Geomorphic evolution of Okains Bay, Banks Peninsula, New Zealand from 1941 to present

Gabe Seidman[1,2], Sam Hampton[1], Josh Borella[1]
[1]*Department of Geological Sciences, University of Canterbury, Christchurch, New Zealand*
[2]*Department of Geology, Oberlin College, Oberlin, OH, USA*

Keywords: coastal hydrosystem, estuary, pocket beach, coastal embayment, aerial photogrammetry

Abstract

Coastal hydrosystems like Okains Bay are important both economically and ecologically, but they are also particularly fragile features. Past work has determined that changes to the morphology of these systems is largely dependent on changes to sediment supply in the long term and punctuated events like earthquakes, storms, and tsunamis in the short term. Many workers believe systems like estuaries, in the absence of punctuated events, exist in a state of 'dynamic equilibrium,' and self-regulate towards a standard morphology. Aerial photogrammetry has proven to be a cheap, effective, and intuitive way to analyze morphological changes over time. An qualitative analysis of Okains Bay as a whole was used to assess broad changes to its morphology. Additionally, three representative features were chosen and their movements over time were measured to assess progradation patterns within the bay. Evaluating the effects of punctuated events on the progradation patterns of these features was complex because of uncertainty in which events affected Okains Bay, and the importance of distinguishing between near-field and far-field results. However, it can be concluded that far-field events tend to lead to greater progradation, whereas near-field events will tend to bring sediment out of the system and cause either slower progradation or active retrogradation. Northwest-southeast trends in progradation rate help show how currents differentially carry sediment to different parts of the bay. It will be important to continue to monitor Okains Bay to see how it adjusts to recent punctuated events and to consider developing management strategies for several possible scenarios.

1. Introduction

Many kinds of coastal hydrosystems, such as coastal embayments and estuaries, have long been recognized as both economically and ecologically valuable (Traini et al., 2015). However, coastal hydrosystems are also notably dynamic, fragile structures, sensitive to a wide range of inputs. Features like estuaries and coastal embayments are temporary, and naturally change shape and fill in with sediment over time (Wassilieff, 2006). However, because of their dynamic nature, it is important to assess how these systems and their surrounding features respond to different inputs in both the short term and the long term. Understanding how coastal hydrosystems initially develop and proceed to change over time has important implications for both coastal management and hazard mitigation efforts. Such an understanding will become increasingly important as sea level rise takes its course and more people move to coastal areas, amplifying already existing coastal management issues (James et al., 2012). This study uses an analysis of aerial photographs of Okains Bay on Banks Peninsula, New Zealand in conjunction with a literature review to assess the system's development in both the short term and the long term, evaluate possible causes of changes to its morphology, and compare these findings to ideas found in the literature. The results highlight the importance of continuing to study and monitor coastal hydrosystems, especially in an environment prone to punctuated events.

2. Geologic setting

Okains Bay is located on the northeast coast of Banks Peninsula (Figure 1). Banks Peninsula consists of the remnants of two Miocene-Pliocene aged shield volcanoes (Stephenson and Shulmeister, 1999). The bays of Banks Peninsula, including Okains Bay, were formed by end-Pleistocene flooding of valleys created by lava flows (Stephenson and Shulmeister, 1999). The small, embayed beaches of these bays are usually bounded on two sides by rocky headlands, which allows only limited longshore sediment movement between them (Hart et al., 2008). Compared to larger bays and open coastal areas within Canterbury, there has been a relatively small amount of research done on Banks Peninsula beaches (Hart et al., 2008).

Compared to other bays on Banks Peninsula, Okains Bay is relatively sheltered (Hart et al., 2008). The beach at Okains Bay is 0.9 km long, confined by basaltic walls (Stephenson and Shulmeister, 1999). Low dunes extend up the valley behind the beach, with a distance of 8 km between the beach and the drainage divide at the top of the valley (Stephenson and Shulmeister, 1999). The sand at Okains Bay is light-coloured, composed primarily of quartz (Hart et al., 2008). While the beach sand comes from greywacke-derived continental shelf deposits, the hinterland of the bay is basaltic. (Stephenson and Shulmeister, 1999). A definite classification of Okains Bay is difficult to determine, but within the literature it is primarily discussed as a coastal embayment, an estuary, or a pocket beach. It is a microtidal, dissipative beach with prevailing northeast-southwest winds (Moghaddam, 2014). Although the bay is relatively exposed to high-energy Pacific swell waves due to its orientation, its rocky headlands limit the direct entry of these waves into the bay (Moghaddam, 2014). A small river, the Opara Stream, flows northeast and enters the bay at its northern end, forming a small estuary (Stephenson and Shulmeister, 1999). This estuary was initially formed as a result of an 1868 far-field tsunami that inundated the entire valley floor, making the river shallower via silt deposition (Ogilvie, 1990; Kain, 2016).

Infilling of Okains Bay began following sea-level stabilization in the mid-Holocene, with sediment sourced mainly from the Southland Current (Stephenson and Shulmeister, 1999). Over time, due to the curvature of Pegasus Bay and the surrounding area, the Southland Current built up a banner bank north of Banks Peninsula. This banner bank is now considered the immediate source of sediment for the northeast bays of Banks Peninsula, including Okains Bay (Stephenson and Shulmeister, 1999). Holocene progradation of the bay is indicated by a dune and ridge complex on its northeastern side (Stephenson and Shulmeister, 1999).

3. Past work

3.1 Coastal hydrosystems -- terminology and classification – Categorizing Okains Bay

The dynamic nature of coastal systems has historically made developing a classification scheme difficult, especially since such systems are so variable on global, and even regional scales. Hume et al. (2016) developed a categorization scheme specifically for New Zealand coastal hydrosystems, using a hierarchy classification with six levels: global, hydrosystem, geomorphic class, tidal regime, structural class, and composition (Table 1). The scheme is presented at the geomorphic class level because it is considered the most important from a management perspective on multiple scales (Hume et al., 2016).

Categorizing Okains Bay within this system is somewhat difficult, not only because of the newness of Hume et al.'s hierarchy, but also because Okains Bay has not been extensively covered in the literature. Hume et al. broadly categorize the bays on Banks Peninsula as coastal embayments (Hume et al., 2016). However, Okains Bay has been referred to as an estuary in previous publications (Stephenson and Shulmeister, 1999), and its entrance is not wide as suggested by Hume et al.'s hierarchy (Table 1). Hume et al.'s (2016) given definition of tidal river mouth also fits Okains Bay fairly well, further complicating things (Table 1). However, Hume et al. (2016) recognize that 'estuary' is a vague term, and acknowledge that the use of the word, along with many other terms like 'lagoon', 'wetland', or 'coastal lake', vary widely depending on location, discipline, and author. Because relatively little has been written on 'coastal embayments,' literature on 'estuaries' was reviewed for the purposes of this study.

3.2 Estuaries

a. Definition and classification

Estuaries are a somewhat controversial topic, and are defined and categorized a number of different ways depending on the context in which they are being discussed. According to Arnoldo Valle-Levinson (2010), one of the earliest comprehensive definitions was proposed by Cameron and Pritchard in 1963, in a paper that defined an estuary by three criteria: it must be a semi-enclosed coastal body of water; it must have free communication with the ocean; and ocean water must be diluted by freshwater derived from land. Cameron and Pritchard (1963) made us of several schemes to categorize estuaries: based on water balance; based on geomorphology; based on vertical salinity structure; and based on hydrodynamics (Valle-Levinson, 2010). Pye and Blott (2014) further detailed the evolution of the estuary concept, expanding upon the categorization scheme introduced by Cameron and Pritchard (1963) but also noting that their definition is insufficient because it does not include the lower tidal reaches of rivers where water levels are influenced by tidal forcing but water is entirely fresh. Pye and Blott (2014) also introduced further definitions from the literature. Of these definitions comes from Dionne (1963), who defined an estuary as an inlet of the sea that extends as far as the upper limit of the tidal rise, divisible into three parts: a marine or lower estuary, freely connected to the open sea; a middle estuary, with strong mixing between seawater and freshwater; and an upper or fluvial estuary, characterized by freshwater but subject to daily tidal influence (Pye and Blott, 2014). Another definition from Fairbridge (1980) divided estuaries into two types, restricted and unrestricted, depending on entrance type (Pye and Blott, 2014). Table 2 summarizes these classification schemes (Table 2).

Based on these schemes, Pye and Blott (2014) developed further criteria to separate estuaries from other features such as a tidal inlet. They cite the following features as definitive: presence of tidally-influenced freshwater at the estuary's head; a marked lateral salinity gradient; the occurrence of a turbidity maximum at the inner part of the estuary; periodic erosion and re-deposition of bed sediment by river floods; and a spatial transition from tidal freshwater marsh, through brackish marsh to saltmarsh, reflected by varied sedimentological and biotic features.

