly, physical barriers such as roads.

[a] Williams, 2010.
[b] Based on samples M26, M16, SR5 and SR6.
[c] Based on samples M13, M26, M16, SR2 and SR5.
[d] Williams, 2010 and samples M26, M16, SR5 and SR6.

calculate decadal-scale sedimentation rates within marshes on MNWR. The finer-grained, more organic-rich sediment between the marker beds was assumed to be inorganic flood sedimentation and organic sedimentation that had been subjected to compaction over a decadal time scale. The average sedimentation rate of this part of the marsh deposits was 0.38 cm/year; assuming that the long-term average contribution of Hurricane Harvey's flood deposit to marsh accretion is 2.8 cm, this represents about 7 years of the average annual accretion rate on the marsh.

The finding that Hurricane Harvey's flood deposit is equivalent to 7 years of average sedimentation on MNWR marshes demonstrates that terrestrial flooding can deliver significant amounts of inorganic sediment to coast-parallel fringing marshes. The flooding generated by Hurricane Harvey was record-breaking and undoubtedly has a very low return period; however, smaller floods, such as the one on the Neches River in 2016 (Fig. 3c) presumably also deliver terrestrial sediment to marshes in the study area and at a higher frequency. Policies with a goal of encouraging sediment accretion in coastal marshes should recognize the potential contribution of terrestrial flooding and design water control structures that divert flood waters into marshes rather than bypass them.

6. Conclusions

Hurricane Harvey's extraordinary rain event generated massive flooding throughout southeastern Texas and resulted in the inundation of low-lying coastal marshes by sediment-laden terrestrial flood waters. On McFaddin National Wildlife Refuge, flood waters reached a height of approximately 1.35 m and deposited a blanket of muddy sediment, up to 7 cm in thickness, over much of the marsh below 0.9 m elevation. Flood waters entered the marsh via multiple pathways, including multiple breaches of the Gulf Intracoastal Water Way and via interconnected lakes and tidal creeks. Results suggest that the magnitude and distribution of Hurricane Harvey's flood sedimentation was weakly controlled by elevation and more strongly controlled by proximity to flood sediment pathways. The magnitude of flood sedimentation was similar to that of Hurricane Ike's washover sedimentation, but the two deposits differ strongly in terms of sediment sources, sediment pathways, spatial distribution, morphology and character. The study shows that terrestrial flooding can cause widespread aggradation of coastal marshes; in the case of Hurricane Harvey, a single flood event generated the equivalent of seven years of “normal” marsh sedimentation. This is a significant finding in view of the threat of submergence posed to many marshes by rising sea levels. Coastal management agencies should recognize that terrestrial flood waters are a potential source of marsh accretion and take steps to encourage the delivery of flood sediments to marshes.

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References

Bianchette, T.A., Liu, K.-b., Qiang, Y., Lam, N.S.-N., 2016. Wetland accretion rates along coastal Louisiana: Spatial and temporal variability in light of Hurricane Isaac's impacts. Water 8 (1). https://doi.org/10.3390/w8010001.
Blake, E.S., Zelinsky, D.A., 2018. National Hurricane Center Tropical Cyclone Report Hurricane Harvey. National Hurricane Center, 9 May 2018.National Hurricane Center Tropical Cyclone Report Hurricane Harvey. National Hurricane Center, 9 May 2018.
Blum, M.D., Roberts, H.H., 2009. Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. Nat. Geosci. 2, 488–491.
Cherry, J.A., McKee, K.L., Grace, J.B., 2008. Elevated CO2 enhances biological contributions to elevation change in coastal wetlands by offsetting stressors associated with sea level rise. J. Ecol. 97, 67–77.
Fagherazzi, S., 2014. Coastal processes: storm-proofing with marshes. Nat. Geosci. 7, 701–702.
Falcini, F., Khan, N.S., Macelloni, L., Horton, B.P., Lutken, C.B., Mckee, K.L., Santoleri, R., Colella, S., Li, C., Volpe, G., D'emidio, M., Salusti, A., Jerolmack, D.J., 2012. Linking the historic 2011 Mississippi River flood to coastal wetland sedimentation. Nat. Geosci. 5, 803–807.
Gedan, K.B., Kirwan, M.L., Wolanski, E., Barbier, E.B., Silliman, B.R., 2011. The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm. Clim. Chang. 106, 7–29.
Google Earth, 2017. McFaddin National Wildlife Refuge, Texas. https://www.google.com/earth/.
Heiri, O., Lotter, A.F., Lemcke, G., 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. J. Paleolimnol. 25, 101–110.
Hill, T.D., Anisfeld, S.C., 2015. Coastal wetland response to sea level rise in Connecticut and New York. Estuar. Coast. Shelf Sci. 163, 185–193.
Hodge, J., Williams, H.F.L., 2016. Deriving spatial and temporal patterns of coastal marsh aggradation from hurricane storm surge marker beds. Geomorphology 274, 50–63.
Khan, N.S., Horton, B.P., McKee, K.L., Jerolmack, D., Falcini, F., Enache, M.D., Vane, C.H., 2013. Tracking sedimentation from the historic AD 2011 Mississippi River flood in the deltaic wetlands of Louisiana, USA. Geology 41, 391–394.
Lane, P., Donnelly, J.P., Woodruff, J.D., Hawkes, A.D., 2011. A decadally-resolved paleohurricane record archived in the late Holocene sediments of a Florida sinkhole. Mar. Geol. 287, 14–30.
Li, H., Yang, S.L., 2009. Trapping effect of tidal marsh vegetation on suspended sediment, Yangtze Delta. J. Coast. Res. 25, 915–936.
Liu, K.-b., Li, C., Bianchette, T.A., McCloskey, T.A., Yao, Q., Weeks, E., 2011. Storm deposition in a coastal backbarrier lake in Louisiana caused by Hurricanes Gustav and Ike. J. Coast. Res. 64 (SI), 1866–1870.

