An investigation into the temporal variations of Morecambe Bay's geomorphology in relation to known cockle bed settlements using integrated remote-sensing.

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Abstract

The temporal variations of Morecambe Bay's morphology including channel movement, accumulation, elevation and sinuosity are mapped using integrated remote sensing combining Landsat with LiDAR. The aim is to investigate spatial relations of morphological change to known cockle populations surveyed by NW-IFCA. This research seeks to inform the sustainable management practices of NW-IFCA by contributing to the presently small body of research into Morecambe Bay as a highly dynamic intertidal environment. Analysis identified areas of accumulation and erosion; discussion concluded these processes could have influenced the observed fluctuations in distribution and density of cockle populations, particularly between 2009 and 2010. This supports the consensus of Morecambe bay as a highly dynamic environment and proposes integrated remote sensing as an effective method for inferring morphological change. It goes on to suggest an integrated methodological approach is required for confidence in the factors influencing cockle populations.

Keywords — LiDAR, Landsat, Intertidal, Mapping, Temporal Variations.

Word count – 7,971

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3. Introduction

In the contemporary climatic state, channels are known to be changing and moving in response to factors such as sea level rise, tidal ranges, storm events and associated storm surges, alterations to sediment input and output, erosion rates and discharges of waves and rivers. Consequent changes in width, depth and sinuosity of the channels along with sediments elevation and type has the potential to influence morphology of intertidal flats. The intertidal zone between mean low water and mean high water level found in Morecambe bay is an important habitat for the *Cerastoderma edule*, termed cockles (Masselink et al., 2011) Franklin, 1972). The spatial extent and conditions of intertidal flats are impacted by channel movements, therefore, a need to understand the bays recent channel movements in relation to the cockle bed locations is indicated.

Importantly, present-day climate change threatens coastal areas, with the occurrence of storm events predicted to increase in the next century (Van Oldenborgh et al., 2015; ICOASST, 2017). Channel disturbances due to heavy rain, freshwater influx from the catchment, and storm surges all have impacts upon intertidal sand flats -the cockle's habitat (Woolmer, 2013). Sediment, and the cockles themselves, are moved as the channels in the Sands move (Woolmer, 2013). Consequently, understanding of these morphologic changes in contribution towards sustainable management is increasingly imperative to delicate, but key ecosystem and socio-economic components such as the cockles in dynamic coastal environments. Morecambe bay's ecosystem could be negatively impacted if cockle beds are not sustainably managed to ensure a food source for protected migratory bird species, the oystercatcher (Franklin, 1972).

In addition, the contemporary value of the cockle industry, which exports mainly to Europe, is placed at over £19 million; cockle prices start at £600 per tonne however, can reach £2-3 thousand per tonne depending on size and quality (Whitton, 2013; NW-IFCA, 2017). The management of cockles across the UK is consequently subject to byelaws which place restrictions on cockle fishing in relation to limiting vessel sizes, engine powers, dredge sizes, minimum cockle sizes, maximum damage rates, bed closure during certain seasons, fishing times and the requirement of fishing permits (Woolmer, 2013). On account of both the socio-economic importance, and the environmental importance, the North Western Inshore Fisheries and Conservation Authority (NWIFCA) tightly regulates the industry in Morecambe bay; there are currently just 160 fishing permit holders in the bay (NWIFCA, 2017). Therefore, in context of its importance to cockle populations inhabiting the intertidal flats of Morecambe Bay, geomorphology with a particular focus upon channel movements should be investigated due to cockle's significance; both as important components of the food chain for susceptible wading bird species and the socio-economics of Morecambe Bay.

Taking an integrated remote sensing approach, a combination of Light Detection and Ranging (LiDAR) and satellite imagery from the orbiting satellite Landsat, are the chosen resources for this study. Landsat coverage provides worldwide opportunity to observe spatial and temporal changes to landscapes in 2D (Heywood et al., 2011). Meanwhile, LIDAR is favoured for coastal and channel mapping, with studies using LIDAR to decipher coastal erosion, beaches and movements in the Netherlands, Belgium, California and the UK using the technique (Deronde, 2006; Sallenger Jr et al., 2002; Mason et al., 2010). LiDAR is increasingly utilised due to the provision of 3D digital terrain and surface models however; the spatial and temporal coverage of LiDAR is more limited than Landsat. Intertidal habitats in particular, are studied using these techniques due to their importance as an interface between the terrestrial environment (including freshwater rivers) with the marine environment (Mason and Garg, 2000).

3.1 Aims and Objectives

Mason et al.'s research composes the main body of knowledge during the first decade of the 21st century (2000, 2006 and 2010) and provides valuable foundations into channel movements. However, there is insufficient knowledge surrounding the Morecambe bay's channel movements in recent years and more research of this nature is required to understand changes in Morecambe bay. The relation of these movements to the cockle beds is absent from literature with a particular lack of studies into cockles in Morecambe Bay itself.

Therefore, the aim of this dissertation is to investigate the temporal variations of geomorphology within Morecambe Bay in relation to the spatial distribution and density of cockle bed settlements. To investigate this, the first objective is to examine the temporal variations of channel movements in the Lune channel in relation to the cockle bed settlements at Pilling Sands and Middleton Sands through the mapping of a time series of channel movements and known cockle bed locations. Following this, the second objective is to determine temporal variations of elevation in relation to known cockle bed locations through analysis of topographical data on Geographic Information Systems to produce mapped elevation changes and known cockle bed locations. The third objective is to infer patterns of cockle population change over the last decade or so through qualitative and quantitative observation and mapping. The aim and objectives intend to explore whether there is sufficient (data collected at both wide spatial and temporal scales) cockle and morphological data to infer possible relationships. Therefore, these objectives seek to provide foundations for greater understandings of the sediment and channel dynamics to inform the sustainable management practices of the cockle resources by NWIFCA.

This dissertation will begin by reviewing the known channel dynamics, locations, cockle interactions, historic use of satellite imagery such as Landsat and LIDAR in the analysis and modelling of such channel movements and broader coastal environments worldwide. It will then move on to core of the project, clarifying the methodology and study area, presenting the results, patterns and notable trends of the data, before discussing the results in context of the aim of this project and existing channel and coastal morphological research. Finally, this report indicates the observed factors contributing to a dynamic intertidal landscape and their relation to the spatial distribution of cockle beds and populations. The report then concludes with a recommendation for future research to consider an integrated research approach combining morphologic analysis with bathymetric and chemical/biological methodological analysis.

4. Literature Review

This review addresses literature concerned with channel movements, the measurement of channel morphology using remote sensing methods and the broader environment of Morecambe Bay. Presently, impending threats from climate change are predicted to intensify, with the occurrence of storm events such as Storm Desmond in 2015 expected to increase and global sea levels rising by 3mm per year (Scott and Mason, 2006; Chu et al., 2013; iCOASST, 2017; Viles and Spencer; 1995; van Oldenborgh et al., 2015; Grotzinger and Jordan, 2014), Therefore, the impacts to processes occurring in channels and Morecambe Bay are complex.

4.1 Processes of Morphological Change in Channels

Chu et al. (2013) recognises the interaction of sediment transport processes, tides, wind, waves, bank erosion and high magnitude events in stimulation of channel movements (both migration and meandering). The rate and magnitude of sediment transport processes are dependent upon grain size, density, porosity and shape of sediment grains which influence the cohesivity of the sediment (Woodroffe, 2003). For example, if grain sizes are less than 63µm, electrostatic forces create cohesion requiring more energy for entrainment, however the less dense the sediment, the more easily entrained it is by a low velocity flow (Masselink et al., 2011).

This transport is one of the key influences upon coastal morphology however, the key source of energy required for sediment entrainment is wave and tidal flows. (Woodroffe, 2003). Fluid dynamics such as momentum created by velocity, viscosity and volume of tide and wave currents enable entrainment of sediment (Masselink et al. 2011; Woodroffe, 2003). Particularly, tidal energy is a dominant factor in embayments like Morecambe Bay and the Lune estuary (Dronkers, 2016; Woodroffe, 2003). However, the available energy also changes in relation to elevation gradients and tide heights, with higher velocity currents influencing mid-intertidal zones (Masselink et al. 2011).

Mason et al (1999) also points towards long term patterns of erosion and accretion related to channel movements. However, more recently, Scott and Mason (2006) suggest channel movements are explained by impacts of secondary currents rather than the broader context of erosion and accretion processes. Secondary currents, created by unequal forces generating transverse velocities to the longitudinal flow, circulate, which instigates erosion and accretion (Priego-Hernández and Rivera-Trejo, 2016). In contrast, later findings propose changes to channels in Morecambe bay as a consequence of the higher currents associated with flood tides, while also suggesting seasonal changes have the potential to impact intertidal morphological change (Mason et al., 2010).

4.2 Morecambe Bay channel migration and significance to cockles.

Mason et al. (1999) found changes of the Kent channel and the Ulverston channel of up to 2km and movement of main channels of the Lune estuary from westerly, to north-westerly due to significant erosion. This channel movement was discovered through the analysis of land-sea boundaries (Waterlines) from Synthetic aperture radar images (SAR) during a period of 3 years from 1991-1994 (Mason et al., 1999). Since this 20th century research, Mason et al., (2010) found tidal and fluvial forcing mechanisms caused the Ulverston channel to move 5km and straighten from 1991-2004. However, as highlighted by Chu et al. (2013) there is a profusion of research into channel movements across river environments and scarcity of such research in tidal environments, thus signifying an opening for research into contemporary channel movement.

Aldridge (1997) identifies that the irregularity of the tide (tidal asymmetry) in Morecambe Bay has a significant control on sediment movement with the difference in magnitude between ebb and flow currents a factor in the net transport of sand. The bay is known to experience morphological change due to the “significant depths of fine sand in many parts of the bay” (Mason and Garg, 2000. P. 81), demonstrated by the migration of the Kent, Ulverston and Lune channels (Aldridge, 1997; Mason et al., 1999). Elsewhere, in reaches of the Upper Yellow River and beyond, channel migration also occurred where sediments were easily erodible in addition to seasonal precipitation and tidal currents impact (Wang et al., 2016; Jang and Shimizu, 2005; Choi and Jo, 2015). This supports Mason and Garg's proposition that channel migration rates are influenced by material differences but also indicates sediment movement is not only due to the composition of the sediment but the natural forces acting upon it. Morphological change due to this sediment transport impacts the ecosystem functions of the bay and environmental habitats of cockles with implications for anthropogenic utilisation of Morecambe Bay (Scott and Mason, 2006).

Cockles are mobile within sediment and evidence indicates bathymetric shifts result in cockle displacement (Callaway et al., 2013). However, despite the dynamic intertidal flat inhabitant's adaption to environmental stressors, extreme storms can cause habitat disturbance, loss and cockle mortality due to scouring of sediment and cockles from channels and beds (Woolmer, 2013). Pressures upon coastal environments housing commercial fisheries such as those studied by Pierce et al. (2011) include burdens of land use, nutrient run off and degradation of bays that intertidal zones like Moreton Bay share with Morecambe Bay. Therefore, the historical activity of Morecambe bay's channels and the importance of this morphology to sustainable management of the intertidal zone to preserve intertidal habitats for aquatic organisms, indicates it is a significant area to investigate (Viles and Spencer, 1995; van Leeuwen et al., 2010; Datta et al. 2010).

4.3 Measurement and analysis of channel morphology.

Traditional numerical morpho-dynamic modelling is used to predict future change. However, this type of modelling inadequately reproduces "natural complex morphological evolution patterns" of tidal channels (Chu et al., 2013. p.1) because, despite empirical models' use of equations and field measurements to improve predictability of future processes, the field data required is difficult to extract from dynamic intertidal flats and coastal channels (Woodroffe, 2003). Consequently, models often produce under and overestimations of channel morphological change due to the assumptions and simplifications that the models are founded upon (Aldridge, 1997; Chu et al., 2013). Therefore, modelling is an insufficient method for data collection and analysis surrounding channel morphology without more accurate methods of data collection and analysis such as remote sensing techniques to validate the findings of numerical models (Courault et al., 2005).

Until the 1990s, observational data was sparse compared to numerical measurements (Aldridge, 2997) however contemporary laser technology has generated improved sources of topographic data (Heywood et al., 2011). Remote sensing techniques include satellite images that are produced through the reflection of light radiation from the earth surface such as LANDSAT. Landsat 7 ETM+ functions across 8 spectral bands (blue, green, red, near infrared, shortwave infrared, thermal, shortwave infrared and panchromatic) and Landsat 8 OLI/TIRS expands upon Landsat 7 to include Coastal and Cirrus Bands (Barsi et al., 2014; USGS, 2015; Holden, 2017). This data source has been used for decades to investigate channel movements; as far back as the 1980's channel migration and deposition patterns along the Brahmaputra River were determined by Bristow et al. (1987).

