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Linking Water Quality and Beach Morphodynamics in a Heavily Impacted Tidal Creek in Myrtle Beach, South Carolina

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By

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Dedication

The ability for me to reach my goals and dreams would not be possible without the support of my mother, Robin Hoffnagle, for whom this is dedicated to. I would not be who I am, where I am, or have the ability to go where I need to go without her love and support. I will also extend this dedication to my father, Timothy Hoffnagle. His love for the outdoors has greatly influenced my love for nature and the sciences and his memory pushes me to live life every day.

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Abstract

The morphological changes of small tidal creeks, driven by coastal processes, can pose risks to infrastructure and engineered coastlines and often rely on dredging to maintain them. These changes along the beachface can negatively affect the health of associated estuaries where open exchange between the ocean and creek basins is vital. This study used Real Time Kinematic-Differential Global Positioning System equipment to survey a small tidal creek in Myrtle Beach, South Carolina that often experiences migration to the south and requires dredging to maintain an open exchange between the ocean and the estuary. In order to understand the relationships between the geomorphology of the beachface and the water quality within the creek basin, various geomorphic features were extracted from topographic surfaces using ArcGIS. Our results revealed that net sediment deposition had a strong correlation to changes in the Singleton Swash Tidal Range/Ocean Tidal Range ratio. These results suggest a reduction in tidal currents, caused by the restricted tidal range, may lead to a more stratified water column, having implications for ecosystem health in the swash basin. Dredging, which reduced the elevation in the creek channel, was immediately followed by an increase in the SSTR/OTR ratio; re-establishing open exchange with the ocean. While a permanent engineered solution is planned for Singleton Swash, this study provides insight into the dynamics of Singleton Swash in its natural state.

Keywords: *tidal creek morphology, ArcGIS, water quality, coastal management*

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%	Percent
ΔS	Change in Salinity
ESRI	Environmental Systems Research Institute
D8	Eight direction flow model
DO	Dissolved Oxygen
e.g.	For example
GIS	Geographic Information System
m	meters
$\pm m$	Discrete lag
$month^{-1}$	per month
N	Number of discrete samples
N/A	Not Applicable
NAD83	North American Datum of 1983
NAVD88	North American Vertical Datum of 1988
OTR	Ocean Tidal Range
P_e	Terminus of creek channel
P_t	Transition point
ppt	parts per thousand
R	Correlation function

RTK-DGPS	Real Time Kinematic Differential Global Positioning System
S	Sinuosity index
S_o	Straight line distance
S_t	Total distance of creek channel
SSTR	Singleton Swash Tidal Range
SSTR/OTR	Singleton Swash Tidal Range/Ocean Tidal Range ratio

Introduction

Tidal creeks are important transition zones in the coastal environment, providing essential ecosystem services characterized by diverse hydrological and watershed processes (Levin et al., 2001; Lichter, Zviely, and Klein, 2010; Mallin and Lewitus, 2004). The effectiveness of tidal creek functionality is limited by their ability to facilitate the transport of material, nutrients and water from the terrestrial drainage basin to the coastal ocean via tidal flushing (Levin et al., 2001; Sanger et al., 1999; Mallin et al., 2004; Morris, Davidson, and Huntley, 2000). Tidal creek mouths, crossing the beachface, are subject to morphologic change resulting from a variety of coastal processes (Barnhardt, 2009; Bertin et al., 2005; Tanski, 2012).

Coastal processes at work could include tidal currents, littoral drift, direction and magnitude of wave energy, intermittent weather events, and the characterization of the local sediment supply (Barnhardt, 2009 Tanski, 2012). The characterization of the local sediment supply and its relationship with littoral drift play a large role in the morphological changes occurring around coastal tidal creeks because of the rapid shifts of sediment within the beach face area. The movement of sediment onto the beachface from off-shore sand bars or delivered in conjunction with littoral shift can change the beachface on a seasonal basis (Tanski, 2012). Winter beaches normally experience increased frequency of storms thus removing sediment from the beach zone and depositing sediments onto off-shore sandbars. In contrast, typical summer beaches, also referred to as fair weather beaches, tend to accumulate sediment as these sandbars shift landward and re-build the beachface increasing the width of the beach (Masselink and Pattiaratchi, 2001).

Shifting sands on the beach can divert or infill tidal creek mouths, thereby limiting water exchange between back barrier estuaries and the coastal ocean (Cleary and FitzGerald, 2003). In extreme cases, water quality in the estuary can be compromised due to diminished tidal flushing. Diminishing flushing capacity can result in a variety of management issues in the coastal environment (e.g., eutrophication, hypoxia, poorly functioning drainage of developed areas, and erosional threats).

Potential impact to infrastructure and water quality from dynamically unstable tidal creeks results in the need to implement management strategies that can benefit from applied data-driven sampling techniques. Larger-scaled tidal inlets in coastal environments, especially those in heavily populated areas, commonly rely on a variety of engineering strategies and dredging activities to maintain open navigational channels and facilitate proper drainage (Barnhardt, 2009; Bertin et al., 2005). Smaller tidal creeks crossing the beachface may seem less problematic as they may not be significant in a navigational capacity. These smaller creeks can, however, still result in substantial, though localized, environmental issues (Lerberg, Holland, and Sanger, 2000; Mallin et al., 2004). Similar to the larger inlet systems, one management strategy for small tidal creeks involves dredging the main channel, which creates a more direct path across the beach between the estuary and ocean (USACE, 2009). Though the spatial scale of such projects may seem insignificant, the frequency of dredging, due to the highly dynamic nature of the beachface, can result in costly efforts to maintain coastal water quality and protect infrastructure.

Due to the wide range of factors involved and complex interactions between them, it is inherently difficult to quantify the linkages between the effect of dynamic morphology on flow through a tidal creek and how that translates to the resulting water quality in the estuarine setting. Thus, the main objective of this study is to understand the connection between spatiotemporal changes in the morphology of a tidal creek mouth and the water quality in the associated estuary using experimental methods (e.g., ArcGIS and RTK-DGPS). Extensive work has examined the evolving morphology of coastal tidal inlets or water quality in estuaries, but studies designed specifically to characterize changing beach morphology and quantify resulting effects on estuaries have been limited (Bertin et al., 2005; Cleary and FitzGerald, 2003). Understanding the water quality response to the morphologic evolution of tidal creeks will contribute to understanding the most effective management approach for such systems in heavily populated areas. One such area is Long Bay, the cuspate shaped shoreline located in northeast South Carolina.

1.1. Study Area

Long Bay is characterized by a stretch of mainland-attached sandy beaches, roughly 100 kilometers long (Figure 1). The coastal area is heavily impacted by development and local drainage is extensively engineered. A series of 15 tidal creeks, locally known as swashes, provide important conduits for landscape drainage and typify the linkages between beachface morphodynamics and estuarine water quality. Such environments provide a unique setting to examine changes in tidal creek morphology and resulting estuarine water quality within a manageable study domain. This study focuses on Singleton Swash in Myrtle Beach, SC (Figure 1), where local residents frequently report changes in estuarine flushing that seem to occur in response to beachface morphodynamics. This region also experiences periodic hypoxia events and the role these swashes play in the formation of hypoxia events is unclear. The connection between the morphodynamics of the beachface and the influence on water quality could provide more insight to the collective understanding of coastal hypoxia in this region.

Singleton Swash is one of 15 small tidal creeks found along Long Bay and is situated in Myrtle Beach within the greater Grand Strand area. This coastline is classified as wave dominated and is affected by a microtidal range of approximately 1.5 meters on average (Barnhardt, 2009). Littoral drift in this area of Long Bay and in nearby coastal areas (e.g., North Carolina) generally flows to the south (Barnhardt, 2009; Cleary and FitzGerald, 2003). The Singleton Swash wetland area drains roughly a 6.8 square kilometer watershed that includes a popular golf and beach resort, hotels and condominiums (USACE, 2009). The main creek channel is approximately 2 kilometers long and the landward terminus of the creek channel includes a shallow brackish pond adjacent to a wet detention pond that delivers freshwater overflow (a function of precipitation) through a weir structure. The remaining creek channel cuts through the creek basin area until it reaches the ocean, becoming morphologically unstable as it crosses the dynamic beachface.

The region surrounding Singleton Swash is characterized by a sediment starved inner shelf, and seasonal wind direction changes, which contribute to the geomorphic evolution of the tidal creek mouth position through time. Periodically, Horry County will dredge the creek mouth to straighten the channel, thus reducing erosional risks to nearby beach property and enhancing the exchange between the estuary and ocean. Since 1999, the county has spent over $400,000 to manage this site (USACE, 2009). Horry County and the Army Corp of Engineers are currently working on their strategic plan for a more permanent, hard engineered solution for Singleton Swash. Therefore, this study serves as an ideal natural baseline. In 2014 (part of the study period), the creek channel was dredged between July 29th and August 4th.

Real Time Kinematic-Differential GPS (RTK-DGPS) surveys were conducted periodically in order to quantitatively assess specific features of the dynamic beach morphology. Water quality measurements including salinity, temperature, dissolved oxygen saturation and water level were measured at least biweekly throughout 2014. Examination of these parameters provides a basis to construct a conceptual model of beachface evolution through time and resulting water level and water quality impacts. Correlation analysis of various pairs of these parameters will allow for quantitative relationships to be determined between beach morphodynamics and resulting water level and water quality impacts. The quantitative analysis will help to refine the conceptual model and establish a baseline for the behavior of the coupled beach-estuarine water quality system. Additional data, collected in future studies, will either confirm or challenge the model proposed here. Finally, this work represents a robust methodology for characterizing a dynamic tidal creek system impacted by anthropogenic activities.

Methods

2.1 Geomorphology

Using elevation data gathered from accurate surveying techniques and water quality data, an analysis of topographic features of the tidal creek mouth can be studied in the context of changes in the environmental quality of the estuary. This analysis is achieved using a GIS database including several temporal and spatial layers characterizing the morphology and various morphological parameters (e.g., sinuosity, sediment volume, and channel elevation) to analyze the deflection of Singleton Swash.

2.1.1 Data acquisition

The morphology of the tidal creek mouth and surrounding beach area at Singleton Swash were surveyed periodically over the course of 2014. The surveys were completed at low tide over an area of approximately 68,425 m^2. The survey area was between the low tide line and the stable vegetated dune in the shore perpendicular direction and 500 m, spanning the creek channel, along shore (Figure 2). This area encompassed the range of creek mouth configurations that have been observed in historic aerial photographs dating back to 1953. The vegetation line at the base of sand dunes in front of the Sand Dunes Beach resort (where the swash channel crosses the beach) marks the location between the morphologically stable channel landward of the dune, and the highly variable channel crossing the beach.

Capturing spatial and temporal dynamics of the beach is challenging, though effectively accomplished with the use of Real Time Kinematic-Differential Global Positioning System (RTK-DGPS) measurements (Brasington et al., 2000, Lane, Westaway, and Hicks., 2003, Lane, 1997, Mitasova et al., 2005). Data were acquired with

Hypack surveying software and an Ashtech Z Extreme GPS receiver connected to a virtual network broadcasting Cellular Radio Module (CRM) corrections for 10 cm horizontal and 20 cm vertical accuracy and a sampling frequency of 10Hz. At least twenty transects parallel to the coastline were spaced 5-7 meters apart and were approximately 300-475 meters in length. Approximately 15-20 shore perpendicular lines, spaced approximately 25 meters apart, were also measured, completing a sufficiently dense grid to reveal sediment gains and losses within the study area (Figure 2). Surveys were completed in two stages. The first stage was completed on foot and required walking through the swash, while the second stage completed the larger area surrounding the creek channel using a motorized vehicle. Each survey took approximately 4 hours to complete.

This sampling design provided a high enough density of elevation points to create a five meter resolution grid throughout the dynamic swash mouth in ESRI ArcGIS v10.2. Original GPS data were converted from a text file to a GIS grid workspace using Dmagic and Fledermaus visualization software. All data were geo-referenced in the South Carolina State Plane coordinate system; horizontal datum NAD83, vertical datum NAVD88. The incorporation of these data into a GIS database provides a unique short-term geospatial data set for subsequent quantitative analysis of the tidal creek evolution.

2.1.2 Spatial and temporal analysis of tidal creek features

A variety of hydrology tools in GIS was used to objectively delineate the creek channel as seen in Figure 3. From the original topographic raster, the fill tool (hydrology toolbox) was used to fill in sinks or remove peaks resulting from erroneous rounding of elevations (Tarboton, Bras, and Rodriguez-Iturbe, 1991). The flow direction tool, based on the eight-direction (D8) flow model, was then used to create a raster showing the direction of flow out of each cell determined by the nearest steepest slope (Jenson and Domingue, 1988; Tarboton, 1997). This raster output served as the input for the flow accumulation tool which identified where accumulation occurred based on the summation of the flow directions into each downslope cell. This technique was used to isolate where concentrated flow occurred, thus identifying stream channels (Tarboton, Bras, and Rodriguez-Iturbe, 1991). The creek channels were then digitized to evaluate elevation and sinuosity for spatial and temporal analysis of the evolution of Singleton Swash. A sill feature was subjectively digitized (solid black line in topographic surfaces) and was defined as the dynamic feature on the south side of the creek channel.

Elevations were determined at the transition point (P_t) and at the highest elevation within the creek channel. The transition point was always found at the landward side of the surveys where the stable part of the channel meets the unstable part of the dynamic creek channel. The stationary transition point characterizes the elevation of the beachface creek channel before the creek channel enters the landward side of the creek basin. The maximum elevation characterizes how the elevation within the creek channels entirety changes over time. The length of the actual digitized creek channel (S_t) was measured as well as the straight line distance (S_o) between the start (P_t) and end (P_e) of each monthly channel position. Channel sinuosity was then calculated as S_t/S_o in order to reflect the changes in the meandering nature of the creek channel over time (Lichter, Zviely, and Kleing, 2010).

2.1.3 Spatial and temporal analysis of the sediment in the sampling period

Differences in elevation were determined via the raster calculator in GIS to observe erosional and depositional spatial trends. Pairing the digitized creek channel with the identification of erosional areas can provide important spatial awareness of sediment movement and resulting changes in position of the creek channel.

The net gain and loss of sediment through time was quantified using the GIS Cut Fill tool which calculated the volumetric change between two surfaces. In order to minimize the estimation errors due to area differences of each sample period, a centralized box with an area of 50,859 m^2, was used to compute the volumetric changes. This volumetric calculation was conducted to evaluate the amount of sediment eroding or deposition within the beachface.

2.2 Water quality

In order to understand the linkage between channel position and estuarine water quality, a suite of basic water column parameters was collected at Singleton Swash. These parameters included water level, temperature, salinity, and dissolved oxygen. This suite of parameters provides information to estimate water column stratification (an indicator of mixing) and fundamental ecosystem responses (dissolved oxygen saturation).

2.2.1 Data acquisition

Temperature, conductivity, salinity and dissolved oxygen were measured with an YSI 650MDS hand held meter connected to a 600XL Sonde deployed from a canoe. Between January-April 2014, data were collected bi-weekly during spring tide at slack high water. From May to September 2014, sampling occurred weekly to reveal water quality dynamics associated with fortnightly tidal cycles. Each sampling effort consisted of measurements collected along a single transect in both upstream and downstream directions during peak high tide, ensuring tidal stage consistency across all data. Along each transect, 8 stations were sampled at the bottom and surface in order to observe any indication of stratification in the water column (Figure 4).

A time series of continuous water level, salinity and temperature was also recorded with HOBO loggers every 15 minutes at one location within the creek channel throughout 2014 (Figure 4). A complimentary set of atmospheric pressure measurements (located on nearby Apache Pier), used to calibrate the total water level, were also collected every 15 minutes. A time-series of continuous ocean water level was retrieved from Springmaid Pier (NOAA gauging station 8661070; tidesandcurrents.noaa.gov).

2.2.2 Analysis of tidal range and basic water quality parameters

The tidal range in the swash channel was estimated from water level data in order to examine the potential effect morphological changes have on restricting tidal exchange. A reduction in tidal range impacts the magnitude of tidal currents, and therefore, can reduce the amount of mixing within the swash. A lack of mixing can result in degraded water quality (Roman et al., 1993). For both the ocean and Singleton Swash, tidal range was computed by taking the derivative of the time series of the water level, i.e., the slope of the water level. To reduce noise upon computation of the derivative, the data were first smoothed using an 8-point running average filter (equal to a 2 hour average in time) in both directions to ensure zero-phase shift in the smoothed data relative to the original data. A slope of zero indicates a maximum or minimum in the original water level data; thus identification of when the slope crosses zero indicates the maximum and minimum water levels. After the zero-crossings of the slope are identified, the values of consecutive min/max points were subtracted to calculate the tidal range. The tidal range was then averaged for periods bounded by the RTK-DGPS survey periods in order to facilitate correlation analysis between geomorphic parameters and water level change (see section 3.3). These averaging periods were long enough to remove any influence of the Spring/Neap cycle, revealing the variability in the tidal range resulting from non-astronomical forcings (e.g., beach elevation change). Singleton Swash Tidal Range/Ocean Tidal Range ratio (SSTR/OTR) was computed as the ratio between the tidal ranges measured in Singleton Swash relative to the NOAA open-ocean water level data to reveal the percentage of the ocean tidal range transmitted into Singleton Swash.

Analysis of water quality data included computing monthly averages of salinity differences and dissolved oxygen saturation (%) as proxies for stratification and ecosystem health, respectively. Salinity differences (ΔS) were used as a proxy for stratification rather than temperature because salinity is less influenced by time of day and seasonal trends than temperature, and due to the interfacial nature of this system salinity is likely a large driver of water density in the swash. For each sampling station the surface and bottom salinities were averaged on a monthly basis separately and change in salinity (ΔS) was then calculated by subtracting the bottom average salinities from the surface average salinities. Thus, a negative change in salinity (ΔS) would indicate a stable water column and the magnitude of change is an indicator of the magnitude of stratification. These monthly averages for each station were then averaged to characterize the salinity structure for the entire swash basin, removing the potential influence of station variability.

