Analysis of Sediment Erosion and Deposition Across High Marsh and Tide Channel Sites in Wellfleet, Massachusetts.

By

Donnie Kirk

July, 2016

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Bare spots associated with vegetation die-off along a tidal channel and adjacent marsh platform in the “Gut” in Wellfleet, MA area are a direct result of winter storms and increased crab herbivory. Sediment transport from bare spots and channel banks over a two-year time period are captured with the aid of repeat high-definition surveys using terrestrial laser scanning (TLS) techniques. Cross-sectional and morphometric analysis of the tidal channel reveal a statistically significant change in channel size and shape with reference to the amount of elevation change from erosion and deposition. Greater than sixty percent of the topographic changes in the marsh channel are the result of erosional processes. Cellular statistics across the marsh platform revealed less change than the channel. Depositional hotspots occur in areas of sudden wetland dieback, while erosion occurs in small depressions adjacent to the tidal channel. More than fifty percent of the marsh platform displays no change over the two-year measurement period.

Analysis of Sediment Erosion and Deposition Across High Marsh and Tide Channel Sites in Wellfleet, Massachusetts.

A Thesis

Presented To the Faculty of the Department of Geography, Planning, and the Environment.

East Carolina University

In Partial Fulfillment of the Requirements for the Degree

Master of Science

Geography

by

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July, 2016

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ACKNOWLEDGEMENTS

I would like to thank my fellow graduate colleagues for being supportive throughout this whole process. The greatest thing to come out of getting a master's degree were the friendships that I made. I would also like to thank my family for also being supportive and understanding. I don't know what I would have done without that foundation.

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Chapter 1: Literature Review

National Park scientists in conjunction with other researchers monitor and analyze the abiotic and biotic characteristics of numerous coastal marsh systems throughout the Cape Cod National Seashore. Research results from these efforts are used to implement policies and mitigation plans in order to limit the loss of marsh ecosystem functions. Salt marshes are valuable in terms of coastal stability, carbon sequestration, and habitat. They are also a particularly dynamic ecosystem and therefore require continuous studies. My thesis is designed to aid in these efforts by specifically examining how sudden wetland dieback (SWD) impacts the sediment dynamics between the marsh surface and an adjacent tidal channel.

Of particular concern to NPS scientists is the decline of grasses in high-marsh locations where these losses have been hypothesized to accelerate the rates of elevation change and loss of peat (Smith et al., 2012). The aforementioned habitat shifts, vegetation changes, and sediment loss throughout salt marsh ecosystems are predicted to increase in extent in response to climate change related factors. Specifically, accelerated sea level rise, increased intensity and frequency of storms and drought will lead to dramatic shifts or loss of salt marshes as coastal habitats. Over the past 15 years, NPS scientists have collected marsh elevation data using surface elevation tables (SET) that are widely spaced across broad sections of the Cape Cod National Seashore marsh systems. Although these data provide an idea of marsh elevation change, they do not represent an accurate depiction of the spatial distribution of the changes. A need exists, therefore, to provide spatially contiguous and accurate high-resolution topographic data to establish rates of salt marsh elevation change and the loss of peat.

The thesis is broken down into two major sections. The first section (Chapter 1) is designed to provide the current state of knowledge of the research related to SWD and marsh sediment dynamics. In this section, I highlight the findings of the peer-reviewed scientific literature as it relates to changes in the sediment transport within salt marshes. I use this information to place my research into the context of the existing literature and show a need for increasing the spatial and temporal resolution topographic data to assist in understanding the sediment exchanges between the high marsh and the adjacent tidal channel.

The second portion of this thesis designed as a peer-reviewed article to be later submitted for publication in a scientific journal. The article is focused on providing a more spatially robust analysis of sediment dynamics with a single marsh in the Cape Cod National Seashore. The results presented in this chapter of the thesis represent a three study using terrestrial laser scanning to capture topographic change and use the topographic change data to construct a morphological sediment budget to estimate of the sediment transport. Findings from the study are important scientific community as they increase our awareness of marsh dynamics and also possess relevant information for park scientists and managers to determine how rapidly marshes change and to what extent is the change continuous or episodic through space and time. TLS surveys record data at decimeter spatial resolution and centimeter vertical resolution, which is much finer than the ongoing ground surveys (20-meter spatial resolution and decimeter vertical resolution) being conducted by the NPS. For example, the 20-meter survey grid does not capture channel flow or soil structure (e.g. crab burrows), whereas the TLS surveys will capture features as small as rills adjacent to channels and on barren portions of the marsh.

Coastal sediments are continuously modified as a function of varying wave energy and tidal fluxes. Salt-water marshes in particular are highly dynamic features that play an important role in protecting the coastline from erosional processes. Yet many salt-water marshes around the world are experiencing rapid rates of erosion and a loss of sediment. Recent estimates specify that approximately 20% of salt-water marshes may disappear over the next 100 years (Webb et al. 2013; Smith 2009).

Salt marshes are important components of coastal ecosystems. Commercial fisheries are particularly reliant on the diverse species of fish that rely on marsh habitat for their basic biological functions. A salt-water marsh provides the necessary protection for different stages of the lifecycle for many fish and crustacean species that are preyed upon by many of the larger commercial fish species (Boesch and Turner 1984; Enright et al. 2012). Salt-water marshes are also a source of protection for coastal communities against ocean storms. Dense vegetation present in a marsh system slows the water flow down, reducing wave energy and the potential for coastal erosion (Fagherazzi et al. 2012).

Vegetation is also critical to maintenance of marsh topography. High tides and storms transport sediment that has a greater chance of catching and settling within the vegetated areas. Sediment deposition increases marsh elevation, which helps the marsh sustain itself over time. Without the belowground root mass of the vegetation, the sediment has nothing to bind it together and keep it from eroding (Smith 2009; Fagherazzi et al. 2012; Kirwan and Megonigal 2013). Sediment can quickly wash away with the outgoing low tide when it has no binding agent (i.e. the root mass). The velocity and turbidity of the water that flows into and out of a marsh is important to marsh deposition rates. As the distance increases from the tidal creeks, the settling velocity decreases because flow is impeded by vegetation. Depressions in elevation can result further from the channel because of less accretion (Kirwan 2008). Larger particles carried in by the high tide cannot be transported under lower flow velocities. Large proportions of the coarsest sediment load are deposited on the tidal creek banks. Smaller particles are transported onto the marsh interior by the high tide and typically are not re-suspended with the falling tide because of a reduction in shear stress within the canopy (Christiansen et al. 2000). Coastal floods or wind driven high-tides are the main transfer of larger particles to the marsh interior, and more floods encourage a larger amount of deposition (Christiansen et al. 2000; Smith 2008), as well as spring and neap tides (Gabet 1998). Wave activity is a control on sediment deposition in macro-tidal marshes because waves directly contact the marsh surface during storms, although vegetation can dampen flow velocity and dissipate wave energy (Van Proosdij et al. 2006). Marshes are also capable of deposition even when the sediment supply has been stopped, albeit at a slower rate (Ma et al. 2014). Root production at and below the ground surface is also a significant source of deposition (Davidson-Arnott 2010). Seasonal sedimentation patterns control levels of deposition on the marsh. Storms during the winter months typically produce conditions conducive for sediment deposition. Since marsh depositional rates are not constant, these sporadic storms and events are important for the marsh's survival (Ma et al. 2014). Although temporal variations in storm strength and frequency are known to be the sources for high deposition and erosion rates, the lack of short term data makes it difficult to determine the extent of these rates (Ma et al. 2014). The ice from winter storms can freeze to the substrate and is thickest along the banks of the tidal creeks, causing erosion and/or deposition and a change in cross sectional area of tidal rivers. Drift ice can make its way up the channel and onto the marsh platform, and as it melts, deposits sediment and plant detritus (Gordon and Desplanque 1983). Deposition is temporally variable based on specific sites and the storm effects to that specific marsh (Proosdij et al. 2000; Ganju et al. 2013;Gordan and Desplanque 1983). Vegetation is also less dense and shorter during the winter and early spring months, so inundation over the surface is less disturbed by the vegetation and therefore sediment can settle (Davidson-Arnott 2010).

Sea-level rise also contributes in some ways to the amount of deposition and erosion that takes place in a salt-water marsh (Kirwan and Megonigal 2013; Baldwin et al. 2001; Cazenave and Cozannet 2013; Webb et al. 2013; Smith 2009; Cadol et al. 2014). Tidal marshes adapt to increasing water level by gaining elevation via accretionary processes (Cadol et al. 2014). If the level of accretion is high enough, the marsh will increase elevation with respect to sea-level rise. Past studies have shown salt-water marshes are dynamic enough to adapt to sea level rise fairly quickly if not constrained by landward movement or anthropogenic affects (Kirwan and Megonigal 2013; Fagherazzi et al. 2012).

Along the Eastern Seaboard of the United States, *Spartina alterniflora* (Smooth Cordgrass) dominates the low marsh zones. This species of cord grass is particularly resistant to longer periods of inundation. Therefore, it is more likely to combat sea-level rise then other species (Baldwin et al. 2001; Smith et al. 2012). Species of Marsh Hay (*Spartina patens*) and Rush (*Juncas roemerianus*) typically dominate the high marsh zones (Ogburn and Alber 2006; Smith et al. 2012; Smith 2009; Kirwan and Megonigal 2013).

Many coastal areas in Louisiana, Florida, Georgia, South Carolina, New England, Virginia, Delaware, and California have reported Sudden Wetland Dieback (SWD) in the last decade (Alber et al. 2008). SWD results when above ground vegetation is lost, leaving behind bare-earth. The exact causal mechanism(s) have not been determined to date, but bare patches may result from subsequent *Uca pugnax* (Fiddler crab) burrowing into the below-ground root mass and reducing the potential for regrowth of vegetation (Alber et al. 2008; Smith and Green 2015). The low marsh platform usually displays the first signs of vegetation loss in SWD scenarios. Vegetation on the low platform is important because it controls the drainage pattern of the marsh (Rosso et al. 2006). Slow drainage often produces concavities on the marsh and can lead to drowning of marsh vegetation in these locations. These bare earth patches also typically take a greater time to drain from inundation than areas not exhibiting SWD (Smith et al. 2012). Vegetation loss along tidal creek banks can cause the bank to slump. Slumping is also found in locations where the tidal influx carves out the below ground sediment and removes the support of the sediment above, which causes the sediment to break off and fall into the channel bed (Gabet 1998). Vegetation litter (wrack) brought in with tide disturbs vegetation in the bends of the tidal channel, creating an increased situation for slumping potential by killing the surface vegetation and sub-surface root structure holding the bank in place (Lottig and Fox 2006). Channel widening and sediment deposition downslope and closer to the ocean side of the marsh are often associated with slumping (Kirwan et al. 2008). Lateral channel migration can also be inhibited by slump blocks protecting a bank from erosion, and instead flow velocities within the channel contributing to erosion are diverted to the adjacent side of the channel, creating a stable erosion and depositional pattern (Gabet 1998).

Deposition on the marsh platform is controlled by flooding, even in SWD situation. A flooding regime was established for the Gut marsh in Cape Cod by implementing loggers and tide gauges to measure the amount of time a particular section of the marsh was inundated (Baldwin et al. 2001). In the Gut, the seaward edge of dieback areas was flooded 45% of the time while the healthy marsh area was only flooded 15% of the time (Smith et al. 2012), suggesting that these areas are inundated past the optimal depth for vegetation growth. Vegetation biomass increases with water depth up to an optimal depth (approximately 40 – 60cm below mean high tide) and is conducive for sediment trapping and deposition (Morris et al. 2002).

Past methods of analyzing sediment transport in the Cape Cod area include many different techniques and numerical models. The difficulty of numerical models is that they typically do not include all of the aspects that are responsible for the changing sediment conditions of salt-water marshes, such as anthropogenic effects and ecological determinants like crab herbivory (Smith 2009; Fagherazzi et al. 2012; Enright et al. 2013). In short, numerical models are site specific and cannot be applied to the entire marsh. Although numerical models are now incorporating more non-linear phenomenon into their analysis, it is important to actually go in and analyze specific sites where the wetland is experiencing dieback (Webb et al. 2013).

Aerial photography such as color IR photography (Smith 2009), long-wave imagery (Puleo et al. 2014), digital imagery based off of RGB values (Smith and Green 2015) and lidar to determine the overall dimensions of marsh loss have been used as well (Webb et al. 2013; Rosso et al. 2006; Colon-Rivera et al. 2012; Hladik and Alber 2012; Mason et al. 2006). However, aerial photography and remote sensing techniques such as lidar are often coarse-scale and do not have the resolution to give a very detailed analysis of the dynamics of the dieback sections of the marsh (Webb et al. 2013).

Using aerial photography and lidar also make the classification of bare earth and vegetation extremely difficult when analyzing sections of marsh because of resolution errors (Puleo et al. 2014; Huising and Pereira 1998). Typically, lidar data classifies the first return as vegetation and the last return as bare earth (Schmid et al. 2011). However, the returns are based off of 1 point/m^2 in some cases, which is too low of a resolution to measure marsh erosion. Studies have increased the likelihood of bare earth classification with a lower error range with lidar by incorporating DGPS surveys and increased laser pulse rates (Guarnieri et al. 2009).

Another approach recently used for topographic analysis is Structure-for-Motion (SfM). This is where a multitude of digital pictures are taken and overlap to produce a point cloud from camera locations, color gradients, and overlapping, high-quality pictures. This would be a viable technique for many topographic areas, however the dense accumulation of vegetation on the marsh make the SfM difficult to capture individual vegetation and bare earth points (Westoby et al. 2012).

Positive results have been found using the RSET-MH (Rod surface elevation table marker horizon) method. This method relies on a vertical rod placed into the marsh substrate and measures the vertical accretion that takes place in relation to sea-level rise. RSET provides a highly accurate representation of marsh elevation, however to utilize this method, many of these instruments would have to be set up in a multitude of locations along the platform and set to the same reference system to be of any use in this study (Webb et al. 2013).

Terrestrial laser scanning (TLS) is a valuable tool to aid in analyses of sediment transport in salt-marshes. TLS is a more viable technique in studying salt-water marshes in Cape Cod because it has a very high resolution and can determine the amount of sediment load that has been eroded/deposited in an aspect of centimeters. In terms of technology, it is the most precise data collection scenario that exists for terrain analysis (Slob and Hack 2004). TLS has also been used in the past for terrain analysis studies such as debris flows (Staley et al. 2011;2014; Wester et al. 2014; Wasklewicz and Hattanj 2009), coastal processes (Rosser et al. 2005; Guarnieri et al. 2009), aeolian studies (Nield et al. 2011) and river morphological components (Brasington et al. 2012; Heritage and Milan 2009). Vegetation and ground return separation from TLS data in a tidal lagoon in Venice were used to determine the actual bare-earth elevations of the marsh (Guarnieri et al. 2009). Classifying bare earth surfaces within TLS can be difficult at times, and requires the large point clouds returned from TLS (how much) to be broken up based on intensity values (Guarnieri et al. 2009), elevation ranges (Brodu and Lague 2012), or by using cellular statistics (Brasington et al 2012; Guarnieri et al. 2009).

Digital elevation models (DEMs) are used to analyze erosional and depositional habits of the topography with the classified TLS data (Guarnieri et al. 2009; Hodge et al. 2009; Rosser et al. 2005). DEM's are reliant on a multitude of components, including the resolution of the data points, the likelihood that bare earth points were obtained, and the spatial distribution of the data points across the study area (Heritage et al. 2009). All of these qualities can be specific to separate surveys, so understanding the error is crucial to obtain an accurate portrayal of the study site (Milan et al. 2011). Examining the quality of the DEMs are also important in determining if the true elevations are being portrayed (Wheaton et al.2010). As point accuracy declines with distance from the scanner, error is produced within the DEM with respect to scanner location (Lichti and Jamtsho 2006; Brasington et al. 2012).

DEM quality and accuracy have been assessed using various statistical techniques as well (Wheaton et al. 2010). The standard deviation, mean, and Root Mean Squared Error (RMSE) have been incorporated into studies to understand the distribution of the error within the DEM (Staley et al. 2014;Wheaton et al. 2010; Heritage et al. 2009; Milan et al. 2011) and to provide vertical accuracy references to the data. While the standard deviation can measure the dispersion of the data, this might not account for various outliers within the data. The data dispersion is an important item to consider and using one source of data dispersion analysis can lead to an over or underestimation of the elevation ranges of the study area and provides no information about the spatial distribution of elevation error (Oksanen and Sarjakoski 2005; Heritage et al. 2009; Coveney et al. 2010).