Prandle, Lane, and Manning (2005), building upon the previously established categorization of estuaries, sought to establish new typologies for describing estuarine morphology. Their aim was to construct new frameworks based on the primary forcing parameters of tidal amplitude and river flow in order to provide new context for examining the sensitivity of estuaries to various climate change scenarios. Based on these parameters, they developed a typology using terminology similar to Cameron and Pritchard's (1963) geomorphology-based scheme, but in more quantitative terms. Table 3 summarizes Prandle, Lane, and Manning's (2005) scheme (Table 3).

b. *Estuary development*

There has been much discussion on which factors contribute to estuary development. Although several factors have been identified and their effects quantified, most authors recognize a significant amount of uncertainty in any such assessment due to the sensitive, complex, and open nature of estuary systems. Dronkers (1986) argued that estuary evolution depends most essentially on sediment supply and its transport in the long term and abrupt morphology changes caused by storm surges or engineering works in the short term.

i. *Long-term change*

Dronkers (1986) expands on his first factor by arguing that sediment supply and transport in itself depends on several other influences: river inflow, sediment characteristics, wind waves and swell, and current velocity distribution and variations during a tidal cycle. In their findings in a study on long-term morphological change of the Changjiang Estuary in China, Wang et al. (2013) mostly agree with Dronkers, arguing that the major factors contributing to long-term evolution are river flow, sediment discharge, tide currents, and wave fields, along with anthropogenic activities. They argue that recently, since approximately the 1950s, human impacts have outweighed natural forcing factors as agents of long-term morphological changes. Traini et al. (2015), in a study comparing natural evolution and human impacts on the development of the Vilaine Estuary in France, found similar results. They concluded that the primary natural controls on estuary development are morphology, which control accommodation space, hydrodynamic parameters like river discharge, wind-waves, and tides, and breaking wave activity. Like Wang et al. (2013), they argue that human impact has become increasingly important relative to natural forcing, such that the 1970 construction of a dam 8 km from the river mouth has overtaken natural factors as the primary contributor to morphological change in the estuary.

The concept of long-term estuary equilibrium has been much discussed over the past several decades. One common way of thinking of estuary evolution is the concept of dynamic equilibrium, which is the idea that the ratio of certain estuarine dimensions, including channels and tidal flats) remain constant over time but the estuary overall rises in elevation or moves laterally (Pye and Blott, 2014). Many authors have used the concept of dynamic equilibrium as a way of thinking about what an estuary does between large changes in morphology. Wang et al. (2013), for example, found that the Yangtze estuary in China was approaching a state of dynamic equilibrium because coastlines and thalwegs had become straighter and more aligned with the progradation direction of the offshore tidal current. However, dynamic equilibrium remains a controversial idea. According to Pye and Blott (2014), dynamic equilibrium may be a common situation for estuaries, but cannot be assumed. They found that dynamic equilibrium arises when a balance is achieved between contemporary sediment supply, estuary morphology, and the sediment transport capacity of estuary flows. Estuaries may approach this state in the absence of sudden changes, but it should not be assumed that estuaries will tend towards self-regulation because a range of states is possible depending on the type of forcing and antecedent conditions (Pye and Blott, 2014).

ii. Short-term change

A primary goal of this study is to determine how short-term geologic events such as earthquakes, tsunamis, and storm surges can affect the development of coastal hydrosystems such as estuaries. Cooper (2002) found that in the case of flooding events caused by storm surges or tsunamis, tide-dominated and river-dominated estuaries react differently. In tide-dominated estuaries, there is preferential erosion of noncohesive barrier and tidal delta sediments, with the middle reaches of the estuary largely unmodified. In river-dominated estuaries, vegetation causes increased cohesion of sediments and stabilization of bars, so higher magnitude floods are necessary to cause significant change. However, river-dominated estuaries may take decades to adjust to post-flood conditions, while tide-dominated estuaries respond more rapidly and adjust fully within months to years.

In a study of the impact of the December 2004 tsunami on the Vellar Estuary in India, Pari et al. (2008) found that sand dunes of varying elevations may act as natural barriers and cause varied impact along a coastline. The tsunami caused a loss of beach sediments for about a year following the event, and replenishment occurred the year following. Rodriguez-Ramirez et al. (2016), studying how extreme wave events such as tsunamis were recorded in the rock record at the Guadalquivir Estuary in Spain, found that extreme wave events like tsunamis and storm surges may lead to the development of a wide range of geomorphological and sedimentary features, such as washover fans, paleocliffs or erosion scarps, coarse gravel deposits, crevasse splays, and sedimentary lags. In another study on the same estuary, Rodriguez-Ramirez et al. (2014) concluded that neotectonic activity, which can affect sedimentation rates, create new features, cause sea level oscillations, and cause subsidence, should be included as a factor that affects estuary development in the short term.

.

3.3 Coastal hydrosystem management and hazard mitigation

Understanding how a coastal hydrosystem like Okains Bay develops can have implications for how that area is managed. In addition to long-term changes, short-term shifts, especially those caused by geologic events such as earthquakes, tsunamis, and storm surges are particularly important to evaluate from a management point of view. New Zealand, an especially tectonically active environment, is especially prone to these events. One recent event, the 2010-2011 Canterbury earthquake sequence (CES) included the moment magnitude (M_w) 7.1 Darfield earthquake and M_w 6.2, 6.0, 5.9, and 5.8 aftershocks, all of which had lasting effects across the region (Quigley et al., 2016). The more recent 2016 M_w 7.8 Kaikoura earthquake also had lasting effects across the region.

A recent study on the effects of the CES on the Avon-Heathcote estuary in Christchurch City demonstrates how changes to an estuary can affect a management situation. The sequence, particularly the 22 February 2011 earthquake, caused changes to bed height and bathymetry, broad-scale liquefaction, and input of raw wastewater into the rivers and estuary. Through LiDAR and ground surveys, ECAN found that the northern part of the estuary subsided 0.2 - 0.5 m, while the southern part rose 0.3 – 0.5 m (ECAN, 2011). This deformation, along with liquefaction, had long-lasting effects on water transport, the estuarine ecosystem, and food safety in the area (ECAN, 2011). Quigley et al. found that estuarine flora and fauna were especially affected by the CES. These flora and fauna are particularly sensitive to salinity and tidal elevation changes, and vertical deformation caused by the CES forced them into non-preferred zones (Quigley et al., 2016). Another study found that on a broad scale, increases in tectonic and liquefaction-induced subsidence, urban waterway profile changes, and sediment regime changes associated with seismic activity will lead to more frequent and severe inundation hazards in the future (Hughes et al., 2015).

Although the changes to Okains Bay, both in the short term and the long term, are not likely to resemble the changes to the Avon-Heathcote estuary, the studies detailed above show how important coastal hydrosystems are as resources and how fragile they can be. These assessments underline the necessity of understanding the causes of changes to these systems, especially at a time when coastal areas are becoming increasingly populated and sea level rise is becoming more of an issue. By evaluating changes to Okains Bay over the past ~75 years, this study aims to develop an understanding of what has caused these changes and how they may affect coastal management practices.

3.4 Aerial photogrammetry – history and progress

This study uses the GIS program ArcMap and Corel Draw in conjunction to analyze aerial photographs and assess how the Okains Bay estuary has changed over time. Aerial photography has a long history as a tool used to examine landscape evolution over time. As technology has developed and become more accessible and inexpensive, so has aerial photography. Early workers were enthusiastic about how the use of aerial photography would develop in future years. Colwell (1965) wrote that at the time, there were two schools of thought regarding how information might be best obtained from aerial photos. One school believed that the extraction of information from photos was a highly subjective process, and that the human analyst must be familiar with the topic being studies and have the ability to apply obscure logic. Another school believed that recognition was achieved by simple observations of size, shape, shadow, tone, texture, and pattern characteristics, an analysis which could potentially be accomplished by a machine. Colwell separated data extraction into two categories.

Photogrammetry, defined as the art of obtaining reliable measurements by means of photography, usually led to the creation of maps. Photo interpretation, meanwhile, was the examination of images to identify and interpret objects. Another early proponent of aerial photography, Steiner (1965), argued for the use of aerial photography specifically for mapping land use, citing practical use in projects like acreage determination, land classification, soil and vegetation surveys, outdoor recreation and wildlife planning, floodplain studies, urban impacts, crop yield estimations, and more.

Bowden and Brooner (1970) provided a compelling case for aerial photography as a data gathering tool. They detail several key reasons why aerial photographs, when properly interpreted, are effective analytical tools: they provide an improved vantage point; they often offer better resolution than the unaided human eye; human vision is spectrally limited compared to the photographic spectrum; aerial photographs can provide a historical archive; one can determine distances, vectors, and areas with more accuracy than on the ground; operation and processing is very simple; and equipment is cheap, compact, and lightweight. Compared to these advantages, the disadvantages Brooner and Bowden present are fairly tame: there is a need for clear weather and adequate sunlight; there is a delay time between exposure and processing; and photographic sensors do not provide broad data – they only record a document graphic record of on point in time. Steffensen and McGregor (1976) verified several of these advantages with an ecological study of the Avon-Heathcote Estuary in Christchurch. They found that aerial photography, a simple, inexpensive method, could be used to produce reasonable accurate maps of the benthic algae, drainage pattern, and shoreline of the estuary. They concluded that comparatively simple techniques can provide very useful and relatively accurate results at an affordable cost with little equipment and training.

Photogrammetry developed quickly following initial studies like those above. Since the turn of the century, aerial photography techniques have been increasingly used alongside other, more advanced methods. Hapke and Richmond (2000) demonstrated that although a variety of techniques were available by this time for monitoring morphology changes, aerial photography remained a useful and relatively accurate method of assessment. They argued that although a common technique, regular beach profiling, was accurate, large spacing between profiles led to gaps in spatial data, which aerial photo analysis could help to rectify. This study begins to show how technological advancements affected the use of aerial photography as a tool. Hapke and Richmond recognized inherent distortions that can occur in aerial photography resulting from the geometry of the camera system, the change in the position of the aircraft between photos, and ground relief, and processed their imagery to remove these errors. They also used these aerial photos to created digital elevation models (DEMs). Hapke and Richmond's concern with accuracy became an important part of aerial photo analysis as time passed. Hughes et al. (2006) investigated how the process of georectification, or the matching of an unreferenced aerial photo to a referenced map in a GIS software, may contribute to error in the measurement of lateral channel movement. Noting that GIS and remote sensing were playing increasingly significant roles in geomorphological studies, they found that georectification is a very sensitive process, largely because its controls are user-defined, with the human user selecting ground control points (GCPs).