Dissolved oxygen (DO) is an indicator of ecosystem health but may decrease if there is substantial stratification in the water column (Livingston, 1996; Smith, Lefler, and Mackierman, 1992) because it suggests limited mixing. Increased or high levels of stratification can limit full water column mixing, thus restricting the water-air exchange. Bottom DO saturation values (%), averaged on a monthly basis for each station, were interpreted in the context of changes in salinity (ΔS) as a proxy for ecosystem health. These monthly averages for bottom DO saturation were averaged for all stations to characterize the DO for the entire swash basin.

2.3 Analysis of Morphology and Water Quality Indicators.

Cross correlation functions were used to quantify relationships between morphological changes of the creek mouth, tidal range (SSTR/OTR), stratification (ΔS), and water quality (DO). Correlation functions, rather than linear regression analysis, were used to resolve time lags in the connection of these different phenomena because they were not expected to occur synchronously. For example, it was expected that a reduction in tidal range could result in increased stratification several days later.

Linear interpolation was used to resample tidal range, elevation, sinuosity, ΔS, and DO saturation (%) on a seven day sampling rate in order to standardize the sampling interval. Note that mean values of the time series are removed prior to computing correlation functions. Correlation functions are normalized such that auto-covariances at zero lag are unity, more specifically:

$$R(m) = \frac{\sum_{n=1}^{N-|m|} x_{n+m} y_n}{[\sum_{n=1}^{N} x_n x_n \sum_{n=1}^{N} y_n y_n]^{1/2}} \qquad \text{for } m \geq 0$$

$$R(-m) = \frac{\sum_{n=1+|m|}^{N} x_{n+m} y_n}{[\sum_{n=1}^{N} x_n x_n \sum_{n=1}^{N} y_n y_n]^{1/2}} \qquad \text{for } m < 0 \qquad (1)$$

where N indicates the number of discrete samples, m is the discrete lag (described in Table 1), and the two variables being correlated are x and y. For example, x could be tidal range and y could be elevation. For these data, $N = 30$ and the sample rate is 7 days. Changes in tidal range were correlated with elevation to determine whether a change in the elevation of the tidal creek was related to a restricted tidal range. Subsequently, tidal range was correlated with ΔS to elucidate whether a reduction in tidal range results in increased stratification. Finally, ΔS is correlated with DO to evaluate whether increased stratification results in lower bottom DO.

By defining and analyzing the relationships between the various components of Singleton Swash, the relationship between changes in creek morphology and resulting impacts to the swash water quality can be tested. The process expected to occur can be described by this mechanism: 1) morphological changes result in restricted tidal ranges within the swash, 2) mixing becomes limited by lack of robust tidal flushing, and 3) stratification increases, further limiting mixing to the point of ecosystem degradation.

Results

A comparison of several high-resolution topographic surfaces and the correlation analysis between water quality and beach morphology parameters reveals the relationship between morphodynamics, creek channel response, and back barrier water characteristics. Webcam images provided by Coastal Carolina University were also used to further support the morphological changes observed in the topographic surfaces. While the intent of this study was to understand the natural migration of the creek channel mouth, the data also provide important insight regarding the immediate response to the occasional dredging the creek channel at Singleton Swash.

3.1 Creek channel morphology

The position and orientation of the channel and the overall morphology of the beachface showed considerable variation throughout seven months suggesting there is a seasonal dynamic to the beach-estuary system (Figures 5-10). As shown in Figure 5, in March 2014 (late winter), starting at the transition point located at the dune, the creek channel extended to the northeast but quickly curved sharply and deflected to the southwest. In general, the configuration of the creek channel crossing the beachface was less sinuous (1.525) in March than during subsequent months (e.g., June sinuosity was 1.761). By April, the creek channel sinuosity decreased (1.462) and the creek mouth deflected farther south compared to March. As the creek channel deflected to the south during March and April, the sill feature also extended to the south, tracking behind the creek channel (indicated by the subjective black solid line in Figures 5 and 6).

Throughout the summer months, the beachface morphology changed rapidly as the creek channel deflected towards the northeast and became more sinuous shown in

Figures 7 and 8. In June, the main creek channel no longer deflected to the southwest but deflected back north in a more S-shaped configuration with the creek mouth directly across the beach from the transition point. Along the southern portion of the mapped study area, there were small, hummocky patches of elevated sand deposits. The sill feature also shortened substantially by June. By early July, the creek channel near the transition point curved farther north, deflected sharply back to the south, and in general moved more landward compared to June (Figure 7 B). In the intertidal zone close to the ocean, the creek channel mouth became shallower. The sill feature, during this time (July 8^{th}), started to curve towards the sand dunes located in front of the beach resort property (Figure 8B). In late July, the creek reached its maximum sinuosity (2.113). The shoreward channel segment migrated farther landward, and began to erode the dune, shown in Figures 7C and 8C. The sill feature extended slightly in length and curved farther landward. There was also a small rock out-crop exposed during the July 29 survey (Figure 7C). This outcrop may function as a perturbation initiating the consistent diversion to the north when creek channel morphology begins to change on the upper beachface.

The creek channel was repositioned by dredging at the beginning of August, 2014. An elevation survey was conducted following the dredging and the channel was configured in a straight, shore perpendicular orientation, shown in Figure 9A. The addition of dredged sediment to the upper beachface in front of the beach resort property is evident in the early August elevation map (Figure 9A). This sediment was deposited in the former creek channel location covering up the small rock out-crop, shown in Figure

10A. As part of the dredging activity, sand was mined from the sill feature, shortening the length and removing the curved portion present in the July elevation survey.

By mid-September, following the channel straightening, the main channel began to deflect to the southwest as sediment was eroded from the southwest bank (Figure 9B). The small rocky out-crop, previously covered up by the dredging activity, was exposed again as sediment eroded from the landward side of the creek channel (Figure 10 B). As the channel began to deflect southward along the beach, shoals were observed near the cree**k** mouth on either side of the channel.

The patterns of sediment deposition and erosion between each survey are revealed in elevation difference maps, shown in Figure 11. These difference maps were constructed between each set of contiguous surveys, where the initial (dotted line) and final (solid line) creek channels were delineated. In each difference map, erosion occurred along the most recent creek channel and deposition occurred where the original creek channels were located. The difference map from July 29 and August 11 (Figure 11D) included the channel dredging. The scale of the dredging operation is shown in the large depositional (blue) and erosional (red) events over the original and final creek channel locations (Figure 11D). Between the August and September surveys (Figure 11E), following the dredging operation, there was a large net erosional event where the dredge material deposition occurred in the previous month suggesting a rapid return to more natural conditions.

Geomorphic feature data, transition point elevation, maximum elevation, and sinuosity, for each elevation mapping were extracted are provided in Table 2 and Figure

12. The elevation of the transition point and the maximum elevation during each mapping peaked (relative to NAVD 88 reference datum) immediately before dredging at 0.375 m and 0.456 m, respectively (Figure 12). Once dredging occurred, the elevation at the transition point reduced to -0.088 m and the maximum elevation within the channel reduced to 0.191 m. Sinuosity, an indicator of the meandering nature of the creek channel, increased throughout the summer and reached its maximum of 2.11 immediately before dredging (Figure 12). The dredging and channel repositioning project conducted by Horry County, SC reduced the sinuosity to 1.17.

The elevation difference maps effectively calculate the change in sediment volume between each mapping period. The study area overall varied between net erosional and net depositional throughout 2014 (Figure 13). Calculations of the sediment gained or lost with in the beachface area are reported with respect to the number of days between each survey in Table 2 and Figure 13). During the first mapping interval, over 70 days between April and June, there was a total of -7400.860 m^3 of sediment lost on the beachface. Following this period of rapid erosion, the beachface showed much less erosion between June 19 and July 08 (20 days, total loss of -604.9499 m^3). Between July 8^{th} and July 29 (21 days) the beachface transitioned into a depositional mode with a net gain of 1845.810 m^3. The dredging of the creek channel created an artificial erosional event of -226.147 m^3 over a period of 13 days.

3.2 Tidal range and water quality parameters in the swash basin

Water level within the back barrier drainage basin is an indicator of the exchange with the ocean through the swash channel crossing the beachface. For this study, water level within the back barrier basin of Singleton Swash has been continuously measured with a pressure transducer since January 2014. This time series data is shown in Figure 14. The oscillations in water level within the swash basin exhibited the spring and neap tidal patterns observed in the ocean tides (Figure 14). The Singleton Swash tidal range (SSTR) diminished during the period of January-July 2014 as the connection with the ocean facilitated less exchange leading up to the channel straightening. The comparison between the water level variability in Singleton Swash and the ocean tides forms the Singleton Swash Tidal Range/Ocean Tidal Range (SSTR/OTR) (Figure 15) as discussed in section 2.2.2. This ratio highlights the reduction in tidal range within the swash basin relative to the ocean. The SSTR/OTR ratio reached its maximum of 0.357 in June, but leading up to the dredging event, the SSTR/OTR decreased to its minimum of 0.200 at the end of July. The SSTR/OTR ratio was restored immediately after dredging to 0.301 in August indicating an improved exchange between the estuary and ocean.

Salinity was measured at surface and bottom at several sampling stations (Figure 4) throughout the swash basin as an indicator of water column stratification, shown in Table 3. A negative salinity difference (bottom subtracted from surface) indicates a stratified or stable water column. The monthly averaged measurements from each station were averaged across all stations in order to characterize the average stratification level for the entire swash basin. Water column stratification was variable in the swash basin throughout the sampling period. The average ΔS was largest for 2014 in March and September, at -1.138 ppt and -1.075 ppt, respectively. During the summer months, the peak salinity difference was July at -0.628 ppt. Immediately after dredging ΔS decreased to -0.209 ppt (Figure 16).

Dissolved oxygen (DO), is often considered a proxy for ecosystem health. If the beach morphology is affecting the water quality in Singleton Swash, a negative ecosystem impact in the form of low dissolved oxygen conditions could occur. Thus, DO saturation was also measured throughout the basin. Dissolved oxygen saturation varied throughout the sampling period with highest saturations in August (99.3%), shown in Table 3. The lowest DO saturation was recorded during May (76.3%) (Figure 17). The monthly averages indicated that dissolved oxygen saturation did not reach hypoxic conditions, generally categorized by saturations below 28 % (Buzzelli et al., 2007).

3.3 Correlation analysis

Correlation analysis was used to evaluate the relationships between the geomorphic features of the beachface, the SSTR/OTR ratio, and water quality parameters in the swash basin. Positive and negative correlation coefficient values represent direct and inverse relationships and the magnitude of the correlation coefficient indicates the strength of the relationship. Correlation values are provided in Table 4. Data were interpolated to seven-day increments prior to the correlation analysis. Therefore, the lag response for any pair of correlated parameters can only be interpreted to the nearest 7-day period. For example, a 0 lag indicates that a response to a driver occurred sometime between 0 and 7 days, a 1 lag indicates a response between 8 and 14 days. Refer to Table 1 for further explanation of each discrete lag.

Correlations between geomorphic features and the SSTR/OTR ratio revealed that the morphology of the beachface affects the SSTR/OTR ratio within the swash basin. The feature that exhibited the strongest control on the SSTR/OTR ratio was the net sediment gain/loss with a correlation coefficient, R, of -0.882 (0 lag), shown in Figure 18.

As the beachface entered an erosional phase by early June, the SSTR/OTR ratio in the swash basin increased. By summer, the beachface entered a depositional phase immediately reducing the SSTR/OTR ratio in the basin. After dredging the creek channel, artificially causing erosion, the SSTR/OTR ratio immediately increased (July to August).

The elevation at the transition point also had a strong relationship with the SSTR/OTR ratio (R= -0.647, 1 lag; figure 19). While the elevation at the transition point increased in the creek channel, a corresponding decline in the SSTR/OTR ratio suggests a restriction in the tidal flow. After dredging, the elevation at the transition point was lowered allowing an increase in the SSTR/OTR ratio (Figure 19A). The correlation between these two variables was strong but was not an immediate response. This suggests that changes in elevation at the transition point likely effect the SSTR/OTR ratio within 8-14 days.

The maximum elevation within the creek channel also exhibited a strong inverse relationship with the SSTR/OTR ratio (R= -0.631, 1 lag). The tidal range in the swash basin was the lowest when the elevation within the creek channel reached a maximum of 0.456 m (Figure 20A). The response of the SSTR/OTR to changes in maximum creek elevation occurs on the same time scale as the response to change in transition point elevation (8-14 days) (Figure 20B).

Sinuosity exhibited a strong direct relationship with the SSTR/OTR ratio (R= 0.802, 6 lag; figure 21B). Through the spring (April- May), sinuosity increased in conjunction with observed increases in the SSTR/OTR ratio. However, at the end of May, the SSTR/OTR ratio started to decrease while sinuosity continued to increase. By the summer, the SSTR/OTR and sinuosity exhibited an inverse trend (Figure 21A). This correlation analysis suggests that the relationship between these two variables is delayed such that changes in sinuosity could lead changes in the SSTR/OTR ratio within 43-49 days.

Correlations were also calculated between pairs of geomorphic features in order to characterize any beach elevation variability through time (e.g., transition point elevation may drive changes in sediment gain or loss). Transition point elevation exhibited a moderate direct relationship with the net sediment gain/loss (R= 0.413, 0 lag) shown in Figure 22B. When the transition point elevation increased, the beachface was in a depositional phase. Due to the dredging activity, the transition point elevation was lowered and the beachface entered an erosional phase (Figure 22A). The changes observed in the transition point elevation would affect the occurrence of erosion and deposition within 0-7 days.

The maximum elevation of the creek channel exhibited a weaker correlation to the net sediment gains/loss than the transition point (R= 0.314, 2 lag), shown in Figure 23. This suggests that a sedimentation event would be completed 8-14 days after the elevation with in the creek channel reached its maximum.

Correlation analysis was also conducted between the transition point elevation and the maximum elevation within the creek channel. There was a strong positive correlation between these two variables (R= 0.879, 0 lag), shown in Figure 24B). Increased maximum elevation in the creek channel co-varied with an increased transition point elevation. After dredging, each parameter decreased in elevation (Figure 24A). The response of the maximum elevation occurred 0-7 days after observed changes in the transition point elevation.

After connections between the geomorphic features and their effects on the SSTR/OTR ratio were established, correlation analysis could be conducted to reveal relationships between changes in the SSTR/OTR and water quality in the swash basin. Stratification in the swash basin can be an indicator of reduced tidal currents, which is based on the changes in SSTR/OTR ratio in this study (i.e., smaller SSTR/OTR indicates smaller tidal currents). For this sampling period, a strong positive correlation exists between the SSTR/OTR and the salinity structure of Singleton Swash (R= 0.728, 0 lag), shown in Figure 25B. The SSTR/OTR increased in May and the salinity difference in the swash basin was small. By July 29, the SSTR/OTR reached its minimum and the salinity difference was at its maximum, suggesting the water column was stratified due to the restricted tidal range. Immediately after dredging (0-7days), the SSTR/OTR increased, and the salinity difference was reduced (Figure 25A).

Changes in the salinity within the water column can have detrimental effects on the dissolved oxygen saturation, where increased stratification can result in less mixing effectively reducing dissolved oxygen saturation in combination with biological activity. The response in dissolved oxygen saturation to changes in the salinity structure revealed an inverse relationship (R= -0.625, 0 lag) shown in Figure 26B. This suggests increased stratification within the water column would result in increased dissolved oxygen saturation within 0-7 days. This is highly unlikely as enhanced mixing is a condition that usually results in an increase in DO saturation, whereas increased stratification limits mixing.

Discussion

The dynamic nature of the mouth of Singleton Swash is observed in a series of topographic surfaces in order to understand how the morphology of the creek channel and beachface relates to the ecosystem health of the associated back barrier estuary. Between March and September, 2014, changes are quantified including the migration of the creek channel, change in creek channel shape, evolution and landward retreat of the sill feature and identification of erosional and depositional hotspots. These various beachface features in the Singleton Swash study area are typical results of well-known coastal processes (Bertin et al., 2005; Tanski, 2012).

Astronomical tides likely contribute significantly to geomorphic features observed at Singleton Swash. Asymmetric tides, with the flood tide faster and shorter than the ebb tide, were measured by the United States Army Corps of Engineers (2009). Water level within the swash basin is also controlled by landward inputs. The main source of freshwater comes from storm water runoff, which enters the swash from the surrounding landscape but also includes flow from a large wet detention pond. Periodic weather events and resulting flow into the system are not enough to dominate the energy of the tide. Therefore, the flood tide dominance found at Singleton Swash is likely the most important driver of water and sediment into the mouth of Singleton Swash, supporting the fundamental importance of tidal effects on morphological changes (Kitheka, 1988; Ensign et al., 2013).

Our data suggest that the amount of sediment depositing or eroding in the sampling area is the most significant factor affecting the tidal range within the swash basin. When the mouth of Singleton Swash becomes a depositional system, we observe a reduction in the SSTR/OTR ratio, however this process does not occur instantaneously. The role each of the other factors, including the transition point elevation and maximum elevation of the channel, on the SSTR/OTR ratio are significant and their relationship to the sediment flux should be considered. Correlation analysis revealed a direct response of a deposition event with increasing transition point elevation and increasing maximum elevation (R= 0.413, 0 lag, R=0.314, 1 lag) (Figures 22 and 23). A 0-7 day lag between the transition point elevation and net sediment deposition indicates a rapid response of sediment deposition within the study area to increasing elevation at the transition point. As tidal currents transport material into the thawleg of the creek channel, sediment accumulates at the transition point. Once the transition point reaches an upper elevation threshold within 7 days, sediment begins to deposit elsewhere in the creek channel completing a net sediment deposition in the study area (Figure 27C).

When the transition point and the surrounding area reach their maximum elevation, the deposition event is completed and a reduction in the SSTR/OTR occurs. The lag between the two signals indicates a rapid response (within 7 days) of the SSTR/OTR ratio to sediment deposition within the study area. The accumulation of sediment in the mouth and resulting impact on tidal range is a well-documented phenomenon, described in many other studies (e.g., Cleary and FitzGerald, 2003; Oliverira et al., 2006). Cleary and FitzGerald (2003) demonstrated that landward movement of sand into the mouth of Mason inlet, North Carolina greatly decreased the tidal prism from $1.9x10^6$ m^3 in 1995 to $0.7x10^6$ m^3. After successful dredging of the inlet, the tidal prism increased to $4.2x10^6$ m^3.