While DEMs account for the elevation within the study area, a DEM of difference (DoD) can provide how much elevation change has occurred from one DEM to another. These elevation changes can then be converted into volumetric changes by multiplying the elevation change by the surface area of each cell (Wheaton et al. 2010). The sum of these volumes produce a net sediment budget, which is helpful in understanding how much sediment is in the system of a study area (Harrison and Bloom 1977), and how it has changed. Cross sections of the tidal channel(s) can also be used to further validate sediment erosion and deposition. Tidal channel morphometry typically follows the same patterns, with total cross sectional area increasing linearly with tidal drainage area (Yu et al. 2014). Channel networks also change structure because of headward growth and tributary initiation (Coco et al. 2013).

The research presented herein is designed to analyze the tidal creek and marsh interior sediment transport over periods of high energy tidal conditions found during the winter and spring months. Furthermore, the topographic data collected during this study also permit an analysis of the marsh channel morpho-dynamics. Data have been gathered over a three-year period with a goal of aiding Cape Cod National Seashore personnel with management schemes that will combat the causal mechanisms associated with marsh decline. By understanding the dynamic changes of the salt-water marsh in the Gut, Numerical models using findings from the current study can incorporate the topographic dynamism and provide a better approximation of future marsh responses under varying human, natural, and climate change scenarios.

CHAPTER 2: Article to be Submitted for Peer-review

Introduction

Salt water marshes are complex geomorphic features composed of a vegetated marsh platform, intertidal flats, and tidal channels, with elevation increasing slowly from the seaward edge. Organic matter accumulation and sediment input must continue to increase the elevation of the marsh surface to exceed sediment loss and increasing water heights associated with rising sea-levels and periods of increased wave energy (Christiansen et al. 2000; Kirwan 2008). Sediment transport in salt marshes has been investigated using methods such as sediment trapping (Christiansen et al. 2000), suspended sediment concentrations (Ma et al. 2014; Van Proosdij et al. 2006;), and measuring elevation change (Cadol et al. 2014), as well as particle size distributions (Christiansen et al. 2000). These types of studies require multi-year assessment of the marsh in order to obtain an accurate understanding of the erosional and depositional processes at work.

Sediment can accumulate on the marsh by catching and settling within the vegetation. The vertical accretion of a marsh is spatially variable and is dependent on the rate of deposition, flow velocity, and sediment supply (Davidson-Arnott 2010; Christiansen et al. 2000). Macro-tidal (>10m tides) marshes in particular accumulate by wave energy and flooding events. Wave activity is a control on sediment deposition in macrotidal marshes because waves directly contact the marsh surface during storms, although vegetation can dampen flow velocity and dissipate wave energy (Van Proosdij et al. 2006). Increased flow velocity inhibits the settling of suspended particles. Sediment accumulation also varies with respect to the proximity of the tidal creek. As the distance increases from the tidal creek, the settling velocity decreases because the flow is impeded by vegetation. Larger particles carried into the tidal creek by the high tide cannot be supported by the lower flow velocities found on the platform, and therefore most sediment is deposited in the tidal channel creek banks. Smaller particles are transported onto the marsh platform by the high tide and typically are not re-suspended with the falling tide. Marshes are also capable of deposition even when the sediment supply has been stopped, albeit at a slower rate (Ma et al. 2014).

The magnitude and the spatial variability of sediment transport change relative to the time of the year. Storms during the winter months typically produce conditions favorable for deposition and erosion. Since the depositional rates of a marsh are not constant, these sporadic storms and events are important for the marsh's survival (Ma et al. 2014). The ice from winter storms can freeze to the substrate and is thickest along the banks of the tidal creeks, causing erosion and/or deposition and a change in cross sectional area of tidal channels. Drift ice can make its way up the channel and onto the marsh platform, and deposits sediment and plant detritus as it melts (Gordon and Desplanque 1983). Vegetation is also less dense and shorter during the winter and early spring months, so inundation over the surface is less disturbed by the vegetation and therefore sediment can settle (Davidson-Arnott 2010). Although temporal variations in storm strength and frequency are known sources of high deposition and erosion rates, the lack of short term data makes it difficult to determine the extent of these rates of change (Ma et al. 2014).

Multiple techniques have been developed to annually measure marsh accretion and erosion in an attempt to extract marsh sediment dynamics. Rod Surface Elevation Table Marker Horizon (RSET-MH) is a technique that provides a fixed, horizontal plane to measure distance to the substrate surface (Webb et al. 2013). This gives a reference plane to measure accretion levels. Although this gives a confidence interval of 1.3mm, this isn't an accurate portrayal of the entire marsh surface because of the lack of instruments implemented across the surface. Airborne laser scanning (ALS) has been implemented to record elevation values, however at the coarse resolution of the returns (~1m spatial resolution and +15cm vertical resolution) and the high amount of vegetation biomass limit the likelihood that the elevation value returned is actually bare earth or the small amounts of vertical change are measurable from the ALS. Terrestrial Laser Scanning (TLS) on the other hand is capable of a spatial resolution of approximately 200 returns/m^2 and allows for the small scale changes seen in a marsh system (Guarnieri et al. 2009). Another important aspect of marsh changes are seasonal and annual fluctuations in channel morphometry. Channel morpho-dynamics are a direct response to hydrological and sedimentological dynamics occurring over space and time within the marsh.

Here, I examine sediment transport and channel morpho-dynamics of a saltwater marsh, which is recovering from SWD. SWD is not a long-term condition for many marshes, but there is little quantitative evidence regarding the spatial and temporal changes of sediment transport found in sites experiencing SWD. In addressing sediment transport in a marsh recovering from SWD, I address two specific research questions:

1. ***What is the spatial and temporal variability in the magnitude of sediment erosion and/or deposition across high marsh and tidal channel sites where marsh die-off is present?***
2. ***How does marsh channel morphometry change annually?***

Findings from these research questions are particularly relevant to monitoring possible marsh recovery from SWD. SWD is not a long term condition for marshes, but a better understanding the rate and volume of erosion or deposition can provide managers with a better understanding of the potential rate of recovery and some of the implications of changing marsh dynamics as climate changes in the future. Furthermore, findings increase our understanding of the spatial patterns of sediment transport in salt marsh systems that have heretofore been investigated with instruments and approaches that have not been as spatially explicit because they rely on methods that are plot-based or at coarse resolution.

Study Area

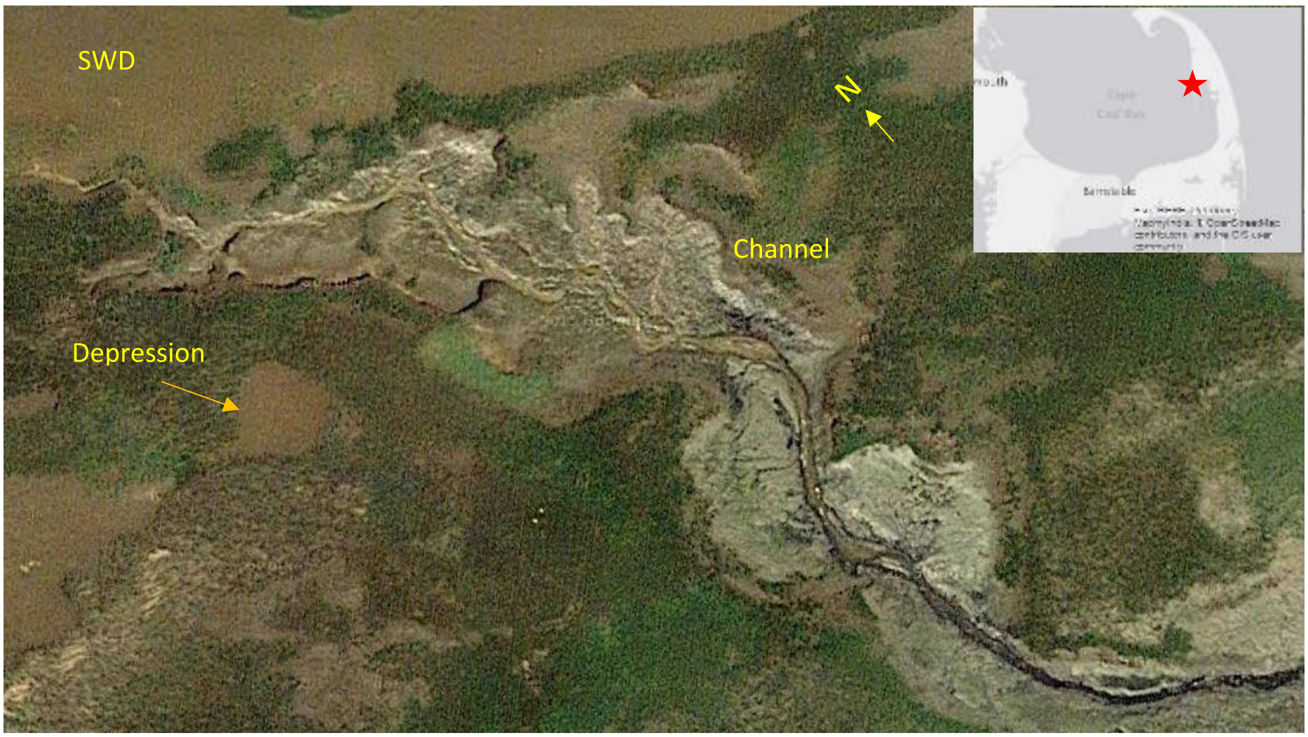


Figure 1: Study Site of "The Gut" marsh.

Our study area consisted of a 0.02km^2 section of marsh in Wellfleet, Massachusetts (Fig. 1). The marsh has formed behind a small spit of sand that connects Griffin Island and the Great Island of Cape Cod, Massachusetts. The spit blocks incoming wave energy from the open ocean and produces relatively calm waters of Wellfleet harbor. This calm environment is partially responsible for the formation of salt marshes on the ocean side of the site, which has been given a vernacular name “the Gut”, creating further protection to the harbor from storm effects and erosion. The marsh is characterized by a macrotidal semi-diurnal regime, meaning that accretion levels of sediment are dependent on the fluctuation of the tidal system throughout the marsh. The stability of the Gut is primarily dependent on littoral sediment transport along the Cape Cod Bay Shore (Portnoy 2003).

The Gut is composed of a high marsh dominated by *Spartina patens* (Salt marsh hay) and a low marsh dominated by perennial grass *Spartina alterniflora* (Smooth cordgrass). *Spartina alterniflora* is further divided into short and tall forms (Gallagher et al. 1988), which occur along specific topographic gradients. On the seaward edge of the marsh, the tall form of *Spartina alterniflora* is prominent because of the ability of the root system to protrude deeper into the loose sediment and take hold. Tall forms of *Spartina alterniflora* are also found on the marsh flat and on tidal creek banks within the marsh, while short forms of *Spartina alterniflora* are found high up on the marsh flat and typically form the boundary between the low and high marsh.

A high rate SWD has taken place within the Gut. The above ground vegetation is dying and leaving behind the root system within the substrate. A mass of roots and mud that is unable to facilitate regrowth of above ground vegetation is all that remains after the onset of SWD. A mudflat develops in the absence of vegetation. Sediment deposition is hindered without the above ground vegetation and there is nothing for suspended sediment to catch on when it is brought in with the incoming tides. This opens up the marsh to erosion. Decreased sediment yield from the Herring River Dike is has also caused parts of the marsh to subside (Portnoy 2003).

Methods

Data Collection

Repeat TLS surveys using two Leica ScanStation C10 scanners produced xyz point clouds of the tidal channel and adjacent low marsh platform surface. The point clouds represent information to conduct an analysis of marsh topographic changes from 2013 - 2015 following techniques described in Staley et al. (2014), Lisenby et al., (2014), and Wester et al., (2014). Eight Leica Geosystems High Definition Survey planar targets (15.25 cm) placed on 1m pieces of rebar hammered flush to the surface of the marsh at the margins of the tidal channel serve as ground control points (GCP) and allow repeat surveys to be conducted using a set of Cartesian coordinates established in the first TLS survey. The GCP aid in the registration of the multiple survey positions and are used to assess data uncertainty (Staley et al. 2014). A consistent scanning field-of-view (FOV), horizontal and vertical point spacing (2 cm) and range (30 m) are used in the scanning process. Multiple scanning positions are conducted to limit shadowing effects and to ensure capture of all sections of the tidal creek.

Point Cloud Registration

Individual point clouds are registered using Leica Geosystems Cyclone v 9.x to create a full 3D representation of the marsh topography. A common set of Cartesian coordinates permit continuous referencing of the data over multiple years. Manual cleaning of the point cloud is initially performed within Cyclone (Brasington et al. 2012). Items such as target poles, scanners, sun glint from the lens, and people are common features removed during this portion of the of data post processing.

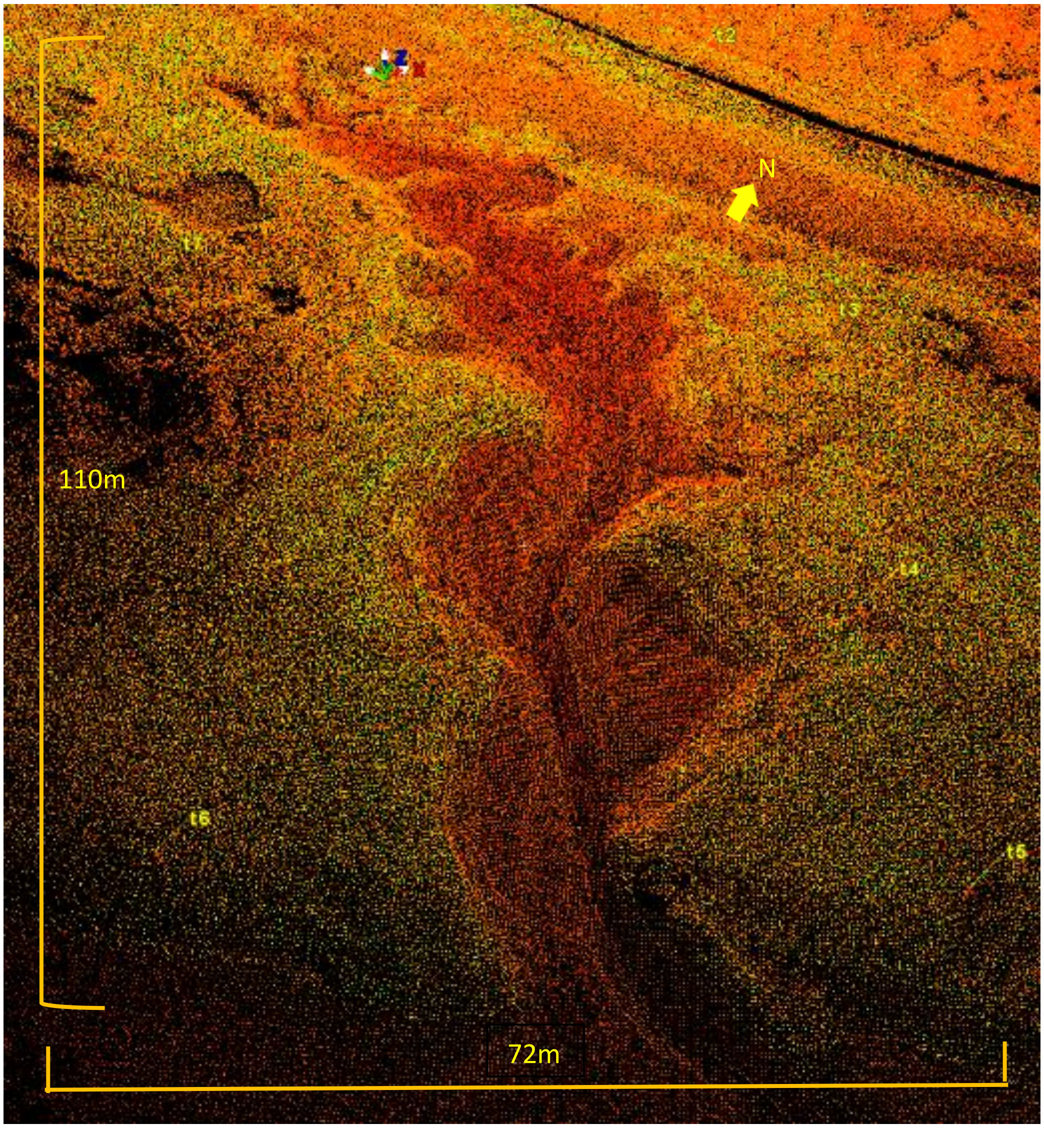


Figure 2: High Resolution TLS survey of the Gut Tidal Channel and adjacent marsh platform.