Other remote sensing techniques involve the active production of remotely sensed imagery from both radar based energy sources such as synthetic aperture radar (SAR) and laser beam energy sources such as Light detection and ranging (LiDAR) (Heywood et al., 2011). As a comparatively new source of data, LiDAR uses multispectral sensors to record the laser reflection and is increasingly utilised for analysis of coastal changes. Cambell (2007) stated that "LiDAR provides a highly accurate, detailed representation of terrain" (p. 253) from which elevation data is then manipulated to produce Digital Terrain Models (DTMs) (Niemeyer et al., 2014). DTMs are useful to indicate both natural and human induced changes and modifications to channels, allowing targeted management of human interaction with channels such as those monitored by NW-IFCA (Lane and Holden, 2011).

However, Raper (2011) identified that despite the prominence of environmental processes environmental and societal impacts, there are few detailed raster representations of environmental processes. This lack of raster imagery is potentially due to the limited availability of such raster datasets that have detailed resolutions. Additionally, D'Alpaos et al. (2017) notes tidal channels are less researched, which opens a gap for use of raster mapping to indicate channel movements in Morecambe bay.

4.4 Summary of literature

Factors that cause channel movements are somewhat contested, but general consensus is that movements are shaped by a combination of tides, waves, sediment transport processes (erosion and accretion) and events such as seasonal changes or storms (Chu et al., 2013; Mason et al 1999; Mason et al, 2010). Literature indicates that Morecambe bay is accustomed to channel movements and changes in morphology, however despite Masons historic research, there is a gap in research for contemporary investigation of such movement (Chu et al., 2013) with channel movements in relation to cockle beds absent from literature.

Overall, LiDAR is presented as the most suitable remote sensing method to measure and analyse channel movements in Morecambe bay, as opposed to LANDSAT and traditional numerical modelling of morpho-dynamics (Heywood et al. 2011; Cambell, 2007; Lane and Holden, 2011). Therefore, geographical literature signifies a scope and foundation for investigation of temporal variations of Morecambe Bay channel movements in relation to cockle settlements using remote sensing.

5. Methodology

5.1 Site description

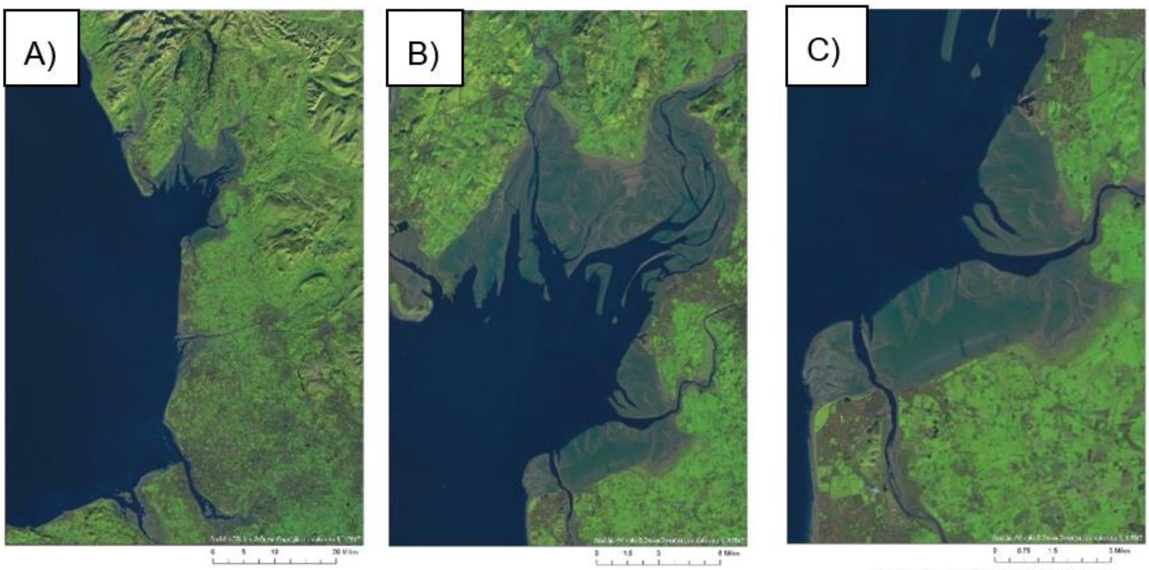


Figure 1: Satellite images from Sentinel 2 (2017) A) the Northwest coast of the UK, B) Morecambe Bay, C) The study area of the south bay, with the river Wyre at Fleetwood to the south west and the river Lune at Lancaster to the east in addition to the intertidal sand flats of Pilling Sands (southern-most sand flat) and Middleton Sands (north-eastern sand flat) either side of the Lune Channel.

Morecambe bay is situated on the north-west coast of England, a dynamic zone in which the rivers Kent, Lune, Wyre, Leven meet the Irish sea (figure 1). The bay holds Sites of Special Scientific Interest (SSSI), Marine Protected Areas (MPA), Marine Conservation Zones, European Marine Sites, Wetlands of International Importance (Ramsar site) and National Nature Reserves (NW-IFCA, 2017). The channels in the bay are shaped by tidal asymmetry in which the magnitude of flood tides is higher than that of ebb periods (Mason et al., 2010). The sediment is transported anti-clockwise around the bay as a result of the predominance of flood currents in the southern Heysham channels and dominance of ebb tides in the more northern Grange channels (Aldridge, 1997). Morecambe bay is 68% intertidal sand and mudflat and is one of the largest intertidal areas covering over 33 thousand hectares across which fine sand dominates the channel beds and mud is found further out towards the Irish Sea (Davidson, 2016; Mason and Garg, 2000; Aldridge, 1997). Morecambe bay is a macrotidal environment with tidal ranges reaching over 10m, with the potential

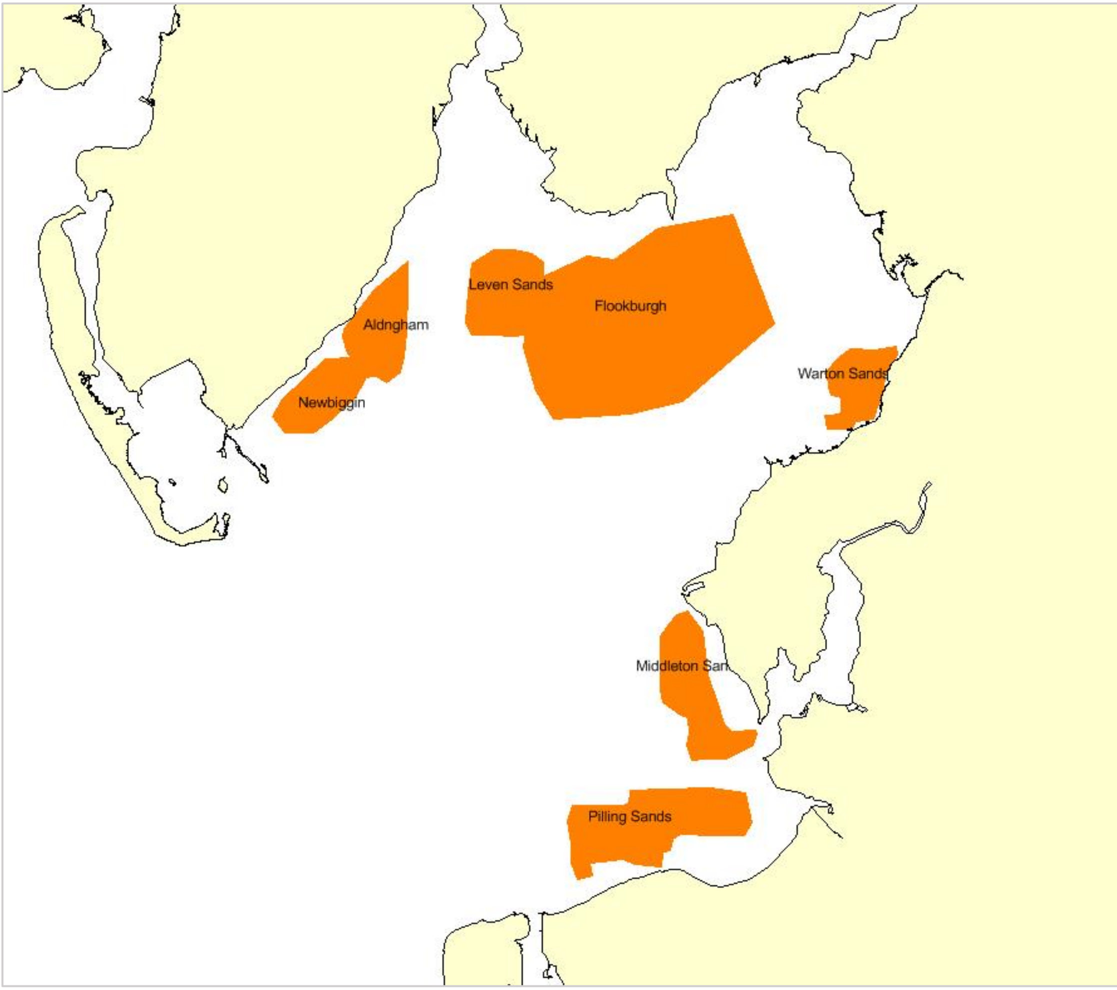


Figure 2: 7 cockle fisheries in Morecambe bay that remain in 2016, including the focus of this study: Pilling Sands and Middleton Sands (NW-IFCA science team, 2016)

to exceed velocities of 1.3m/s^{-1} (Aldridge, 1997). In addition, Morecambe bay ecosystems are close to multiple species distribution limits thus, are quick to be impacted by and exhibit the effects of climatic change (Adam, 2000).

Since 2004, there have been 12 cockle sites (NW-IFCA Science Team), however only seven of these including Newbiggin, Aldingham, Leven Sands, Flookburgh, Middleton Sands and Pilling Sands (figure 2) have remained stable cockle fisheries over the years (NW-IFCA Science Team, 2016). This research looks specifically at the channel migration surrounding the intertidal sand flats, between Fleetwood and Lancaster, of Pilling Sands and Middleton Sands (Figure 1.c).

5.2 Data collection and Processing

5.2.1 Cockle population and spatial distribution datasets

NW-IFCA provided survey data from the 13-year period for both Pilling Sands and Middleton Sands. The data was mainly collected through surveying at points on a predetermined grid, however some surveys were opportunistic in nature thus, their GPS location was recorded at different sites to the common grid points used. To investigate cockle populations, the science team use a quadrat and wooden blocks to make the sandy surface more fluid. This fluidity causes the cockles to rise out of the sand to the surface, allowing the Science Team to count the number of adults observed in the $2m^2$ quadrat. Only adult cockles are counted, meaning cockles must fit size requirements to be included in the survey. This information is logged into spreadsheets with the GPS coordinates by NW-IFCA.

These surveys were then plotted on ArcMap 10.1, a geographic information system (GIS). The symbology of the sites was processed appropriately to indicate the distribution of the total number of adult cockles at each coordinate on each site, for each year. This data allowed the qualitative assessment of cockle bed locations for general trends and anomalies. The cockle data was then overlaid onto the other investigated factors of elevation and movement.

5.2.2 LiDAR and Elevation mapping

ArcMap, was used to process the remotely sensed, LIDAR digital terrain model (DTM) tiles obtained from the Environment Agency's open data source for the years of 2004 and 2010. These secondary categorical datasets were obtained with the aim to produce primary maps for NW-IFCA, which with both qualitative and quantitative analysis will help to inform NW-IFCA about the physical conditions of intertidal sandflats that the cockles inhabit.