Although elevation and deposition affect the tidal regime, it is important to note, in most cases, that Singleton Swash does not become completely decoupled from the ocean. Oscillations of the water level are still observed even when the SSTR/OTR dampens suggesting that water is still entering the swash basin, but in smaller volumes per time. Wind-driven wave energy may be an important factor contributing to the transport of water into the Singleton Swash basin (Oliveira et al., 2006; Orescanin et al., 2014; Ruggiero et al., 2001). Orescanin et al (2014) showed with predictive modeling that water levels in coastal bays and estuarine ecosystems more accurately match observed levels when the addition of wave energy and wave heights are considered. Although not quantified in this study, the potential effects of wave energy may be critical to allow the flood tide to bypass increased beachface elevation following deposition. The reduced freshwater input and the limited coastal processes in the swash basin effectively reduce the role of the ebb tide. This restriction extends the duration of the ebb tide, so the water level never reaches its minimum level before the next flood tide.

We hypothesized that sinuosity of the creek channel would exhibit an inverse relationship to the SSTR/OTR ratio (i.e., increased sinuosity would decrease SSTR/OTR). However, correlation analysis of this relationship revealed a strong direct relationship with a delayed response (R= 0.802, 6 lag) (Figure 21B). This suggests that sinuosity is not a large driver of tidal range reduction, and must involve other factors that may not have been quantified in this study. For example, changes in flow resulting from changes in tidal range may influence the sinuous nature of creek channels. Pestrong (1972) and Hughes (2012) consider flow conditions primarily responsible for changes in sinuosity. Pestrong (1972), specifically, demonstrated in various studies that flow conditions were the major constraint in determining the sinuosity of unvegetated mudflats. Varying conditions including tidal current speed, tidal asymmetry, and bedform characteristics control the meandering nature of channels (Hughes, 2012).

There are many implications if restriction of the tidal range occurs. A sufficient tidal range is needed to regulate nutrient exchange between the ocean and surrounding coastal ecosystems, maintain ecozonation along various marsh gradients, and foster proliferation of feeding and spawning activities of various pelagic organisms (Cox et al., 2003; Roman et al., 1984). If the tidal range does become restricted, losses in vegetation cover, changes in water column stability and changes in the biochemistry of the swash basin could be expected. Sea level rise and climate change can also pose risks to areas similar to Singleton Swash. An increase in sea level could propagate the movement of more water into the swash basin which would flood the local watershed, pose risk to properties that are already adjacent to the swash basin and reduce the amount of suitable habitat for various organisms (Galbraith et al., 2002). Climate change will most likely increase the number and intensity of storms, thus increasing the frequency of erosional events (Webster et al., 2005).

Many researchers consider salinity to be an important indicator of ocean circulation due to the effect that currents and tidal flow can have on the stability of a water column (Dame et al., 2000; Livingston, 1996). A reduction in the SSTR/OTR in Singleton Swash essentially leads to slower tidal currents in and out of the swash channel providing favorable conditions for stratification development and intensification. In this case, when tidal range ratio is large (June), the tidal currents could freely enter the swash maintaining a well-mixed water column. As the elevation increases in the creek channel the SSTR/OTR ratio reduces, tidal currents become smaller and there is an immediate response in the salinity vertical structure (July) (Figure 25). In order to best characterize the response throughout the swash basin, salinity measurements were averaged throughout the entire basin.

The stable, stratified nature of the water column in Singleton Swash during late July may limit oxygenation of bottom waters. Correlation between DO saturation (%) and salinity revealed an immediate inverse response from bottom DO saturation to salinity stratification of the water column (R= -0.625, 0 lag) (Figure 26B). However, this implies that increased stratification leads to increased DO saturation which does not follow the typical understanding of the relationship between water column stratification and DO saturation (Buzzelli et al., 2007). Normally, the persistence of stratification of the water column in conjunction with microbial respiration would result in reduction of dissolved oxygen levels. Reduced levels of dissolved oxygen and occurrence of regional hypoxia (especially in summer) have resulted in large fish kills periodically in the Long Bay area (Sanger et al., 2012). The role of tidal creeks in these regional hypoxic episodes is not clear, though they have been hypothesized to be sources of excess nutrients or other degraded water quality parameters in the coastal ocean. Though correlation analysis suggests a connection between the tidal range and the magnitude of stratification, the inverse relationship between DO and ΔS indicates there must be other factors (e.g., creek dimensions and eutrophication) affecting the DO saturation in Singleton Swash.

The dredging of Singleton Swash is one way to effectively manage an ecosystem characterized by changing morphology. Singleton Swash represents a unique environment that is controlled by natural processes but involves management decisions based on concerns communicated from residents in the local community. Thus, the complicated topic of successful management of Singleton Swash should involve input from local community leaders combined with applied science techniques to determine cost-effective and sustainable strategies.

For Singleton Swash, consideration of a long-term solution, proposed by Horry County, includes the construction of a cement culvert in order to stabilize the main creek channel. This culvert would extend from the dune line, across the beach, to the intertidal zone. Such an engineered solution is carefully designed with discharge rates measured in order to predict whether or not the culvert will be continually swept clean of sediments. Only in practice will the true functionality of this type of solution be revealed. Event-driven sediment deposition (e.g., storm waves) may deposit such large loads of sediment that the structure could be filled and actually further inhibit exchange between the estuary and ocean. On the other hand, continual maintenance with heavy equipment to move sand may not be a cost effective management technique for the long term.

Conclusions

The use of highly accurate GPS equipment and the analysis of topographic surfaces indicated the mouth of Singleton Swash was dynamic as the beachface characteristics evolved over time. There were many features of the beach that change including the elevation of the creek channel, sinuosity, and location of erosional and depositional hotspots.

Correlation analysis indicated that these changes had an impact on the tidal range, limiting the mixing of the water column. Specifically, the completion of a sediment deposition event was the strongest driver for the reduction of the SSTR/OTR ratio as it responded immediately. However, large amounts of sediment do not deposit instantaneously but instead build up gradually which explains the relationship of the elevation at the transition point and the maximum elevation to the net sediment deposition. The elevation at the transition point increases to a threshold, which then causes sediment to deposit in the surrounding area of the beachface, which may take between 0-7 days. As soon as this occurs, a sediment deposition event is completed and immediately causes a decline in the SSTR/OTR ratio. Changes in the SSTR/OTR ratio revealed an immediate response in the stability of the water column in the swash basin. As the SSTR/OTR ratio declined, the salinity difference between the top and bottom of the water column increased creating a more stratified water column. This study revealed that stratification was not a controlling factor in DO saturation levels, providing a good basis for future work.

As a management technique, Singleton Swash is dredged periodically to reduce erosional risks and re-establish an open connection between the swash basin and the ocean. In 2014, the dredging activity immediately caused the SSTR/OTR ratio to increase as sediment was eroded from the beachface and the elevations at the transition point and throughout the creek channel were lowered. The increased SSTR/OTR ratio promoted water column mixing and re-oxygenated the water (Figure 27).

This study could be improved upon by including analysis of creek channel dimensions, extending sampling periods, measuring discharge variability in the swash channel, and analyzing wind field and wave climate data. The difference in surface and bottom salinities (ΔS), as an indicator of water column stratification, was used because water depth was not considered. Future work could include measurement of water depths to interpret the magnitude of water column stratification in the context of computed density gradients. The impact of freshwater flow from the wet detention pond and characterizing the tidal prism would add to the understanding of the hydrologic conditions of Singleton Swash. The understanding of the seasonal changes that occur at Singleton Swash could benefit from higher frequency of sampling and include a sampling period ranging several years. Characterizing the wind-driven waves and currents in the coastal ocean will aid in the understanding of the role that longshore current plays in the changes of the beachface area.

While this research provides important insight into the properties that control the tidal range and water quality parameters within its natural setting, long-term monitoring will most completely characterize the system. The methodology developed for this study includes careful construction of digital elevation models of the beach face as it changes through time. Such data can be analyzed and correlated with estuarine to ocean water level ratio. The water level can, in turn, be correlated with water quality parameters to quantitatively link beachface morphodynamics to estuarine ecosystem health.

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Tables

Table 1. Discrete lag and corresponding time period

Lag	Time Period (days)
0	0-7
1	8-14
2	15-21
3	22-28
4	23-35
5	36-42
6	43-49
7	50-56
8	57-63
9	64-70
10	71-77

Table 2. Extracted quantitative data of geomorphic features and determination of tidal range ratio

Sampling Date	Sampling Period (days)[a]	Elevation of Transition pt. (meters)	Highest Elevation of Channel (meters)	Sinuosity	Net Sediment Gain/Loss (m^3)[b]	SSTR/OTR Ratio[c]
03/12/14	30	0.046	0.160	1.525	N/A	0.275
04/10/14	29	-0.021	0.177	1.462	271.870	0.278
06/19/14	70	0.044	0.204	1.761	-7400.860	0.357
07/08/14	20	0.073	0.174	1.918	-604.949	0.303
07/29/14	21	0.375	0.456	2.113	1845.810	0.200
08/11/14	13	-0.088	0.191	1.173	-226.147	0.301
09/16/14	36	0.128	0.200	1.064	2262.838	0.271

[a]The number of days between each sampling date (Sampling period for 03/12/14 was pre-set to 30 days).
[b]Sediment gains and losses based on a 50,859 m^2 masked area where (+) values are deposition and (-) values are erosion between each sampling period.
[c]The ratio between the tidal range of Singleton Swash and the tidal range of the ocean and expresses the change in tidal range for the sampling period.

Table 3. Monthly averages of tidal range ratio and water quality parameters of the Singleton Swash water basin.

Sampling Period (days)[a]	SSTR/OTR Ratio[b]	Sampling Date	ΔSalinity (ppt month^{-1})	Bottom DO (% SAT month^{-1})
30	0.275	3/10/2014	-1.138	93.1
29	0.278	4/16/2014	-0.177	N/A
70	0.357	5/16/2014	-0.081	76.4
20	0.303	6/17/2014	-0.224	85.6
21	0.200	7/17/2014	-0.628	88.9
13	0.301	8/16/2014	-0.209	99.3
36	0.271	9/14/2014	-1.075	94.5

[a] The number of days used to determine the average SSTR/OTR ratio.
[b] The ratio between the tidal range of Singleton Swash and the tidal range of the ocean.

Table 4. Results of the correlation analysis between the geomorphic features of the beachface, and the tidal range and water quality parameters in the associated back barrier estuary of Singleton Swash.

	SSTR/OTR Ratio		Sediment Net/Gain Loss		Maximum Elevation		ΔSalinity		Bottom DO	
Variable	R[a]	Lag[b]	R	Lag	R	Lag	R	Lag	R	Lag
Transition Point Elevation	-0.647	1	0.413	0	0.879	0	-	-	-	-
Maximum Elevation	-0.631	1	0.314	1	-	-	-	-	-	-
Sinuosity	0.802	6	-	-	-	-	-	-	-	-
Sediment Net Gain/Loss	-0.882	0	-	-	-	-	-	-	-	-
SSTR/OTR Ratio	-	-	-	-	-	-	0.728	0	-	-
ΔSalinity	-	-	-	-	-	-	-	-	-0.625	0

[a] Correlation function value between each variable, (+) values suggest a direct relationship and (-) values describe an inverse relationship between considered variables.

[b] Correlations were performed on a 7 day interpolation thus a 0 lag in real time represents a response between 0 and 7 days and a 1 lag represents in real time a response somewhere between 8 and 14 days, etc.

Figures

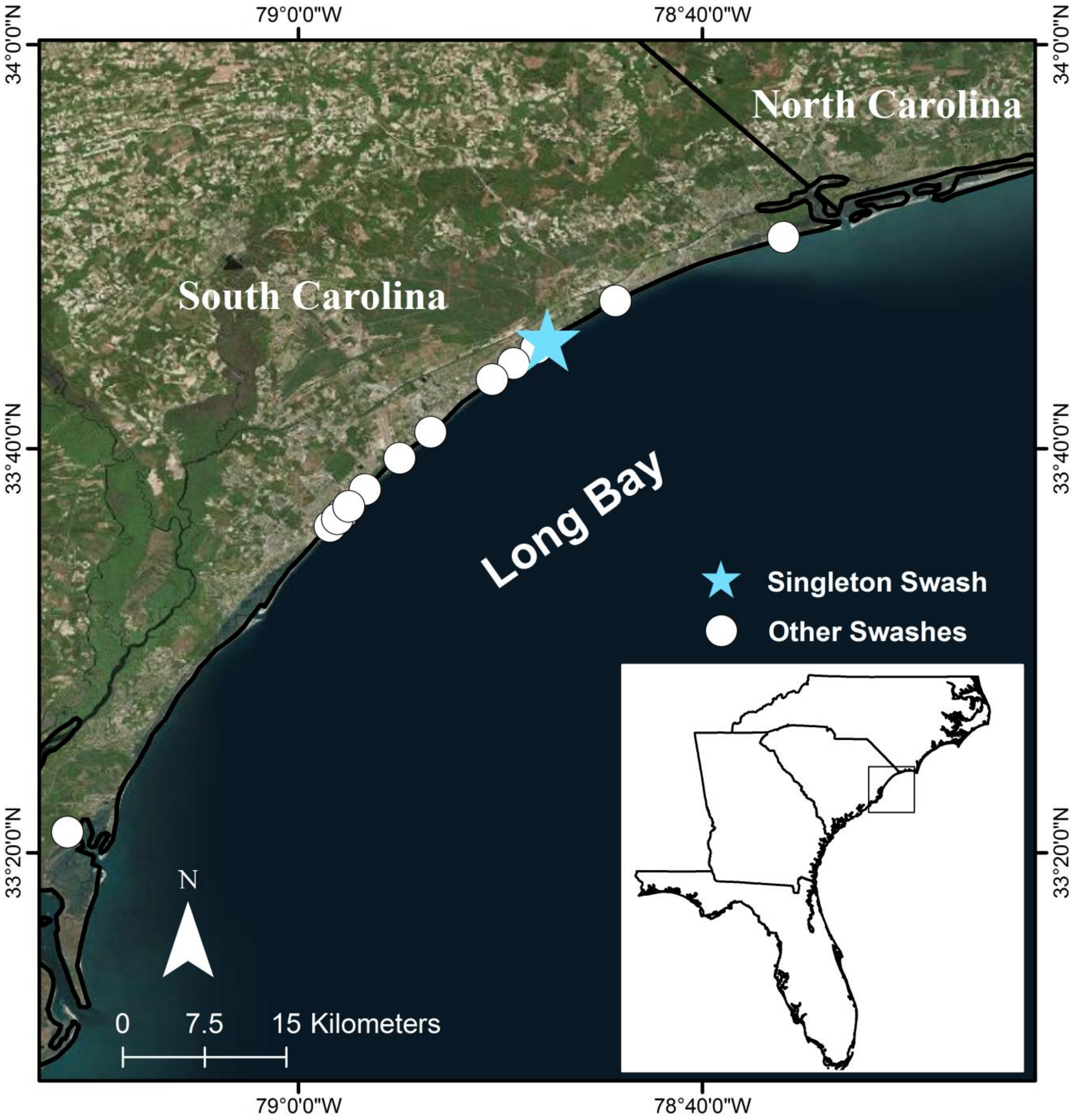


Figure 1. Location of Singleton Swash and surrounding swashes in the Grand Stand area of Myrtle Beach, South Carolina.

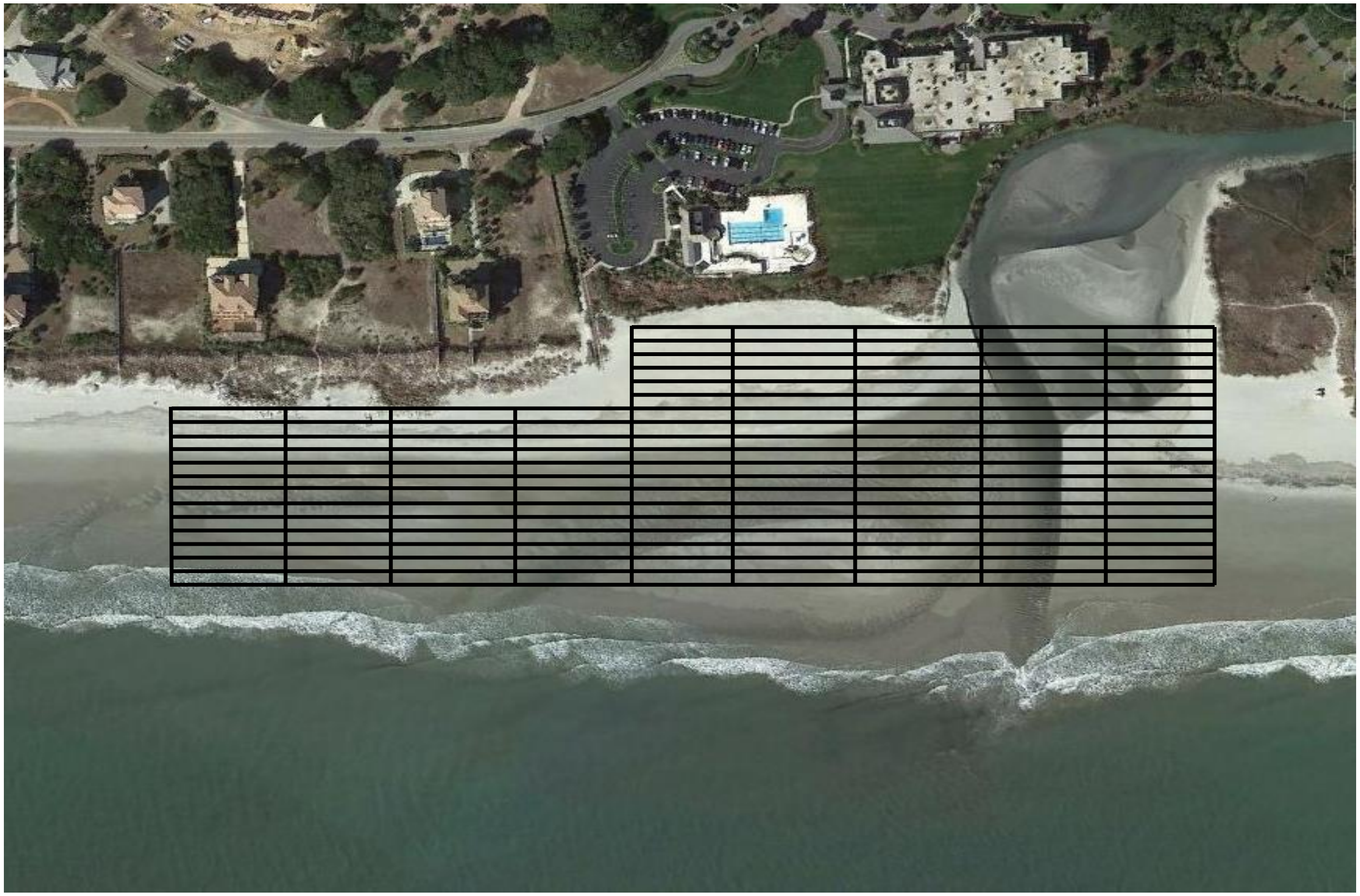


Figure 2. RTK-DGPS survey grid covering the dynamic swash zone. Survey area began along the dune line, extended to the low tide line, and spanned ~350 m along shore.