In addition to Hapke and Richmond, several other studies have used aerial photography in conjunction with DEMs to assess geomorphological change. Schiefer et al. (2007) found that

DEMs can be produced directly from aerial photographs with consistent precision, an approach that can utilize historical photographs that are readily available in many parts of the world. They argue for an approach of generating several DEM surfaces and subtracting sections from one another to quantify landscape change over a period of time. James et al. (2012) worked to recognize and minimize uncertainties in data created with this DEM subtraction method. They argue that cartography is becoming a four-dimensional discipline, with historical reconstructions gaining increased recognition in the field. They found that in the present state, uncertainties in historical mapping using DEM subtraction tend to be relatively large, and further advancements are needed to make it a sufficiently reliable method of study.

4. Methods

Twelve aerial photographs from the years 1941, 1966, 1970, 1975, 1984, 1993, 2002, 2009, 2011, 2014, and 2017 were obtained. The photos from 1941, 1966, 1970, 1975, 1984, and 1993 were obtained from the Canterbury Maps online database. The photos from 2002, 2009, 2011, and 2014 were obtained using Google Earth. The photo from 2017 was obtained first-hand using a drone.

Each photo was imported into ArcGIS and georeferenced to a 2014 (KiwiImage) base map using the Georeferencing tool in ArcMap. For each photo, between five and fifteen control points were used. Control points were chosen based on their permanence and resolution in each photo, and were primarily features around the beach, estuary mouth, and Opara River. After georeferencing, a layout view was utilized to view and export images as .tiff files for further analysis.

Each georeferenced photo was then imported into a blank CorelDrawX7 file, each on a separate page. Features were then traced onto each photo, with each feature within its own layer. These features included the extent of the estuary overall, the channel and any smaller streams coming from it, any visible sand bars, the line delineating the dune from the berm (determined by the beginning of dune vegetation), the line delineating the berm from the spit (determined by the top of a slope descending down the beach), and the line delineating the spit from an accretionary wedge extending offshore (Figure 2). These features were chosen because they are mostly visible in every available photo and are the most likely to change significantly within the timeframe being studied. They were also chosen because a very specific set of parameters could be used to identify them in each photo. A legend was created using for these features using CorelDraw (Figure 4).

After features were traced onto each photo, a new CorelDraw file was opened, and a separate page was created for each feature. The traced lines from each photo were then imported from the original file such that each feature page had a line from each year. The year each line belonged to was identified by varying the lines' colours. Then, a 200 m^2 square was drawn onto the image using the scale and scaled up to a size of 200 cm within the program. Then, for the dune line, all the years' representative lines were scaled by the same amount as the square. The same was done for the berm line and the spit line. For each of these three features, three transects were chosen to represent the southeast, central, and northeast section of the study area. These three transects were labelled T1, T2, and T3, respectively. An additional transect, T4, was also chosen for each of the three features based on their individual movement patterns (Figure 3).

Lines were then drawn along these transects between consecutive timestamps' lines. The length of each of these lines could then be correlated with the distance the feature moved between years along that transect.

Values were entered into Excel as they were obtained. Using these distances, an average progradation rate between each timestamp was calculated, as was total distance moved along each transect. For each feature, the total progradation along each transect was then plotted against time. Then, an inventory was compiled detailing punctuated events, such as storms and earthquakes, that may have contributed to changes in progradation rates within Okains Bay. These events were ranked based on the likelihood that they affected the bay (Table 4). Using Corel Drawl, these events were drawn into the graphs of progradation vs.time. Following this graphical analysis, a composite figure of sedimentation systems at Okains Bay was created as a reference for the process of deposition in the study area (Figure 8).

A number of limitations are inherent to this methodology. Although aerial photo analysis is cheap, relatively accurate, and requires little training, it can sometimes be difficult to resolve features, especially within older photographs. Additionally, aerial photographs only provide a 'snapshot' of one time on one day, and what is seen in any given photo can be dependent on a number of factors ranging from weather changes to daily tidal and fluvial fluctuations. The tide can be determined retroactively for photos that are marked with the time they were taken, but many of the photos do not have such a timestamp. One example of problems this limitation can cause is that sand bars have been outlined in each photo, but it is difficult to determine with certainty whether the presence or absence of these sand bars is due to structural changes or daily fluctuations. Another limitation of aerial photo analysis is that it is inherently qualitative compared to other modes of analysis. However, this limitation was mitigated as much as possible with the creation of a prescribed set of rules for delineating features from one another.

5. Results

5.1 Evolution of chosen features

a. Channel and sand bars

Between 1941 and 1966, there is little change. Two small sand bars develop directly northeast of the bridge. The large sand bar on the northeast side of the estuary changes shape and becomes wider, with its northeast boundary migrating upstream, but its basic position is retained. The estuary's mouth closely hugs the northwestern headlands. Between 1966 and 1970, there is also little change, except a small sand bar develops close to the estuary's mouth. In 1975, the two small sand bars northeast of the bridge are no longer visible, but a larger sand bar can be seen slightly northeast of where they had been. The channel mouth becomes directed in a more southeast direction, no longer hugging the headlands (Figures 4 and 5).

By 1984, another small sand bar can be seen directly southwest of the sand bar that was seen near the bridge in 1975. The estuary's mouth is again directed in a more southeast direction. By 1993, however, it is again directed more northwest, staying close to the headlands as it was in 1966. By 1993, the small sand bar seen in 1984 is no longer there. Between the 1993 and 2002 photos, little change can be seen, except that the estuary's mouth is again directed further southeast. In the 2009 photo, the channel is particularly wide, and the estuary's mouth again hugs the headlands. Between 2009 and 2014, no significant changes can be seen in the photos. The sand bars fluctuate in size, but retain their basic shapes. The estuary's mouth again migrates slightly southeast, but the shift is relatively small compared to previous changes. In 2017, the small section of imagery available shows a wide channel cutting across the large sand bar near the estuary's mouth. The mouth again closely hugs the northwestern headlands (Figures 4 and 5).

b. Dune line

Between 1941 and 2017, the dune line migrated significantly to the northwest, moving a maximum distance of 256 m along T4. The dune line migrated gradually, and there is no evidence of sudden or dramatic shifts. There was, however, a relatively calm period from 1975 to 1993 when the dune prograded at a slower rate than it did otherwise (Figure 6). The movement of the dune line was accompanied by a steady increase in vegetation on the dune and within what is today the campsite (Figure 4). Along T1, the dune line's average rate of movement per year was 1.73 m/yr. Along T2 it was 1.65 m/yr. Along T3 it was 1.73 m/yr, and along T4 it was 2.90 m/yr. The average progradation rate for the dune line along all four transects was 2.00 m/yr (Figure 6).

c. Berm line

Between 1941 and 2017, the berm line fairly consistently prograded outward, moving a maximum distance of 127 m along T1.The berm line moved more erratically than the dune line, and experienced a few punctuated moments of retrogradation (Figure 6). These moments occurred in the years 1975, 1993, 2014, and 2017 (Figure 6). Along T1, the berm line's average rate of movement per year was 1.62 m/yr. Along T2, it was 1.13 m/yr. Along T3 its average rate was 1.07 m/yr, and along T4 it was 0.70 m/yr. The average progradation rate for the berm line along all four transects was 1.13 m/yr (Figure 6).

d. Spit line

Between 1941 and 2017, the spit line moved erratically, following less of a pattern than either the dune line or the berm line. It followed a general pattern of progradation from 1941 to 2014, and has since retrograded significantly since 2014. It moved a maximum distance of 172 m along T4. The pattern of progradation, however, was interrupted by several punctuated moments of retrogradation (Figure 6). These moments occurred in the years 1975, 2009, and 2014. However, not all four transects follow this pattern consistently (Figure 6). Along T1, the spit line's average rate of movement per year was 1.88 m/yr. Along T2, it was 0.94 m/yr. Along T3, its average rate was 0.08 m/yr, and along T4 it was 1.72 m/yr. The average progradation rate for the spit line along all four transects was 1.16 m/yr.

e. Wedge line

The wedge seems to fluctuate between three or four general positions over time, gradually moving back and forth between these positions. These positions correlate with the orientation of the estuary mouth (Figure 4). Today, the wedge constrains the estuary very close to the northwestern headlands (Figure 4).

5.2 *Progradation patterns*

a. Correlation with punctuated events

The dune line's calm period occurred during a time when now punctuated events reached Okains Bay (1975-1997). The dune line's only times of retrogradation were shortly after punctuated events, like the 1975 Ex-tropical storm Alison, the 2010 Chilean Tsunami and 2010-2011 Canterbury Earthquake Sequence, and the 2014 Canterbury and Lower North Island Storm (Figure 6, Table 4). The berm line experienced a spike in its progradation rate corresponding to the 1968 ex-tropical storm Giselle, and a period of retrogradation corresponding to the 1975 ex-tropical storm Alison (Figure 6, Table 4). Additionally, the berm line retrograded significantly around 2014 and 2016, around the time of the Canterbury and Lower North Island Storm and the Kaikoura Earthquake, respectively (Figure 6, Table 4).The spit line follows less of a pattern than the dune line and the berm line, but experienced significant retrogradation around the times of the 1968 ex-tropical storm Giselle, the 1975 ex-tropical storm Alison, the 2007 Lower North Island and South Island Storm, the 2008 North Island Snow and South Island Thunderstorms, the 2014 Canterbury and Lower North Island Storm and the 2016 Kaikoura Earthquake (Figure 6, Table 4). All three features were prograding relatively quickly during the time of the 1960 Chilean Tsunami and retrograded following the 2014 and 2016 events (Figure 6).

b. NW-SE patterns

For each of the three lines analyzed, the locations of the four transects helps assess how that line's progradation may change moving from southeast to northwest along the shore (Figure 3). The dune line progrades faster to the northwest than to the southeast, and progrades especially fast along T4, which points north (Figure 6). The berm line, meanwhile, progrades faster to the southeast than the northwest, and progrades especially slowly along T4, close to the estuary's mouth (Figure 6). The spit line does not follow a clear NW-SE pattern, and is much more oscillatory in its movement than the other two lines (Figure 6).