Extracting a Bare Earth DEM

During each of the three separate scanning campaigns data are sampled early in the season when vegetation density is at its lowest. However, the vegetation density on the marsh platform varied slightly from year to year because we did not always scan on the same date and varying winter/spring climate conditions also impacted the occurrence and amount vegetation regrowth. The highest vegetation density occurs on the marsh platform adjacent to the tidal channel and the point cloud is less dense in these locations. The tidal channel and adjacent marsh platform are analyzed separately because of the differences in point cloud density within these two domains of the study area. The boundary between the channel and the platform is delineated via digitizing the break-in-slope at the channel/platform interface as determined from curvature (assessment of changes in planform convexity, rectilinearity, and concavity), channel cross section, gradient changes, and digital imagery. This results in two separate point clouds that require different post-processing approaches.

A bare earth DEM is required to produce accurate measures of the sediment removal from both the high marsh surface and the tidal channel (Fig. 3). The dense vegetation on the high marsh surface in some of the TLS survey campaigns necessitated the removal of the vegetation. A number of the permutations using the LASground code in LAStools did not produce a segmented point cloud that could approximate a bare earth surface. The vast majority of the permutations of the LASground code produced errors of approximately 30 cm in areas of dense vegetation when compared with hand clean sections of the point cloud. The resulting poor quality returns from LAStools led to another series of methods developed by Brasington et al. (2012) and Guarnieri et al. (2009).

The starting point for the extraction of the bare earth DEM is the determination of the local relief of known bare ground within the study site. The local relief of numerous bare surfaces on the platform are manually assessed in Cyclone and on average the bare surfaces had a local relief of 5cm. This value is further validated with the aid of using a moving window of 10cm to obtain a z-value range analysis of DEMs from known bare ground and ~95% of the bare ground pixels showed ranges below 5cm. Therefore, elevation values of 5cm and under are used

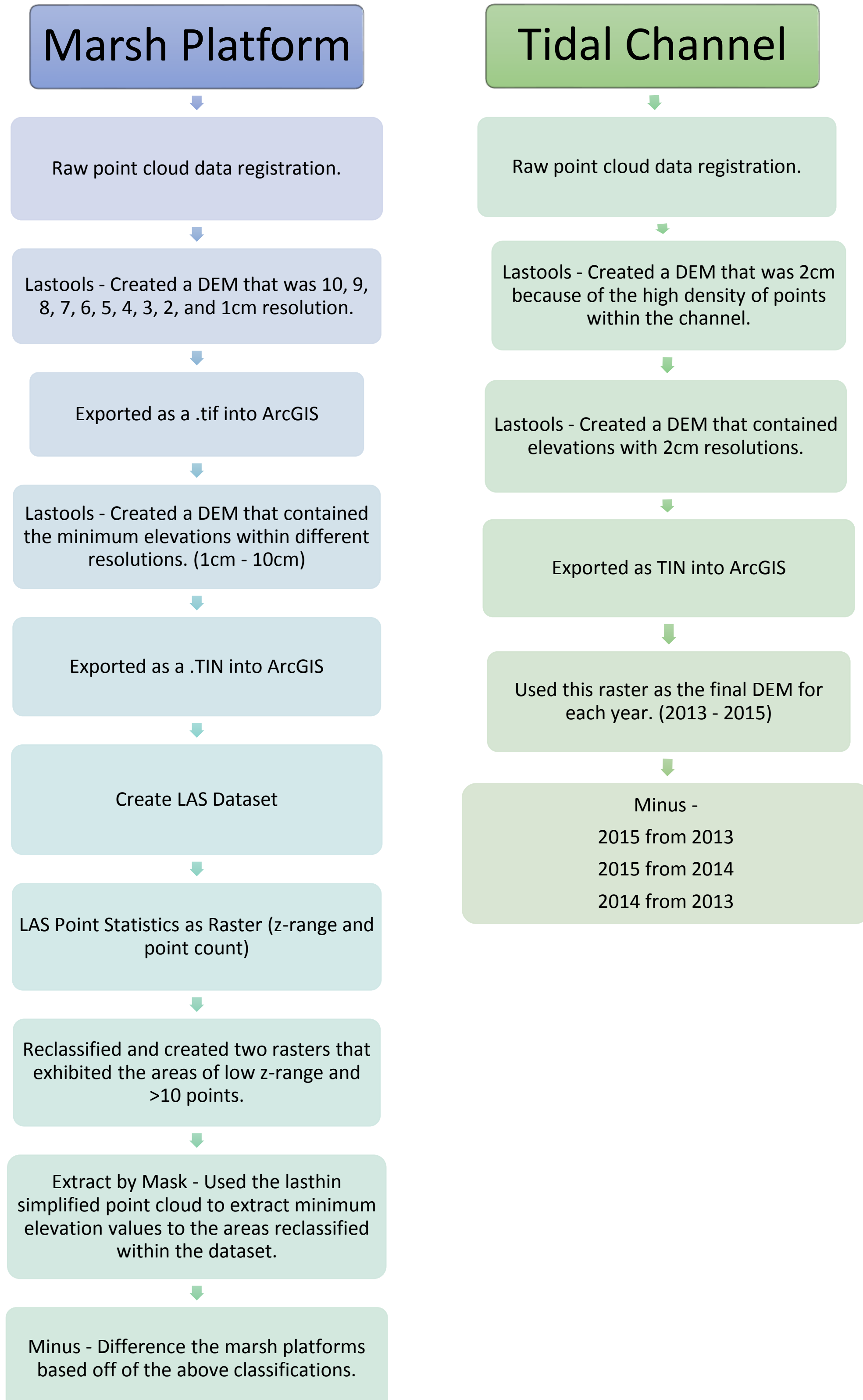


Figure 3: Workflow for processing and analyzing the marsh and tidal channel DEMs

to approximate the location of the marsh topographic surface. Vegetation typically exceeded this z-value range across multiple years.

A 10cm moving window size is arbitrarily selected to determine points exhibiting a z-range ≤ 5cm and containing ≥ 10 points in the window. These areas are considered bare earth and are used in the subsequent analyses (Fig. 5). Filtering the data points in this fashion provides a simple spatial sorting while keeping sample frequency and topographic complexity (Brasington et al. 2012). Cells that did not have these criteria were omitted from the data set. However, this filtering largely removes all vegetated surfaces from the analyses. While this is not ideal, the resulting data provide an initial estimate of sediment transport within the platform areas.

A further assessment of the point densities across the marsh platform indicates the number of points on the edges of the dataset where there is dense vegetation present are diminishing because of the scanning approach. The further away from the single line of surveys taken along either side of the tidal channel (given the duration of a low tide this represents the maximum amount of data we could collect) the greater the loss of data from shadowing effects, which is in part a response to the oblique scanning angles of the tripod mounted TLS.

The variation in the point densities brought into question the resolution of the DEM to use in subsequent analyses. To assess this issue, the original point cloud data are filtered using LASthin code within LAStools to produce a DEM of minimum elevation values across the marsh platform (Guarnieri et al. 2009). A total of 60 bare-earth points are extracted apriori from original TLS point cloud because there are no ground control points established by GNSS or other surveying approaches. These points are compared to corresponding points returned within the lasthin derived DEMs in ArcMap v10.3.1. The RMSE and standard deviation are used to assess the vertical accuracy of the returns across a variety of scales (Wang et al. 2009; Cadol et al. 2014). The values of this are plotted to determine which resolution exhibited the lowest

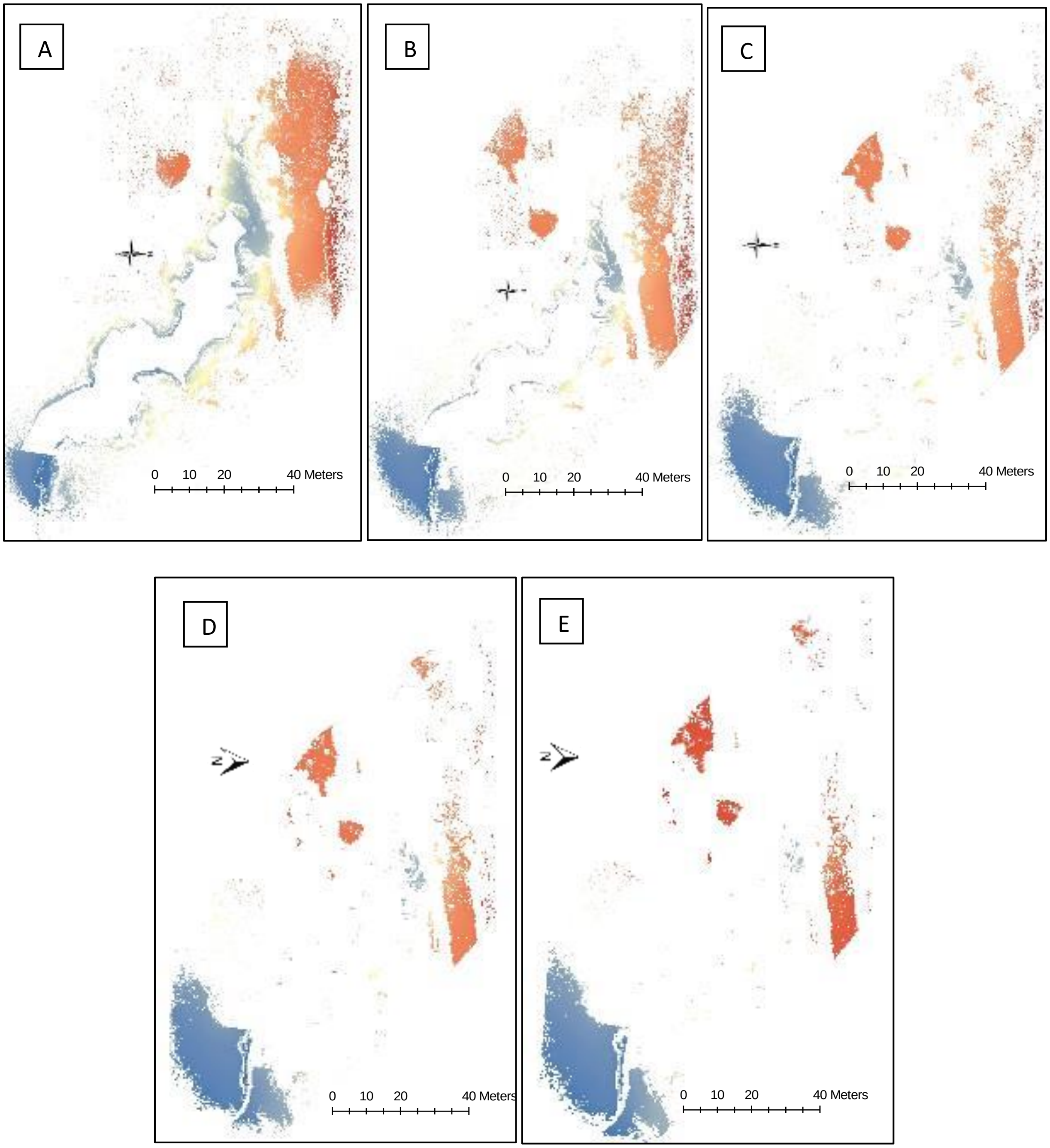


Figure 5: Demonstrating how increasing the window size of the raster cell provides a trade-off in raster cells for analysis. A: 10cm window size; B: 20cm window size; C: 30cm window size; D: 40cm window size; E: 50cm window size.

values or to assess if there was a "shelf" at which the resolution no longer impacted the accuracy of the returns (Fig. 6).

An assessment of the results shows a 3cm provides happy medium between minimal errors, DEM resolution, and computational time in the analysis of the high resolution point cloud. (Guarnieri et al. 2009; Brasington et al. 2012; Wheaton et al. 2010). While a 1cm resolution displays the lowest RMSE and standard deviations, this resolution is not selected because the data are not consistent enough in areas where vegetation still exists to maintain this resolution without introducing spatial error. This value is also low because of the large number of bare ground points in marsh areas experiencing SWD, which reduces the larger error values in the more vegetated areas. The 6cm resolution had similar RMSE and standard deviations to those of the 3cm resolution. However, the high-resolution of the 3cm was selected to reduce mixed pixel errors and to provide more detailed assessment of surficial features as the 6cm would have smoothed some of the topographic complexity within the study site.

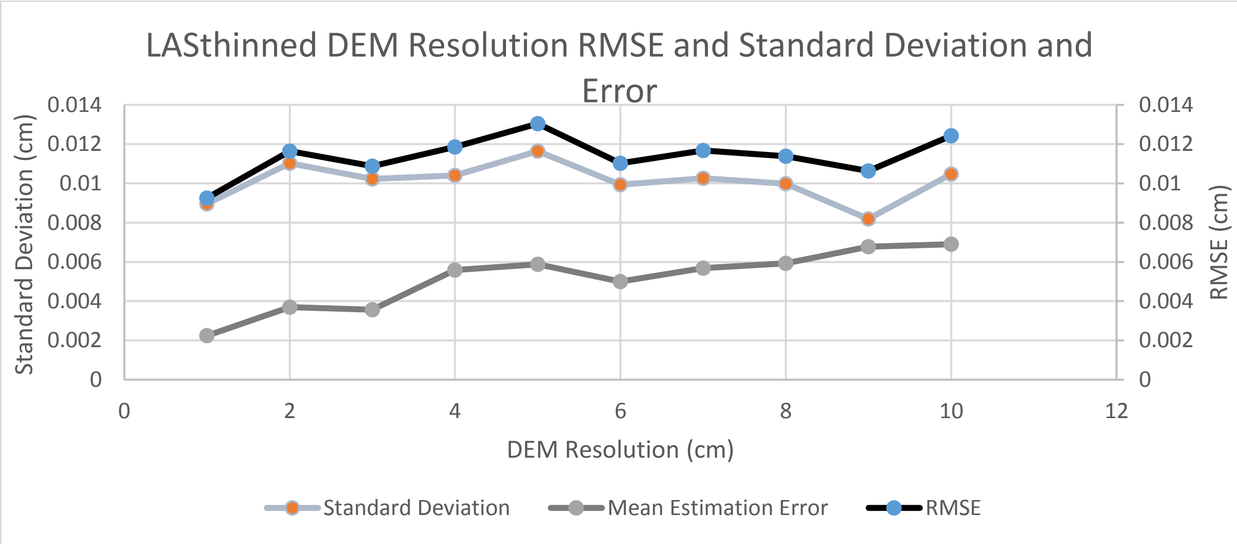


Figure 6: The minimum elevation taken from the LASthinned DEM (bare earth) compared against the returned grid value within ArcMap to determine the amount of error associated with the returned value. This was the spatial error across the dataset.

Marsh Tidal Channel

The point cloud in the tidal channel has a higher point density than the platform because there is less vegetation. The lack of vegetation found within the tidal channel precluded the need filter the data as described for the marsh platform. Furthermore, the lack of vegetation also allowed analyses of the tidal channel to be performed at a higher spatial resolution. A 2cm DEM is created using the BLAST2DEM command in LAStools.

Minimum Level of Topographic Change Detection

A threshold value to detect the minimum level of change is set at 1cm based on previous experience (Staley et al. 2014; Lisenby et al. 2014; Wester et al. 2014; Wasklewicz and Scheinert, 2016). This value is applied in both the marsh and tidal channel morphological sediment budgets. Therefore, all no changes pixels in subsequent analyses are derived from values ranging between -0.01 m to 0.01m. This is a conservative estimate, especially for marsh environments where the annual changes tend to be small, but nonetheless is justified given past experience.

Net Volumetric Calculations

To facilitate the spatial analysis of topographic change within the marsh (erosion, deposition, or no change) the volumetric change is calculated for each time period. Each DoD covers approximately the same area for each time period. The total volumetric change is computed using the DEM data pairs between 2013 – 2014, 2014 – 2015, and 2013 – 2015. This involved calculating the elevation change on a cellular basis and extracting cells with elevation values <0.01m and >0.01m. These cells are multiplied by the area of each cell. This normalized the data so that the volumetric yield could be compared across the different time periods (White and Wang 2003). The sum of the positive and negative values yielded a volumetric calculation for deposition and erosion for each time period. A “no change” value is also recorded by summing the number of cells with elevation values ≤ 0.01m and ≥ -0.01m. The sum of these values yielded a volumetric calculation (by using the below equation):

$$\Delta V = \frac{A_v \times \sum_{(i,j)-1}^{n} \Delta Z_{(i,j)}}{n}$$

where A_v = the area that is being calculated (m^2) and ΔZ = the change in elevation at each pixel and n = the number of pixels (Staley et al. 2014).

Data Uncertainty Measures

Data uncertainty is measured in three ways: (1) assessing the accuracy of the point cloud data and derived surface for each survey, (2) propagating the uncertainty from both surveys into the DoD, and (3) determining the significance of the propagated uncertainty on volumetric measurements obtained by the DoD (Brasington et al. 2003; Lane et al. 2003; Wheaton et al. 2010; Bennett et al. 2012, Staley et al. 2014). A systematic error (SE) and Mean absolute error (MAE) as measured at control point locations are used to assess all potential sources of uncertainty in the x, y, and z directions (Table 2). These measurements accounts for the potential bias or directionality in survey measurements (SE) and provide a measure of the overall uncertainty (MAE).