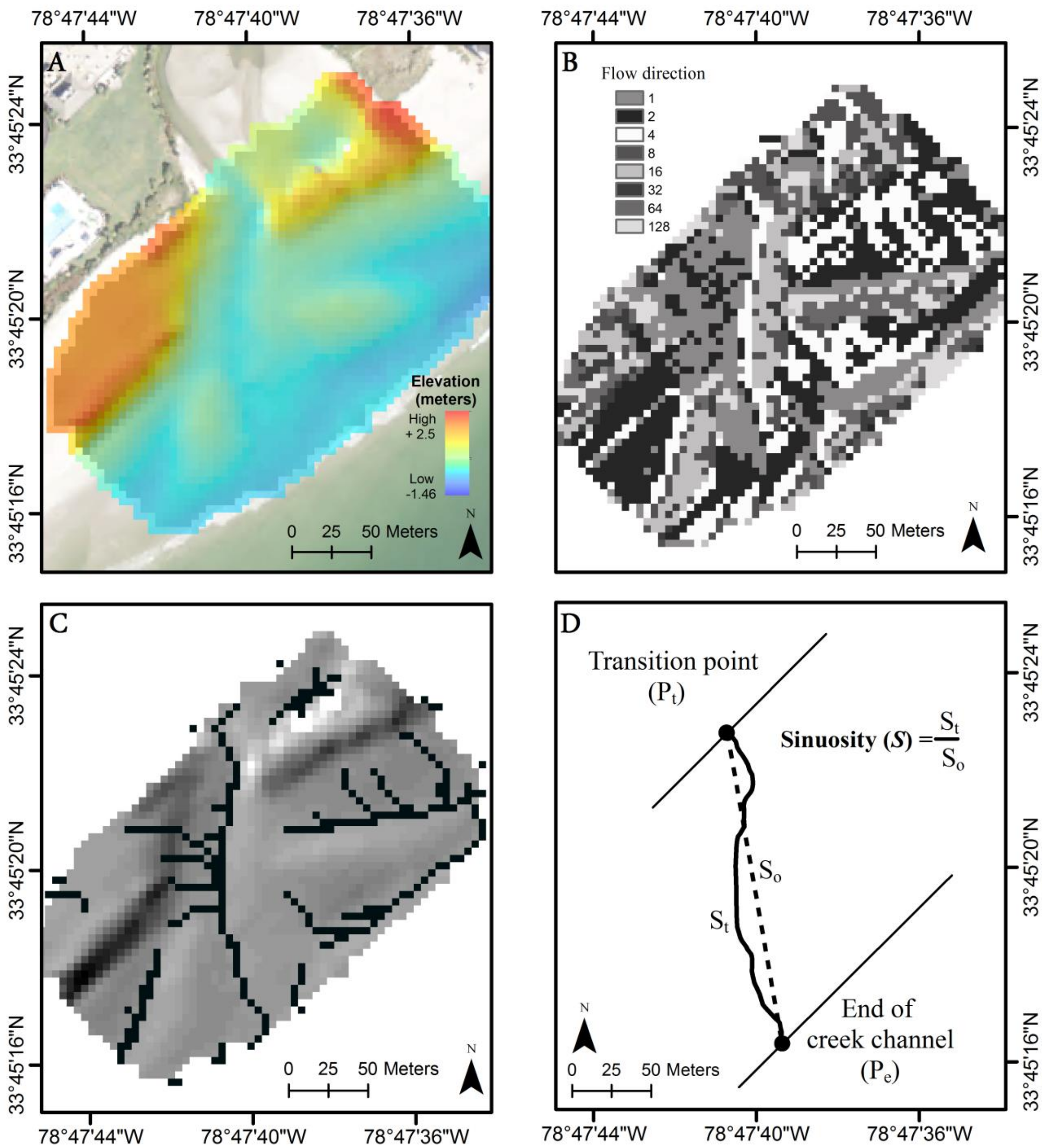


Figure 3. Methodology for extracting quantitative data demonstrated on original data sampled 09/16/14 in the swash mouth: (A) original topographic surface; (B) directional flow tool characterizing flow direction from each cell; (C) flow accumulation tool identifying thawleg of creek channel; (D) digitized creek channel in which geomorphic parameters were extracted (e.g., sinuosity (*S*) and elevation).

Figure 4. Aerial photograph of the Singleton Swash tidal creek and the surrounding watershed. Yellow circles denote sampled stations starting at the ocean and terminating at a wet detention pond outfall. Location of Hobo time-series loggers indicated by orange star.

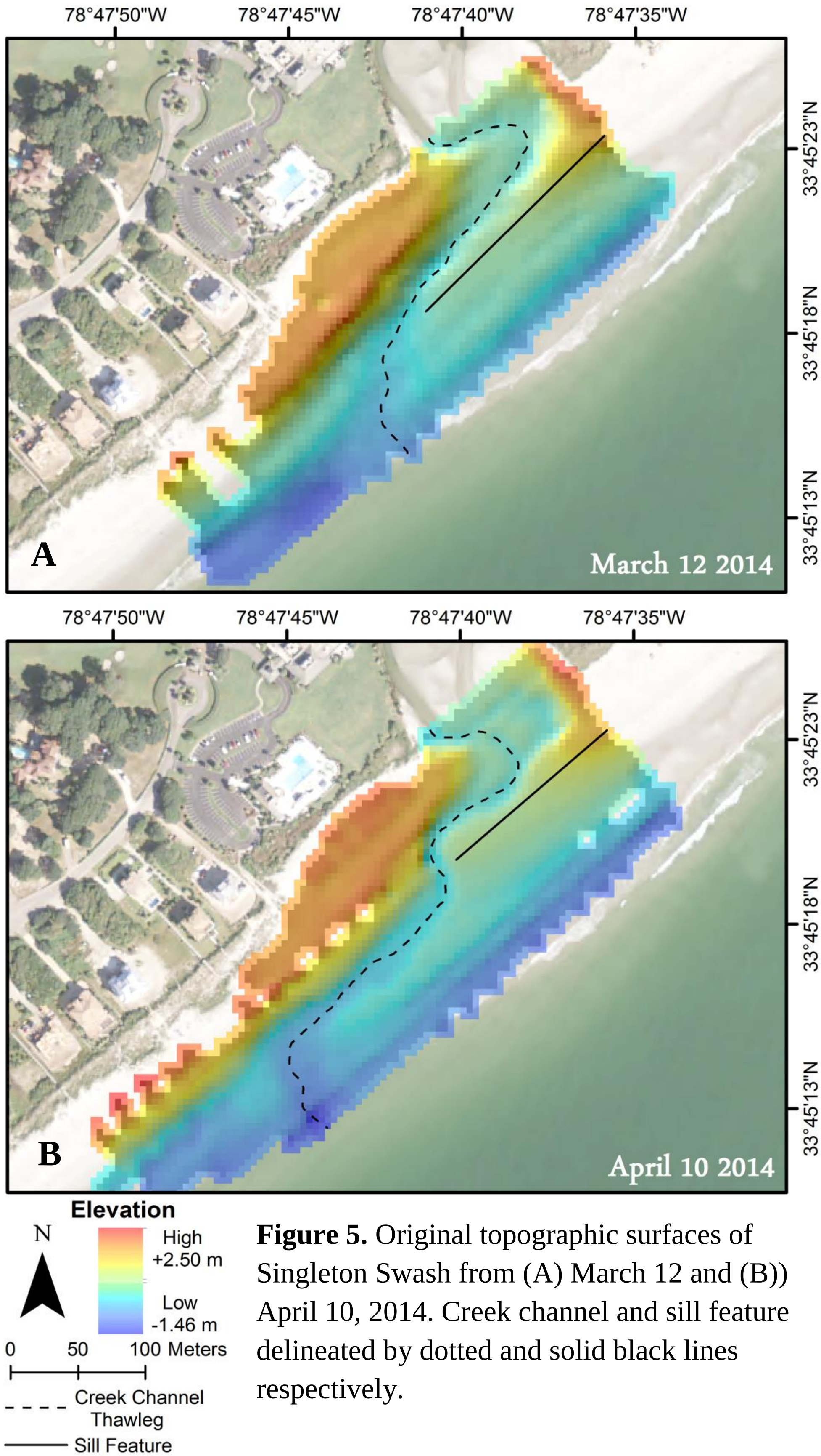


Figure 5. Original topographic surfaces of Singleton Swash from (A) March 12 and (B)) April 10, 2014. Creek channel and sill feature delineated by dotted and solid black lines respectively.

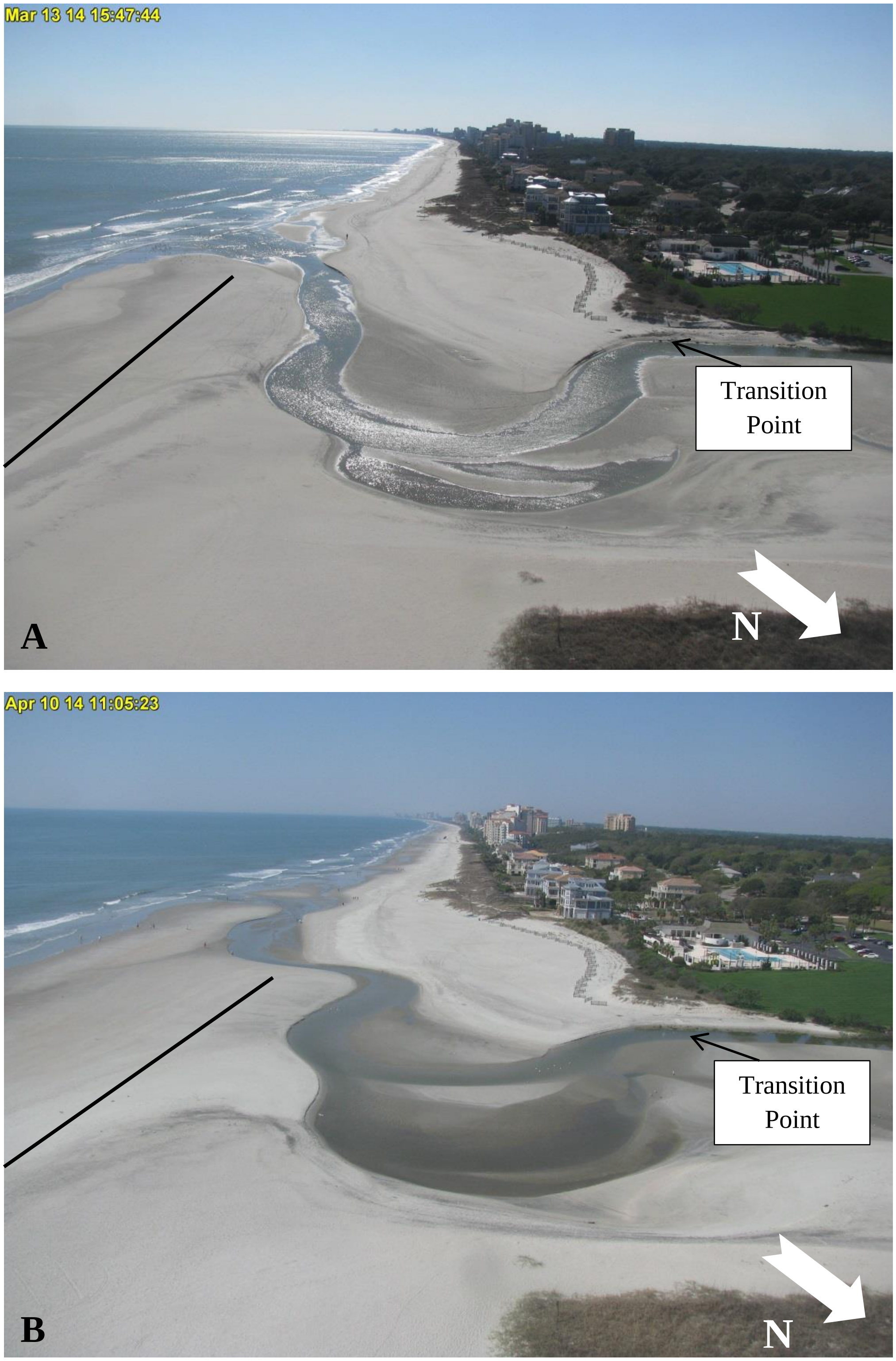
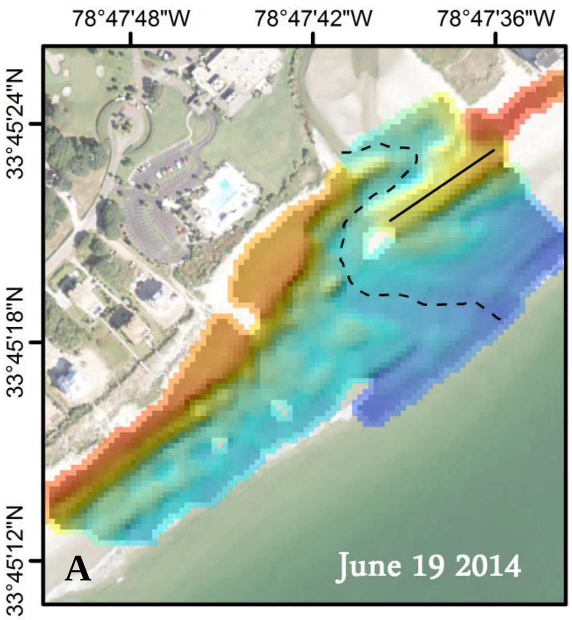


Figure 6. Webcam images of Singleton Swash in (A) March and (B) April, 2014. Solid black line represents sill feature. Images are not geo-referenced, therefore north arrow is approximate.



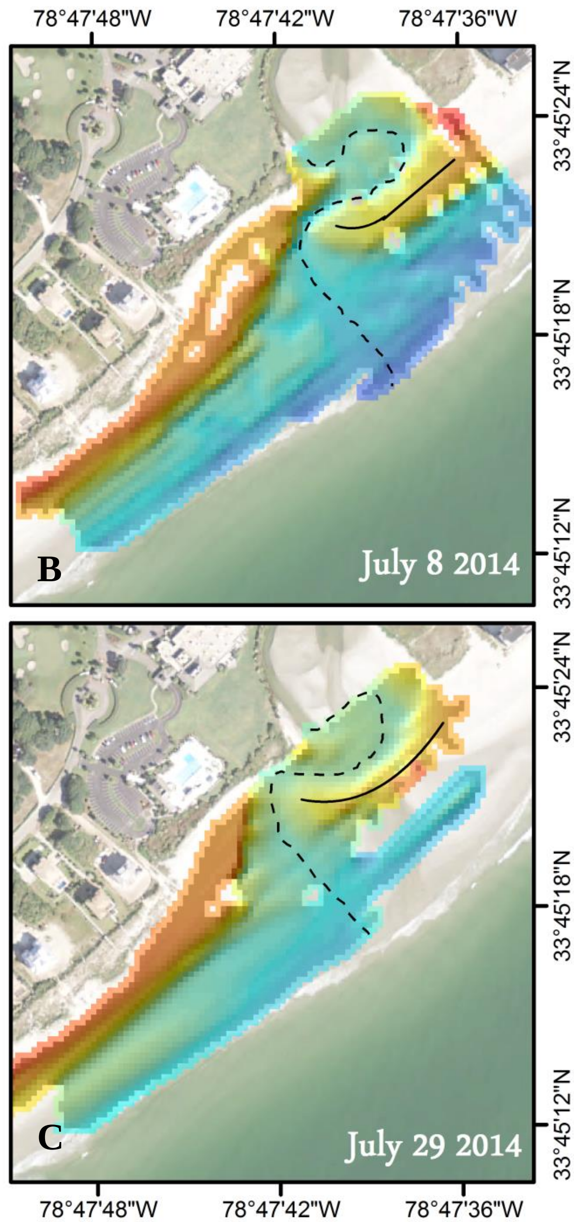
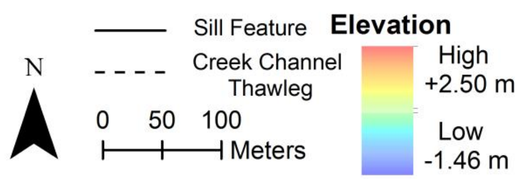


Figure 7. Original topographic surfaces of Singleton Swash during the summer. Creek channel and sill feature delineated by dotted and solid black lines respectively. The topographic surface from July 29th (C) exhibits the orientation of Singleton Swash before the channel was dredged.