Primarily, the tiles were uploaded to the GIS software (ArcMap 10.1) and merged to a single raster for each year available (figure 3.a to 3.b). From this, a map of the elevation changes between 2004 and 2010 was produced using

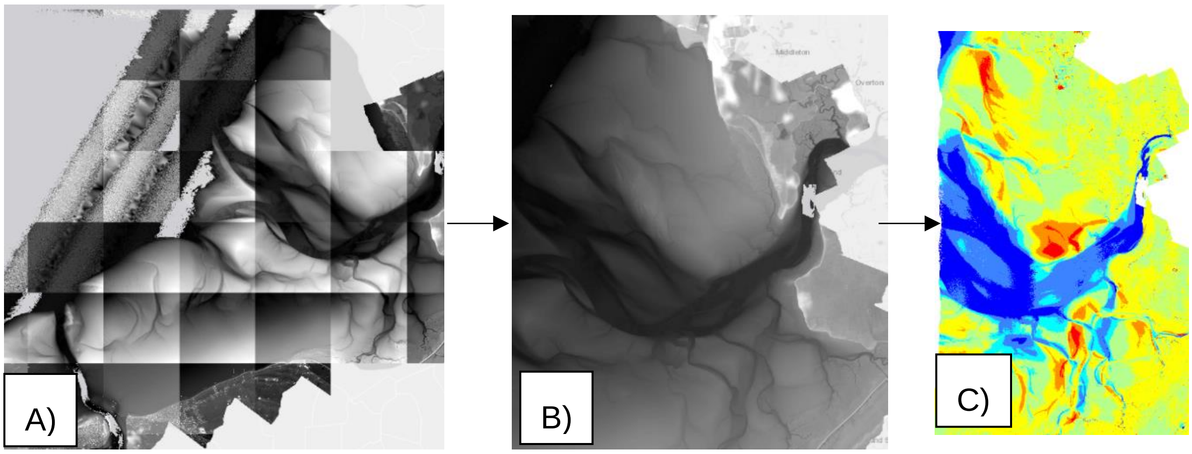


Figure 3: the process of LIDAR analysis from a) mosaic of DTMs, to b) rastered image and then c) a calculated image with classified symbology.

the 'mosaic to new raster' tool. After processing to change the symbology to graduated colours with a suitable positive-negative colour mapping system and altering the classification scheme to 7 classes (figure 3.c), a map visually displaying the elevation changes and thus sites of accumulation and erosion was produced. This was then interpreted qualitatively for analysis of the channel movements and elevation changes in section 8.

This 2004-2010 map of elevation change was then overlaid with cockle bed locations provided the by NW-IFCA science team, which included the numbers of total adult populations at each surveyed point and the coordinates from 2005-2010 for Middleton Sands and Pilling Sands. 7 maps with the cockle bed plots overlaid were produced for qualitative analysis of cockle bed changes in relation to the elevation changes detected.

5.2.3 Landsat and Channel Mapping

Landsat 8, 7 and Global Land Surveys were obtained from USGS Earth Explorer for analysis of quantitative channel movements. Four datasets were chosen from 2004, 2009, 2015 and 2017 as this covered the time period of cockle survey data available and had reduced cloud cover (less than 10% cloud cover). Landsat was deemed more appropriate than LIDAR to look at the channel movement as the coverage of LIDAR data available was limited to 2004 and 2010 at a minor fraction of the coastline.

The datasets with multiple bands were stacked using ERDAS Imagine to create a single image; with multispectral RGB bands symbology altered appropriately

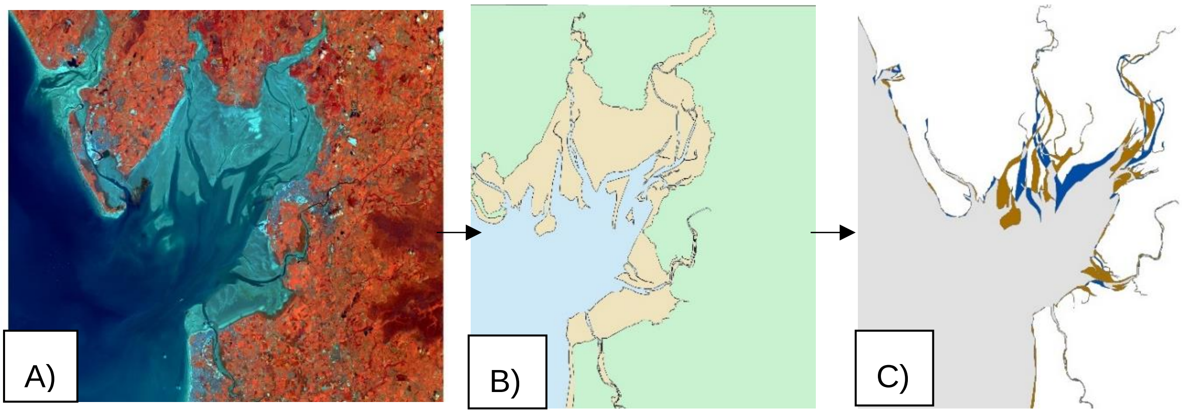


Figure 4: the processing of any Landsat images from the a) ERDAS stacked image, to the b) digitised and then the c) united digitised layers for ready for interpretation.

(figure 4.a). The large images were cropped in ERDAS before being transferred to ArcMap. Within ArcMap, Land, Sandflat and Channel extents (waterlines) were digitised for 2004, 2009 and 2017 (figure 4.b). From this, maps of channel movements over the 13-year period were produced using the Union spatial analyst tool, to indicate areas of changed extent (Figure 4.c). The channel movement maps were overlaid with cockle bed locations provided the by NW-IFCA science team for each available year between 2004 and 2017. This produced 4 maps for interpretation.

Tide Gauge information for the closest time within 15-minute intervals of Landsat acquisition was obtained from the British Oceanographic Data Centre to assess the impact of tidal elevation upon the observed changes in chapters 7 and 8.

5.2.4 EUSeaMap

A dataset mapping sea sediment was obtained from the European Marine Observation Data Network's (EMODnet) 2016 habitat mapping project. ArcMap was used to crop EMODnet's European Nature Information System (EUNIS) habitat map to a suitable extent, and the information for Morecambe bay was then presented overlying a contextual base map.

5.2.5 Sinuosity

An attempt to classify the minor channels sinuosity was made using Dey's categorization of straight as <1.1, sinuous as 1.1-1.5 and meandering as >1.5, using the equation (Dey, 2014):

$$\text{Sinuosity} = \frac{\text{Channel length}}{\text{Centre line}}$$

The channel length was digitised on ArcMap in kilometres and the centre line was measured as the straight-line distance in kilometres from start to finish of the channel in ArcMap (Hunt, 2016). Despite the extent of the 2004 LIDAR DTM being larger, the same distance was used for both to ensure fair comparison. The channel length was the divided by the centre line length of that same channel. The data was processed to produce a graph/table for quantitative analysis in section 7 and 8.

5.3 Ethics

Due to the desk based nature of analysing remotely sensed imagery, ethical issues surrounding the protection of the cockles and their environment, as a site of special scientific interest among other classifications, have been avoided. Field visits to Pilling Sands, involving the accompaniment of NW-IFCA professionals, inflicted no harm to cockles or their environment. Thus, ethical issues remain minimal.

6. Results

6.1 Mapping of channel movement in relation to Cockle populations

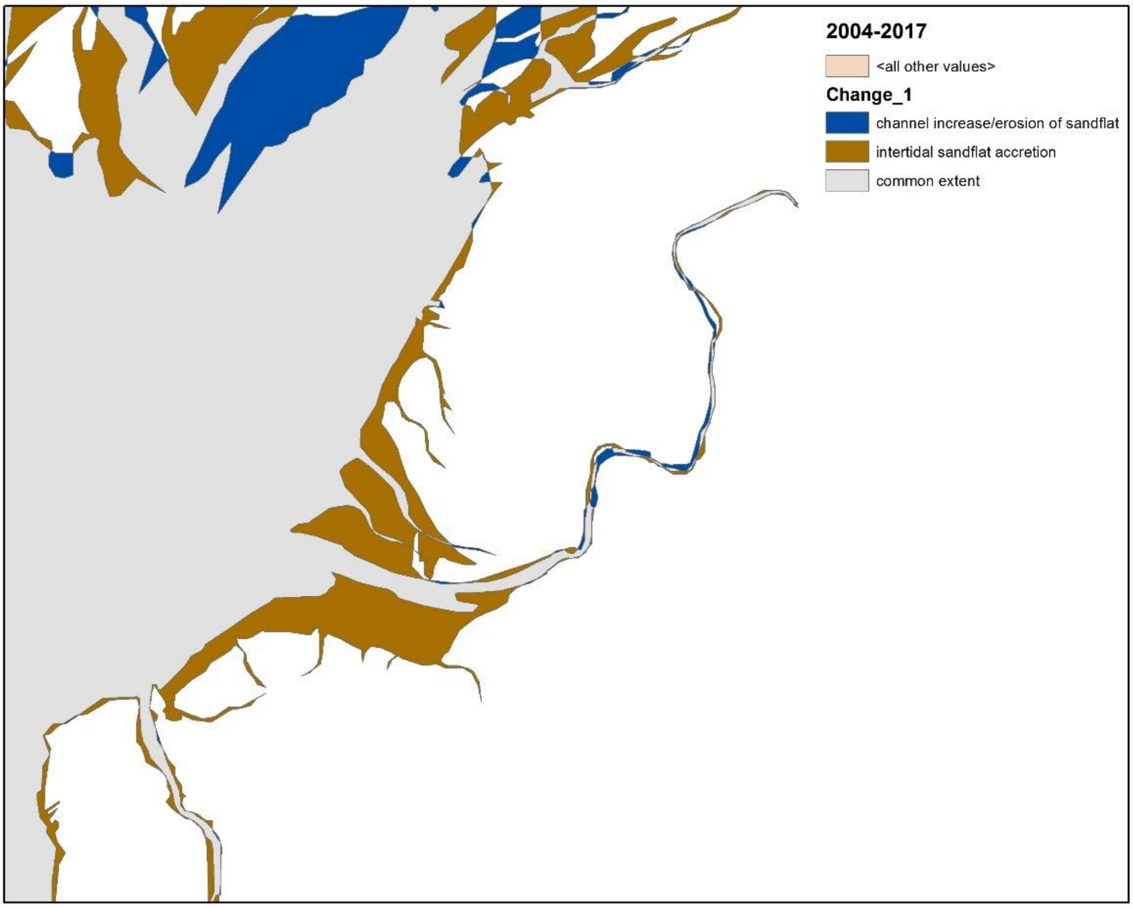


Figure 5: A map of the study area's channel migration between 2004 and 2017 indicating the erosion and accretion that has occurred.

The main finding of the channel movement analysis is the accretion of intertidal sand flat at the mouth of the Lune channel over 13 years, as in 2004 the channel mouth and path was wider, and thus the channel was closer to the study sites of Pilling Sands and Middleton Sands (figure 5). The waterlines producing this difference were found to have a difference in tidal elevation of 1.05m between 2004 and 2017 (Table 1).

Table 1: Tidal elevation in the analysed Landsat Images (Contains data provided by the British Oceanographic Data Centre and USGS, 2015)

Acquisition Date of Data	Acquisition Time of Landsat Image (GMT)	Acquisition Time of Tidal Elevation Gauge (GMT)	Approximate tide elevation at time of acquisition (metres)
07.09.2004	10.58	11.00	3.37
01.06.2009	11.00	11.00	2.45
17.07.2017	11.09	11.15	2.32

Figure 6 and 7 separate the 13-year period showing two different stages of accretion, demonstrating that between 2004 and 2009, the eastern edge of Pilling Sands that neighbours the mouth of the Lune Channel increased in size. Some minor channels and parts of the northern mouth of the Lune were decreased in size. The difference in tidal elevation between the images analysed for 2004 and 2009 was found to be 0.92m (Table 1).

Results show that between 2009 and 2017, there is less sandflat alteration south of the channel mouth as Pilling Sands remaining similar in size, however, an increase in Middleton Sands extent is indicated by the brown-orange block. Figures 6 and 7 show the channels mouth has migrated southerly as the sand-flat size has increased and the main mouth of the channel become narrower. Minor drainage channels across both Pilling Sands and Middleton Sands vary in spatial location and scale, indeed they are shown to vary more frequently than the main channel mouth. The difference in tidal elevation between the images analysed for 2009 and 2017 was found to be 0.13m (Table 1).