Table 1: Systematic error (SE) and Mean Absolute error (MAE) associated with uncertainty in the point cloud.

TLS scan year	Error associated with point cloud (meters)
2013	0.004
2014	0.004
2015	0.005

Marsh Change Detection

ArcGIS v10.3.1 aids in the measurement of marsh topographic changes, which are necessary to produce a morphological sediment budgets. Three annual TLS surveys (May, 2013, 2014, 2015) are used to develop DoD, where the DEM of each previous year is subtracted from the following year (for example, 2015 DEM – 2014 DEM). Positive values from the DoD represent erosion, while negative values indicate deposition. Elevation changes are converted into volumetric changes (Staley et al. 2014; Wester et al. 2014) and in the current study these volumetric changes indicate the annual changes to the tidal channel and marsh platform. Anomalies in the data (>10cm) are few and are extracted from the dataset (See appendix for removed sites).

Tidal Channel Cross-sections and Channel Morphometry

Channel cross-sections are obtained in ArcMap to understand the morphological changes associated with bank erosion or accretion. Qualitative and statistical analyses of changes to the channel morphometry such as the change to width, depth, and width:depth ratios are assessed using a t-test (Wasklewicz and Hattanji 2009). Cross-sections are developed at a 7-meter spacing along the entire length of the tidal channel to evenly distribute the cross-section analysis. Additional cross-sections are also placed at erosional/depositional hotspots as indicated by the DoD analyses.

Results

Marsh Platform

Deposition and no change (≤ 1cm) is most prevalent over the period of 2013 to 2014 (Fig. 7). Less than 1% of the elevation values exceeded 10cm and these measures are associated with areas of particularly dense vegetation, so these are considered anomalies and were extracted from the data (See Appendix A). Qualitative observations suggest these are areas where the vegetation filtering did not perform well. In this study, elevational changes were recorded on areas of SWD on the high marsh. Peak erosion occurs immediately adjacent to the tidal channel to the north, with elevation changes reaching 9±1cm some sections. However, less than 3% of the values exceeded 5cm of erosion or deposition.

A large mudflat (approximately 100m long and 30m wide) on the northern edge of the marsh platform is experiencing the highest amounts of deposition. A bare earth depression approximately 12m long to the west of the channel also shows evidence of predominantly deposition. Deposition accounts for 43% of the change detection, while 2.8% of the change on the marsh platform is erosion. No change is identified in the remaining 53% of the marsh surface examined in the current study. Converting these changes into net volumetric sediment yield shows approximately 2cm of erosion, 12cm of deposition, and 10cm of sediment that exhibited no change (Figure 10).

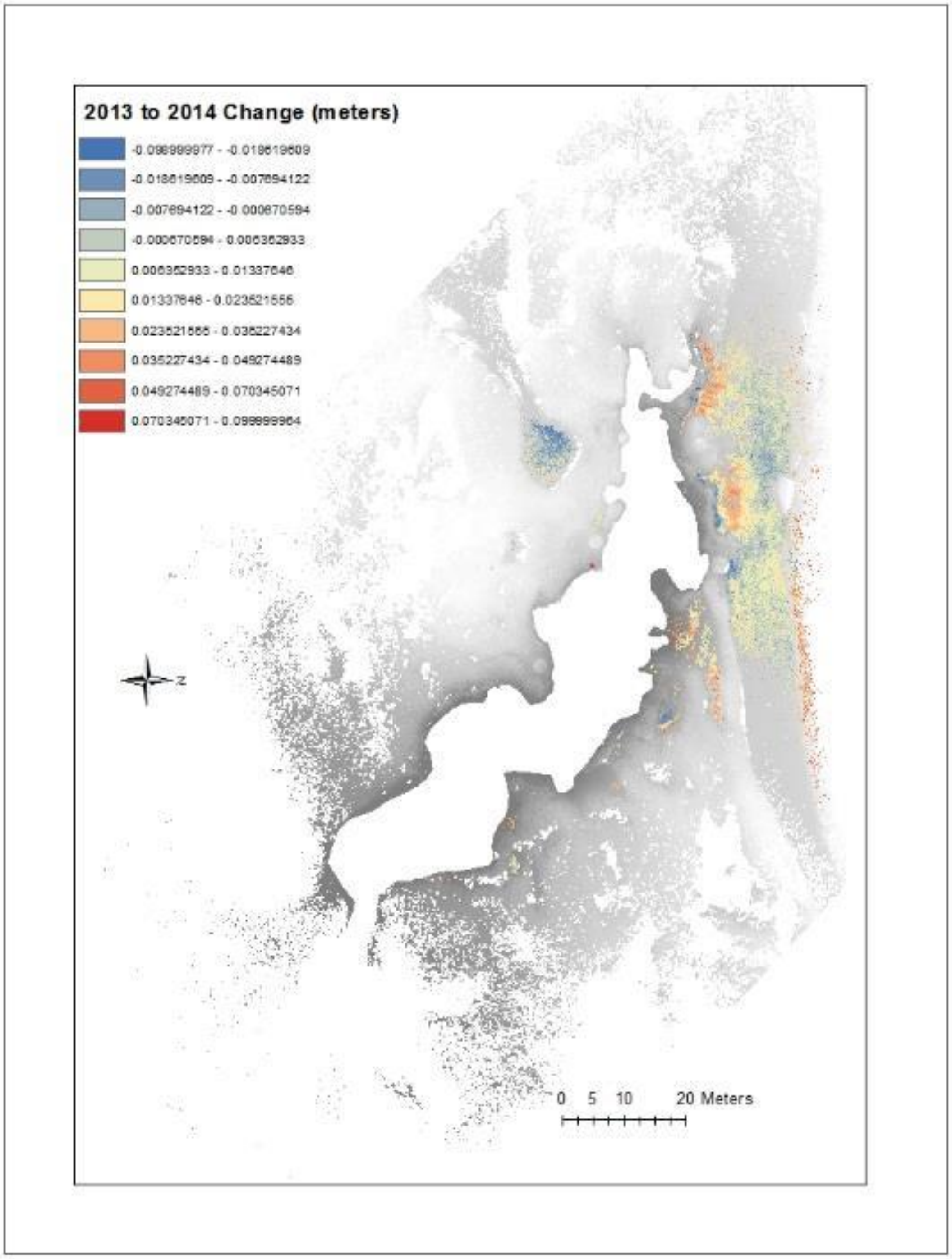

2013 to 2014 Change (meters)
-0.098999977 - -0.018619609
-0.018619609 - -0.007694122
-0.007694122 - -0.000670594
-0.000670594 - 0.006362933
0.006362933 - 0.01337646
0.01337646 - 0.023521556
0.023521566 - 0.036227434
0.035227434 - 0.049274489
0.049274489 - 0.070345071
0.070345071 - 0.098999964
N
0 5 10 20 Meters

Figure 7: Elevation changes from 2013 to 2014. The elevation ranges from 9 ± 1 cm of erosion and 9 ± 1cm of deposition. The threshold of known change was 1cm, so area's that exhibited -1 cm or 1 cm of change were considered no change areas. The gray area represents the entire study area for reference.

A greater amount of deposition is present from 2014 to 2015 on the large mudflat on the high marsh (Figure 8). Deposition is found in several locations that had exhibited erosion from 2013 to 2015 immediately adjacent to the tidal channel. The highest amounts of deposition were found in these bare earth spots, with values ranging up to 9 ± 1cm. However, 9cm was on the high end of elevation change and was probably the result of crab burrows or root masses like in the previous years' results (see appendix). In fact, < 1% of the values recorded were >5cm of deposition or erosion. No change is found for 68% of the values.. This slight recovery indicates that deposition was higher to offset the erosion that was seen in the previous time period. In the 12m depression of bare earth, no change values are more prevalent with some small areas of deposition overtaking the erosion that was previously seen. The net volumetric sediment yield (Figure 10) resulted in -0.105 m^3 of erosion (10% of the total change detected), 0.206 m^3 of deposition (21% of the total change detected), and 0.048 m^3 of no change (69% of the total change detected).

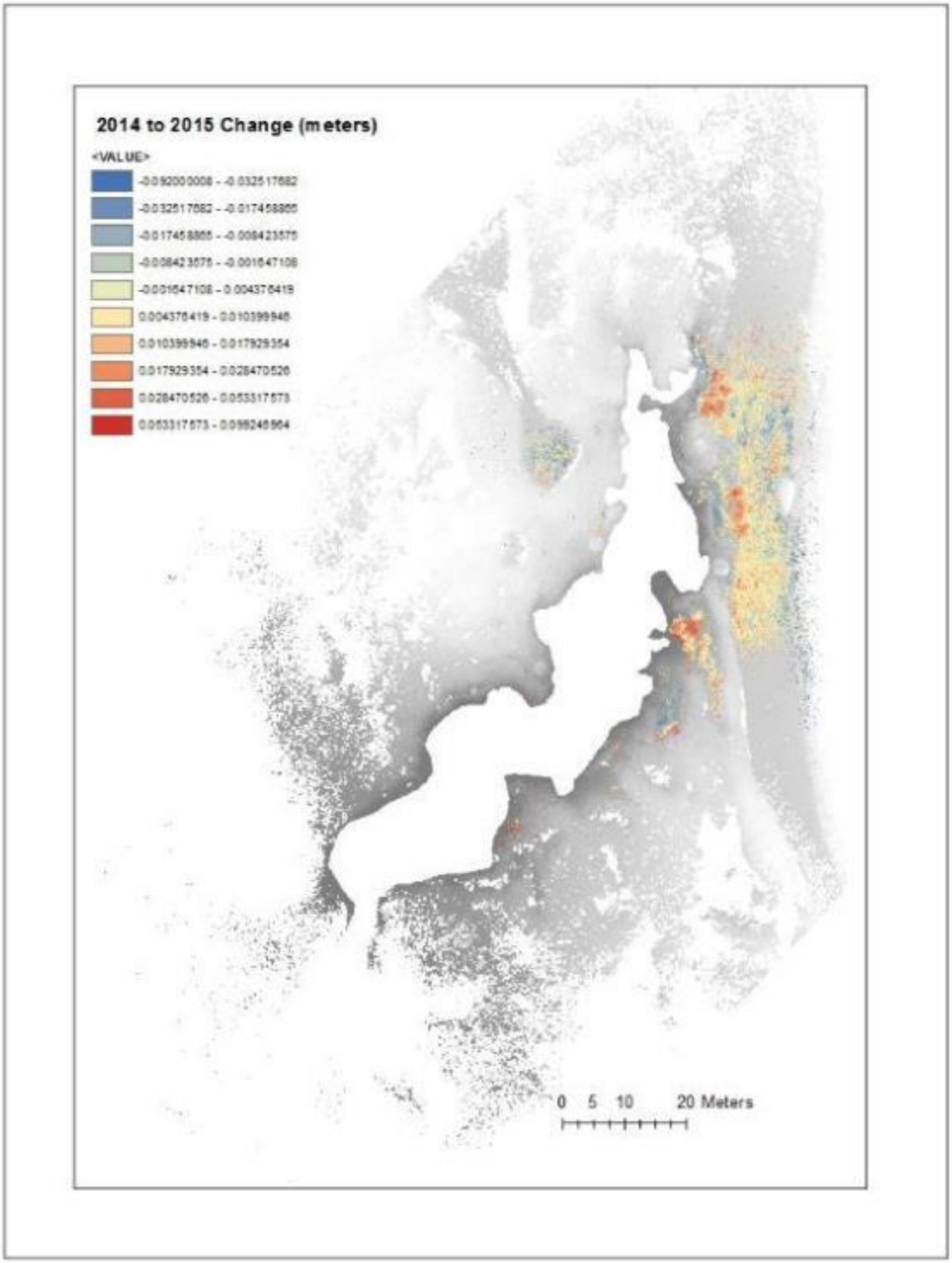


Figure 8: Elevation changes from 2014 to 2015. Areas of red indicate deposition and areas of blue indicate erosion. A higher level of deposition is seen in this year compared to the 2013 – 2014 time period. Yellow to light blue area's indicate no change in the elevation values.

Overall (2013 – 2015), erosion was the most prevalent across the 12m depression. Erosion was prominent immediately adjacent to the channel, bordering the 100m section of mudflat. Areas of large quantities of deposition follow these erosion areas. Only 4% of the values were above 5cm of deposition. Approximately 54% of the values were depositional, indicating that more deposition was happening on the bare earth areas of the high marsh platform than erosion. 38% of the values were no change, and only 5% of the values returned were erosional. The converted volumetric sediment yield showed -0.06 m^3 of erosion, 0.609 m^3 of deposition, and 0.047 m^3 of no change (Figure 9).

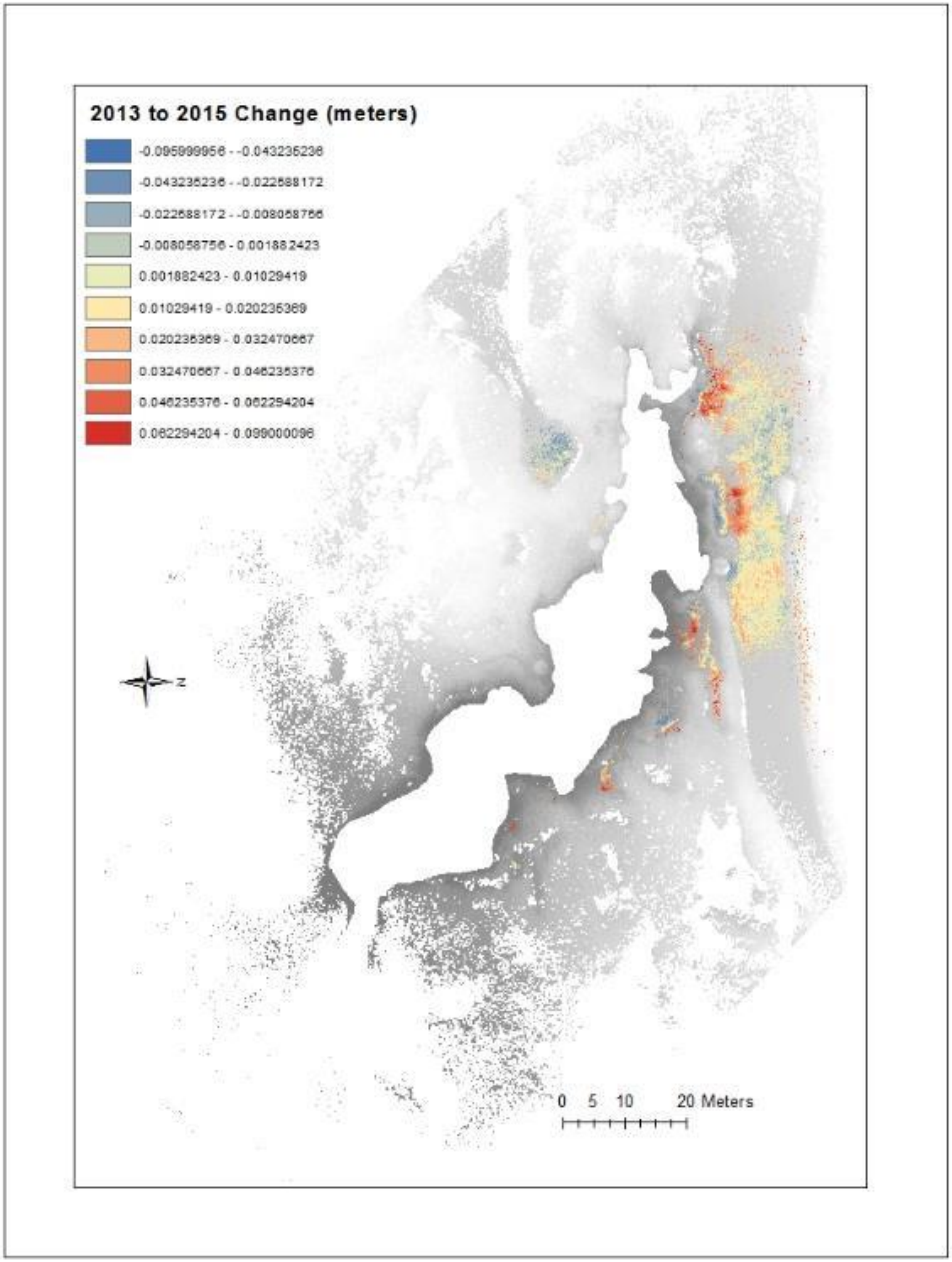


Figure 9: Elevation change over a two year period. Darker red indicates deposition and blue indicates erosion.