Liu, K.-b., McCloskey, T.A., Bianchette, T.A., Keller, G., Lam, N.S.-N., Cable, J.E., Arriola, J., 2014. Hurricane Isaac storm deposition in a coastal wetland along Lake Pontchartrain, southern Louisiana. J. Coast. Res. 70, 266–271 SI.
McCloskey, T.A., Smith, C.G., Liu, K., Nelson, P.R., 2018. The effects of tropical cyclone-generated deposition on the sustainability of the Pearl River Marsh, Louisiana: the importance of the geologic framework. Front. Ecol. Evol. 6, 179.
McKee, K.L., Cherry, J.A., 2009. Hurricane Katrina sediment slowed elevation loss in subsiding brackish marshes of the Mississippi River Delta. Wetlands 29, 2–15. https://doi.org/10.1672/08-32.1.
Möller, I., Kudella, M., Rupprecht, F., Spencer, T., Paul, M., van Wesenbeeck, B., Wolters, K., Jensen, G., Bouma, K., Miranda-Lange, T.J., Schimmels, M.S., 2014. Wave attenuation over coastal salt marshes under storm surge conditions. Nat. Geosci. 7, 727–731.
National Weather Service, 2018. Advanced Hydrologic Prediction Service. https://water.weather.gov/precip/.
NOAA, 2017. National Ocean Service (NOS), National geodetic survey: Hurricane Harvey: emergency response imagery of the surrounding regions. https://storms.ngs.noaa.gov/storms/harvey/index.html#7/28.400/-96.690.
NOAA, 2018a. National Weather Service. Service Assessment, August/September 2017 Hurricane Harvey.
NOAA, 2018b. Water levels. https://tidesandcurrents.noaa.gov/stations.html?type=Water+Levels.
NOAA (National Oceanic and Atmospheric Administration), 2014. NOAA NCEI Coastal Digital Elevation Model - 1/9 Arc-Second Resolution Topobathy DEM: Coastal US. https://coast.noaa.gov/dataviewer/#/lidar/search/.
Ratliff, K.M., Braswell, A.E., Marani, M., 2015. Spatial response of coastal marshes to increased atmospheric CO2. Proc. Natl. Acad. Sci. 112, 15580–15584.
Shepard, C.C., Crain, C.M., Beck, M.W., 2011. The protective role of coastal marshes: a systematic review and meta-analysis. PLoS One 6, e27374. https://doi.org/10.1371/journal.pone.0027374.
Stumpf, R.P., 1983. The process of sedimentation on the surface of a salt marsh. Estuar. Coast. Shelf Sci. 17, 495–508.
Temmerman, S., Meire, P., Bouma, T.J., Herman, P.M.J., Ysebaert, T., De Vriend, H.J., 2013. Ecosystem-based coastal defense in the face of global change. Nature 504, 79–83.
Turner, R.E., 1997. Wetland loss in the northern Gulf of Mexico: multiple working hypotheses. Estuaries 20, 1–13.
Turner, R.E., Baustian, J.J., Swenson, E.M., Spicer, J.S., 2006. Wetland sedimentation from Hurricanes Katrina and Rita. Science 449–452.
U.S. Fish and Wildlife Service, 2018. National wetlands inventory mapper. http://www.fws.gov/wetlands/Data/Mapper.html.
U.S.G.S, 2018. National water information system: web interface. https://waterdata.usgs.gov/nwis/uv.
Walters, D.C., Kirwan, M.L., 2016. Optimal hurricane overwash thickness for maximizing marsh resilience to sea level rise. Ecol. Evol. 6, 2948–2956.
Walters, D., Moore, L.J., Durán, O., Fagherazzi, S., Mariotti, G., 2014. Interactions between barrier islands and backbarrier marshes affect island system response to sea level rise: Insights from a coupled model. J. Geophys. Res. 119, 2013–2031.
Williams, H.F.L., 2003. Modeling shallow autocompaction in coastal marshes using Cesium-137 fallout: preliminary results from the Trinity River Estuary, Texas. J. Coast. Res. 19, 180–188.
Williams, H.F.L., 2009. Stratigraphy, sedimentology and microfossil content of Hurricane Rita storm surge deposits in southwest Louisiana. J. Coast. Res. 25, 1041–1051.
Williams, H.F.L., 2010. Storm surge deposition by Hurricane Ike on the McFaddin National Wildlife Refuge, Texas: implications for paleotempestology studies. J. Foraminifer. Res. 40, 510–519.
Williams, H.F.L., 2011. Stratigraphic record of hurricanes Audrey, Rita and Ike in the Chenier Plain of Southwest Louisiana. J. Coast. Res. Spec. Issue 64, 1921–1926.
Williams, H.F.L., 2012. Magnitude of Hurricane Ike storm surge sedimentation: implications for coastal marsh aggradation. Earth Surf. Process. Landf. 37, 901–906.
Williams, H.F.L., 2017. Assessing the effectiveness of coastal foredune barriers in reducing hurricane washover sedimentation. J. Coast. Res. 34, 503–509.
Yao, Q., Liu, K.-B., Ryu, J., 2018. Multi-proxy characterization of Hurricane Rita and Ike storm deposits in a coastal marsh in the Rockefeller Wildlife Refuge, Southwestern Louisiana. In: Shim, J.-S., Chun, I., Lim, H.S. (Eds.), Proceedings from the International Coastal Symposium (ICS) 2018 (Busan, Republic of Korea). Journal of Coastal Research, Special Issue No. 85. Coconut Creek, Florida, pp. 841–845.