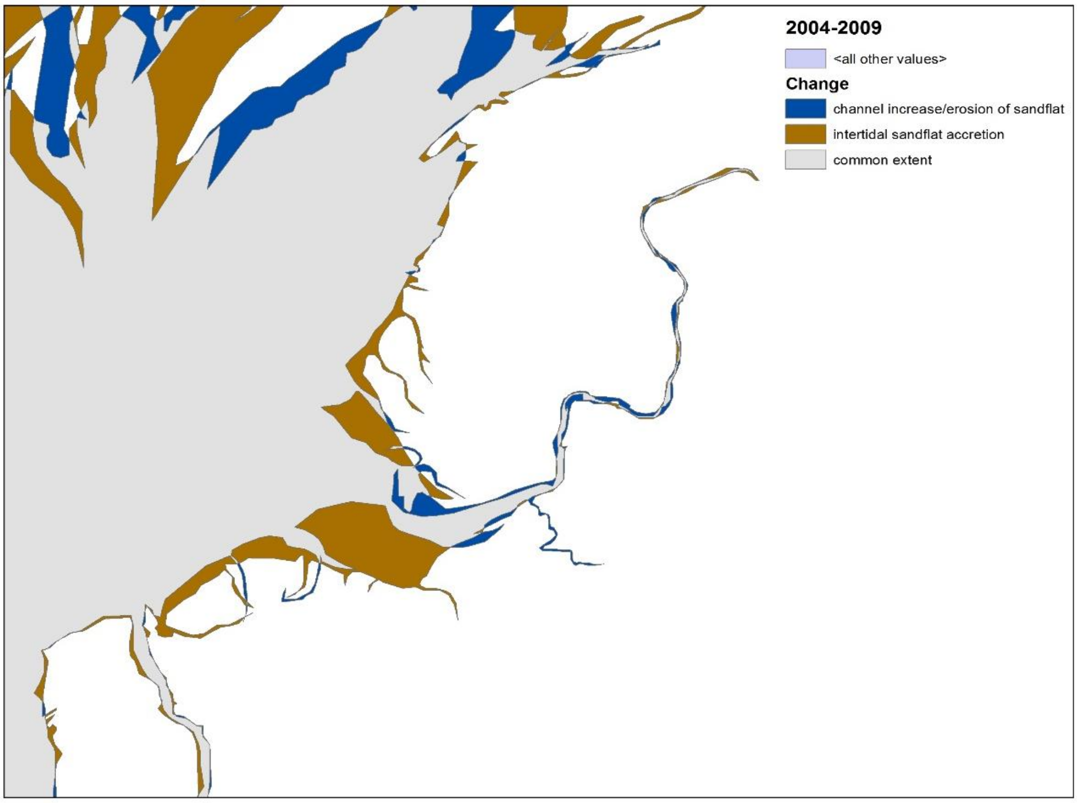


Figure 6: The movement of the Lune channel and surrounding minor channels between 2004 and 2009

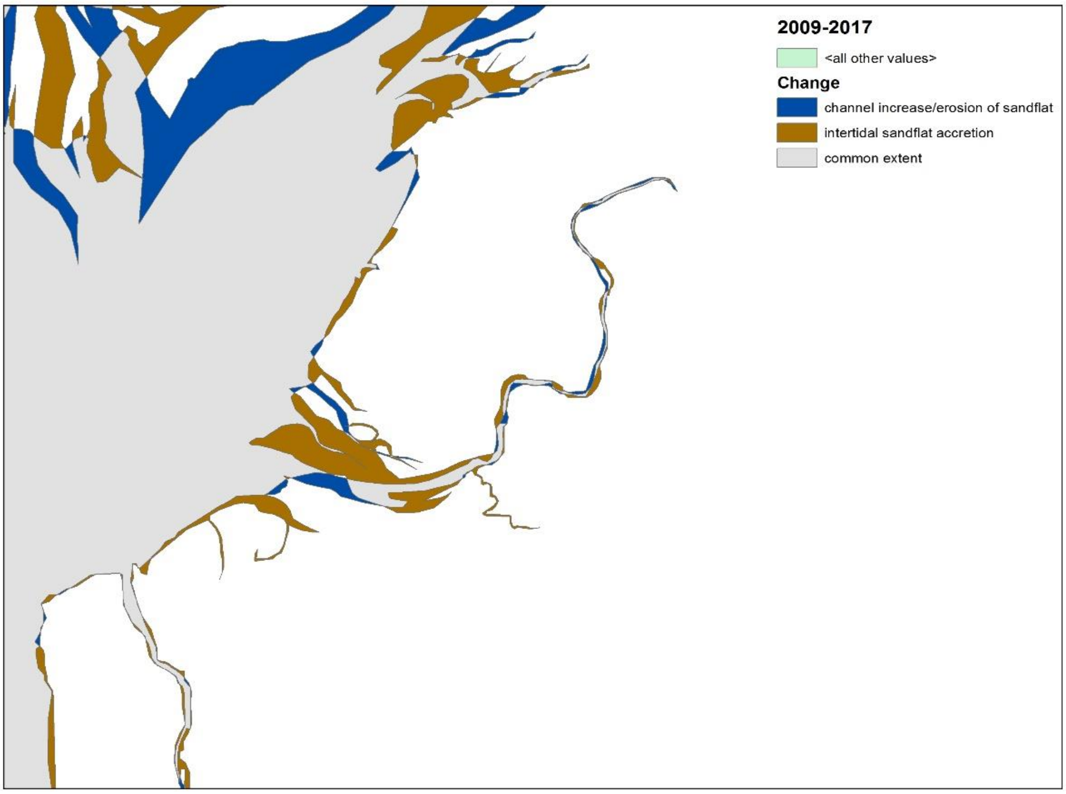


Figure 7: The movement of the Lune Channel and surrounding minor channels between 2009 and 2017

6.1.1 Cockle bed locations in relation to channel movement

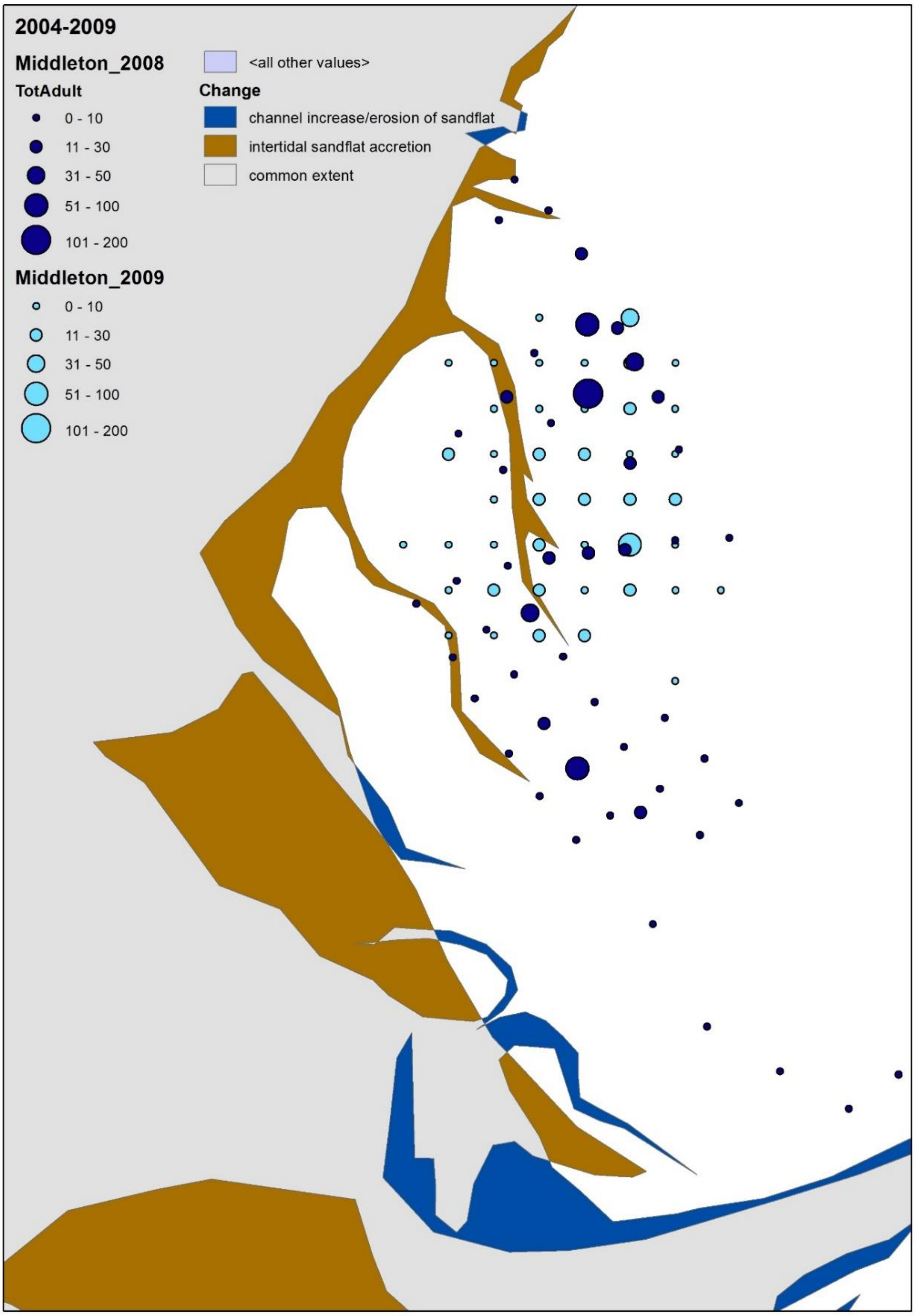


Figure 8: Channel and sand flat changes surrounding Middleton Sands from 2004-2009 overlaid with cockle bed locations for the years 2008 and 2009.

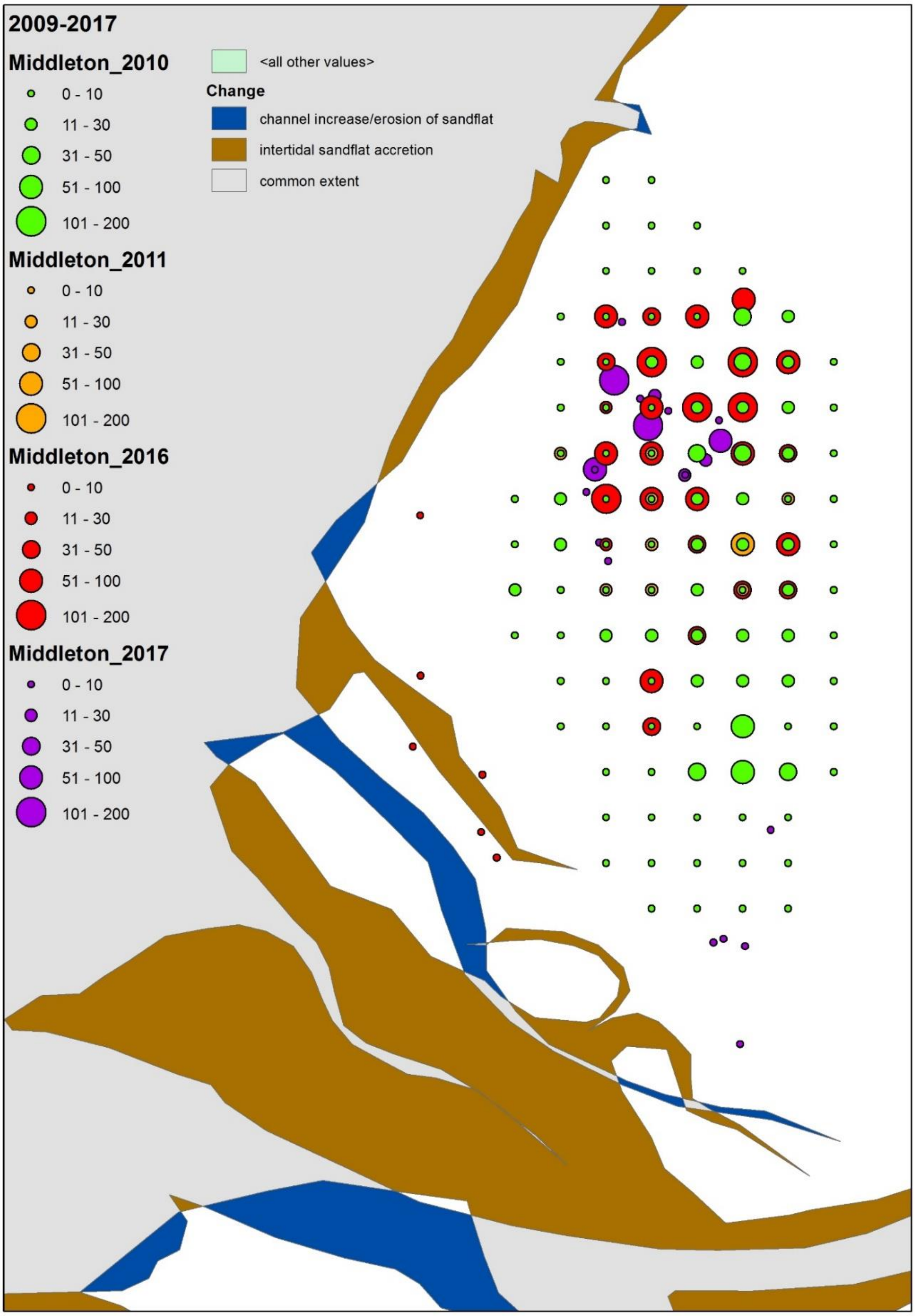


Figure 9: Channel and sand flat changes surrounding Middleton Sands from 2009-2017 overlaid with cockle bed locations for the years 2010, 2011, 2016 and 2017