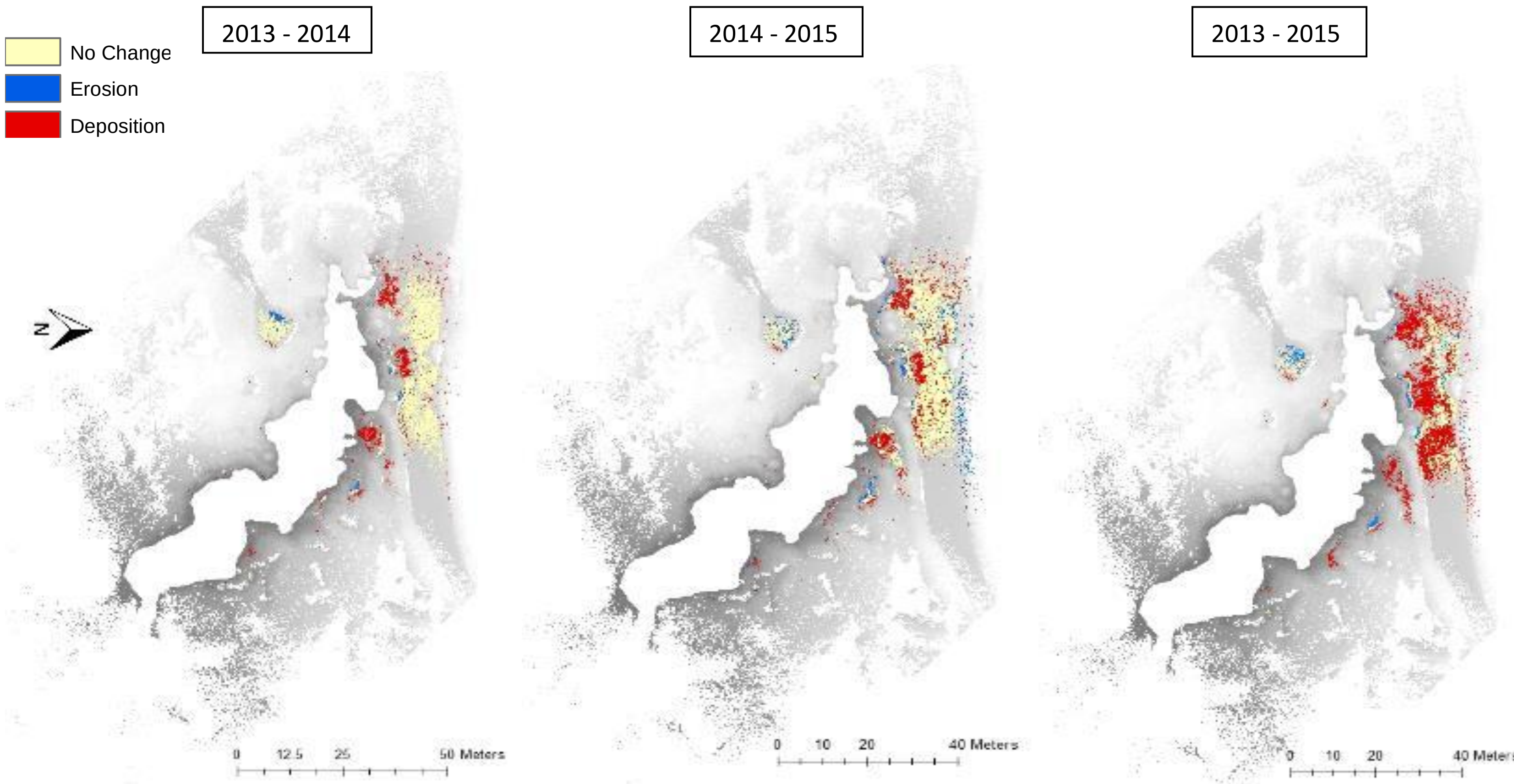


Figure 10: Marsh platform areas of deposition, erosion, and no change.

Years	Erosion m^3 (%)	Deposition m^3	No Change m^3
2013 - 2014	-0.026823 (2.8%)	0.126613 (43%)	0.105473 (53%)
2014 - 2015	-0.105983 (10%)	0.20667 (21%)	0.048607 (69%)
2013 - 2015	-0.06 (5%)	0.609914 (54%)	0.047189 (38%)

Table 2: Net sediment yield for the marsh platform and the percentage of that change over the study area. Deposition was greater for all three time periods. Values of no change were also prominent. Note the hillshades from the original study year in the DoD are shown behind the DoD for context.

Marsh Tidal Channel

A high degree of topographic change is present over the two-year record within the tidal channel and ranges from 10cm of erosion to 40cm of deposition within the channel. The percentage of area that exhibited erosion is greatest at 60%, with 22% of the entire data set showing >5cm of erosion and >5cm of deposition. Approximately 25% of the area exhibits deposition. Areas with the highest elevation change are located near the mouth of the tidal channel and areas adjacent to meander bends. The thalweg exhibits erosion and towards the mouth of the channel as well. Areas of deposition are found on banks opposite those that exhibit erosion, and deposition is also found closer to the channel bank edges. A smaller tributary has formed adjacent to the flow of water, and where these are prevalent, the heaviest deposition rates take place, possibly due to the increased flux of sediment to this area. Evidence of headward erosion is also present, notably by the sheet flow of the smaller tributary into the marsh. No change along the tidal channel accounts for 14% of area along the channel from 2013 to 2014. Converting the tidal channel DoD elevation values to volumetric units show a net erosion of -29.57 m^3 and a net deposition of 11.41 m^3 (Figure 11).

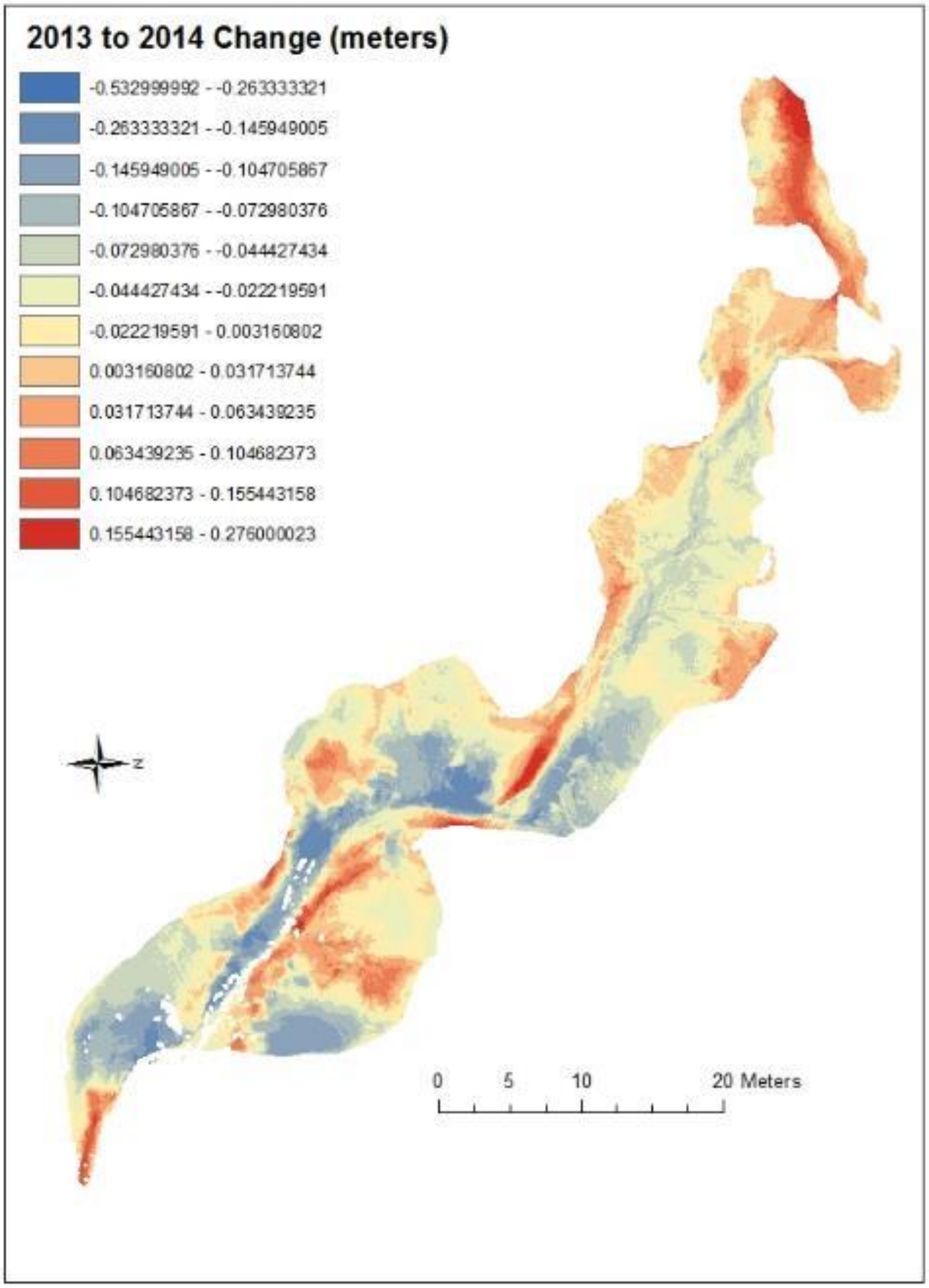


Figure 11: Elevation change within the channel from 2013 – 2014

Erosion is present further along a much larger extent of channel in 2014 -2015 than it did in 2013-2014, and it is concentrated in the lower portion of the channel. Large quantities of deposition (up to 42cm) are identified at the very mouth of the channel. However, only 22% of the entire dataset showed >5cm of change with either deposition or erosion and 37% of the elevation values exhibited deposition. Erosion, although showing less extreme values than the depositional changes seen, is the most prevalent change seen during this time period with 39% of the elevation changes exhibiting erosional values.

A significant change seen during this time period is that the small meander in the channel becomes straighter, with higher rates of deposition occurring on either side of the bend. The net volume of sediment erosion is -12.4 m^3 occurred, and 15.01 m^3 of deposition. The depositional pattern followed the erosional pattern from the previous year, with most sediment staying the same adjacent to the areas of deposition.

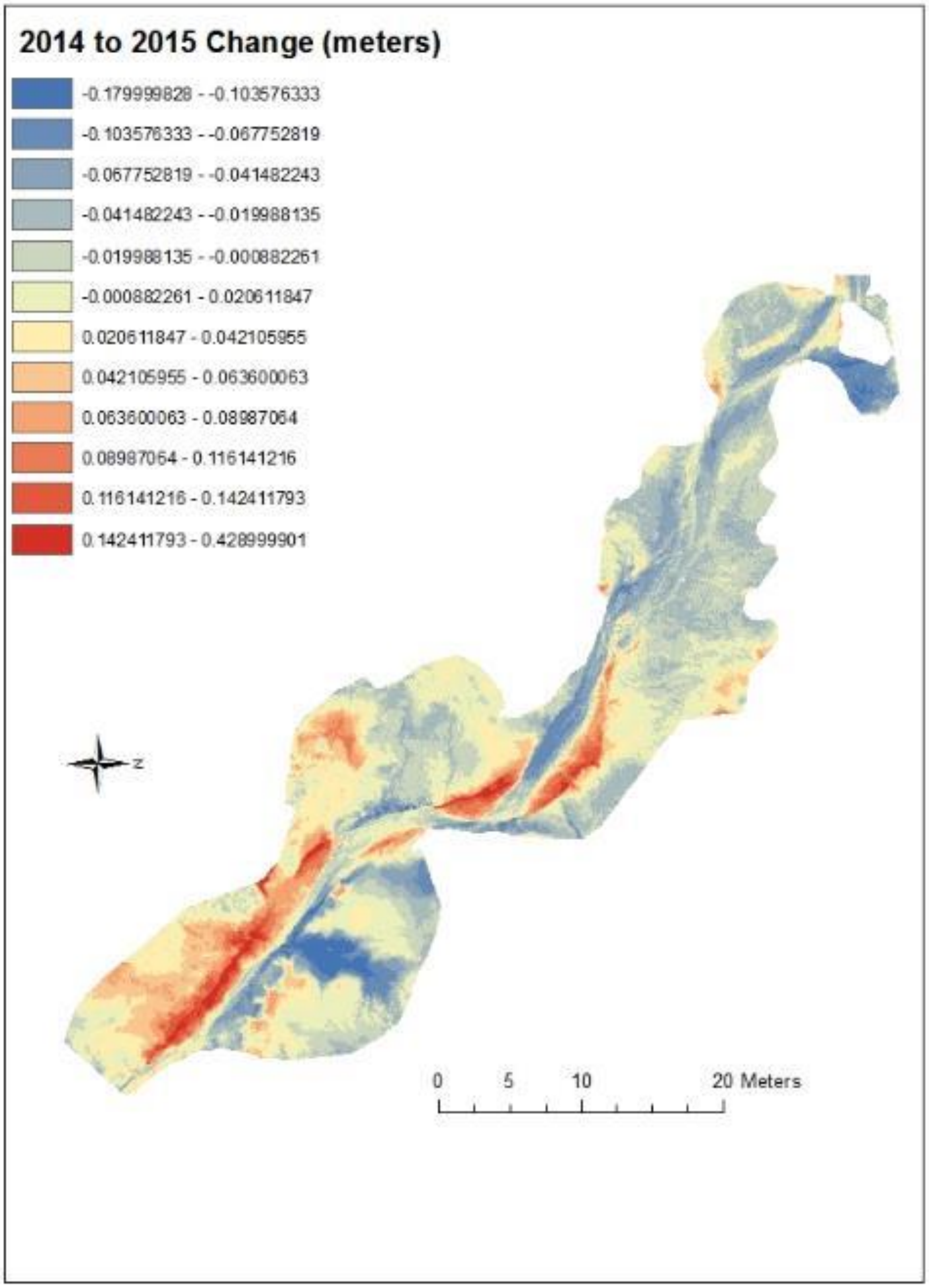


Figure 12: Elevation change within the channel from 2014 – 2015.

From 2013 to 2015, the total net volumetric sediment erosion is -27.85 m^3 and deposition of 8.60 m^3 (Figure 13). Erosion is most prevalent overall during the data collection time period, with 62% of the returned elevation changes exhibiting erosion (Figure 14). Changes of up to 22cm are found on the outside of the two bends found in the channel (Figure 16: Section 5 and 7). The thalweg showed an overall trend in erosion as well. Headward migration of the channel into the high marsh shows areas of erosional elevational changes as the tidal flux eroded into the upper extent of the tidal channel. Channel deposition is greatest towards the mouth of the channel and on the inside of the channel bends. Twenty one percent of the elevation changes are depositional and 38% of all of the elevation changes were ≥ 5cm or more for either deposition or erosion, with only 15% of the changes staying the same during the two years. The significance of the data is revealed in Figure 14 and show's how there is no clear pattern to the erosional and depositional changes throughout the study period.