5.3 *Sedimentological Model*

A basic, preliminary seidmentological model was drafted to demonstrate how sediment reaches Okains Bay and help evaluate the reasons for the changes to the bay's morphology. The figure shows currents approaching from the northeast. These currents, originating from the Southland Current, would be carrying sediment from the banner bank, shown inset (Figure 8). Since Okains Bay is microtidal, wave action dominates. However, the channel plays the important role remobilizing sediment brought in and carrying it back out into the bay.

6. Discussion

The results show that the dune line, the berm line, and the spit line have gained and lost sediment following differing patterns. Broadly, the dune builds gradually, without much oscillation, whereas the spit builds erratically and the berm falls somewhere in between (Figure 6). Additionally, the three features prograde a notably different rates proceeding from southeast to northwest. The results also suggest, but do not necessarily confirm, that the progradation rates of the dune line, berm line, and spit line are sensitive to punctuated events such as earthquakes, storms, and tsunamis. The morphology of the channel itself, however, does not change significantly, with the exception of the direction of the estuary's mouth. These changes are more difficult to correlate with punctuated events. The goal of this discussion is to evaluate possible and probable causes of the various changes to Okains Bay's morphology and relate this study's findings to previous work. A preliminary sedimentological model was created to aid in the discussion of what may have caused these various changes (Figure 8).

The sedimentological model was drafted to differentiate between incoming and outgoing currents and to illustrate how these movements have led to the development of Okains Bay's unique shape (Figure 8). Waves bring in sediment from the banner bank. Some of this sediment is deposited directly onto the beach on its southeastern half. This deposition is evidenced by the outward curve of the beach, at its southeast end, marked on the figure as “Zone of active deposition and progradation” (Figure 8). Meanwhile, the current also brings some sediment sediment into the bay. Because the bay is tide-dominated, this movement of ocean water into the bay is an important moment of sediment flux. In the case of very large waves, the bay can be significantly inundated, and may even be entirely submerged as it was in the 1868 tsunami event that led to the initial formation of the bay's estuary. When the ocean water moves into the bay, it mixes with the channel. It may deposit sediment into the bay, and will also remobilize sediments around the channel. On its way out, the water will take some of this sediment with it, and the channel will push some out as well.

Assessing how Okains Bay changes around punctuated events like earthquakes, storms, and tsunamis can help flesh out the sedimentological model and understand how these events affect the sediment budget. In the case of the channel and sand bars, it is difficult to to tell what effect these events may have had, especially because changes seen in aerial photos may be due to daily tidal fluctuations rather than long-term changes caused by punctuated events. However, it is likely the emergence of new sand bars that retain their positions has to do with depositional events, whereas the disappearance of sand bars has to do with events that take sediment out of the bay. For example, the appearance of the persistent sand bar northeast of the bridge in 1975 may possibly be attributed to the 1975 ex-tropical storm Alison (Figure 4, Table 4). However, it is difficult to say for sure whether it was a punctuated event that caused this change, especially since there is no evidence of the 1975 storm reaching Okains Bay. The shifting of the estuary's mouth may also be due to punctuated events. If an event brings in a large amount of sediment, some of the sediment will be deposited at the northwest end of the beach where the wedge sits. This sediment will push the channel closer to the northwestern headlands. Once this sediment is washed either by another event or by daily tides, the channel will likely migrate to face more of a southeastern direction. Far-field events that carry more sediment are the likely reasons for these wedge buildups.

Evaluating how the progradation of the dune, berm, and spit lines responded to punctuated events provides a more quantitative way of looking at how such events may have affected the sediment budget at Okains Bay. There are several events that the progradation patterns of all three lines suggest may have had significant impacts on the bay's development. The first of these events was the 1960 Chilean tsunami. This was a far-field tsunami, so it is likely this it brought vast amounts of sediment into the bay. This is reflected in the progradation rates of the three lines, each of which prograded very quickly between 1941 and 1966 (Figure 6). Following the tsunami, the next punctuated event that may have affected Okains Bay was the 1968 ex-tropical storm Giselle (Table 4). However, it is unknown whether or not this event affected Okains Bay for sure. However, the storm does coincide with a dip in the progradation rate for the dune line, and the beginning of a period of retrogradation for the berm and spit lines (Figure 6). If it did reach Okains Bay, it is possible that the rain from the storm led to increased fluvial influence on sediment transport within the bay, which would have washed sediment out and led to less progradation. The 1975 ex-tropical storm Alison may have also contributed to this loss of sediment, but there is no record of the storm affecting Banks Peninsula, so it cannot be determined for sure (Table 4).

The period from 1975 to 1997 saw no punctuated events that could have affected Okains Bay (Figure 6, Table 4). Therefore, this period represents what may be referred to as the 'dynamic equilibrium' of the bay, and the pattern exhibited here is likely what the bay would do in the absence of any punctuated events. During this time, all three lines remained relatively stagnant. The dune line experienced almost no net progradation during this time, retrograding slightly from 1975 to 1984, then prograding slowly from then on (Figure 6). The berm line mostly prograded at a relatively slow pace, and the spit line prograded fairly rapidly, but oscillated while doing so (Figure 6). These patterns indicate that progradation is the 'natural' state of things in the bay, given no extreme fluctuations in sediment. This idea is supported by the relict ridges to the SW of the shore (Figure 8).

The period from 1997 to 2002 saw several storm events come through in fairly rapid successions (Table 4). In the case of the dune line, this series of events corresponds to an increase in progradation rate. The berm line's progradation rate, however, does not change much, not does the spit's until after the 2002 event (Figure 6). The dune's increased progradation is likely due to a combination of increased sedimentation on its SW and NW sides and anthropogenic forestation. The berm and spit lines, meanwhile, suggest that these storm events led to the deposition of some sediment, but did not bring in nearly as much as the 1960 tsunami. This makes sense, as the waves accompanying these events would not have been from very far away, and they would have been accompanied by increased fluvial input caused by rain.

In 2002, Banks Peninsula was hit by a flooding event (Table 4). The most obvious effect of this event on Okains Bay is a spike of retrogradation of the spit line (Figure 6). The dune line and berm line, however, continue prograding during this time. There are many possible explanations for this pattern. Flooding may have brought in sediment from far away that was deposited onto the berm and dune, but on in its way out, the water only came through the narrow passage the channel goes through, leading to the incision of the spit. A more detailed analysis of this event's effect on sediment budget would be useful, but unfortunately beyond the scope of this study. Following this flooding event, the pattern of punctuated events becomes more complicated. Between 2007 and 2014, several events including a number of storms, the 2010-

2011 Canterbury Earthquake Sequence, and a 2010 tsunami all occurred within relatively quick succession (Table 4). The proximity of these events to one another makes it difficult to judge how each of them affected the bay individually. However, this series of events does seem to have affected the dune line, berm line, and spit line in unique ways. The dune line continues prograding slowly until about 2011, at which point it began retrograding (Figure 6). The berm line mostly follows the same pattern as the dune line, but there is significant variation from southeast to northwest (Figure 6). The spit line, however, retrogrades sharply after the 2002 flooding event, and then progrades sharply until 2011 (Figure 6). It would be difficult to judge how each of these events affected each of these features individually, but it is clear that this series of events had a significant impact on the morphology of the bay.

Following the 2014 Canterbury and Lower North Island Storm, all three lines entered a period of rapid retrogradation (Table 4, Figure 6). This storm is likely to have increase fluvial output significantly enough to carry large amounts of sediment out from the bay. This pattern was amplified by the 2016 Kaikoura Earthquake, which brought a tsunami wave into the bay (Figure 7, Table 4). Following the Kaikoura Earthquake, all three events continued their pattern of retrogradation, with the spit lines losing sediment particularly fast (Figure 6). This retrogradation has continued into the present day, and it will be important to monitor the system to ensure that it recovers properly. It is likely that, as Cooper (2002) suggests, this system, being tide-dominated, will adjust relatively quickly in the absence of further punctuated disruptions. Monitoring its response will help to further develop the literature on tide-dominated estuaries.

The northwest-southeast patterns of the dune line, berm line, and spit line indicate how sediment is differentially deposited along the shore. The dune progrades significantly more to the northwestern side of the bay (Figure 6). One possible reason for this increased rate to the northwest is stabilization of the dune via anthropogenic effects. Between 1941 and 2017, the dune went from having nearly no vegetation to being home to a large number of trees. These trees likely stabilized the dune and led directly to its growth in the northwest direction, and the parts of the dune with trees will be less prone to erosion and retrogradation. Another possible reason for this pattern is that when sediment is brought into the bay by waves, some of it will get caught by the spit on its way out of the bay, which will lead to progradation of both the dune and the spit on their northwestern ends. The berm, unlike the dune, progrades more rapidly to the southeast than the northwest. This makes sense, as sediment is deposited directly onto the berm on the southeast end of the beach, but on the northwest end it is filtered through the channel and other processes are competing with deposition (Figure 8).