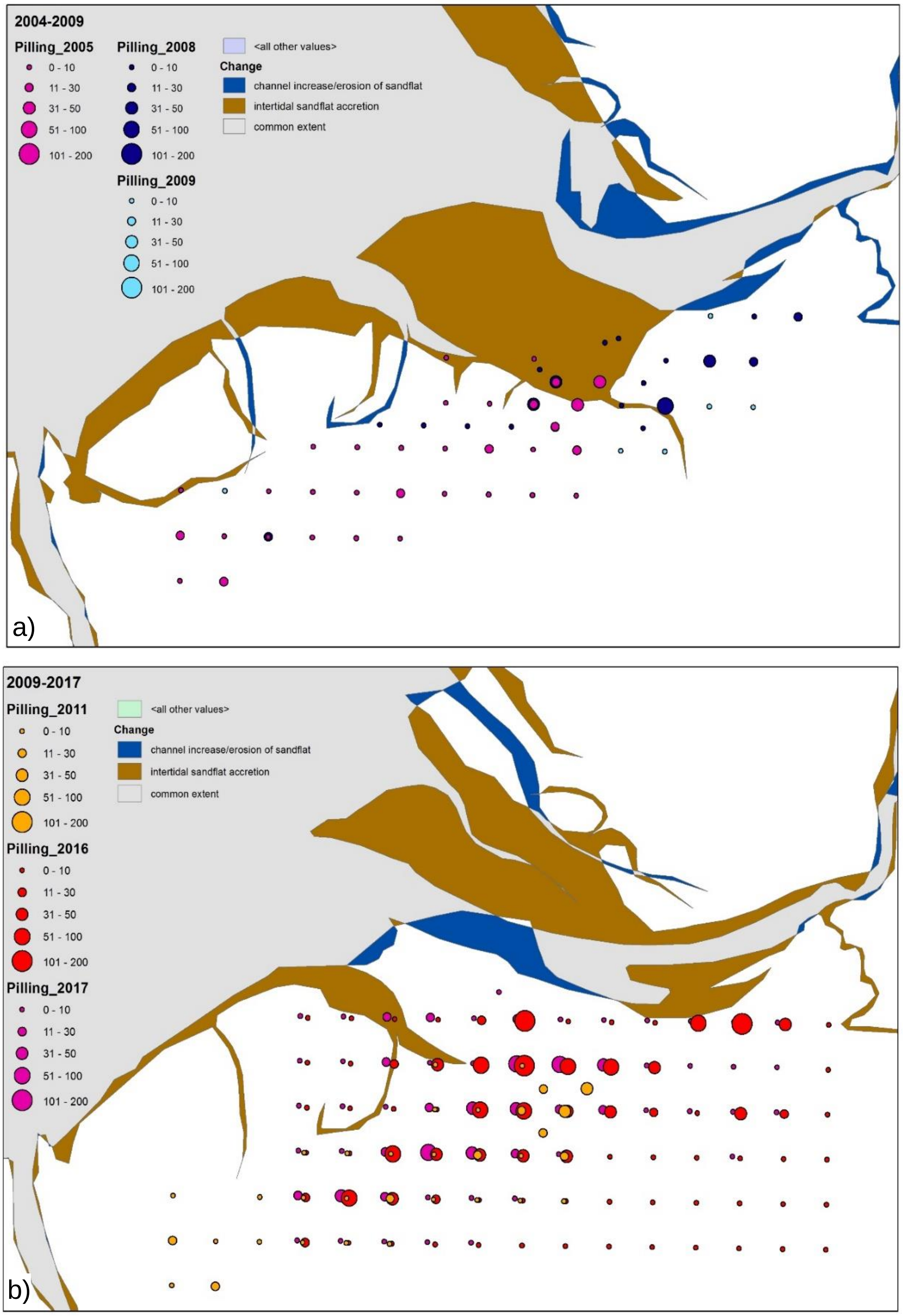


Figure 10: A) Channel and sand flat changes surrounding Pilling Sands from 2004-2009 overlaid with cockle bed locations for the years 2005, 2008 and 2009. B) Channel and sand flat changes surrounding Pilling Sands from 2009-201 overlaid with cockle bed locations for the years 2011, 2016 and 2017.

Figures 8-10 indicate the cockle bed locations in context of the channel movements over the 5 and 8-year periods respectively. At sites where there was accumulation between 2004 and 2009 on Middleton Sands, the cockle populations in subsequent years of 2010, 2011, 2016 and 2017 are higher. On the north-eastern edge of Pilling Sands, cockle populations are higher at sites where accumulation occurred between 2004 and 2009. Populations in Pilling Sands are also higher between 2009 and 2017 at mid points along the sand flat, away from the channel and coast of Morecambe bay.

6.2 Mapping of elevation differentiation and qualitative analysis

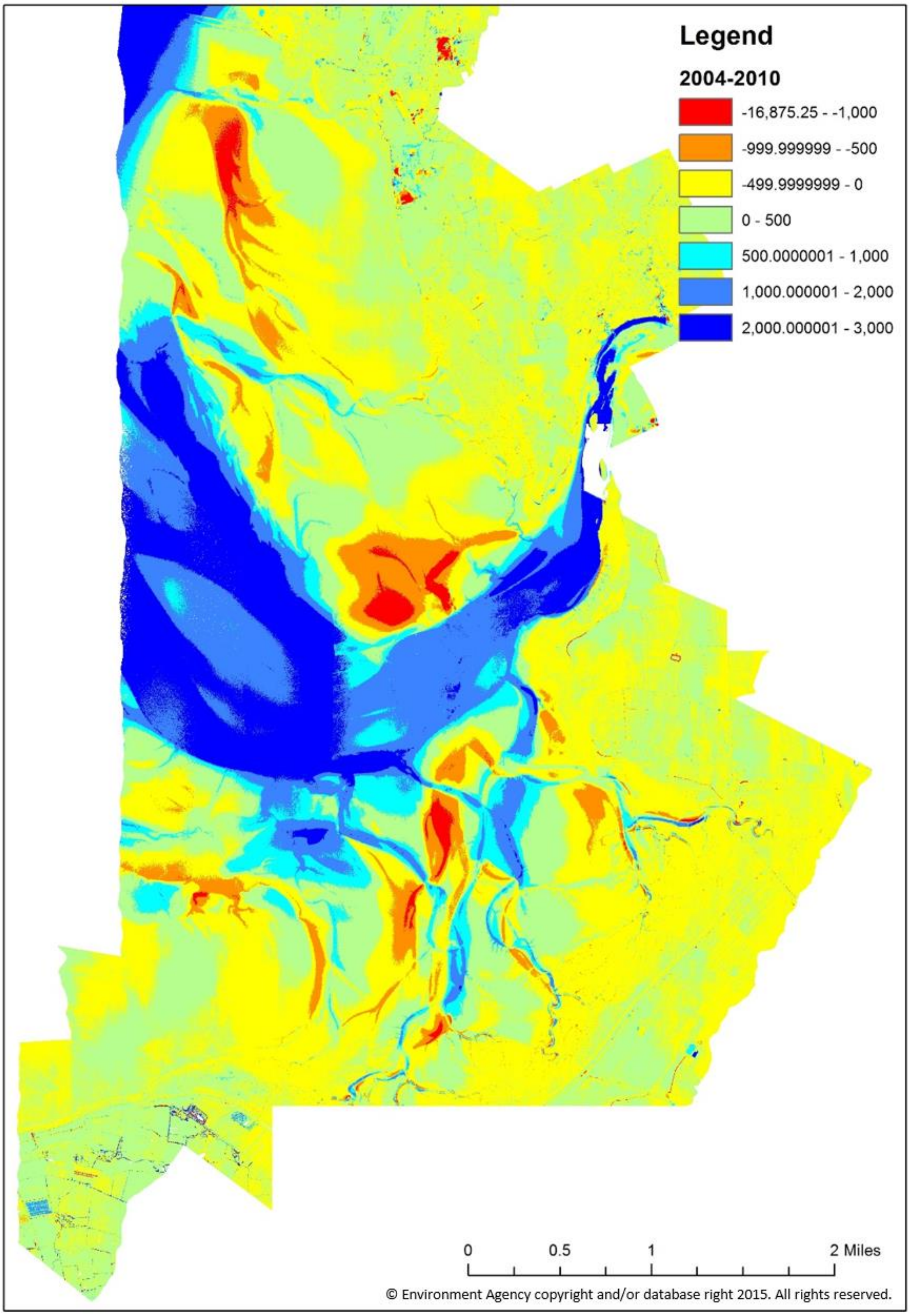
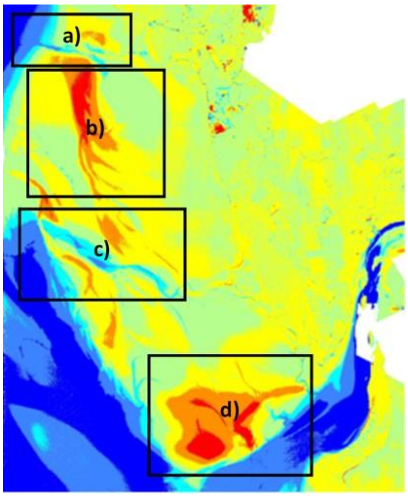
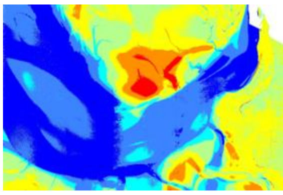
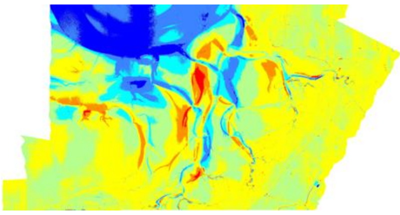


Figure 11: Map of elevation change across the study area between 2004 and 2010 from available LIDAR imagery.

Figure 11 visualises the changes in elevation between 2004 and 2010, the red and orange values indicate elevation increase since 2004 of up to and over 1m. The green and yellow areas indicate areas of no/neutral change with less than half a metre change in elevation. Blue colours indicate elevation decrease of up to 3m since 2004. The changes in elevation illustrated by figure 10 are then qualitatively analysed by reports of the spatial extent (distribution and size of differences) and quantitative changes to elevation, in table 2.

Table 1: Qualitative analysis report of the elevation changes represented by Figure 11.

Area	Elevation difference from 2004-2010
Middleton Sands 	a) At the north-west of the cockle bed site, there is a thin blue horizontal line indicating slight erosion since 2004 above the main Middleton Sands cockle site seen in other images. b) The vertical band of change in elevation by a minimum of -1m between 2004 and 2010 is approximately 1 mile in length. This red band indicates the site was higher in 2010 than 2004. The red wavelike lines towards the south of this spot, further indicate influence of tidal movement upon the accumulated elevation. c) A horizontal line of light and dark blue, indicates elevation changed by up to 2m since 2004, signifying that since 2004, this site has eroded a new minor channel. d) The large blot of red and orange which boarders the main channel of blue across the image indicates a site of

	accumulation in which the elevation of the sand was 1m higher in 2010 than 2004.
Mouth of Lune channel 	The main blue channel across the centre of the image is the mouth of the lune channel and shows changes of -0.5 to 3m as the channel was of a higher elevation in 2004 than 2010. Thus, indicating since 2004 the main channel continues to be a site of erosion.
Pilling Sands 	The mixture of blue lines represents minor channels that filter out into the bay. The lines of blue signify erosion of 1-2m, with up to 3m change at some points. Red areas adjacent to these indicate sediment has accumulated between 2004 and 2010. Some blocks and channels show an increase in elevation of up to 1m from 2004 to 2010.