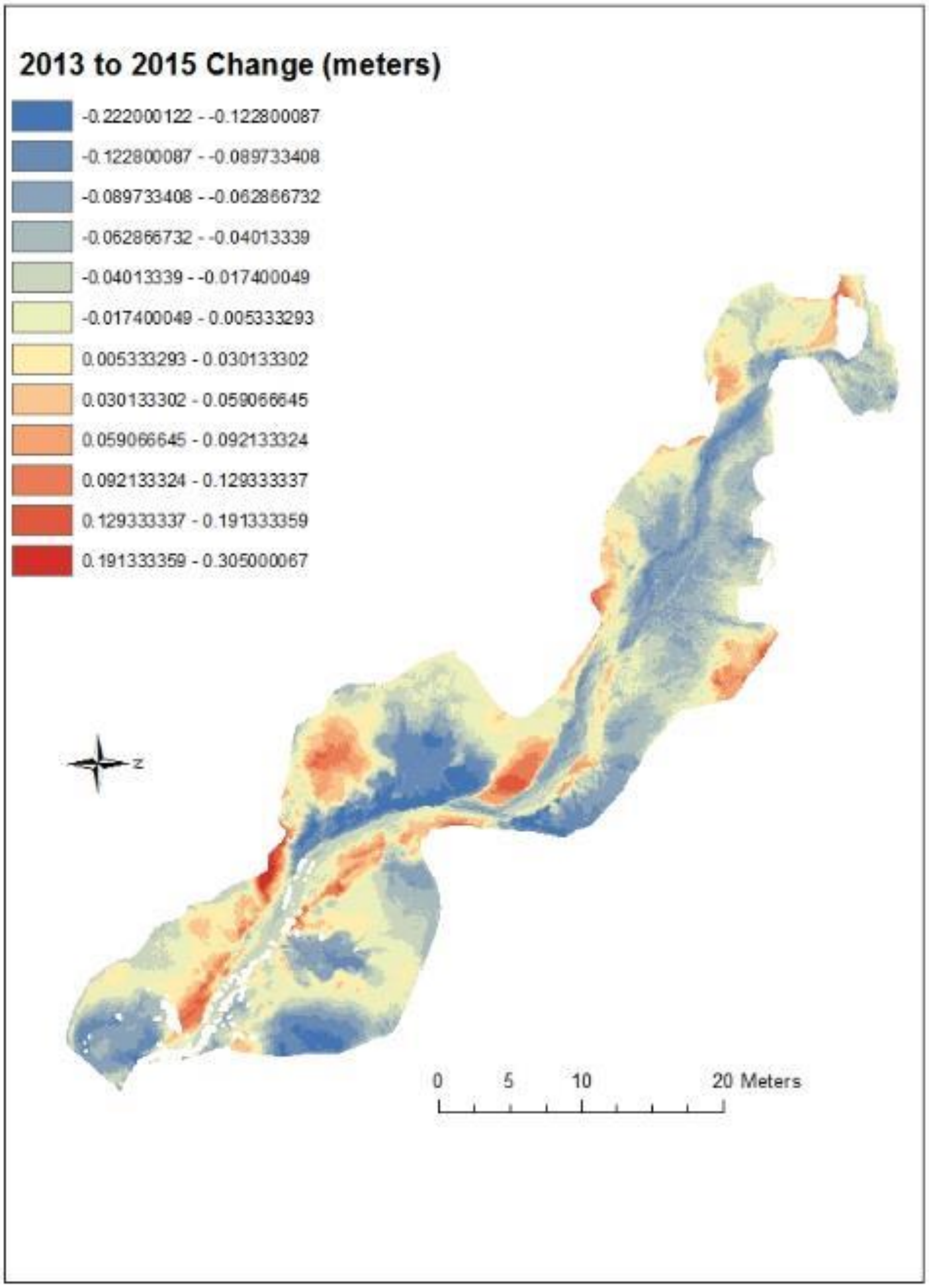


Figure 13: Elevation changes within the channel from 2013 – 2015.

The cross sectional analysis reveals the lower 34% of the channel showed an increase in depth and width over the study period (Figure 16 and Table 4). The elevational change in the lower section of the channel corresponds to the increase in width and depth. The thalweg moved laterally on a yearly basis. At the mouth of the channel, this thalweg moved laterally to the right during 2014 and then retreated back to the left 2m in 2015. Bank movement started occurring at cross-section 3 (Figure 16). The depth of the channel increases up to cross-section 4, then started decreasing as the channel started exhibiting meander bends. The greatest amount of change was seen in the cross-sections in proximity to meander bends (Figure 17: cross-sections 4 – 8). As the depth of the channel decreases through the meander, width increases. The thalweg moved laterally almost 3m to the left at the start of the meander in 2015 (cross-section 4). However, the magnitude of change in the channel width is not statistically significant during 2013 – 2014 and 2014 – 2015. Overall however, there is a statistically significant change in channel width due to small changes throughout both time periods. A 90% confidence interval was established that channel width was significant from 2013-2015 based off of a T-test. The start of a meander that is seen in 2013 and 2014 is not seen in 2015 because of this shift in the channel depth and corresponds to the high deposition rates seen from 2014 to 2015 (Table 2).

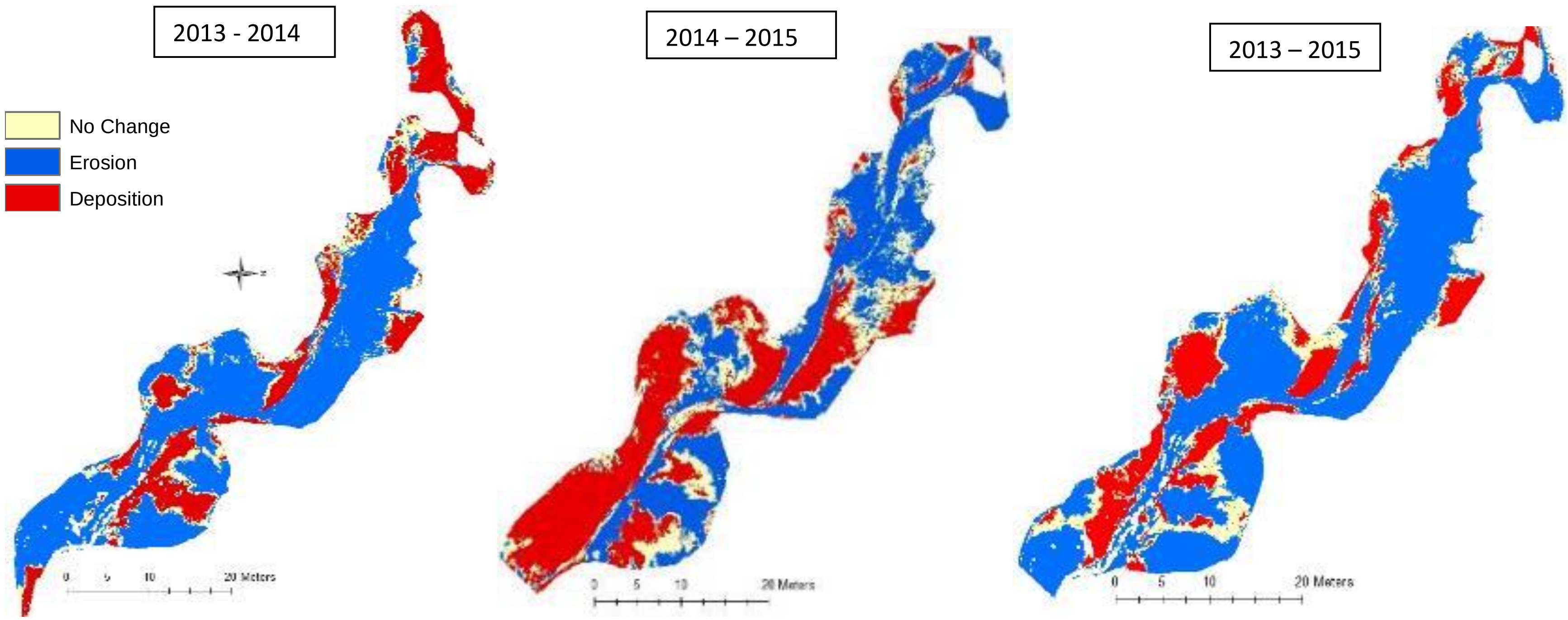


Figure 14: Marsh channel areas of deposition, erosion, and no change.

Years	Erosion m^3	Deposition m^3	No Change m^3
2013 - 2014	-29.5723 (60%)	11.417681 (25%)	122.929597 (14%)
2014 - 2015	-12.4043 (39%)	15.018234 (47%)	190.3159955 (14%)
2013 - 2015	-27.8506 (62%)	8.606886 (21%)	126.722797 (15%)

Table 2: Net sediment yield for the tidal channel. Erosion was greater for majority of the analysis, however in 2014 – 2015, deposition was greater. Note the hillshade from the original year of data as reference for the DoD. The total percentage of change is noted in parenthesis.

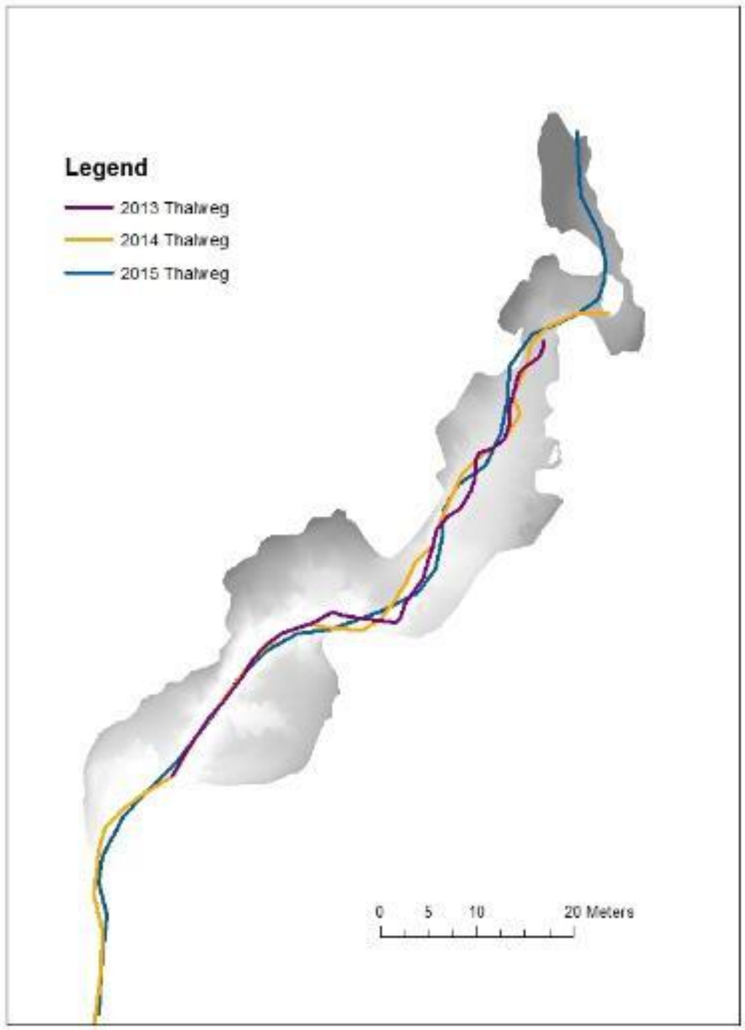


Figure 15: Migration of the Thalweg throughout the study period. The channel background is for reference.

Bank steepness continues to increase throughout the meander until cross-section 8. Erosion is seen on the cut banks while deposition is found on the point banks. As the cut banks get steeper going further up the meander bend, the inner channel becomes narrower and the point bank (the bank opposite the slump block) accumulates more sediment. The increased deposition that during 2014 (Table 2) is accounted for in the deposition found on the point banks in the meander bend. The width of the channel increases upstream as well based on width to depth ratios from year to year.

The 2014 – 2015 time period yields the greatest amount of deposition (Figure 16). The elevation difference seen between 2014 cross-sections and the 2015 cross-sections follow the amount of deposition and erosion seen from the DoDs (Figures 11-13). Cross-sections 5 and 6 are areas within the channel that experience high elevation changes exhibiting deposition. The point bars in these sections continue to expand laterally on a yearly basis. In the bends of the channel, the patterns generally follow the changes saw by Gabet et al (1998). The incision in the center of the channel also changes width and depth on a yearly basis as well as the position of the incision within the confines of the channel. This incision increases in depth in the lower reaches of the channel from 2013 – 2015 but becomes obsolete in the upper reaches of the channel.

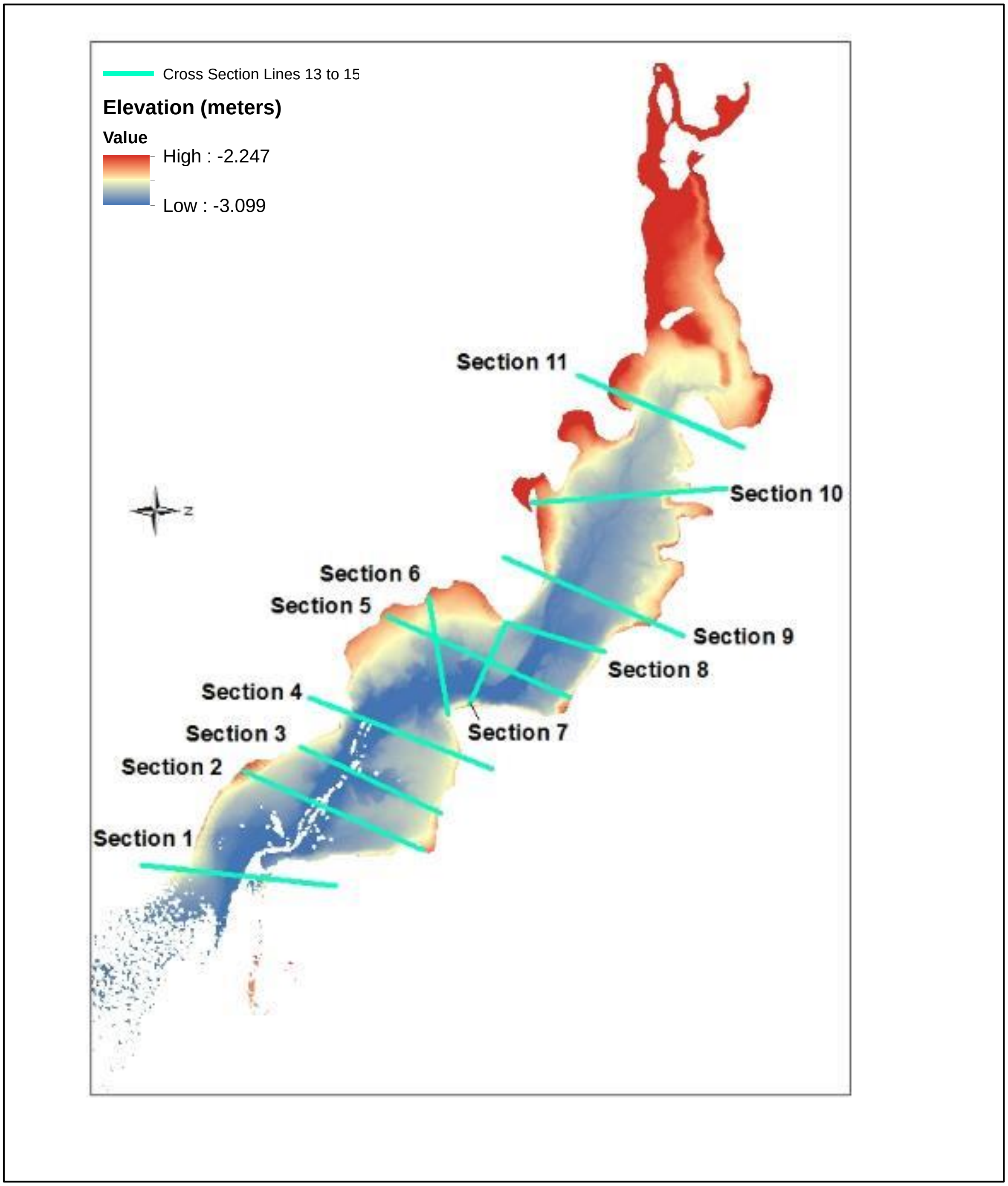
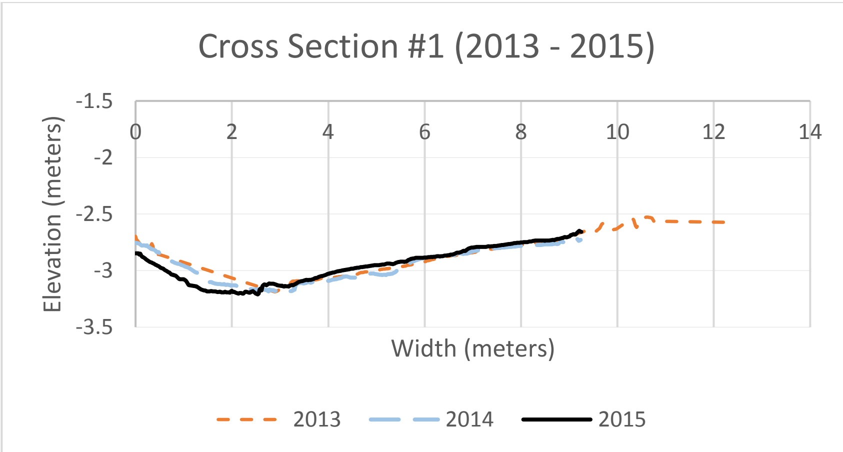
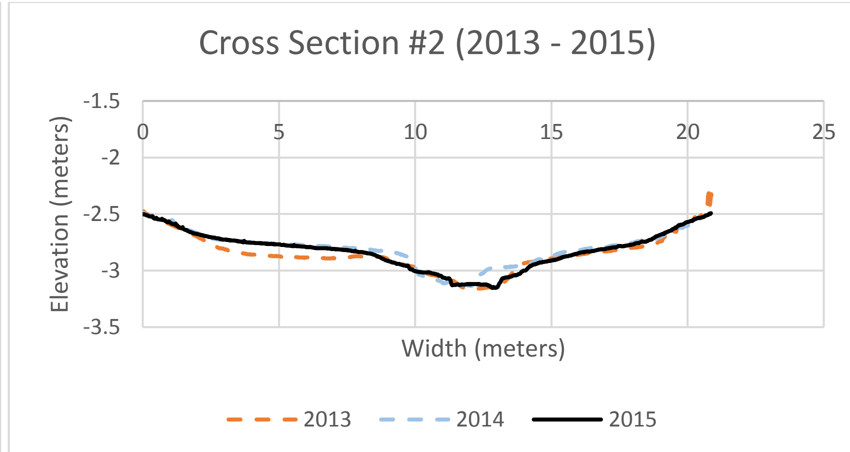


Figure 15: Channel cross section sites for the tidal channel. Cross sections were taken from east to west.