Okains Bay has been noted by previously authors as being unique because of its progradation sequence (Stephenson and Shulmeister 1999). Stephenson and Shulmeister (1999) have suggested that because the sediment at Okains Bay is derived from the continental shelf rather than the local catchment, and because the bay's progradation rate is driven primarily by sediment flux, the bay may be used as a proxy for erosion on the South Canterbury coast. Other authors have agreed that primary factor that affects the development of coastal hydrosystems like Okains Bay is sediment supply. Therefore, evaluating how punctuated events have affected the morphology of Okains Bay may help assess erosion on the South Canterbury coast, which would have wide-ranging implications for beaches across the region. However, it is important to note that retrogradation is not uncommon in Okains Bay, especially recently. Understanding that Okains Bay is not purely progradational will be important not only for managing the bay, but also in understanding processes in all the bays on Banks Peninsula and around the Canterbury coast. Assessing how this retrogradation may continue to develop should be a primary consideration in developing coastal management strategies for Okains Bay. Of particular importance will be monitoring the development of the spit and wedge, as they have the potential to further cut off channel flow into the bay, which will have lasting consequences for sediment transport.

7. Conclusions and Future Work

Because coastal hydrosystems are often very sensitive, fragile features, they can be difficult to satisfactorily model and evaluate. This problem is made even more troublesome by the fact that there is not a well agreed-upon classification scheme for many coastal features. However, aerial photogrammetry combined with GIS has proven to be a relatively cheap, intuitive, and effective way of assessing how such a system has developed and may continue to develop in the future. In the case of Okains Bay, recent trends have shown that patterns of progradation have been changing in recent years. Future research could use more in-depth methods of sediment analysis to develop a more detailed model of sediment transport within the bay. Researchers should also continually relate findings to ideas found within the literature, as it is important to work towards a consistent understanding of coastal hydrosystems on both regional and global levels. Keeping in mind that it is not likely that punctuated events will become less common, it will be increasingly important to continue to monitor the bay's progradation rates and possibly develop preliminary management plans taking into account possible future morphologies.

8. Acknowledgements

I would like to thank my advisors Sam Hampton and Josh Borella for their help throughout the semester. Special thanks to Sam for teaching me how to georeference, helping me draft and design figures, and being a wellspring of information about Okains Bay. Thank you also to NIWA for a day trip to Okains Bay. Additional thanks to Matt Crockcroft for capturing present-day imagery. Thanks also to Deirdre Hart for her assistance in obtaining several sources and helping me to further understand sediment transport. I would also like to extend my gratitude to Frontiers Abroad and all of my classmates for an amazing semester.

Figure Captions

Figure 1 - The studied area, Okains Bay, with Banks Peninsula inset for reference.

Figure 2 - Left: A representative 2014 transect with the dune line (green), berm line (red), spit line (orange), and wedge line (pink) drawn on; Right: cross-section of the transect, showing the relative location of each chosen feature.

Figure 3 - Top: An image of the overall study area with the area shown below squared off; Second: dune line transects; Third: berm line transects; Fourth: spit line transects

Figure 4 – Compiled image of all twelve aerial photographs with geomorphic features traced over.

Figure 5 - Some representative channel morphologies. A grid was used to align the images geographically, with each square representing 2 m^2.

Figure 6 – Graphs of total progradation (sediment accumulated) vs. time for the dune, berm, and spit, with punctuated events overlain.

Figure 7 – Image showing the effects of the 2016 Kaikoura Earthquake at Okains Bay.

Figure 8 – A preliminary sedimentological model of Okains Bay. Processes of particular interest are noted.

Figures

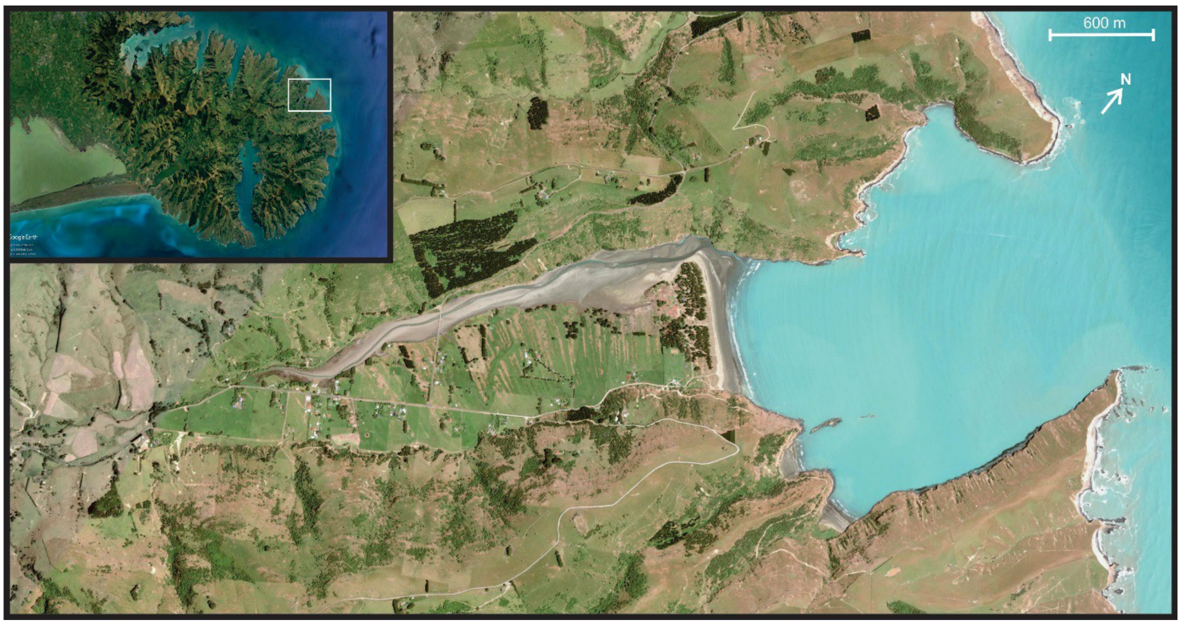


Figure 1.

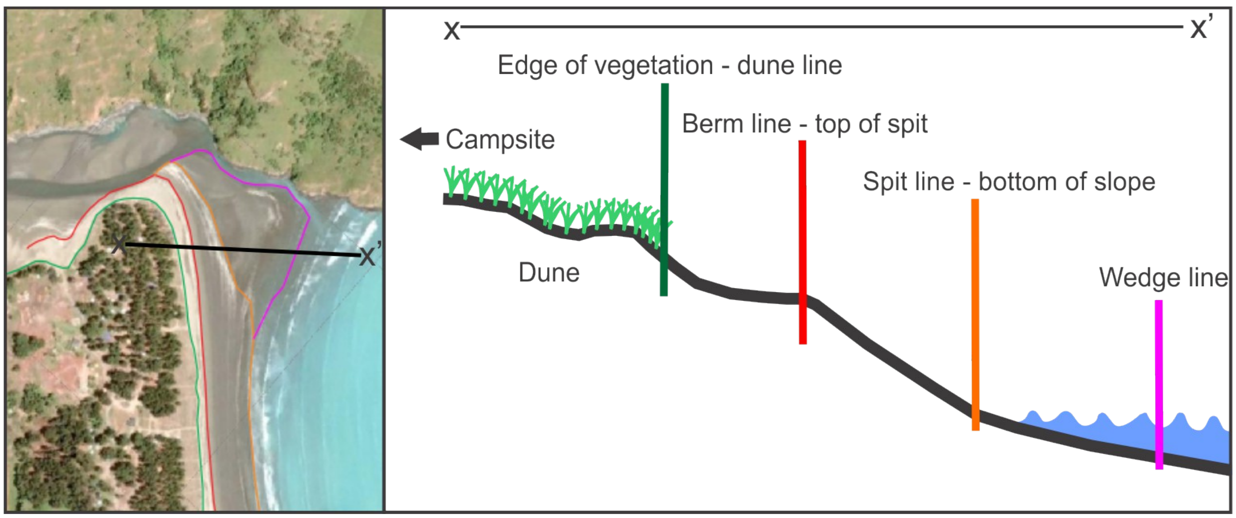

X
X'
Edge of vegetation - dune line
Campsite
Berm line - top of spit
Spit line - bottom of slope
Dune
Wedge line

Figure 2.

Figure 3.

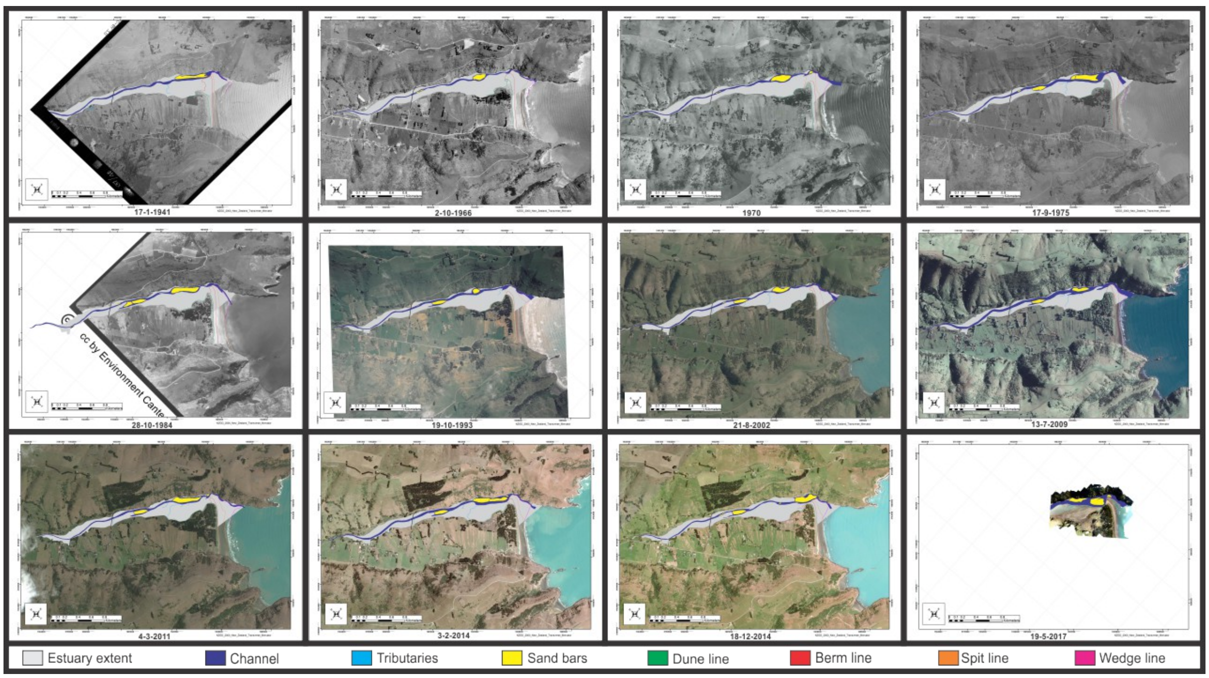

17-1-1941
2-10-1966
1970
17-9-1975
cc by Environment Canterbury
28-10-1984
19-10-1993
21-8-2002
13-7-2009
4-3-2011
3-2-2014
18-12-2014
19-5-2017
Estuary extent
Channel
Tributaries
Sand bars
Dune line
Berm line
Spit line
Wedge line

Figure 4.