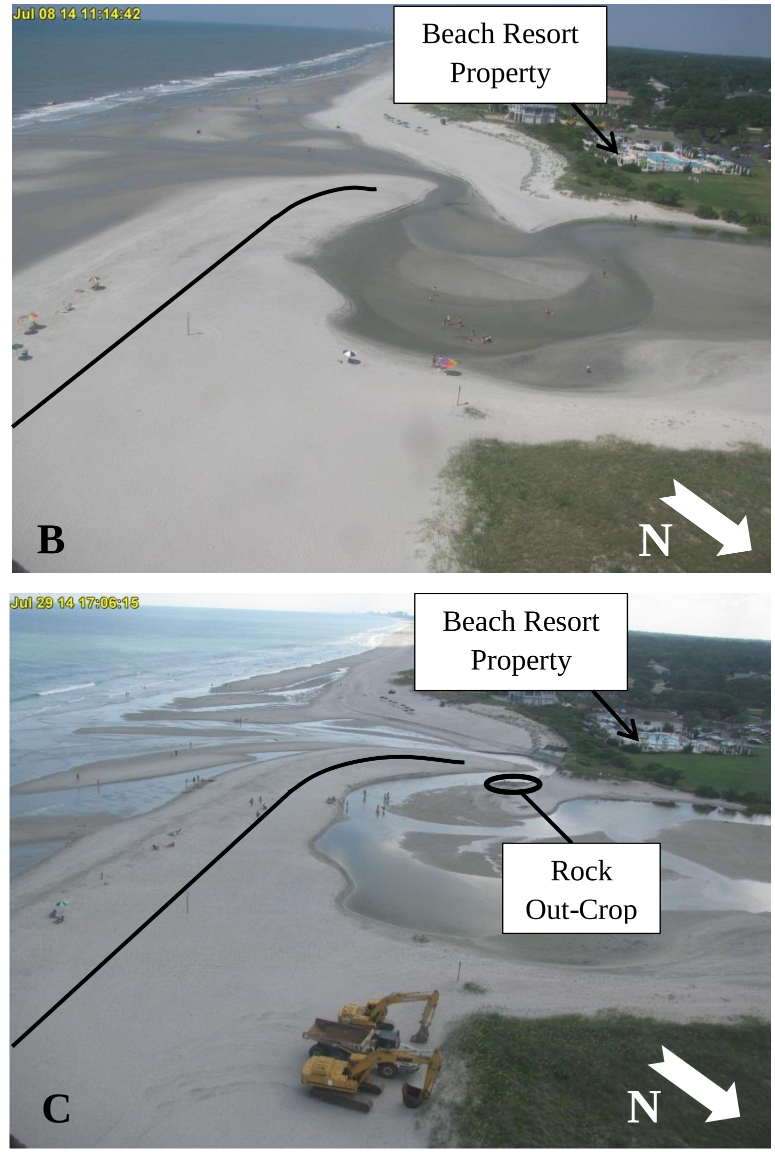


Figure 8. Webcam images of Singleton Swash for (A) June, (B) early July, and (C) late July 2014. Solid black line represents the sill feature. Images are not geo-referenced, therefore north arrow is approximate.

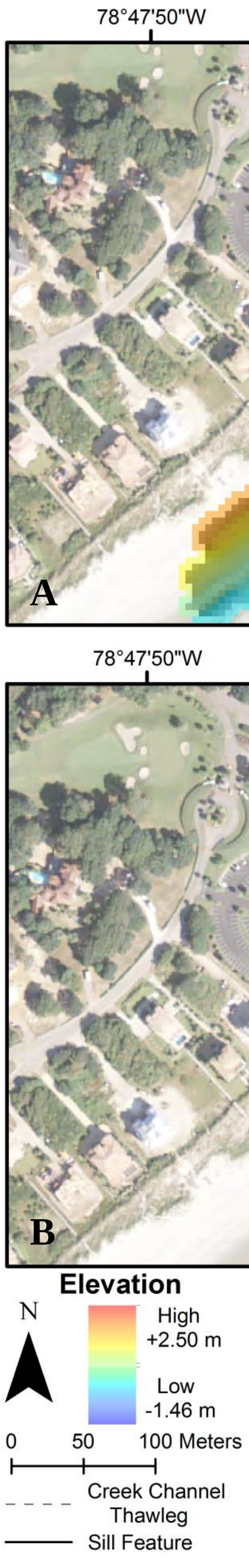


Figure 9. Original topographic surfaces of Singleton Swash from (A) August 11 and (B) September 16, 2014. Creek channel and sill feature are delineated by dotted and solid lines respectively. Topographic surface from August 11 exhibits the orientation of Singleton Swash a week after the channel was dredged.

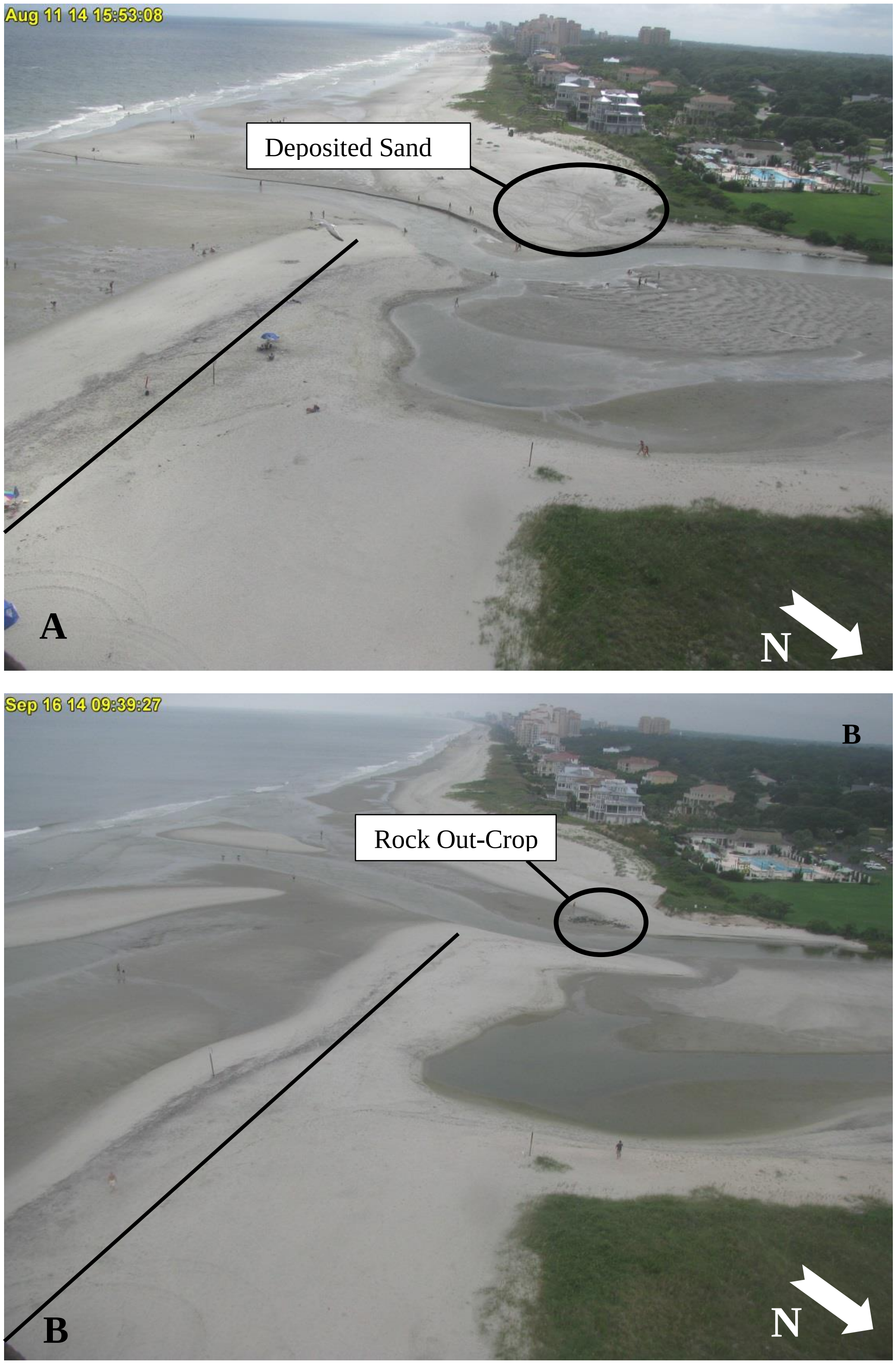


Figure 10. Webcam images of Singleton Swash for (A) August and (B) September 2014. Solid black line represents sill feature. Images are not geo-referenced therefore north arrow is approximate.

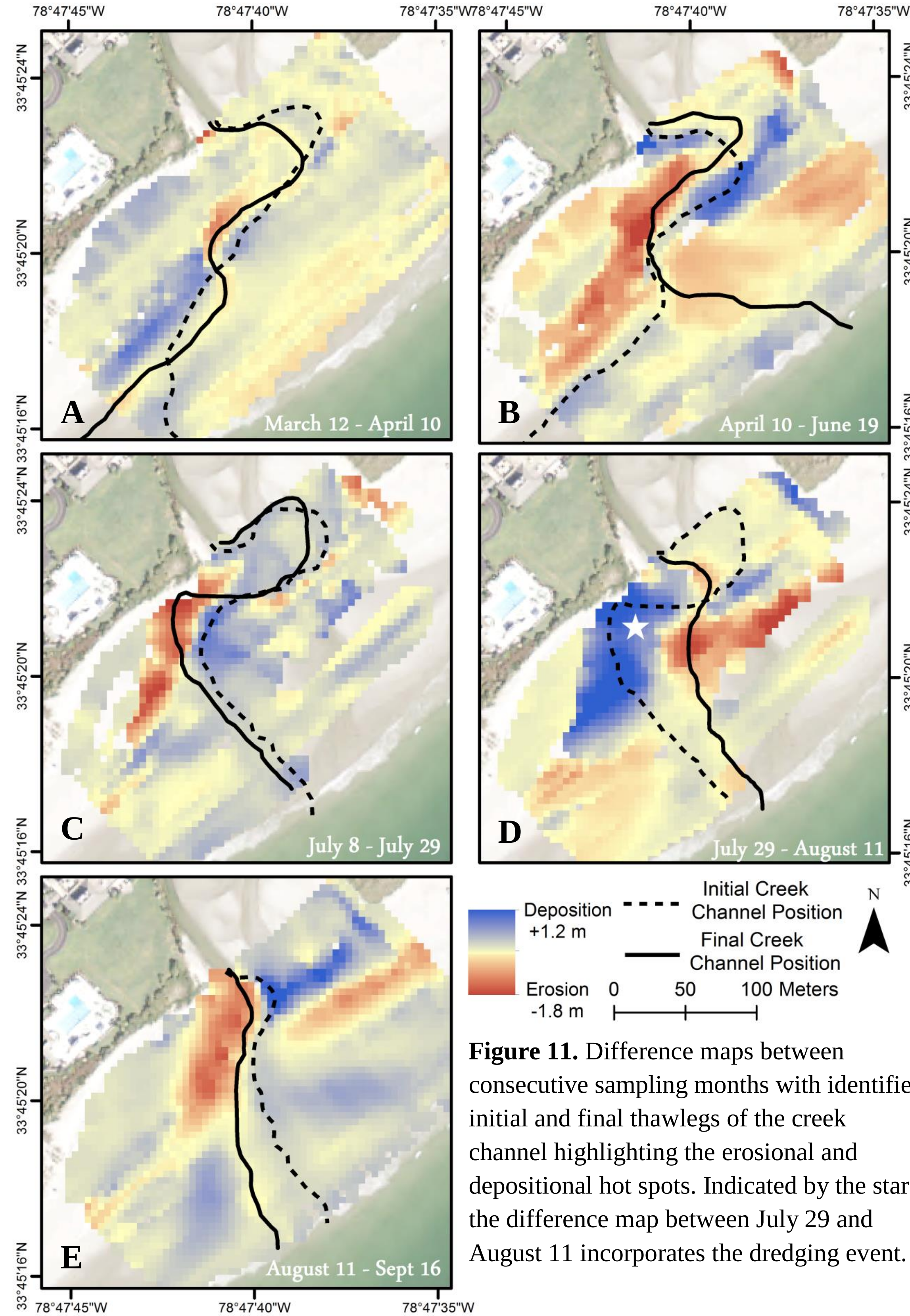


Figure 11. Difference maps between consecutive sampling months with identified initial and final thawlegs of the creek channel highlighting the erosional and depositional hot spots. Indicated by the star, the difference map between July 29 and August 11 incorporates the dredging event.

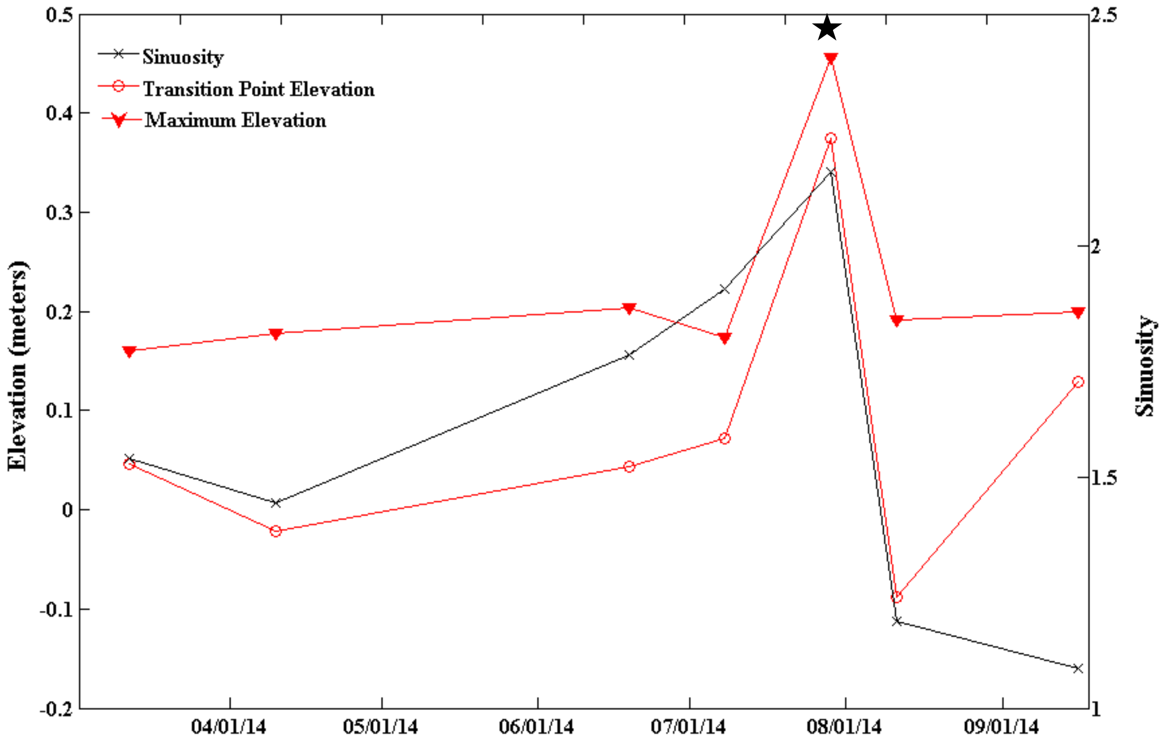


Figure 12. Extracted geomorphic features from each elevation mapping. Elevations are geo-referenced in the vertical datum NAVD88. Sinuosity is an index regarding the meandering nature of the creek channel, where 0= straight, <1.5 = slightly meandering, and >1.5 = meandering. Dredging occurred between July 29th and August 4th, 2014 indicated by black star.

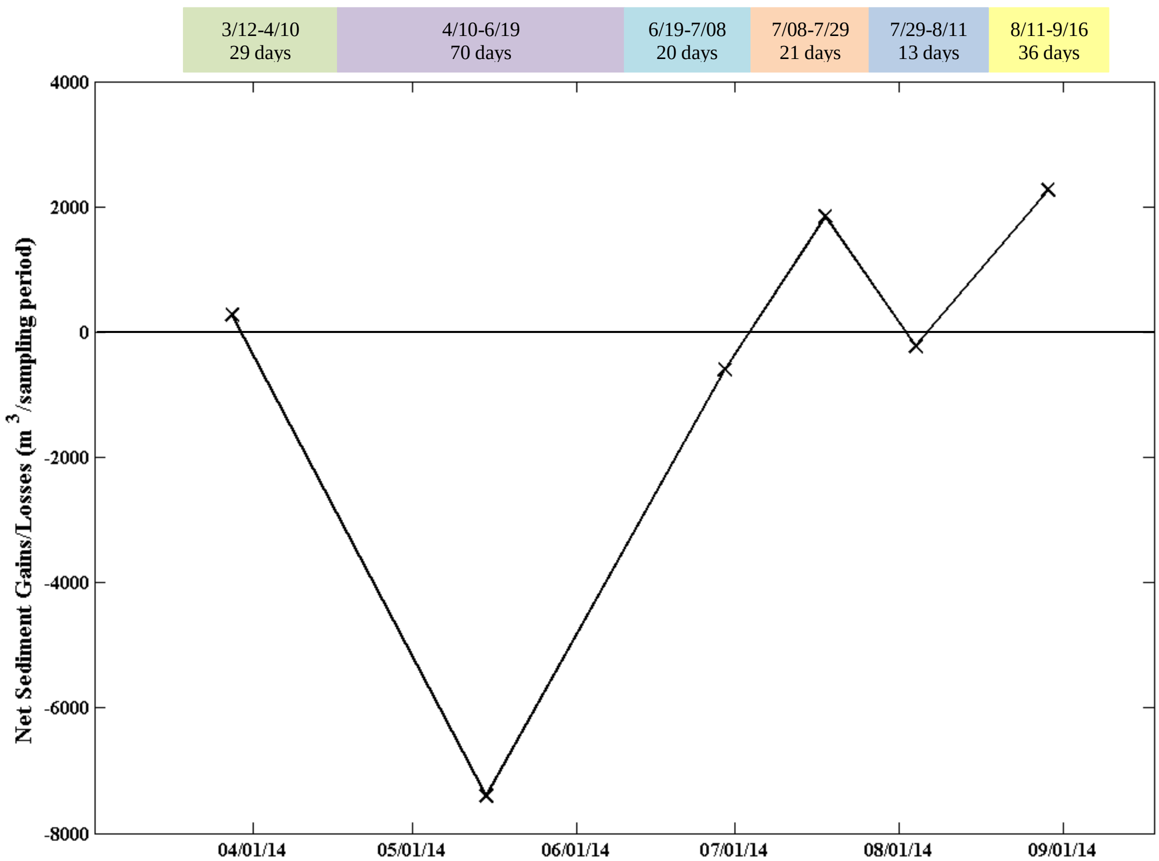


Figure 13. Net sediment gains and losses, where (+) is a net sediment gain and (-) is a net sediment loss. Each data point represents the amount of sediment gained or lost from the beachface between each elevation survey as indicated by color-coded timeline.