6.2.1 Cockle bed locations in relation to elevation

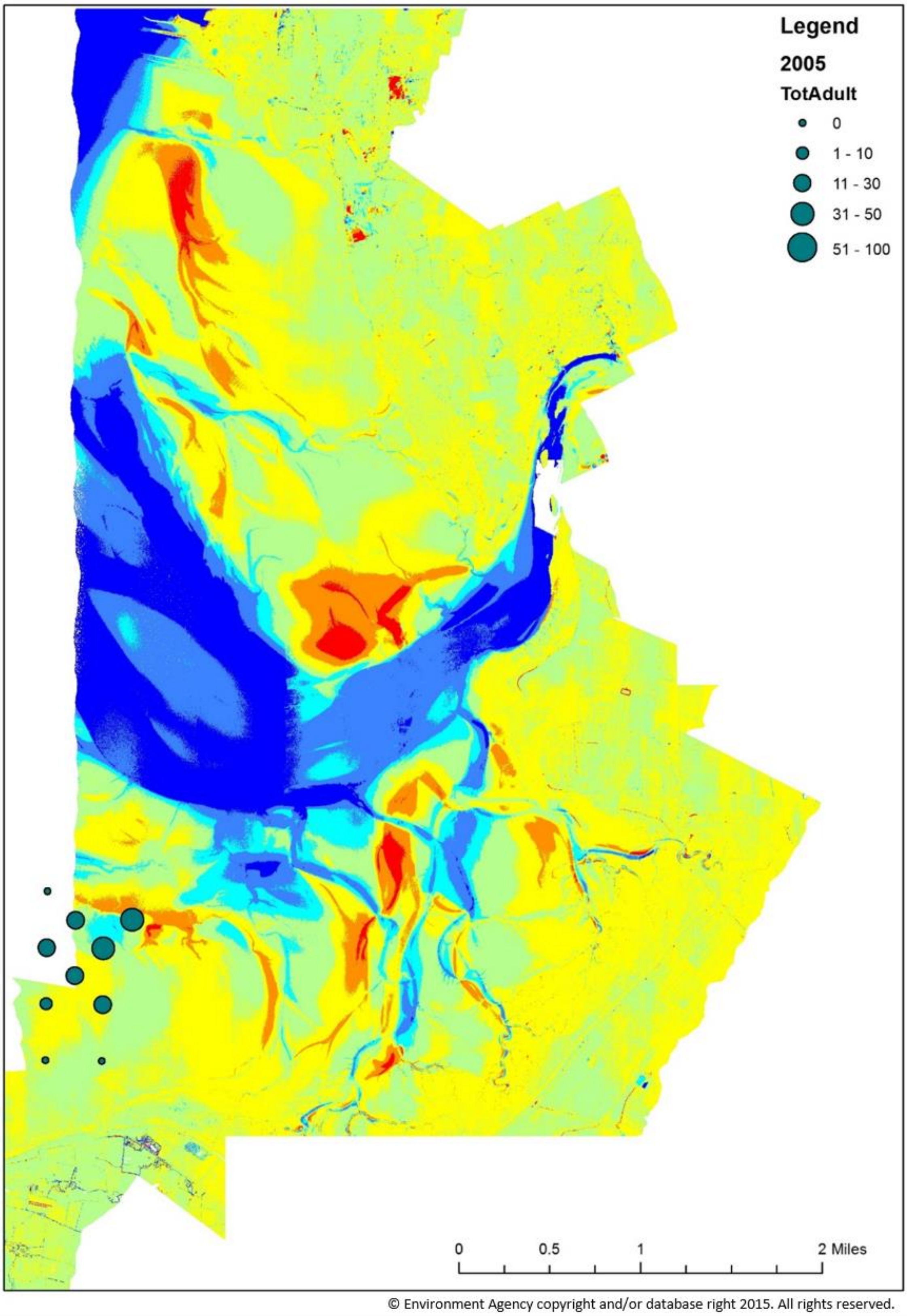


Figure 12: Elevation difference from 2004-2010 overlaid with 2005 cockle survey data of total adult populations.

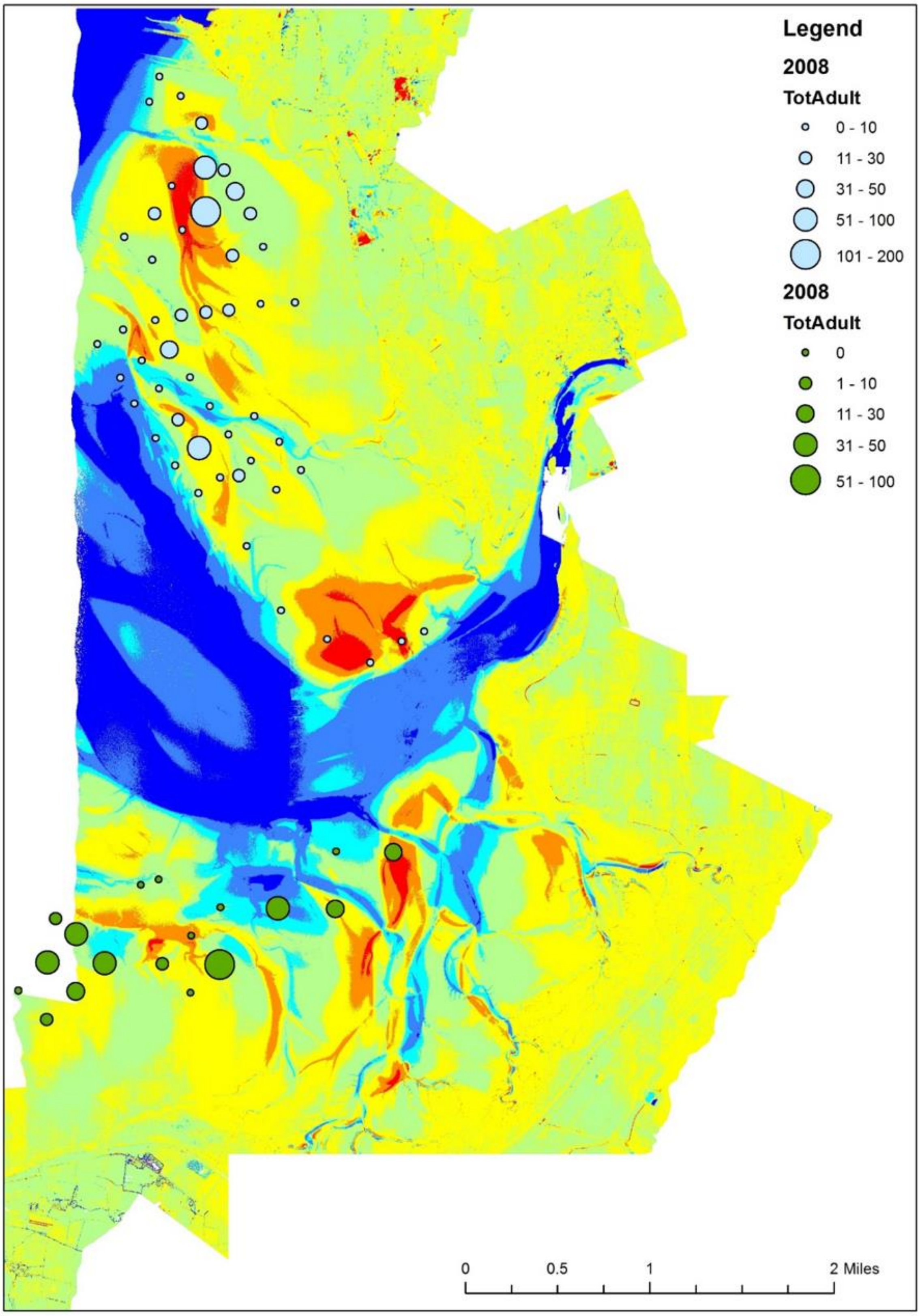


Figure 13: Elevation difference from 2004-2010 overlaid with 2008 cockle survey data of total adult populations

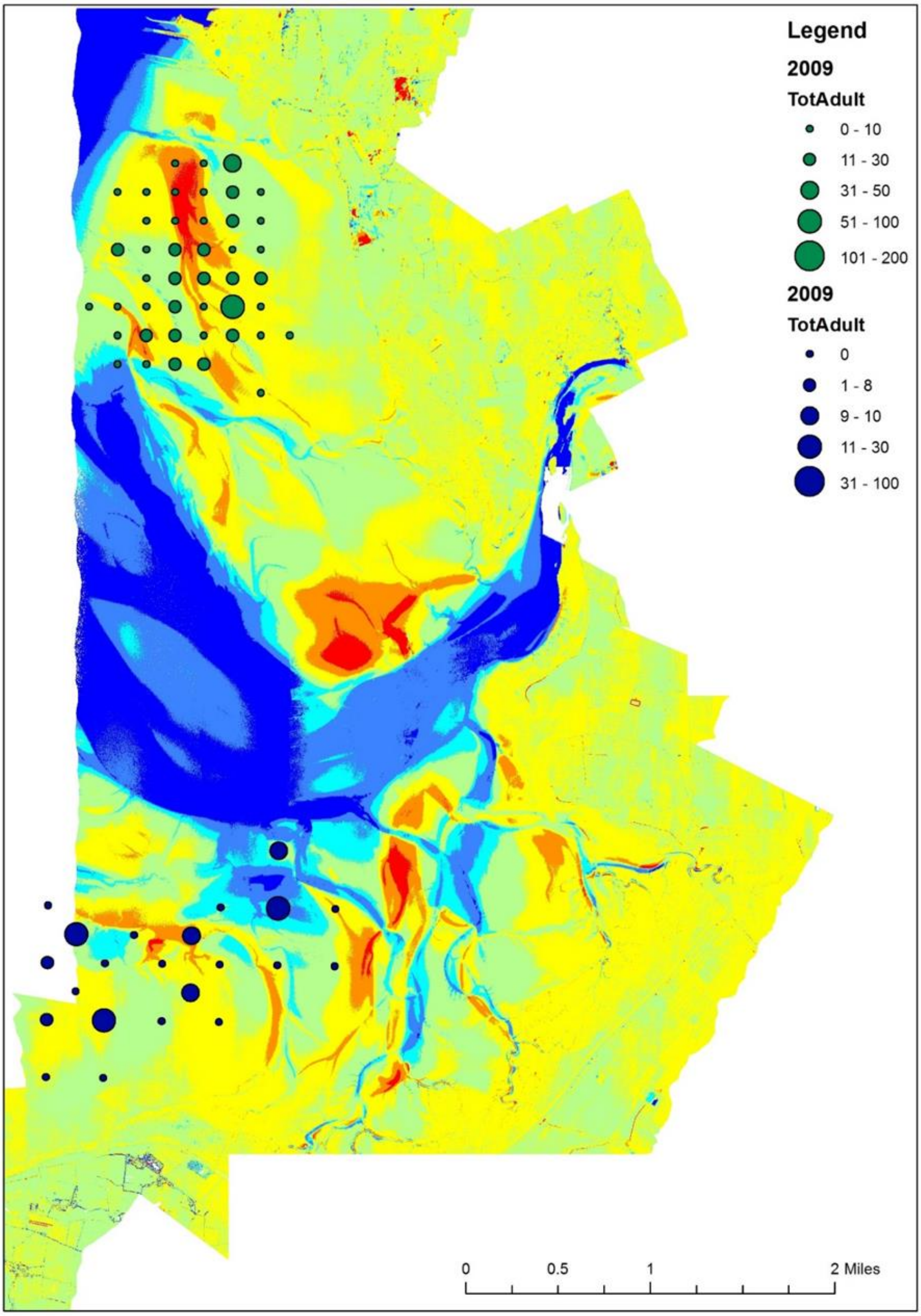


Figure 14: Elevation difference from 2004-2010 overlaid with 2009 cockle survey data of total adult populations