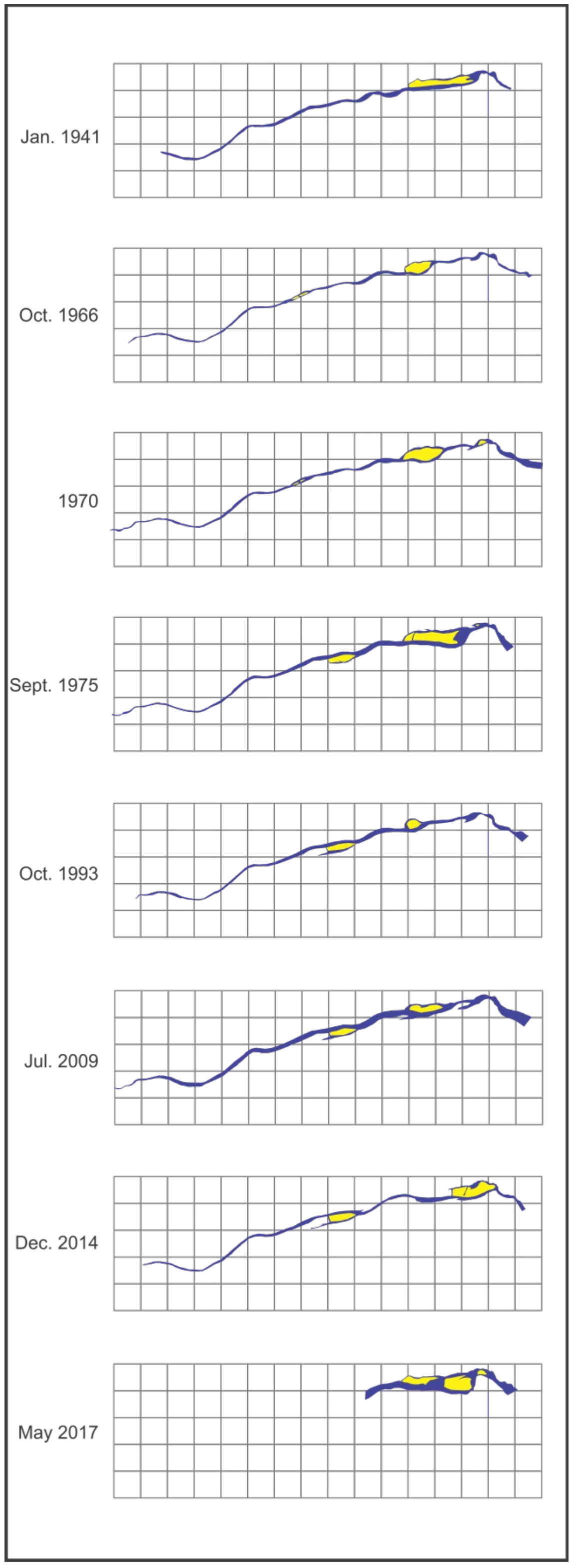
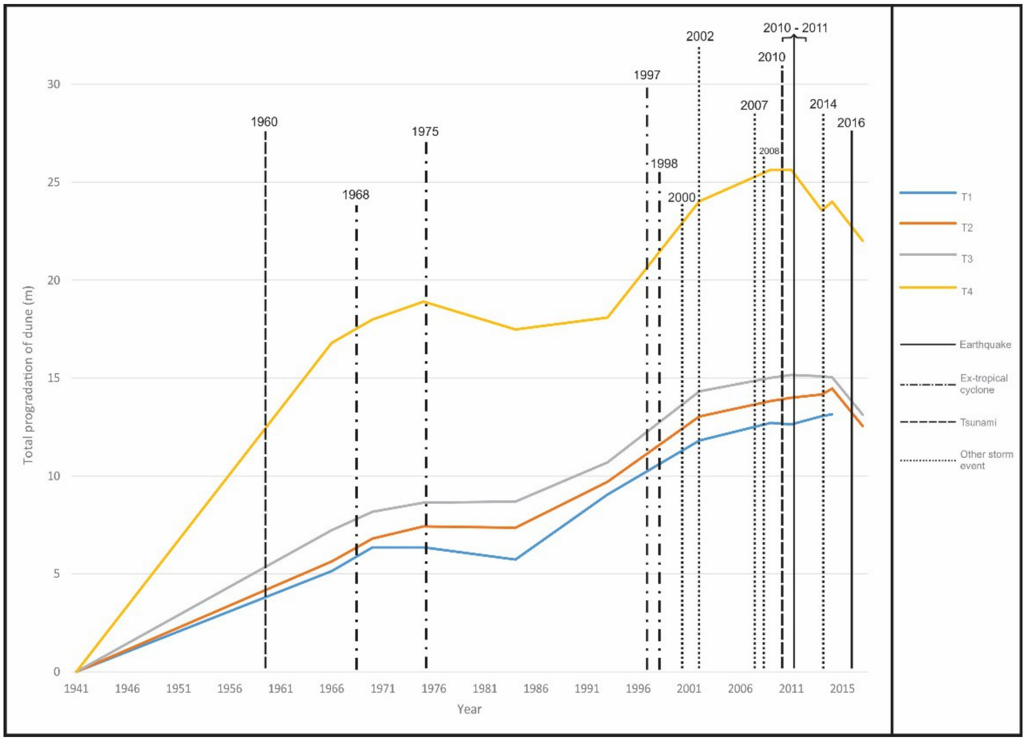
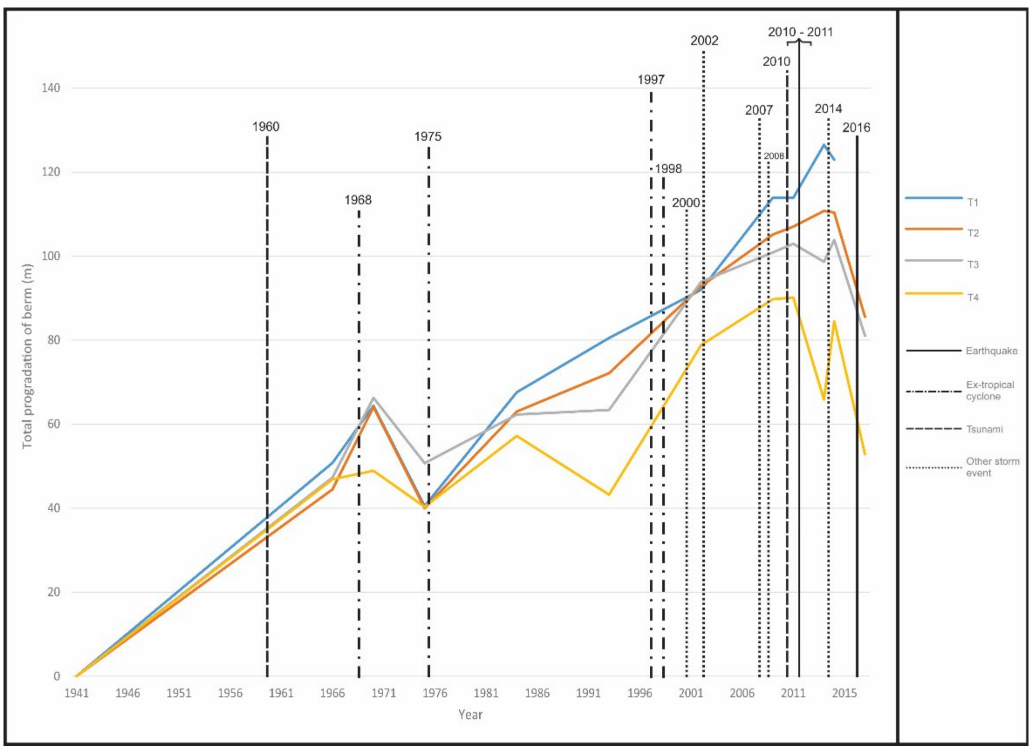

Jan. 1941
Oct. 1966
1970
Sept. 1975
Oct. 1993
Jul. 2009
Dec. 2014
May 2017

Figure 5.