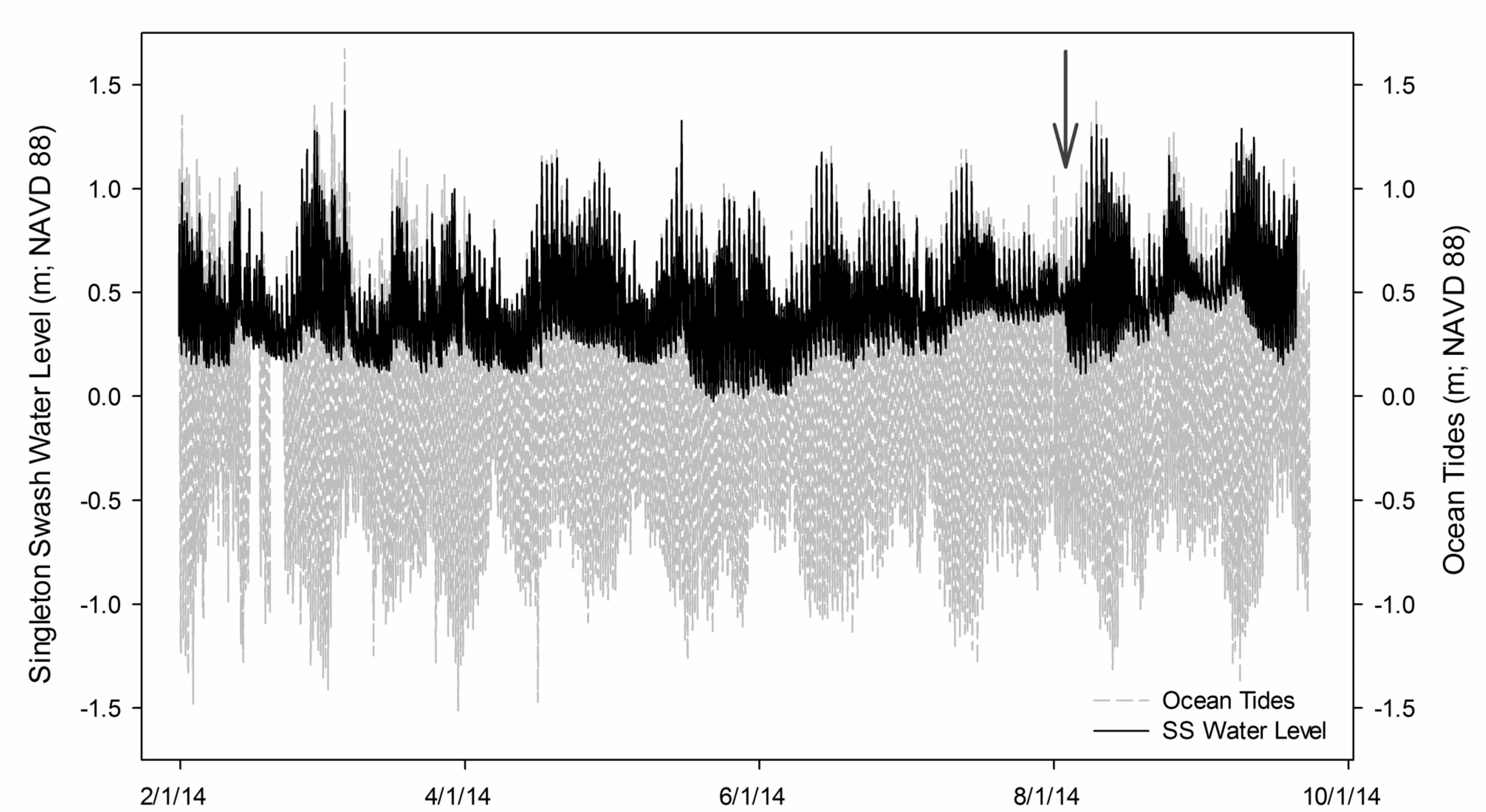


Figure 14. Singleton Swash and local ocean water levels related to NAVD88 during 2014. Black arrow indicates when the creek channel was dredged.

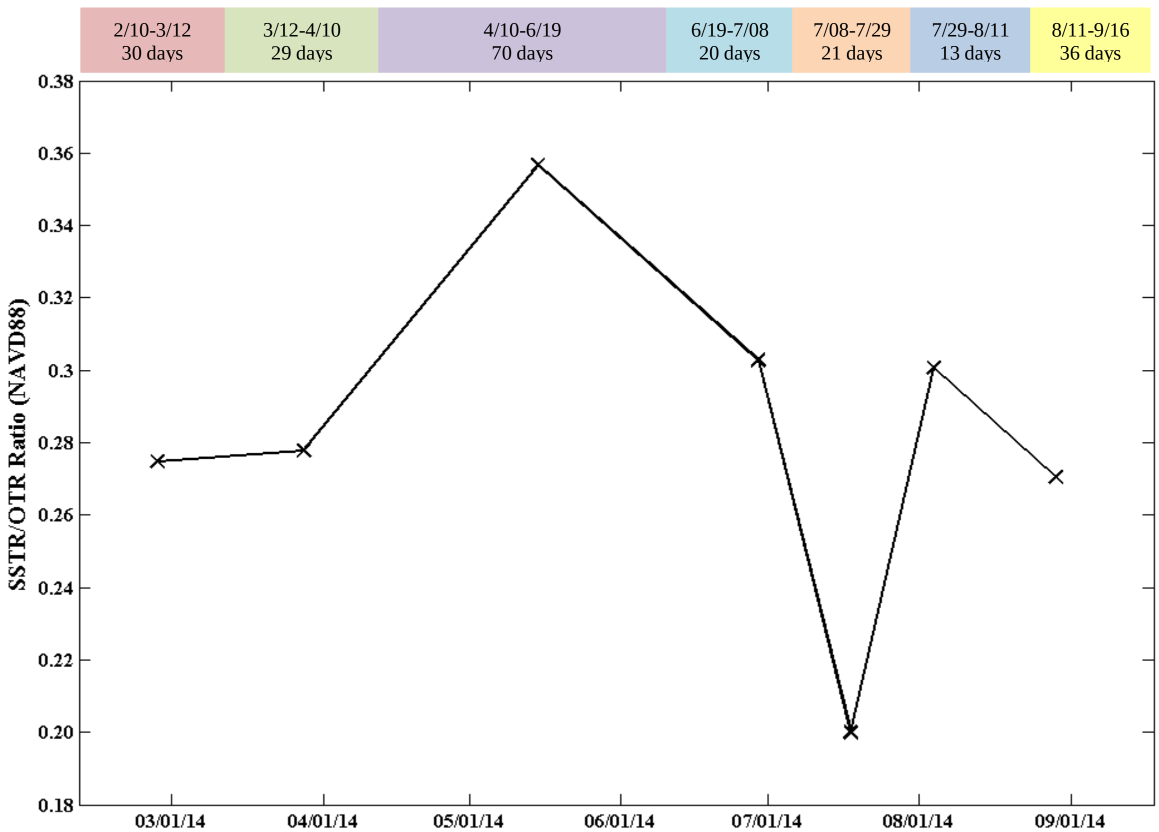


Figure 15. The (monthly averaged) SSTR/OTR ratio versus time. Larger ratios suggest a more open swash channel and a lower ratio suggests a restricted water flow to the swash basin.

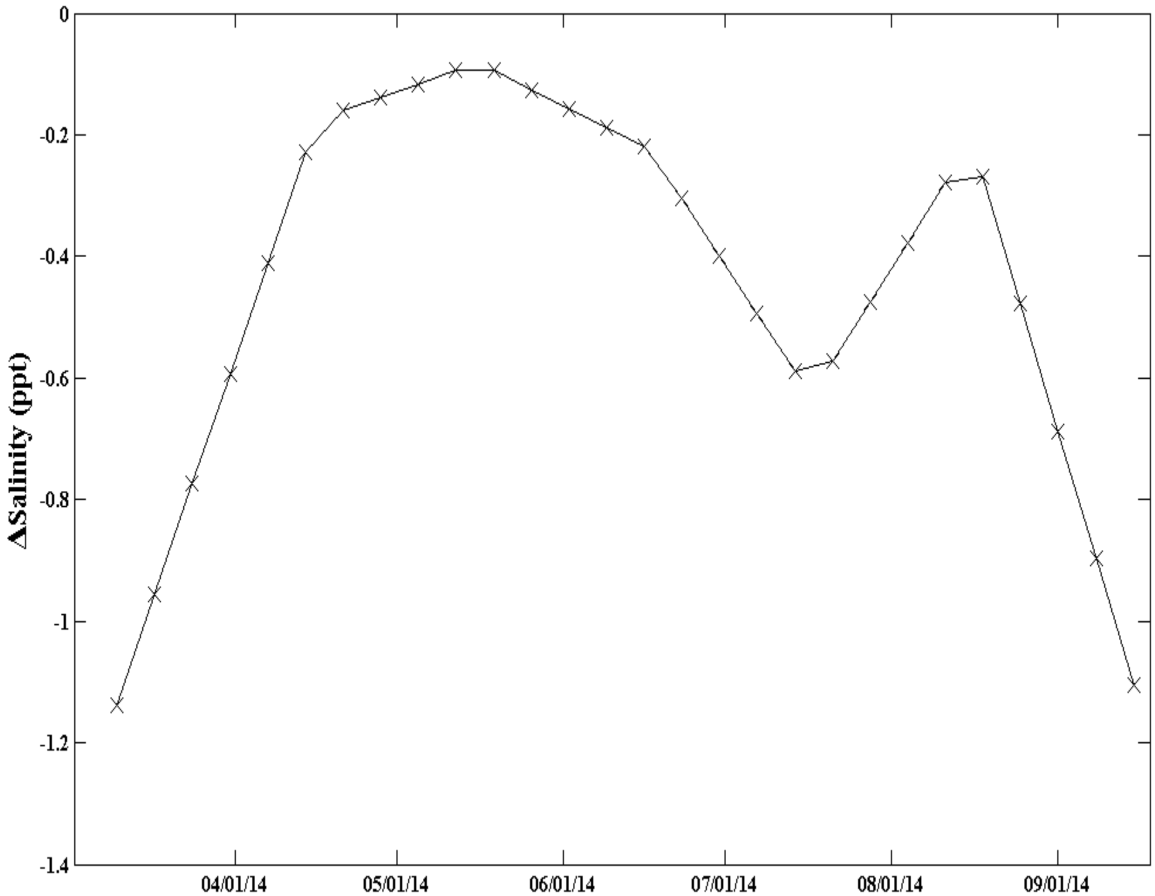


Figure 16. Salinity difference of Singleton Swash throughout the sampling period. A larger difference indicates greater stratification.

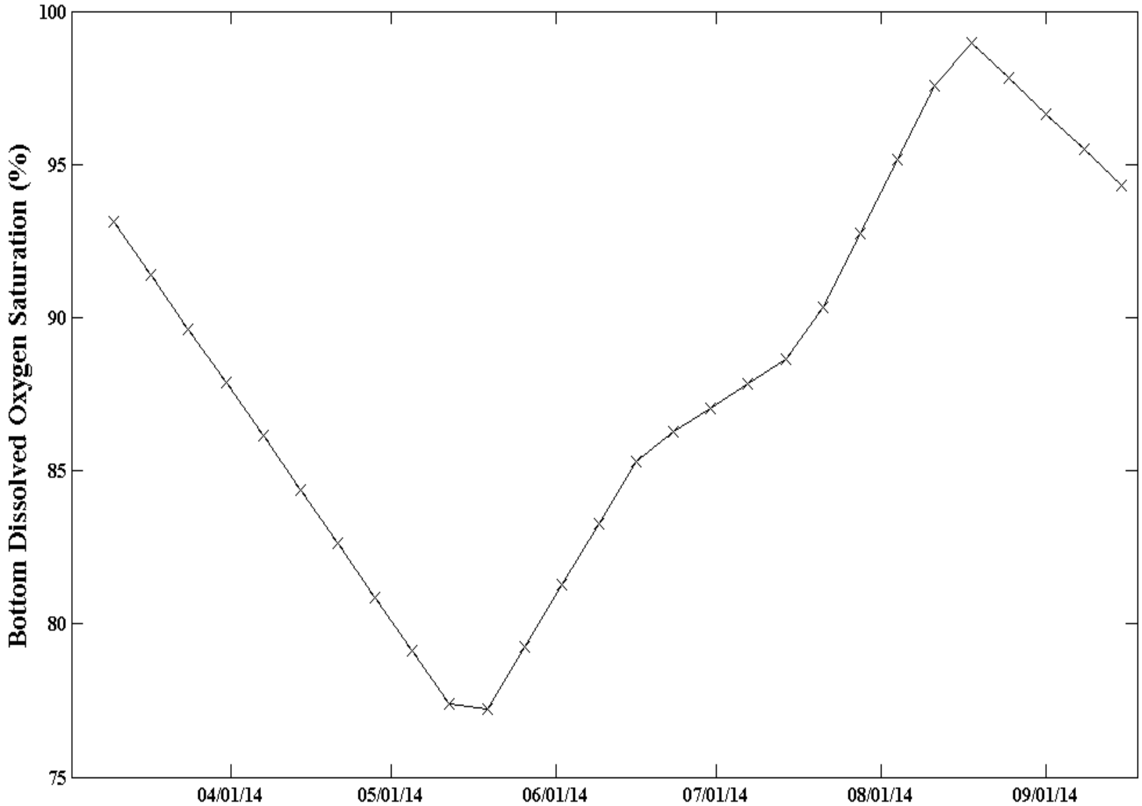


Figure 17. Bottom dissolved oxygen saturation (%) throughout the Singleton Swash basin.

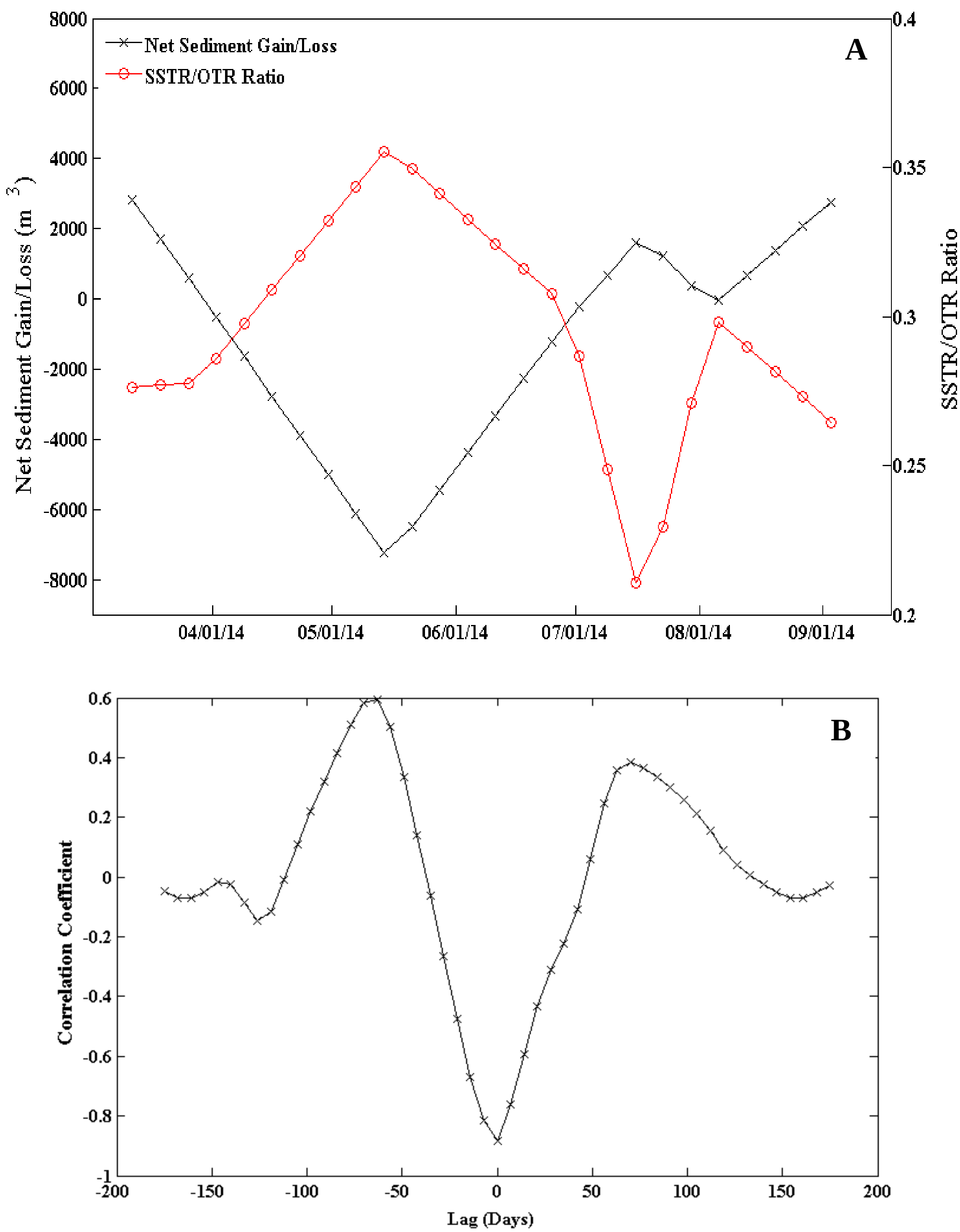


Figure 18. Inverse relationship between the net sediment gain/loss and the SSTR/OTR ratio at Singleton Swash (A) and the result of the correlation analysis (B; maximum R= -0.882, 0 lag).