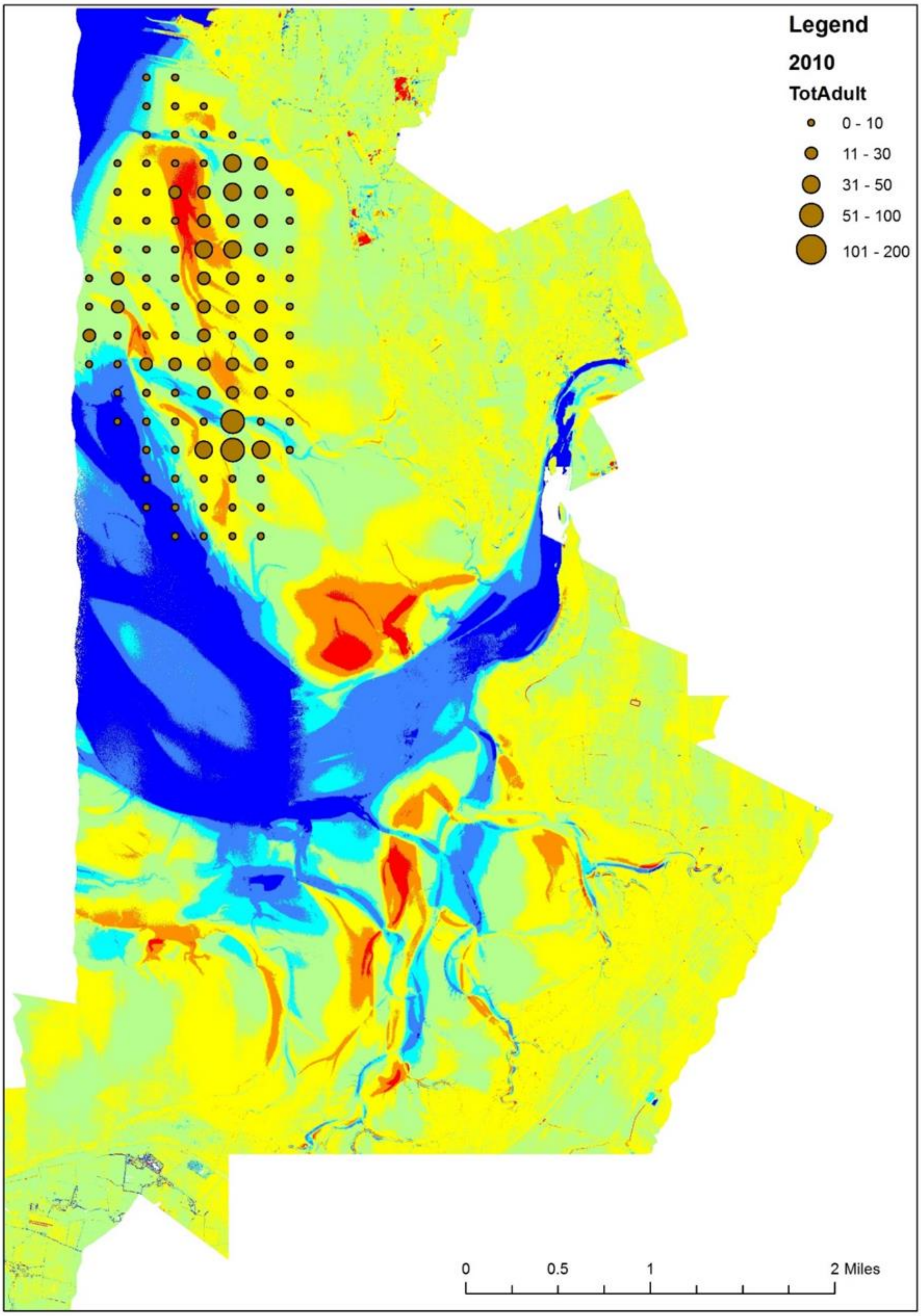


Figure 15: Elevation difference from 2004-2010 overlaid with 2010 cockle survey data of total adult populations

Figures 12-15 demonstrate the spatial distribution and size of cockle populations from 2005-2010 in relation to changes in elevation over the same 5-6-year period. Cockle bed locations were found to have higher adult populations towards the east of Pilling Sands, where a lot of changes in elevation across the 6 years was seen (figures 13 and 14). Cockle bed locations on Middleton Sands appear to be higher towards the north and edge of the site where there are elevation increases (table 2). Some high cockle bed populations are at points where the elevation has been shown to remain the same over 6 years (neutral values of yellow and green in figures 11-15). Population on Middleton Sands are small close to the Lune channel (figure 13).

6.3 Calculation of channel sinuosity

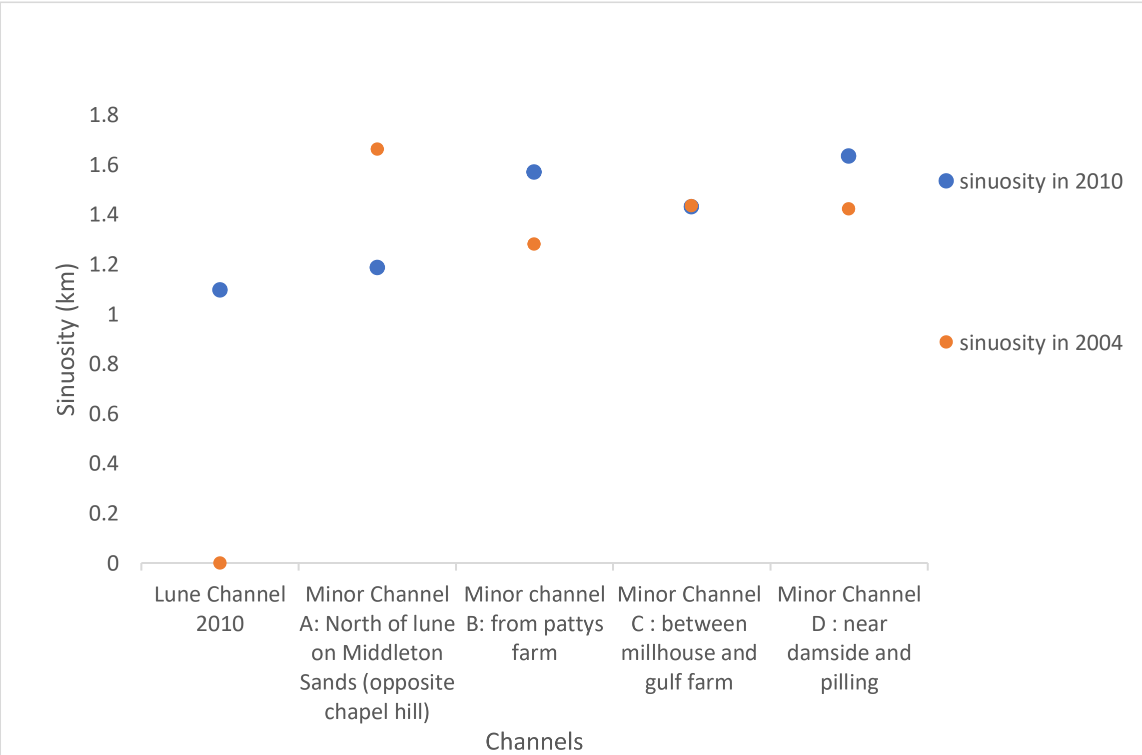


Figure 16: The graph indicates the comparative sinuosity (km) of the Lune and minor channels from the LIDAR images in the Appendix C.)

Using Dey's classification of sinuous channels (2014), all channels measured were calculated to be sinuous with a value of >1.1. Figure 16 indicates sinuosity increased in 3 out of 4 minor channels from 2004 to 2010 (Minor channels B, C, D). Two channels increased from sinuous at values of 1.2 (Minor channel B) and 1.3 (Minor channel D) in 2004 to being classified as meandering, recording values of >1.5 at 1.6. Minor channel A reduced in sinuosity from 1.7 (meandering) in 2004, to 1.2 (sinuous) in 2010. The Lune channel's sinuosity in 2004 couldn't be calculated due to limited visibility in the LIDAR image. The full range of sinuosity calculations and their classifications can be found in Appendix A.

6.4 Cockle Population Trends

6.4.1 Middleton Sands

Middleton Sands saw an increase in adult populations over the 13-year period. Surveys returned samples of between 100-200 cockles at numerous sites, peaking in 2010 when over 35 sites surveys found between 11 and 200, before dropping in 2011 in which only 17 sites sampled had populations of over 11 adults. However, in 2016, the survey found 5 sites on Middleton Sands to have between 101 and 200 adult cockles, more than ever previously observed. (2008-2016 figure 2). At this site, the cockle beds with higher populations were found to inhabit elevations between 1 and 2m.

6.4.2 Pilling Sands

Cockle populations at Pilling Sands were found to be smaller than populations at Middleton Sands, recorded between 0-50 Adults at most sites from 2005 to 2011. Anomalies to this include one site displaying a population of 50-100 in 2008 and 50-100 adults recorded at 4 sites in 2016. Numbers of adults are higher in 2016 and 2017 than previous years. Here, coordinates with higher cockle populations were found to be at sites of around 1-2m elevation.

7. Discussion

7.1 Morphological changes to the Lune Channel and neighbouring intertidal sand flats

7.1.1 Channel Migration

The primary objective, to examine the temporal variations of channel movements in relation to cockle bed locations, led to findings that the mouth of the Lune channel had migrated south between 2004 and 2017. There was accumulation of intertidal sand flats at Middleton and Pilling Sands during the 13-year period, corresponding to the channel migration, movement and overall change. Minor drainage channels on Middleton Sands that were classified as channel in 2004 but intertidal sand flat in 2009 and 2017, corresponds to the elevation findings at these specific areas to the north of Middleton Sands where there was accumulation between 2004 and 2010. Such variation in minor drainage channels on both Pilling and Middleton intertidal sandflat would suggest that these sandflats receive varying inputs of nutrients dependent upon this movement of sediment, which in turn, may influence cockle bed populations and the spatial distribution of these populations.

This increase in intertidal sand flat on both Pilling and Middleton Sands can be explained by Aldridge's documentation of differences between the magnitudes of ebb and flow currents in Morecambe Bay. The observed morphodynamics of the channel and intertidal sand flats are likely due to this asymmetry, as the Lune Estuary has been found to function as a flood-dominant estuary (Halcrow, 2003). Although low level erosion and deposition occur continually due to currents consistent suspension and deposition of coastal sediment, larger levels of deposition and erosion can be caused by episodic high waves (Masselink et al., 2011; Zhu et al., 2016). This supports the suggestion that Morecambe bay's larger levels of erosion and deposition are influenced by high waves, storm surges and climatic variation over the study years. However, it is important to be aware that flood or ebb dominance doesn't automatically lead to deposition or erosion, it is the asymmetry of the ebb and flood tidal velocities and the length of slack periods that is the main control on net sediment transportation in some areas (Environment agency, 2008; Brown and Davies, 2007). This contradicts findings that flood tidal currents cause erosion and ebb currents deposit sediment, indicating how coastal processes influence upon channel morphology is highly dynamic and varied globally (Zhu et al., 2016). Thus, the specific cause of the increase in intertidal sand flat in this study is hard to determine without specific research into the dominance of processes in Morecambe Bay.

7.1.2 Sinuosity

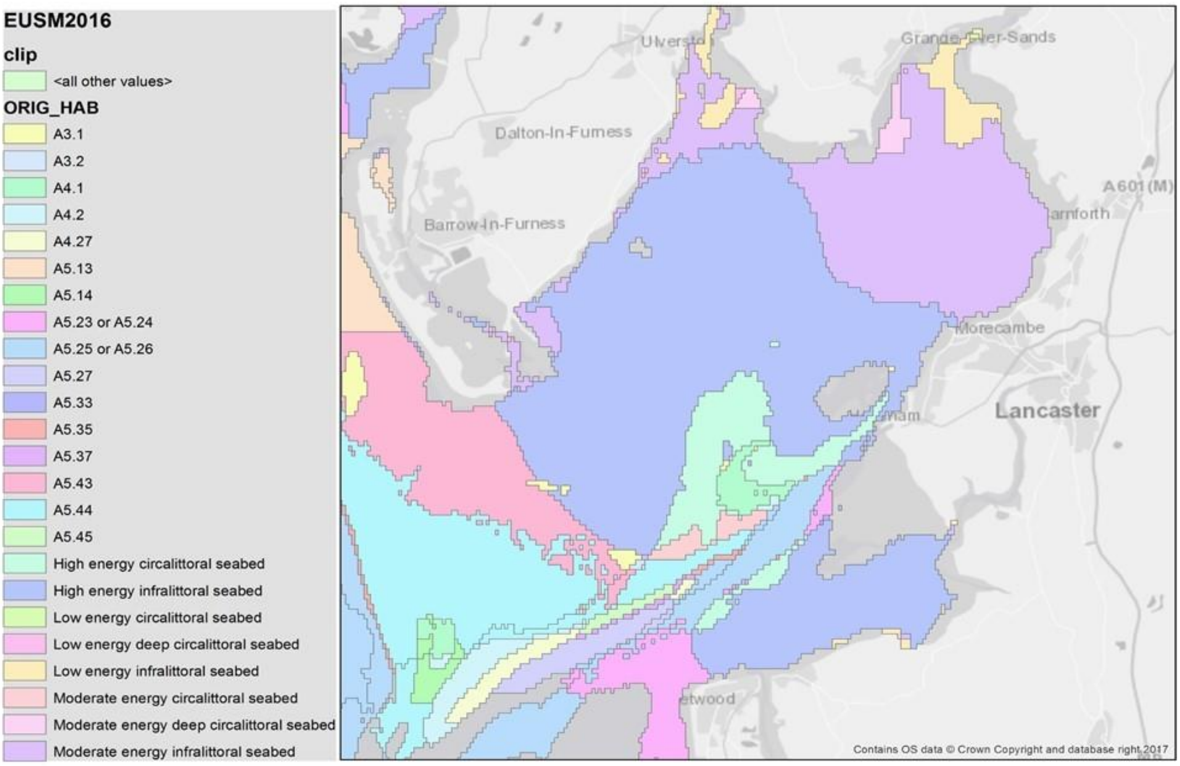
Sinuosity is a key factor influencing the morphology of channels, determining the rate of erosion (Holden, 2017). The velocity of water increases at the outer bank of meandering and sinuous channel bends, which in turn increases turbidity of the water and consequent rates of erosion at bends and deposition elsewhere (Holden, 2017; Masselink et al., 2011). The Lune and surrounding minor channels were found to be sinuous and meandering entities. Thus, demonstrating a dynamic environment between Pilling and Middleton Sands, analogous to the consensus among researchers that Morecambe bay and its intertidal sand flats are a site of morphodynamic change (Aldridge, 1997; Mason et al., 2010).