2010 - 2011
2002
2010
1997
30
2007
2014
1960
1975
2016
2008
1998
25
1968
2000
20
15
10
5
0
Total progradation of dune (m)
1941
1946
1951
1956
1961
1966
1971
1976
1981
1986
1991
1996
2001
2006
2011
2015
Year
T1
T2
T3
T4
Earthquake
Ex-tropical cyclone
Tsunami
Other storm event


2010 - 2011
2002
2010
1997
140
2007
2014
1960
1975
2016
2008
120
1998
1968
2000
100
80
60
40
20
0
Total progradation of berm (m)
1941
1946
1951
1956
1961
1966
1971
1976
1981
1986
1991
1996
2001
2006
2011
2015
Year
T1
T2
T3
T4
Earthquake
Ex-tropical cyclone
Tsunami
Other storm event

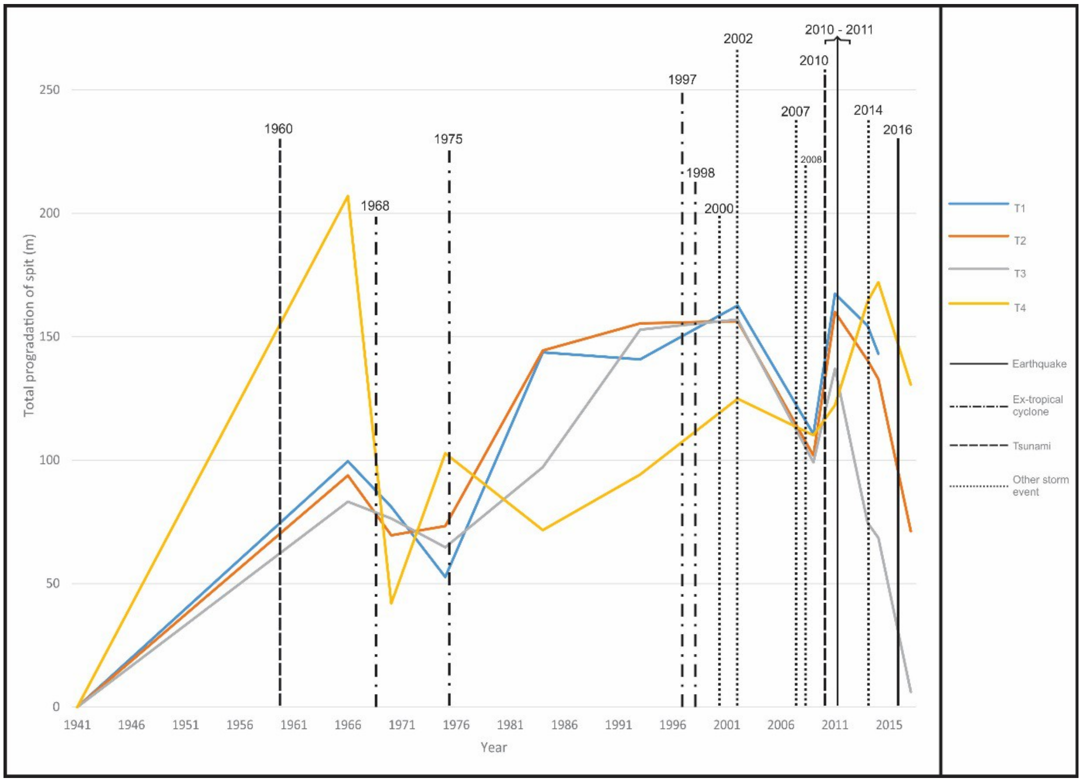

Total progradation of spit (m)
Year
0
50
100
150
200
250
1941
1946
1951
1956
1961
1966
1971
1976
1981
1986
1991
1996
2001
2006
2011
2015
1960
1968
1975
1997
1998
2000
2002
2007
2008
2010
2010 - 2011
2014
2016
T1
T2
T3
T4
Earthquake
Ex-tropical cyclone
Tsunami
Other storm event

Figure 6.

Figure 7.

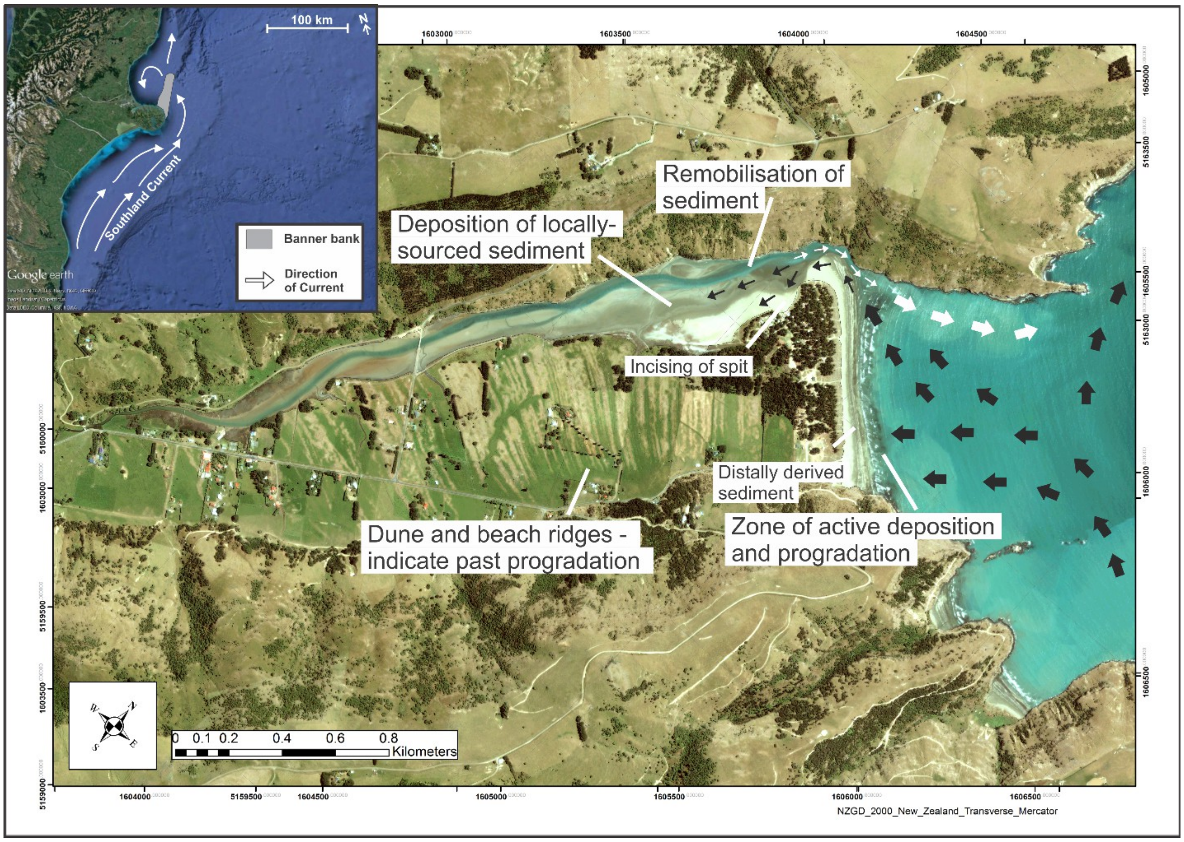

100 km
Banner bank
Direction of Current
Southland Current
Remobilisation of sediment
Deposition of locally-sourced sediment
Incising of spit
Distally derived sediment
Zone of active deposition and progradation
Dune and beach ridges - indicate past progradation
0 0.1 0.2 0.4 0.6 0.8 Kilometers
NZGD_2000_New_Zealand_Transverse_Mercator

Figure 8.

Tables

Table 1: Summary of Hume et al.'s classification system for New Zealand hydrosystems (Hume et al., 2016)

Hydrosystem classs	Geomorphic class	Subclass	Defining characteristics
Palustrine	Damp sand plain lake	N/A	Small, shallow, usually fresh water. No connection to sea.
Lacustrine	Waituna-type lagoon		Large, shallow coastal lagoons, cut off from the sea. Usually fresh water, may have short-lived openings
		Coastal plain depression	Low-lying areas that have been isolated from the ocean
		Valley basins	Slightly deeper-water, found in river valleys
Riverine	Hapua-type lagoon		Narrow, long, shallow river mouth lagoons, usually enclosed except for a narrow outlet. May be large, medium, small, or intermittent
	Beach stream		Are found where a shallow stream crosses the beach face to the sea
		Hillside stream	Flow down from mountains, following a steep path
		Damp sand plain stream	Flow over flat plain into sea, no pond at mouth
		Stream with pond	Shallow pond behind beach
		Stream with ribbon lagoon	Narrow, long, shallow lagoon, parallel to the coast, mostly connected to river
		Intermittent stream with ribbon lagoon	Narrow, long water body, parallel to coast, mostly connected to wetland
	Freshwater river mouth		Has a permanent connection to the sea, occurring where river flow is strong enough to cut a permanent channel to the sea.
		Unrestricted	No delta – sediment carried away from mouth
		Deltaic	Delta is built at mouth as wave energy is not sufficient to carry sediment away
		Barrier beach enclosed	River mouth is restricted by a narrow wave-built barrier
Estuarine	Tidal river mouth (estuary)		Elongate, narrow, shallow, with largely permanent connection to the sea. Similar to freshwater river mouth, but tide-dominated. May be unrestricted, spit-enclosed, barrier beach-enclosed, intermittent with ribbon lagoon, or deltaic

	Tidal lagoon	Shallow basin with simple shorelines and large intertidal areas, with a narrow entrance to the sea. May be permanently open or intermittently closed. Tide-dominated
	Shallow drowned valley	Shallow, with dendritic shorelines. Tide-dominated, with a permanently open mouth. Wide range in size possible
Estuarine/ Marine	Deep drowned valley	Large, deep, mostly subtidal, formed by partial submergence of an unglaciated river valley
	Fjord	Long, narrow, deep, U-shaped basins, formed by flooding of glacial valleys
Marine	Coastal embayment	An indentation in the shoreline with a wide entrance, constrained by rock headlands, exposed to the ocean. Mostly subtidal with small intertidal areas. Swell may enter the bay and resuspend sea sediment.