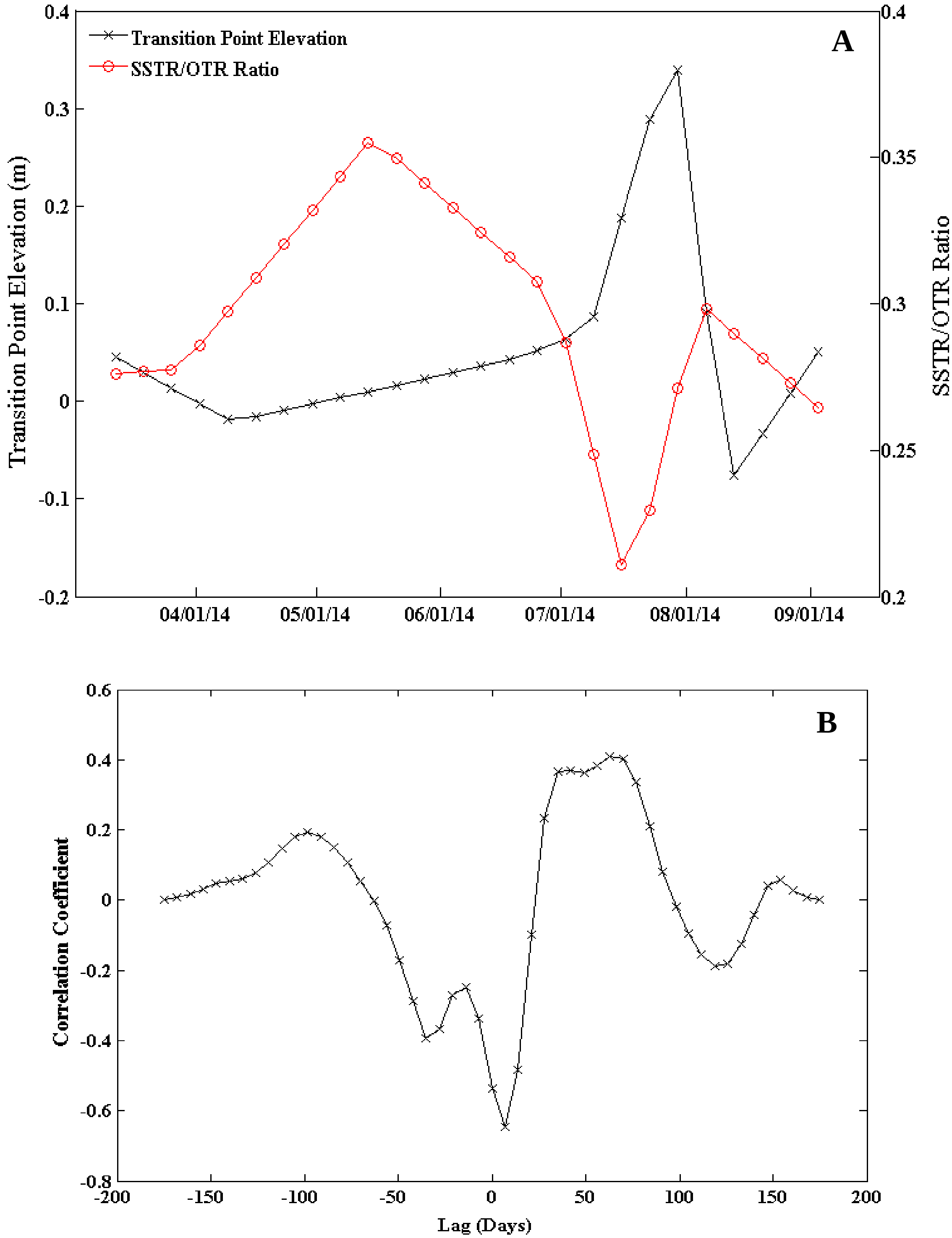


Figure 19. Inverse relationship between the elevation of the transition point and the SSTR/OTR Ratio at Singleton Swash (A) and the result of the correlation analysis (B; maximum R=-0.647, 1 lag).

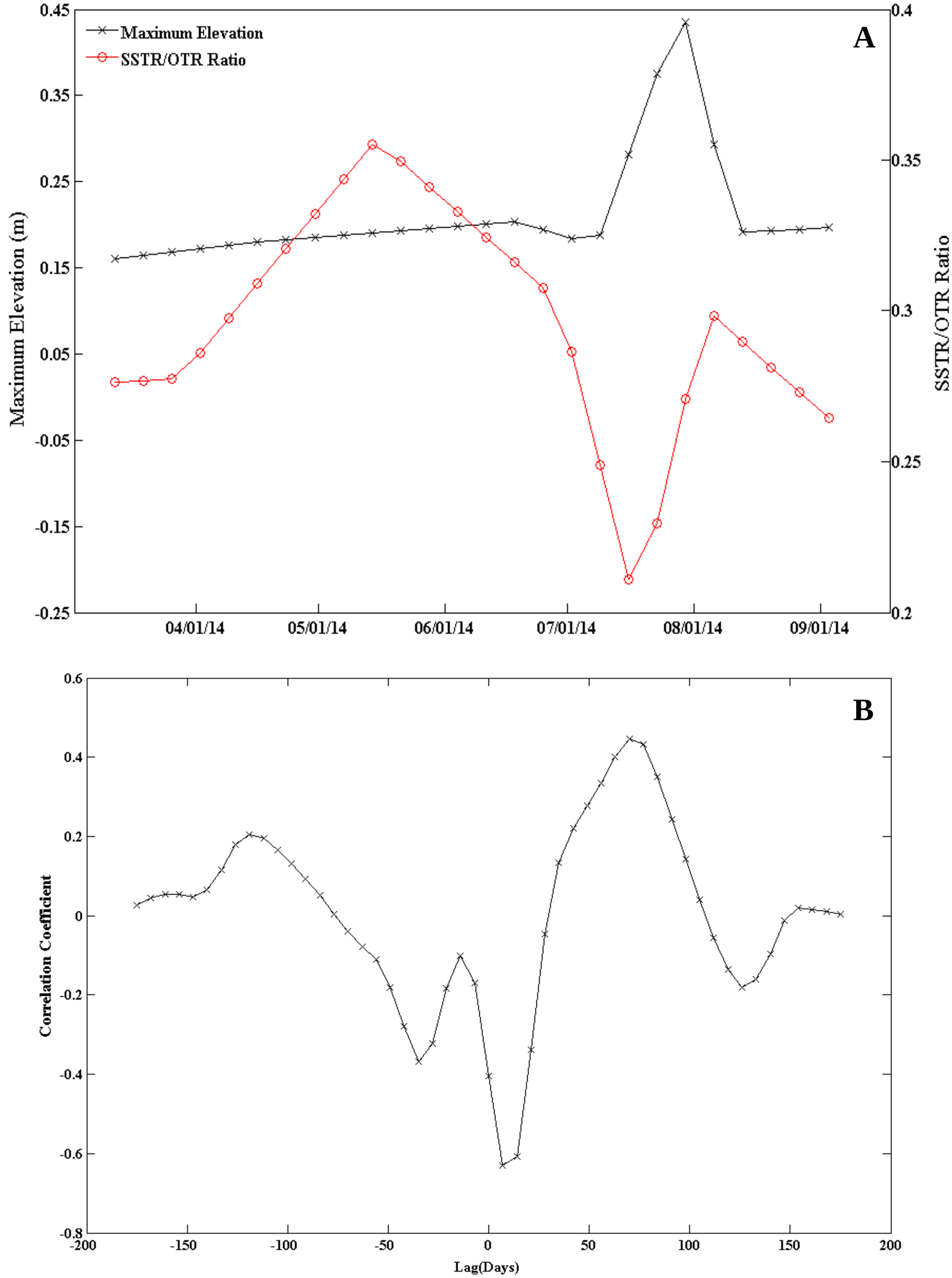


Figure 20. Inverse relationship between the maximum elevation within the creek channel and the SSTR/OTR ratio at Singleton Swash (A) and the result of the correlation analysis (B; maximum R= 0.631, 1 lag).

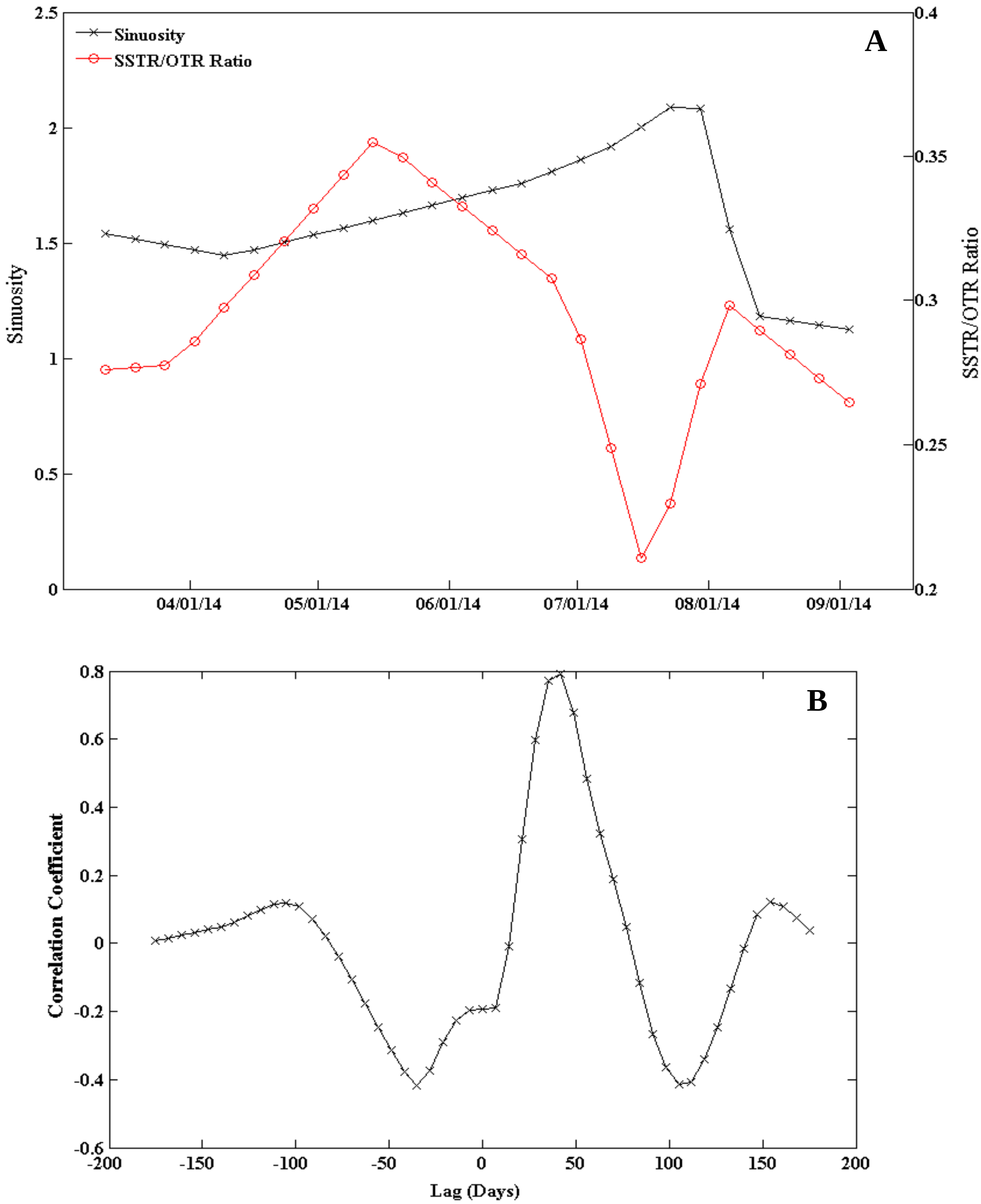


Figure 21. Direct relationship between sinuosity and the SSTR/OTR ratio at Singleton Swash (A) and the result of the correlation analysis (B; maximum R= 0.802, 6 lag).

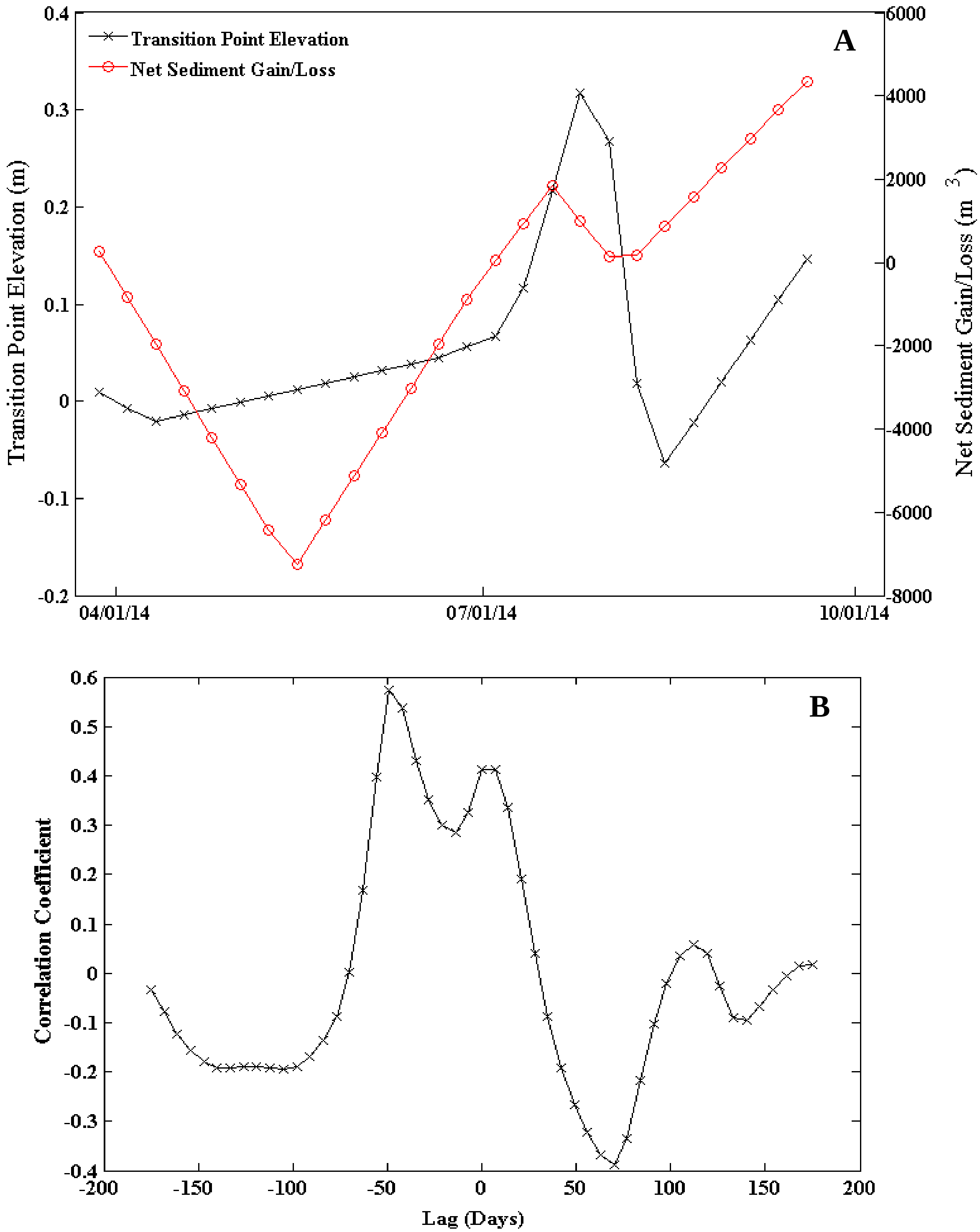


Figure 22. Direct relationship between the elevation of the transition point and the net sediment gain/loss at Singleton Swash (A) and the result of the correlation analysis (B; R=0.413, 0 lag).