Cross Section #1 (2013 - 2015)
Elevation (meters)
-1.5
-2
-2.5
-3
-3.5
0
2
4
6
8
10
12
14
Width (meters)
2013
2014
2015


Cross Section #2 (2013 - 2015)
Elevation (meters)
-1.5
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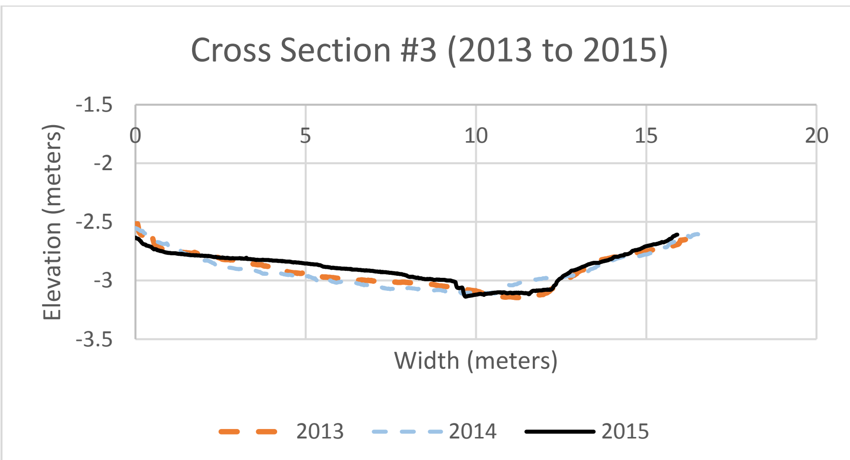
-2.5
-3
-3.5
0
5
10
15
20
25
Width (meters)
2013
2014
2015


Cross Section #3 (2013 to 2015)
Elevation (meters)
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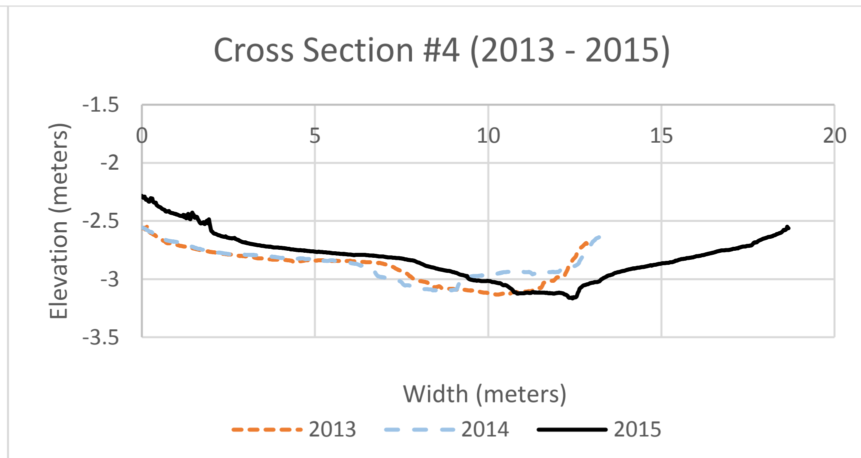
-2
-2.5
-3
-3.5
0
5
10
15
20
Width (meters)
2013
2014
2015


Cross Section #4 (2013 - 2015)
Elevation (meters)
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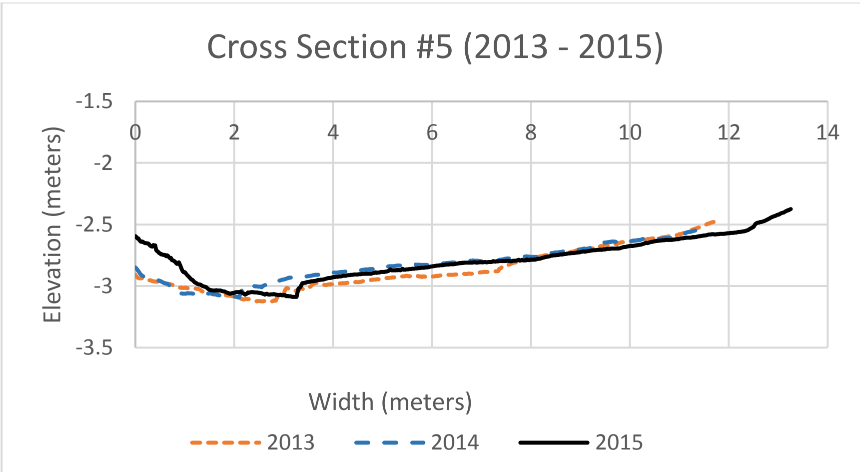
-2.5
-3
-3.5
0
5
10
15
20
Width (meters)
2013
2014
2015


Cross Section #5 (2013 - 2015)
Elevation (meters)
Width (meters)
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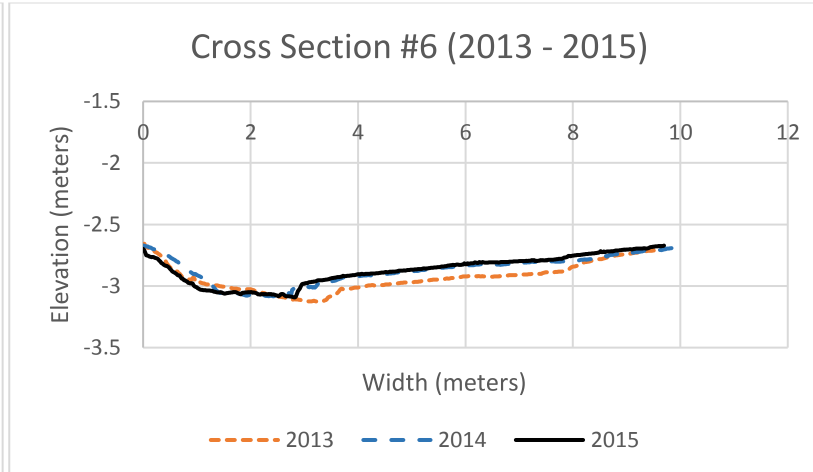
-2.5
-3
-3.5
0
2
4
6
8
10
12
14
2013
2014
2015


Cross Section #6 (2013 - 2015)
Elevation (meters)
Width (meters)
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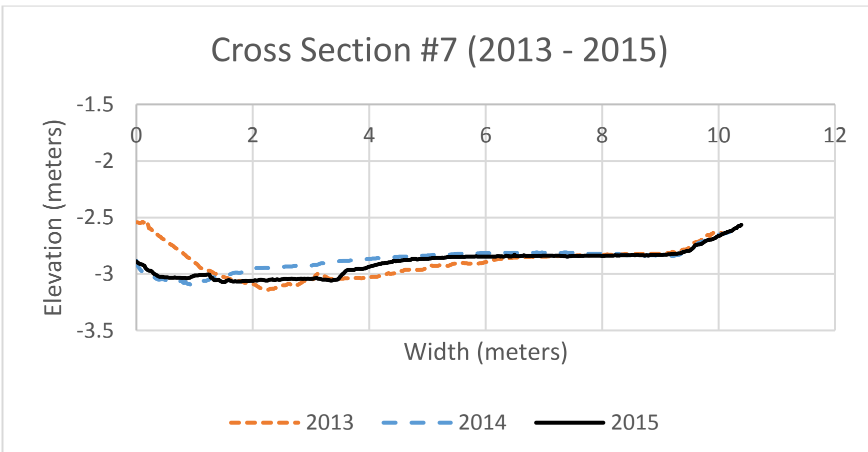
-2.5
-3
-3.5
0
2
4
6
8
10
12
2013
2014
2015


Cross Section #7 (2013 - 2015)
Elevation (meters)
Width (meters)
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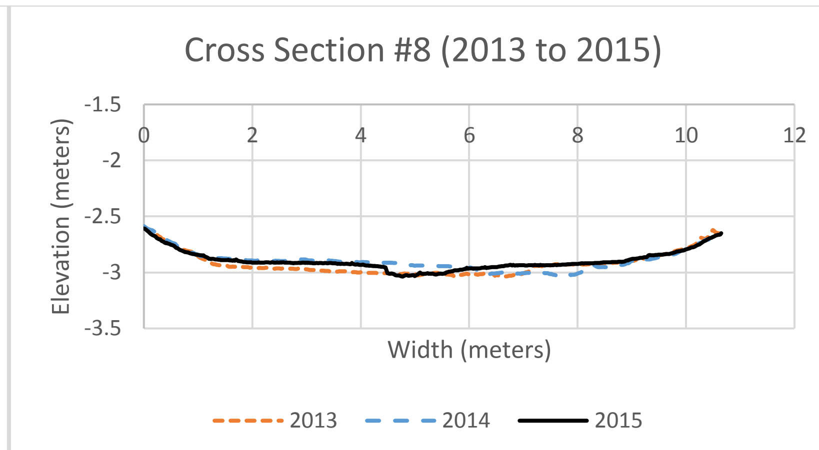
-2
-2.5
-3
-3.5
0
2
4
6
8
10
12
2013
2014
2015


Cross Section #8 (2013 to 2015)
Elevation (meters)
Width (meters)
-1.5
-2
-2.5
-3
-3.5
0
2
4
6
8
10
12
2013
2014
2015

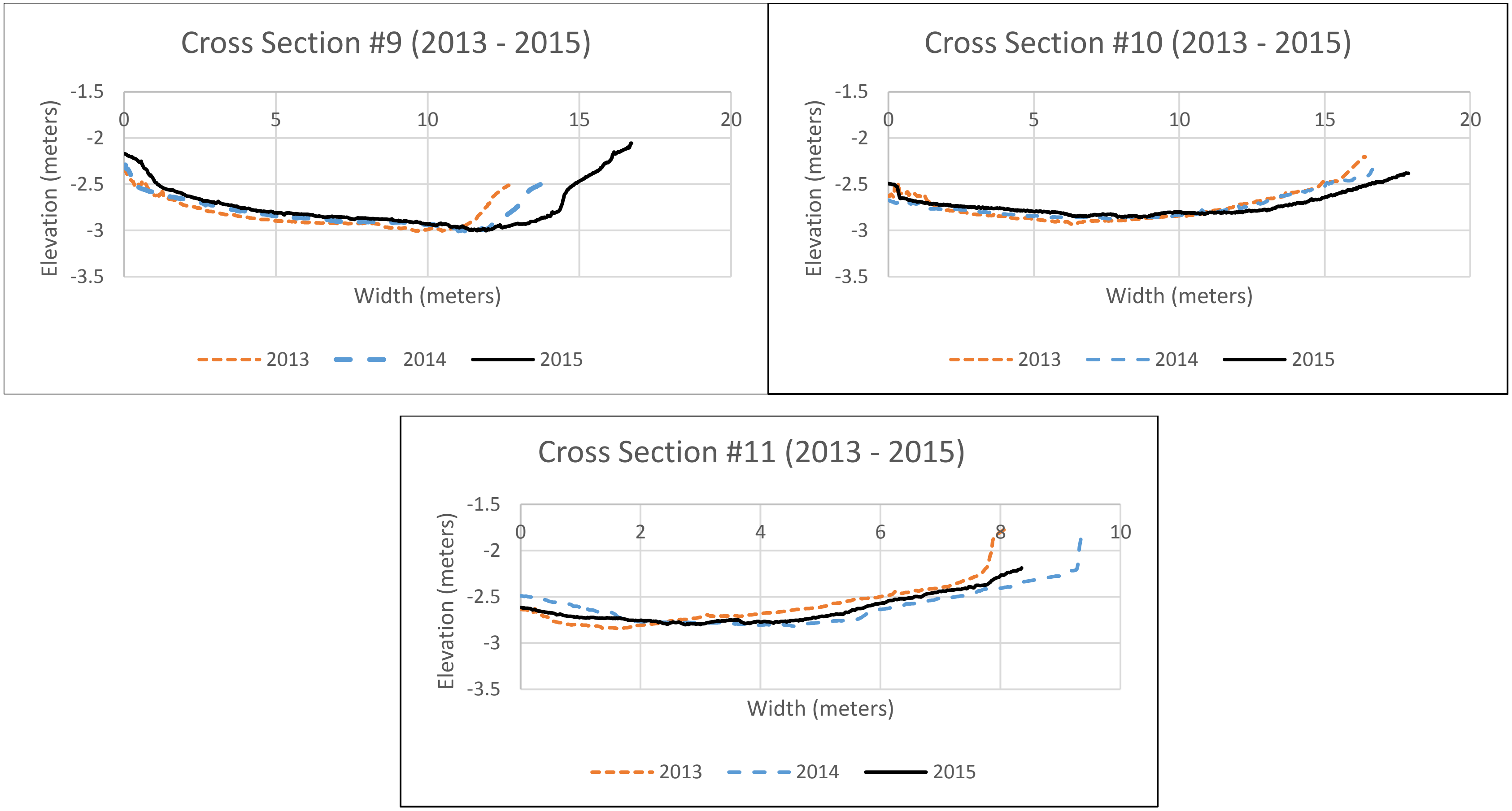


Figure 16: Channel cross sections for 2013, 2014, and 2015. Cross sections were taken from the left bank to the right bank.

Table 3: Width to depth ratio for each cross sectional analysis.

W/D ratio	*Site 1*	*Site 2*	*Site 3*	*Site 4*	*Site 5*	*Site 6*	*Site 7*	*Site 8*	*Site 9*	*Site 10*	*Site 11*
2013	2.9	6.27	4.96	4.08	3.78	3.07	3.14	3.4	4.2	5.31	5.34
2014	2.89	6.244	5.27	4.24	3.63	3.22	3.25	3.48	4.56	5.9	4.53
2015	2.88	6.312	5.08	5.88	4.28	3.14	3.38	3.49	5.55	6.24	2.98
Range	0.02	0.072	0.31	1.8	0.62	0.15	0.24	0.09	1.35	0.93	2.36

Discussion

Deposition across the marsh is not uniform, but is based on certain singular events that distribute sediment such as winter storms (Ma et al. 2014; Richard 1978). The high deposition rate seen in 2014 – 2015 may result from winter storms and extreme high tides. The presence of wrack and hummocking is indicative to this phenomenon (Smith et al 2012; Smith 2009; Lottig and Fox 2007). Anecdotal evidence seen from the field suggests that deposition of coarse material led to the elevation change seen adjacent to the tidal channel was likely caused by spring and neap tides. These temporal variations across the platform are evident in the fluctuations of sediment deposition seen throughout the study period, as well as the erosional and no change values associated with various sections of the marsh platform. An alternate way of analyzing the study area would be to use small sections of the point cloud to compare marsh changes more consistently across the surface on a cloud to cloud basis.

The spatial analysis of elevation changes across the marsh platform were limited to the non-vegetated sites. These areas included a large SWD mudflat to the north edge of the marsh (bordering the road), immediately adjacent to the tidal creek, and a 12m wide depression to the North West of the study area. This depression was likely caused from a lack of sediment supply that is the consequence of its remote distance from the tidal channel. As accretion rates diminish further from the tidal channel, bare earth patches will form (Kirwan 2008). The lack of sediment accretion will only change if vegetation can recolonize the substrate and trap suspended sediment from high tides (Kirwan and Megonigal 2011). Sediment deposition is dependent on the availability of sediment and the opportunity for this sediment to settle (Van Proosdij et al. 2006). In our analysis, there is no evidence that this depression is recovering over this short time period.

From field observations, various root mass and crab burrows were present on the platform. These root structures are left behind when above ground vegetation decays and the crab burrows are from various crab species within the marsh environment such as the Purple Marsh Crab (Sesarma Reticulatum). Some potential bias of the results could be the result of the scanning differencing these small mound elevations rather than true bare earth elevations (See Appendix C)

Volumetric changes indicate much higher rates of deposition across the bare earth sites. The greatest amount of deposition occurred in the period 2014 – 2015 with as much as 20cm of deposition, and 60cm occurred from 2013 – 2015 for an overall change. Depositional changes were seen mostly on the large SWD section to the north of the marsh, which anecdotal data suggests occurs mainly from over wash situations from flooding events. The net erosion rate ranged from 10cm in 2014 – 2015 to 2cm overall from 2013 – 2015. The net change in erosion was 6cm from 2013 – 2015. Temporally, the sediment change rates show a non-uniform rate of change that depends on various geomorphic factors.