Table 2: Estuary classification scheme developed by Cameron and Pritchard (1963) and Fairbridge (1980), based on Valle-Levinson (2010) and Pye and Blott (2014).

Classification Scheme	Estuary Type	Characterization
Water Balance	Positive	Freshwater additions exceed losses
	Inverse	Freshwater losses exceed additions
	Low-inflow	Small influence from river discharge
Geomorphology	Coastal plain	Drowned river valley – formed by Pleistocene sea level increase
	Fjord	Result from marine flooding of glacially over-deepened troughs
	Bar-built	Became semi-enclosed due to littoral drift
	Tectonic	Formed by earthquakes or fractures
Vertical salinity structure	Salt wedge	Distinct wedge of relatively dense, saline water intrudes from the sea landward
	Strongly stratified	Marked vertical salinity gradient with no salt wedge
	Weakly stratified	Only a weak or ephemeral salinity gradient
	Mixed	Little salinity variation with depth
Entrance type	Unrestricted	Funnel shaped entrance
	Restricted	Barred entrance

Table 3: Estuary typology scheme developed by Prandle, Lane, and Manning (2005)

Estuary type	Characteristics
Ria	Short (sandy), deep, steep-sided with small river flows
Coastal plains	Long (muddy), funnel-shaped, with extensive intertidal zones
Bar-built	Short (sandy) and shallow with small river flows and tidal range

Table 4: Inventory of events that may have affected the morphology of Okains Bay, compiled from NIWA's NZ Historic Weather Events Catalog (2016).

Timestamp	Event	Affected Okains Bay?
15 August 1868	Tidal wave	Yes - dramatic inundation of Okains Bay to 1.5 m, initial formation of the estuary – river made shallower by silt deposit
23 May 1960	Tsunami	Yes – known inundation – main bridge washed away and replaced
9 April 1968	Ex-tropical storm Giselle	Unknown – gusts recorded on Banks Peninsula, flooding recorded at Little River
10 March 1975	Ex-tropical storm Alison	Unlikely – heavy rain recorded in Christchurch, nothing on Banks Peninsula recorded
10 January 1997	Ex-tropical storm Drena	Likely – flooding recorded on Banks Peninsula, gusts recorded at Le Bons Bay, adjacent to Okains Bay
28 March 1998	Ex-tropical storm Yali	Unlikely – gusts recorded on Banks Peninsula, but nothing specific
11 October 2000	New Zealand "weather bomb"	Unknown – flooding and gusts recorded on Banks Peninsula
11 January 2002	South Island and Waikato flooding	Likely – Banks Peninsula hit especially hard by flooding
7 October 2007	Lower North Island and South Island Storm	Likely – Banks Peninsula hit very hard by winds, especially Le Bons Bay, adjacent to Okains Bay
22 June 2008	South Island Snow and North Island Thunderstorms	Unknown – heavy rain recorded on Banks Peninsula, especially at Le Bons Bay, adjacent to Okains Bay
28 February 2010	Chilean tsunami	Likely -- was not recorded to have reached Okains

		Bay, but the campground is known to have been evacuated
2010-2011	Canterbury Earthquake Sequence	Yes – the University of Canterbury had equipment in the bay affected by the storm – sediment was shaken up
3 March 2014	Canterbury and Lower North island storm	Heavy rain and winds recorded on Banks Peninsula
14 Nov 2016	Kaikoura earthquake	Unknown – no record

References

Bowden, L. W. & Brooner, W. G. (1970). Aerial photography: A diversified tool. *Geoforum*, *2*(C), 19–32. https://doi.org/10.1016/0016-7185(70)90026-6

Canterbury Maps (2017). Historic Imagery. Retrieved from https://canterburymaps.govt.nz/explore?q=%5BHistoric+Imagery%5D.

Colwell, Robert (1965). The extraction of data from aerial photographs by human and mechanical means. *Photogrammetria*, 20, 211-228.

Cooper, J. A. G. (2002). The role of extreme floods in estuary-coastal behaviour: Contrasts between river- and tide-dominated microtidal estuaries. *Sedimentary Geology*, *150*(1–2), 123–137. https://doi.org/10.1016/S0037-0738(01)00271-8

Dronkers, J. (1986). Tidal assymetry and estuarine morphology. *Netherlands Journal of Sea Research*, *20*, 117–131.

Hapke, C. & Richmond, B. (2000). Monitoring beach morphology changes using small-format aerial photography and digital softcopy photogrammetry. *Environmental Geosciences*, 7(1), 32-37.

Harrison, Justin A.L., Moghaddam, Arash E. (2017). Sediment flux in an earthquake affected complex pocket beach, Okains Bay, New Zealand.

Hart, Deirdre E., Marsden, Islay D., and Francis, Malcolm (2008). Coastal Systems. In *The Natural History of Canterbury*. pp. 653-684.

Hughes, M. L., McDowell, P. F., & Marcus, W. A. (2006). Accuracy assessment of georectified aerial photographs: Implications for measuring lateral channel movement in a GIS. *Geomorphology*, *74*(1–4), 1–16. https://doi.org/10.1016/j.geomorph.2005.07.001

Hume, T., Gerbeaux, P., Hart, D., Kettles, H., Neale, D. (2016). A classification of New Zealand coastal hydrosystems. Report no. HAM2016-062, NIWA.

James, L. A., Hodgson, M. E., Ghoshal, S., & Latiolais, M. M. (2012). Geomorphic change detection using historic maps and DEM differencing: The temporal dimension of geospatial analysis. *Geomorphology*, *137*(1), 181–198. https://doi.org/10.1016/j.geomorph.2010.10.039

Kain, C.L., Wassmer, P., Goff, J., Chague-Goff, C., Gomez, C., Hart, D.E., Fierro, D., Jacobsen, G.E., Zawadzki, A. (2016). Determining flow patterns and emplacement dynamics from tsunami deposits with no visible sedimentary structure. *Earth Surface Processes and Landforms*.

Moghaddam, Arash E. (2014). Pocket beach wave processes and current systems investigated via field and numerical modelling studies with the case study of Okains Bay (Doctoral dissertation).

NIWA (2016). NZ Historic Weather Events Catalog. Retrieved from https://hwe.niwa.co.nz/.

Ogilvie, Gordon (1990). *Banks Peninsula: The Cradle of Canterbury*. Wellington: GP Books.

Pari, Y., Ramana Murthy, M. V., Jaya Kumar, S., Subramanian, B. R., & Ramachandran, S. (2008). Morphological changes at Vellar estuary, India-Impact of the December 2004 tsunami. *Journal of Environmental Management*, *89*(1), 45–57. https://doi.org/10.1016/j.jenvman.2007.01.055

Prandle, D., Lane, A., & Manning, A. J. (2006). New typologies for estuarine morphology. *Geomorphology*, *81*(3–4), 309–315. https://doi.org/10.1016/j.geomorph.2006.04.017

Pye, K., & Blott, S. J. (2014). The geomorphology of UK estuaries: The role of geological controls, antecedent conditions and human activities. *Estuarine, Coastal and Shelf Science*, *150*(PB), 196–214. https://doi.org/10.1016/j.ecss.2014.05.014

Rodriguez-Ramirez, A., Villarias-Robles, J. J. R., Perez-Asensio, J. N., Santos, A., Morales, J. A., Celestino-Perez, S., Leon, A., Santos-Arevalo, F. J. (2016). Geomorphological record of extreme wave events during Roman times in the Guadalquivir estuary (Gulf of Cadiz, SW Spain): An archaeological and paleogeographical approach. *Geomorphology*, *261*, 103–118. https://doi.org/10.1016/j.geomorph.2016.02.030

Rodríguez-Ramírez, A., Flores-Hurtado, E., Contreras, C., Villarías-Robles, J. J. R., Jiménez-Moreno, G., Pérez-Asensio, J. N., Santos, A., Morales, J.A., Celestino-Perez, A., León, A., Santos-Arevalo, F.J. (2014). The role of neo-tectonics in the sedimentary infilling and geomorphological evolution of the Guadalquivir estuary (Gulf of Cadiz, SW Spain) during the Holocene. *Geomorphology*, *219*, 126–140. https://doi.org/10.1016/j.geomorph.2014.05.004

Schiefer, E., & Gilbert, R. (2007). Reconstructing morphometric change in a proglacial landscape using historical aerial photography and automated DEM generation. *Geomorphology*, *88*(1–2), 167–178. https://doi.org/10.1016/j.geomorph.2006.11.003

Steffensen, D. A., & McGregor, F. E. (1976). The application of aerial photography to estuarine ecology. *Aquatic Botany*, *2*(C), 3–11. https://doi.org/10.1016/0304-3770(76)90003-6

Steiner, D (1965). Use of air photographs for interpreting and mapping rural land use in the United States. *Photogrammetria*, 20, 65-80.

Traini, C., Proust, J. N., Menier, D., & Mathew, M. J. (2015). Distinguishing natural evolution and human impact on estuarine morpho-sedimentary development: A case study from the Vilaine Estuary, France. *Estuarine, Coastal and Shelf Science*, *163*(PB), 143–155. https://doi.org/10.1016/j.ecss.2015.06.025

Valle-Levinson, A. (2010). *Contemporary Issues in Estuarine Physics*. Cambridge, UK: Cambridge University Press, pp 1-11.

Wang, Y., Dong, P., Oguchi, T., Chen, S., & Shen, H. (2013). Long-term (1842-2006) morphological change and equilibrium state of the Changjiang (Yangtze) Estuary, China. *Continental Shelf Research*, *56*, 71–81. https://doi.org/10.1016/j.csr.2013.02.006