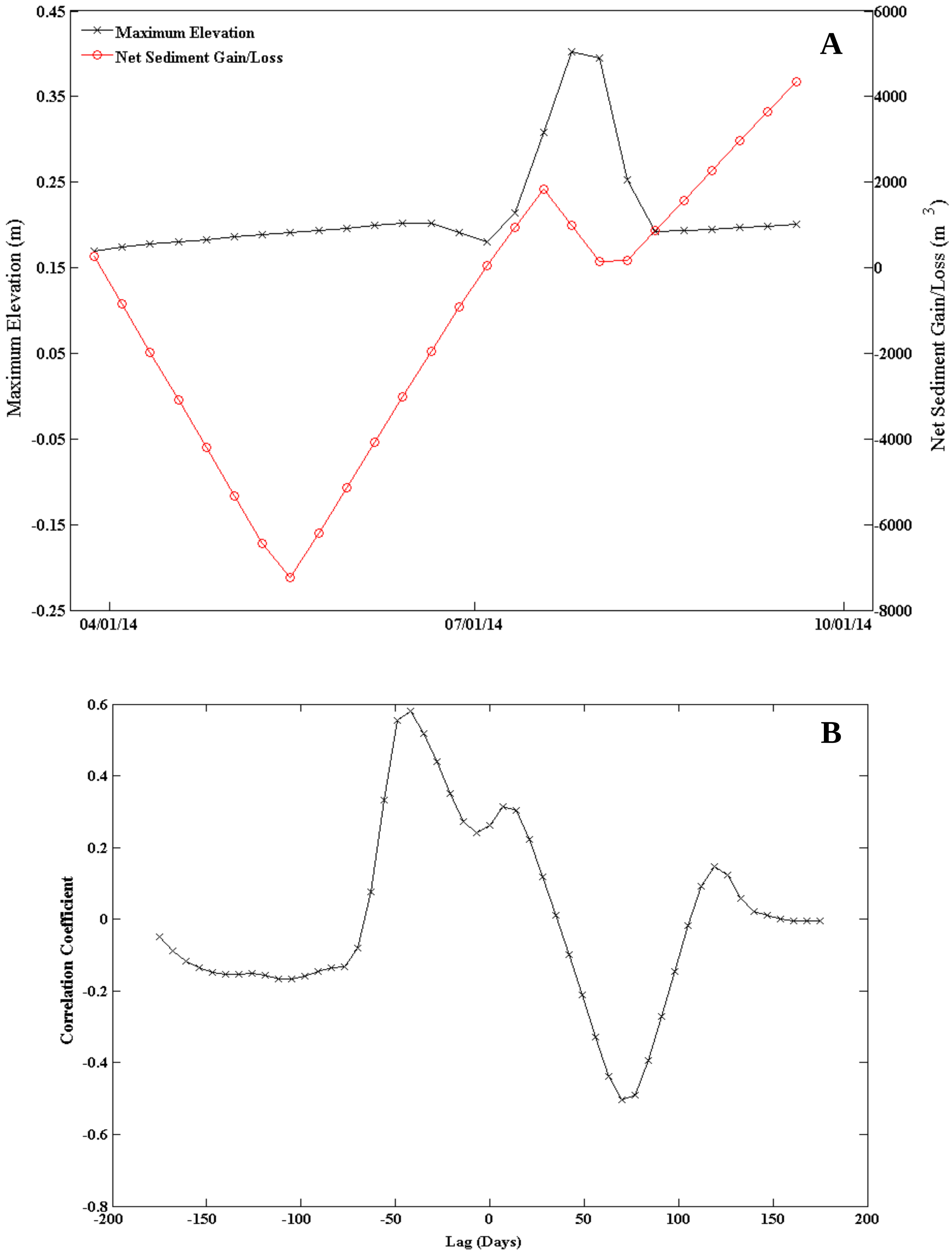


Figure 23. Direct relationship between the maximum elevation for the creek channel and the net sediment gain/loss at Singleton Swash (A) and the result of the correlation analysis (B; R = 0.314, 1 lag)

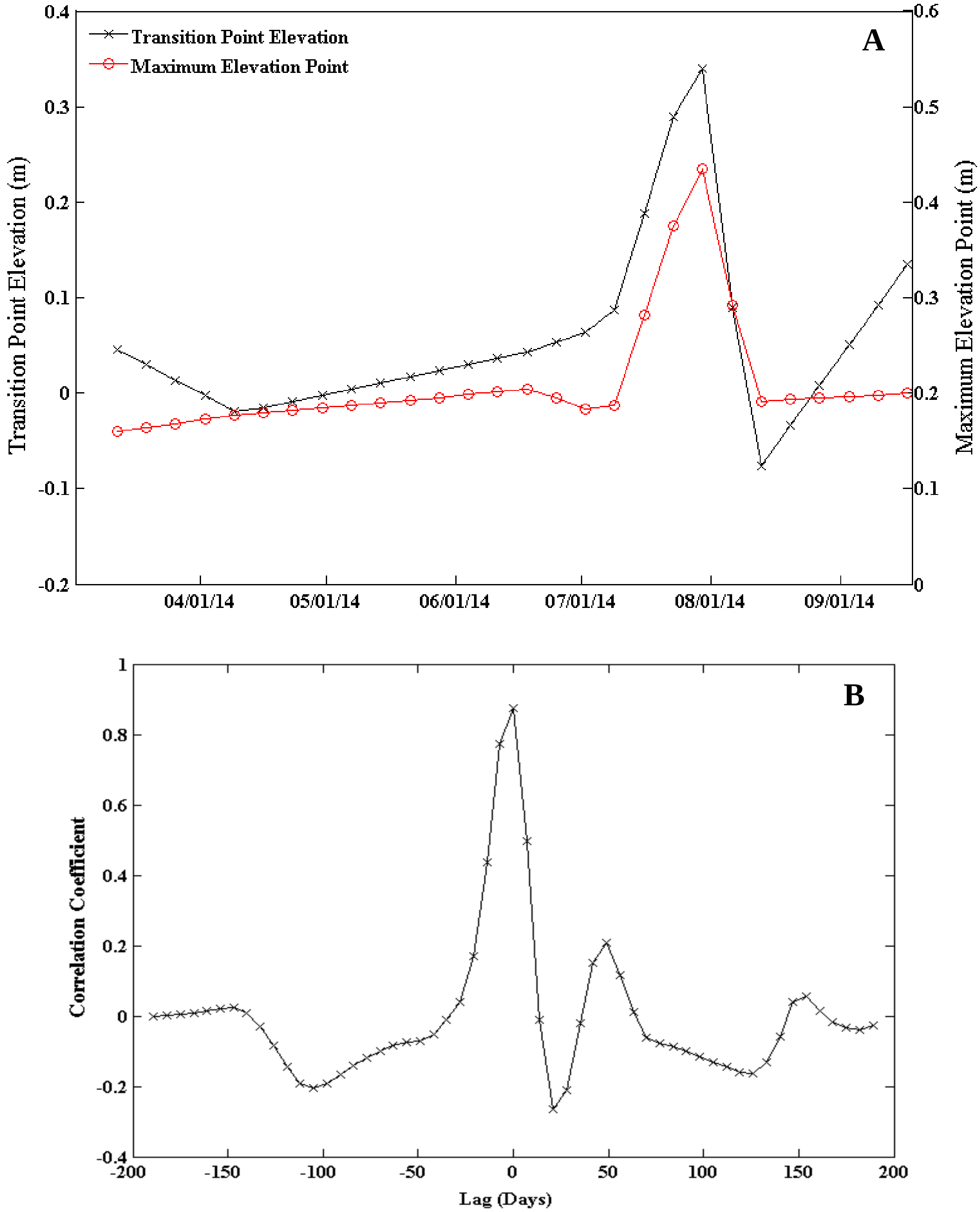


Figure 24. Direct relationship between the elevation of the transition point and the maximum elevation point of the beachface at Singleton Swash (A) and the result of the correlation analysis (B; maximum R=0879, 0 lag).

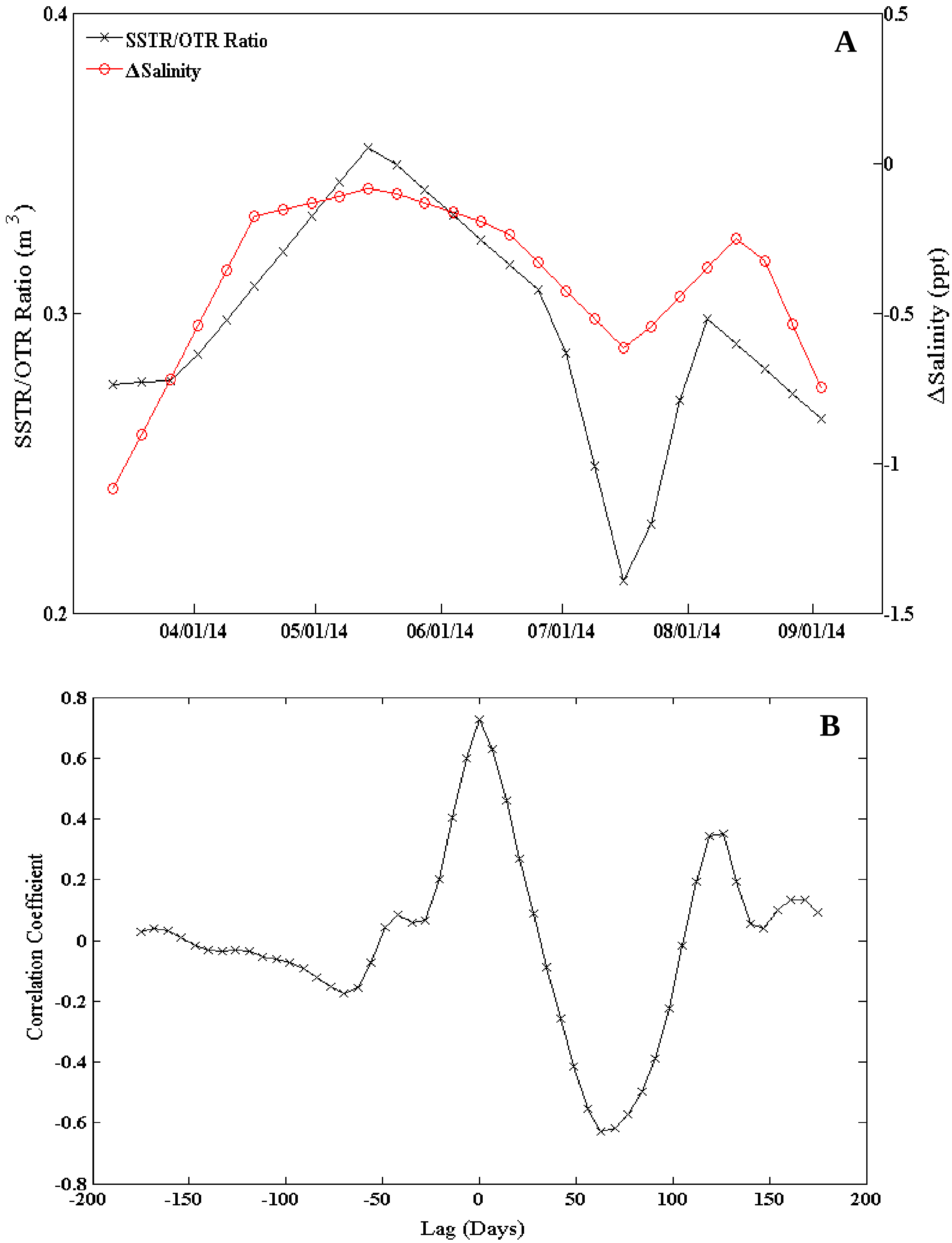


Figure 25. Direct relationship between the SSTR/OTR ratio and the salinity structure in the Singleton Swash basin (A) and the result of the correlation analysis (B; maximum R=0.728, 0 lag).

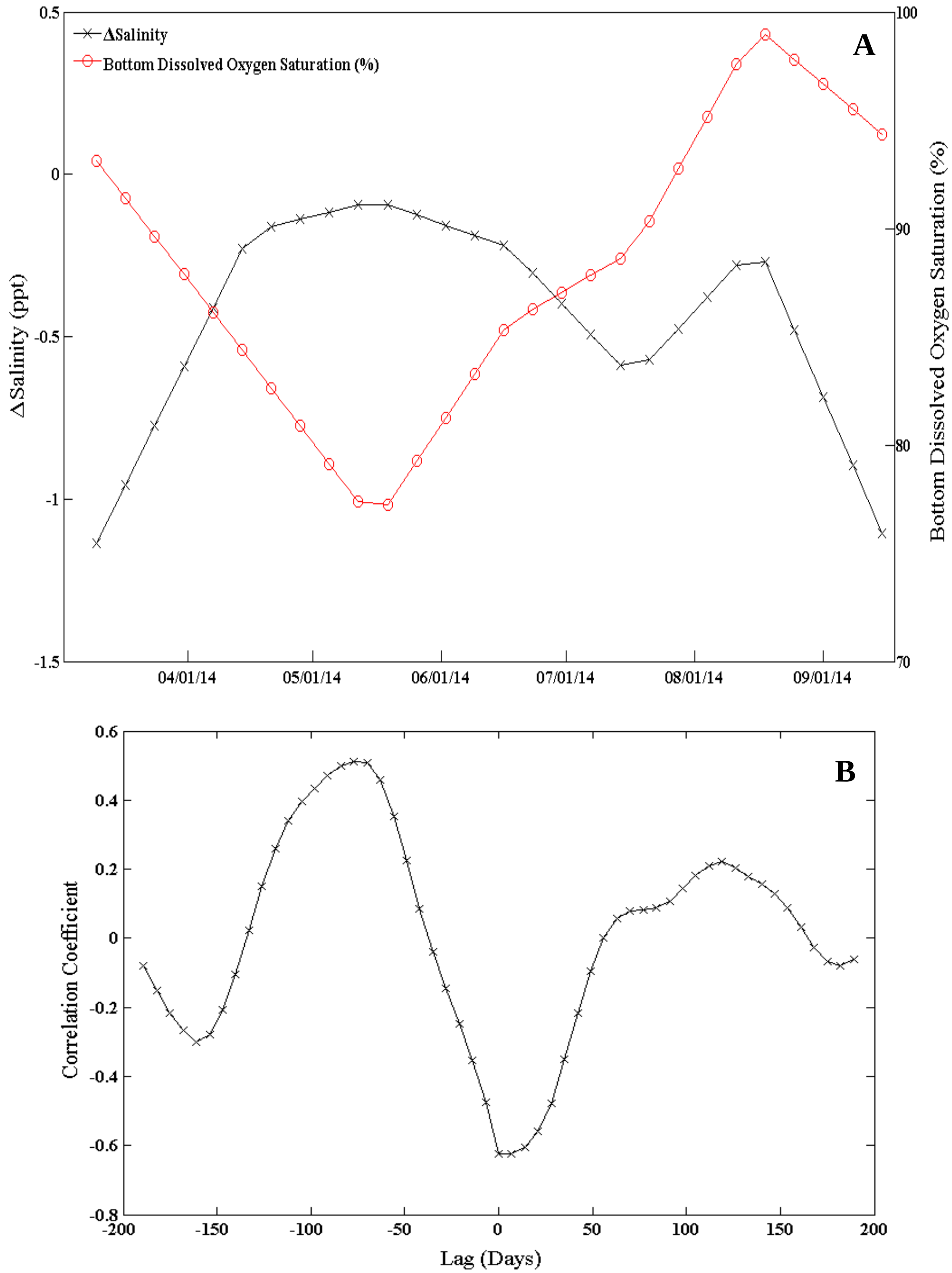


Figure 26. Inverse relationship between the salinity structure and the bottom dissolved oxygen saturation (%) within the Singleton Swash basin (A), and the result of the correlation analysis (B; maximum R= -0.6252, 0 lag).

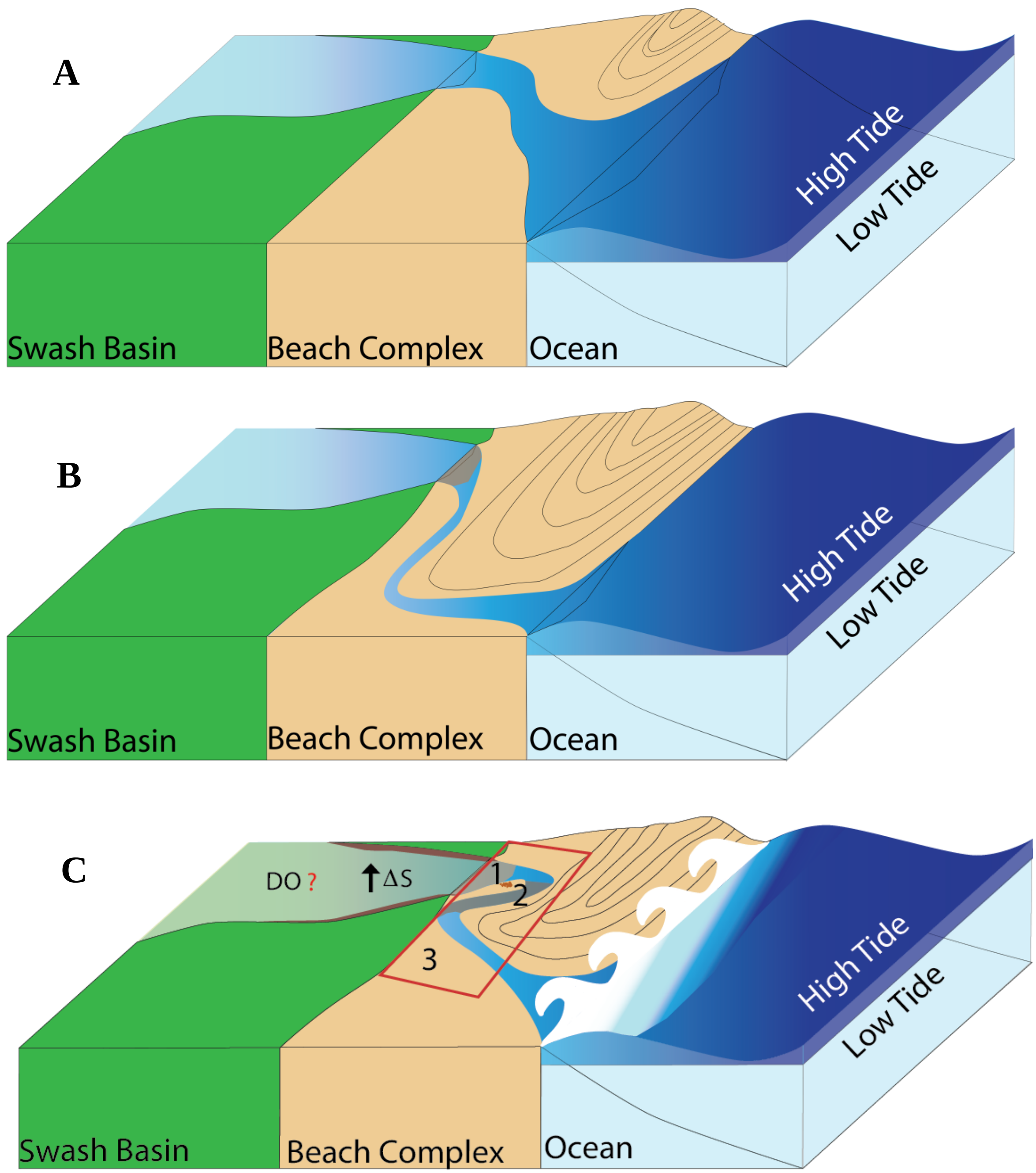


Figure 27. Diagram of the migration process of Singleton Swash. The swash channel crosses the beachface with an open exchange between the swash basin and ocean (A). Coastal processes affect the beachface as seen by the elongation of the sill feature. Changes in elevation at the transition point and sinuosity are observed (B). Once the transition point reaches its upper elevation threshold (1C), sediment is deposited with in the creek channel (2C) and a depositional event is completed (3C). This geomorphic change reduces the tidal range in the swash basin increasing the stratification and eventually reducing levels of bottom dissolved oxygen, affecting the ecosystem health.