Spring tides occurred close to the scanning dates as well, with tidal height showing >12ft in some cases. The increase in tidal height and flow velocity associated with the tides brings in more suspended sediment. Theoretically, the increased flow velocity that occurs further from the channel mouth transports sediment further onto the marsh platform and onto bare spots (Kirwan et al. 2008). The sediment transport to these area's increased during this particular time of the year, and therefore could produce an outcome of higher deposition on areas of bare earth comparative to other times of the year. A seasonal study would need to be done to conclude this hypothesis and to understand on a more temporal basis the effects of sediment transport rates during the winter.

The tidal channel has shown the highest amounts of erosion and deposition in this study, with as much as $-29.5m^3$ of net erosion and $15m^3$ of deposition. The volume of sediment is higher than the marsh platform because of the source of sediment supply. The tidal channel obtains its source of sediment supply directly from the Herring River, while the platform receives its sediment supply from the tidal channel and storm events (Portnoy et al. 2003). The spatial variation of sediment along the tidal channel is initially dependent on the decreased suspended sediment concentrations during the incoming high tide, meaning that majority of the sediment deposition occurs during the high tide. Larger particles carried in by the high tide are not re-suspended by the falling tide, so large proportions of the coarsest sediment load are deposited on the tidal creek banks (Christiansen et al.2000). Smaller particles are transported onto the marsh interior by the high tide. As water flows out of the channel during the falling tide, there is a divergence of the flow as the wetted surface of the marsh gradually increases (Christiansen et al. 2000). The divergence of the flow is caused by the increased flow velocity of the falling tide and the seaward slope. As the high tide flows in through the channel, flow velocity is slower because the slope gradient is uphill rather than downhill (Christiansen et al. 2000). Although the sediment type in this study was not controlled, it is a variable that could potentially account for higher rates of deposition seen within the tidal channel.

Ice is known to be a source of high amounts of deposition (Ma et al. 2014), but due to the lack of short term data, it is unclear how much deposition is actually deposited from this phenomenon. The temporal variations in sediment deposition are indicative of multiple geomorphic phenomenon occurring. Some possible explanations include wrack and hummocking, which is typically brought in by flooding events and storm surges (Lottig and Fox 2007). Erosional rates also vary temporally through the study period in that 2014 -2015 saw an increase in headward erosion on the tidal channel. Headward expansion is normal in the sense that the tidal channel is cutting through elevational gradients as it reaches the high marsh section of the marsh. The erosional pattern seen overall could be indicative of this phenonmenon.

Although a clear pattern was not evident from the channel cross-sections, the geometry of the channel followed past studies of tidal channel morphology with respect to the slumping of the creek banks (Gabet 1998). The meandering that is evident in cross-sections 4-7 (Figure 15) creates areas of erosion on the outside of the bend and deposition adjacent to these bends. Flow velocities through the channel are stronger towards the bottom of the channel (Christiansen et al. 2000), therefore the bottom of the creek banks erode faster than the top substrate. Different erosion rates of the upper and lower banks form undercuts which then fall off into the channel. The slump block retards flow up the channel and sediment builds up on the opposite bank (point bar), creating areas of high deposition (cross-sections 2-4). Erosion typically happens on the slump bank because flow velocity increases in the narrower channel and erodes the slump block. Indications of this phenomenon happening is the migration of the thalweg seen throughout the cross sectional analysis. Cross-sections 3,4, 6, and 7 all exhibit slumping. The cross-sections associated with these sections show a narrower channel and increased incising of the channel bank opposite the slump block.

As flow velocity increases as the channel width decreases (shown by the migration of the thalweg in this study), the slump block becomes a bench as sediment laterally erodes. The banks then become steep, and undercutting of the bank occurs again. This creates a stable geomorphic system that follows the same patterns on a temporal basis. The tidal channel is a first order creek, which are shown to increase in length in areas of low vegetation (Wallace et al. 2005). The increased length comes from head ward growth of the channel into the high marsh. Incision of the channel into areas of low vegetation are indicative of the erosion seen in the upper reaches of the channel. Channel width increases as headward growth takes place as well, showing that as erosion is more prevalent in the upper extent of the channel and temporally as well, the channel is not only getting deeper, but wider as well.

Conclusion

High resolution topographic data acquisition using TLS across a high marsh platform and tidal channel are employed to capture erosional and depositional changes associated with sites affected by SWD. Spatially, the changes seen across the marsh platform are limited to SWD sites. Three years of point cloud data and analysis from high-resolution DEM show depressions adjacent to the tidal channel experience the greatest amount of erosion on the platform. A large section of SWD to the north experiences the greatest amount of deposition, anecdotal evidence suggests that over wash from flooding events have contributed to the deposition rates seen there.

The tidal channel has the highest amounts of erosion and deposition for the two-year period across the study area. Spatially, the channel width significantly changed from 2013 to 2015. From 2013 to 2014, erosion is prevalent across majority of the tidal channel temporally. However, from 2014 to 2015 deposition is greatest and was concentrated towards the mouth of the river. I hypothesize the high rate of deposition seen during this time period is from ice migrating up the channel as indicated from scouring marks found within the channel. Ice flow could have potentially blocked incoming tidal flows from traveling further upstream, limiting the sediment supply. A slight change in the meander is prevalent from 2014 to 2015 as deposition occurs on both sides of the channel, essentially straightening out the meander and is indicative of ice deposits.

Further research could consist of conducting flooding hydrological analyses on a yearly basis to see if the flooding across the marsh corresponds to the higher deposition rates seen in the dieback sections. Our efforts to provide the volumetric estimates and elevational differences on a yearly basis will hopefully help the Cape Cod National Seashore in determining the areas that are more prone to erosion and how fast this erosion takes place. This in turn can lead to mitigation efforts to increase the sediment supply from the Herring River dike.

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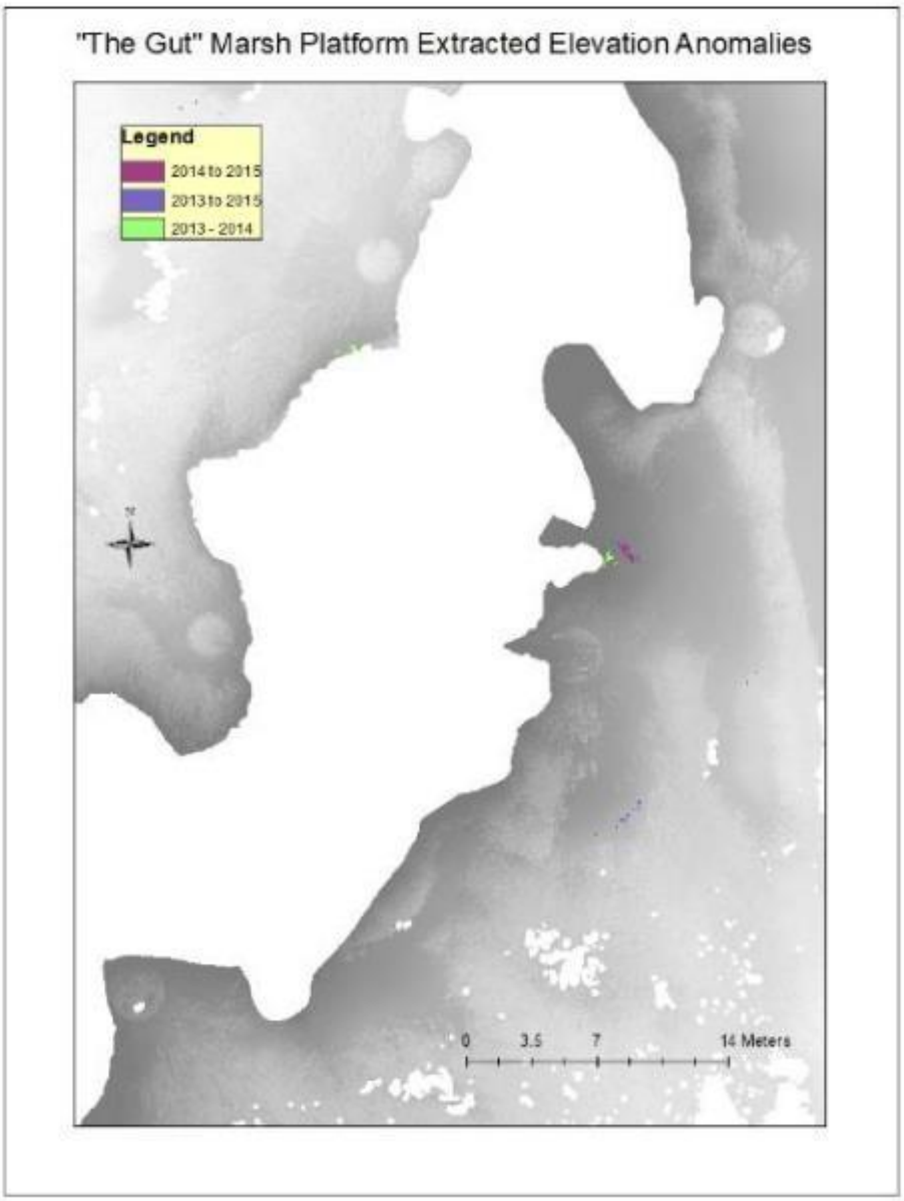
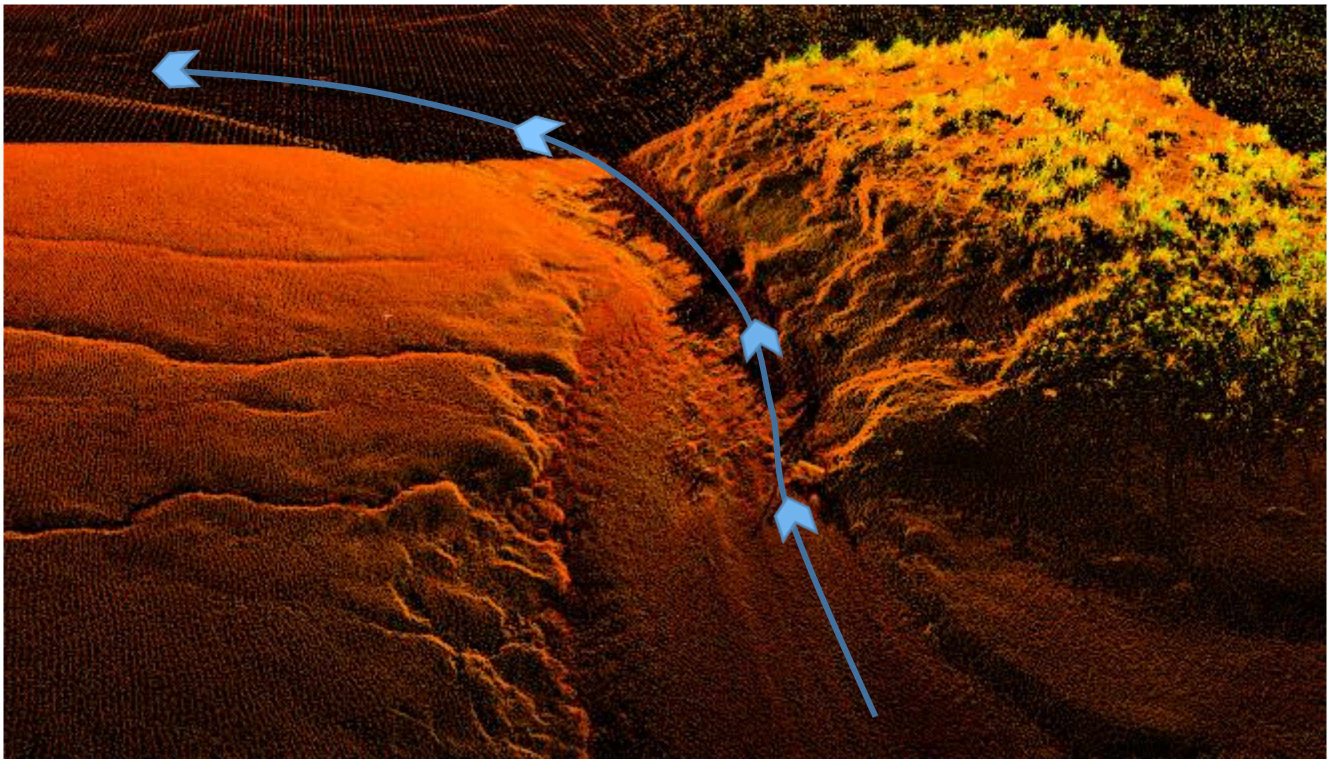
Appendix A

Elevation anomalies for the DoD. Elevations that exhibited >10cm of difference were extracted from the data analysis in order to not skew the data. These data points were analyzed within the point cloud before extraction to determine the reasons why they exhibited so much elevation difference. These points were in areas of shadowing from vegetation and far enough away from the scanner to exhibit less accuracy then points closer to the scanner.



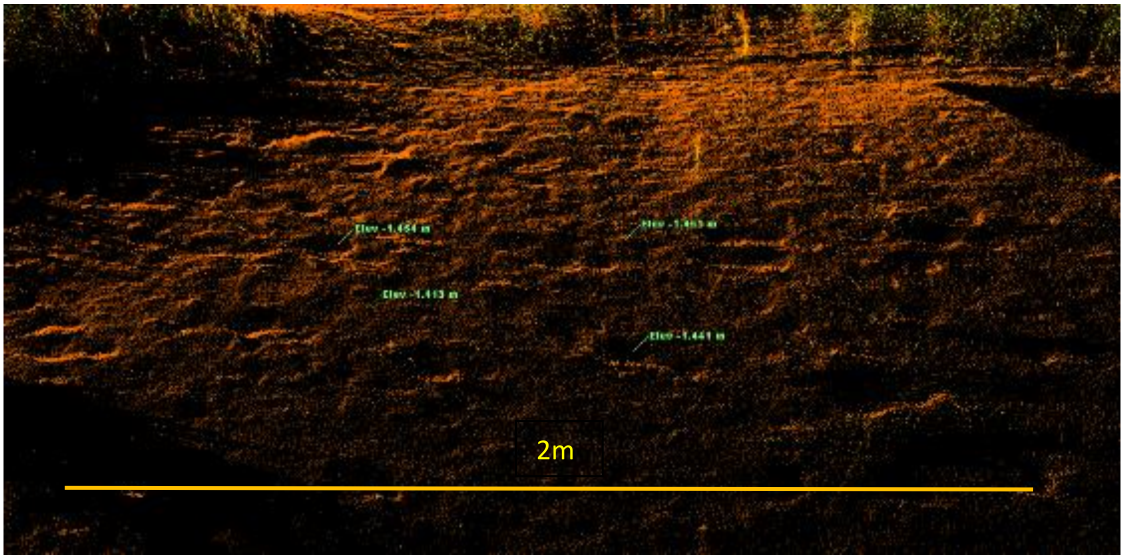
Appendix B

2014 example of how flow velocity effects bank slumping. The incoming flow erodes the bottom of the channel and the top of the bank typically falls into the channel, decreasing channel width and increasing the flow velocity.

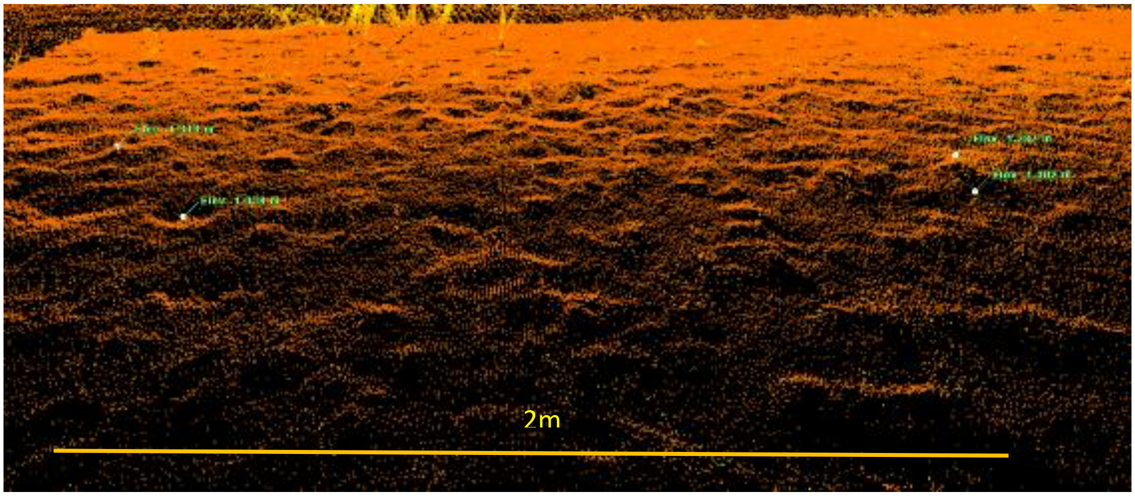


Appendix C

The difference between 2013 and 2014 sections of Sudden Wetland Dieback indicating crab burrows and how elevation changes can change dramatically due to these areas of disturbance**.**



2013



2014