7.1.3 Elevation

In pursuit of the second objective, results indicated increases in elevation by 1m at the areas marked by red in data from 2004-2010 (figures 10-14), which is significant as intertidal sand flats display gradual change. Rectangles marked with red (figure 10) on the land adjacent to Middleton Sands are explained by construction of infrastructures and housing over the six years. The results also indicate blue areas in the figures where elevation reduced by 1-3m.

The decreases and increases in elevation can be explained by the deposition and consequent accretion of sand and fine silty sediment by the fluvial and oceanic water interactions at the mouth of the Lune Channel. These results are supported by Mason et al.’s (2010) findings of small levels of accumulation on the sand flats between 1992 and 2005 and higher levels of erosion at the Lune channel mouth. In addition, the largest area marked with red indicating an increase in elevation between 2004 and 2010 (point d) in Table 1) corresponds to Mason et al.'s (2010) detection of accumulation between 1992 and 2005, which suggest that this accretion has continued since 2005.

Suspension of sediment and subsequent erosion is a mechanism that results in decreased elevation of intertidal zones (Uchiyama, 2007). The elevation changes near the minor channels between Middleton Sands and Pilling Sands at the south of the Lune river drainage channel, indicates in more detail, a site of dynamic accretion and erosion interactions similar to the findings of Mason et al. (2010) for the decade previous to this study. This site could be a potential location of influence upon Pilling Sands as the rogue sinuous minor channels from rivers/streams that didn't join the Lune or Wyre cut across the Sands to the west of Pilling Sands, eroding and depositing sediment at different points across the sand flat. Overall, the indicated accumulation and erosion of sediment shown by the dynamic changes to elevation is likely a result of tidal asymmetry, which was noted by Aldridge (1997) to be an influence upon net tidal transport of fine sand in Morecambe Bay. Findings of a dynamic environment resulting from tidal asymmetry is further supported by the European Marine Observation Data Network's (EMODnet) Seabed Habitat Map (2016) as seen in figure 17 classifying the study area as a site of 'high energy infralittoral seabed' as a consequence of tidal, wave and river energy acting upon the site. High energy infralittoral and lower intertidal zones are problematic for organisms to anchor into the sediment to resist the shear stress, thus are often unvegetated (Masselink et al., 2011)



Information contained here has been derived from data that is made available under the European Marine Observation Data Network (EMODnet) Seabed Habitats project (www.emodnet-seabedhabitats.eu), funded by the European Commission's Directorate-General for Maritime Affairs and Fisheries (DG MARE).

Figure 17: EMODnet EUSeaMap of seabed habitats in Morecambe Bay

7.2 Morphological changes in relation to cockle beds

Concerning the third objective, trends of cockle populations and spatial distribution of cockles were investigated. The hub of higher density cockle populations at the north of Middleton Sands is an area which has been shown to have increased in elevation from 2004-2010 by 1m and impacted by highly dynamic channel migration between 2004 and 2017 causing findings of both deposition/accretion and erosion. This could suggest that cockles require an unstable environment highly influenced by morphological changes, which corresponds to the present knowledge of cockles as highly adapted organisms in response to a variety of environmental stressors (Woolmer, 2003). However, it could also be suggested that the elevation within the mid-intertidal zone provides the cockles with a suitable habitat as they have access to nutrients from in-fluxing waters during tidal cycles containing treated effluence from waste-water plants, surface run-off from the towns of Lancaster and Heysham, and treated waters from Heysham Nuclear Power Station (Jones and Obiri-Danso, 1999)

Investigation into cockle populations at both Middleton Sands and Pilling Sands in relation to elevation analyses demonstrated that sites with an elevation of between 1 and 2m were areas that cockle populations inhabited. This suggests elevation influences the spatial distribution of cockle populations. At Pilling, the main result of increased sand flat between 2004 and 2009 could be an influencing factor in the subsequent increase in cockle population's post 2009.

Suggesting the analysed morphological factors can influence the spatial distribution and density of cockle populations correlates to Woolmer (2013) who implies sedimentary processes resulting from morphological change influences cockle mortality. However, this suggestion also stands separate from this and other bodies of research which propose water quality, temperatures and salinity thresholds as physical environmental factors that impact cockles and correlate to sediment transport factors (Woolmer, 2013; Cheggour et al., 2001; Mirsadeghi et al., 2013)

Therefore, it is sensible to imply that the influences upon the distribution and density of cockle populations in Morecambe Bay are a result of both biological, chemical, bathymetric and morphologic factors in a dynamic interaction, thus the main factors are difficult to determine.

7.3 Limitations

7.3.1 Water/tide levels as sources of uncertainty

Topographic LIDAR doesn't penetrate water thus, there is some uncertainty surrounding the interpretation of the study's elevation results. Similarly, due to the tidal elevation difference of 1m (Appendix b Table 2) between the Landsat images from 2004 and 2010 which were used to digitise waterlines from, there are issues surrounding the comparison of image. This reduce the accuracy of the results as 1m of the observed channel movements is a likely consequence of tide difference. Therefore, the most accurate indication of channel movements is the mapped changes between 2009 and 2017 with tidal elevation differences within 0.13m. However, due to the highly limited environmental and temporal availability of suitable data this limitation is unavoidable.

7.3.2 Image Resolution, Coverage and Availability

Uncertainty is avoided because the LIDAR images are of 2m spatial resolutions (horizontally accurate to the nearest 2m), with vertical precisions of 15cm (Heywood et al., 2011). LiDAR also has high GPS precision geo-referencing however, Landsat data used is only accurate to a resolution of 30m (Heywood et al., 2011).

In addition to this potential for uncertainty in maps produced through the processing and interpretation of Landsat datasets, the range of temporal and spatial coverage of such satellite and remotely sensed images may present uncertainty. Due to the limited production of LIDAR data such as particularly limited coverage of Pilling Sands, and restrictions of Landsat coverage by both time (only taken on 16-day cycles) and environmental factors (cloud cover restricting visibility) the low availability of suitable images brings into question the certainty of temporal variations observed and the overall ability to determine any morphological causation of cockle bed change is made potentially uncertain (Heywood et al., 2011).

Due to these limitations, this method's sufficiency for exploring relations between channel morphological change and cockles is reduced, confirming Raper's (2011) observations. However, an integrated remote sensing approach remains the most suitable for digital investigation of channel morphology, reflected by remote sensing's increased use in coastal and morphological studies (Brock and Purkis, 2009).

7.3.3 Mapping limitations

Mapping as a method of presentation is not designed to show variations over time as, in reality, each map can only represent a bound spatial and temporal indication of change (Raper, 2011). GIS reduces this limitation as they allow temporal dataset's inclusion, however there is incomplete availability of cockle, LIDAR and Landsat data for consistent temporal spans that morphological variations can occur at (hourly, daily or weekly). Therefore, mapping is limited due to spatial and temporal extents. Nevertheless, mapping is imperative to visualise the spatial relations of analysed morphological change.

In addition, the maps produced may have inaccuracies due to the deployed method of manually digitising land, sandflat and channel borders. This is the selection or de-selection of features, the defined scale and the interpretation of the classified of Landsat symbology is open to human bias and error (Heywood et al., 2011). However, this level of error is equivalent to that from the use of alternative methods such as re-classification in GIS software, which will only detect quantitative pixel differences.

7.4 Future Work

Forthcoming research into this area depends upon increased frequency and spatial coverage of future remote sensing in the Morecambe Bay area. This is the main restriction upon determining more detailed, seasonal or storm event morphological variations. In addition to this, the fact that cockle surveys are restricted to particular periods of the year, means that it is problematic to correlate the real impact of winter storms or seasons upon spring and summer cockle surveys. However, there is scope for future research into seasonal variations if wider seasonal and spatial coverage of remote sensing data (LiDAR in particular) became available.

Within the context of current literature, the dynamic and fluctuating morphological changes concur with present research, however, the relation to cockle populations and spatial extent of the cockle beds is a new area of study which requires more research to create an established and sufficient body of knowledge. Therefore, to better determine the main factors impacting cockle populations within Morecambe bay, an integrated methodological approach to research combining morphologic change analysis with chemical, biological and bathymetric analysis is an area for future research.

8. Conclusion

Despite the limitations of partial availability and coverage of remotely sensed datasets and potential inaccuracies due to variations in water level from 2004-2009 that may impact the calculated change of channel extent during this period, use of an integrated remote sensing approach was effective and accurate enough to show migration and movement of channels, elevation changes and sinuosity. Therefore, the combination of LiDAR and Landsat worked effectively to produce mapped morphologic changes in relation to cockle populations.

Mapping of morphologic changes such as channel movements from 2004-2017, elevation from 2004-2010 and sinuosity from 2004-2010 has highlighted the dynamic nature of Morecambe Bay's southern edge. Research into objectives one and two has clearly identified morphologic changes across varying temporal and spatial scales within the selected study area. Analysis of channel movement and elevation increases has identified accumulation of intertidal sandflat at both Pilling Sands and Middleton Sands between 2004 and 2017. This movement and southerly migration of the mouth of the Lune Channel provides conceivable explanation for the increase in expanse and density of cockle populations at Middleton Sands over the 13-year period assessed. However, analysis of elevation also suggests that elevation of the sandflat plays a probable role in the spatial distribution of cockle populations. The minor channels adjacent to the Lune channel were found to be sinuous and meandering, with minor channels across the two intertidal sandflats identified as temporary and dynamic entities, rather than permanent or consistent features.

This clearly dynamic and high energy environment makes it difficult to infer a single morphological feature subject to change that influences the findings of objective three -inferred patterns of cockle populations. Perhaps suggesting that the fluctuations in cockle populations respond to the equally fluctuating morphological factors in action. It is recommended that future research employs an integrated methodological approach to combine morphologic change analysis, chemical/biological analysis and bathymetric analysis to better understand cockle populations.

9. Appendices

9.1 Appendix A: additional tables

Table 2:Sinuosity calculations for the minor drainage channels within the study area and their classification using the Dey (2014) thresholds of <1.1 as straight, >1.2 as sinuous and >1.5 as meandering

Year	Channels	Channel length (km)	Centre line length (km)	Sinuosity	Dey (2014) classification
2004	Lune Channel	NoData	NoData	NoData	NoData
	Minor Channel A: North of Lune on Middleton Sands (opposite Chapel Hill)	2.8	1.7	1.7	meandering
	Minor Channel B: from Patty's farm	4.3	3.4	1.3	sinuous
	Minor Channel C: between Millhouse and Gulf Farm	4.6	3.2	1.4	sinuous
	Minor Channel D: near Damside and Pilling	4.3	3.0	1.4	sinuous
2010	Lune Channel	10.5	9.6	1.1	sinuous
	Minor Channel A: North of Lune on Middleton Sands (opposite Chapel Hill)	2.0	1.7	1.2	sinuous
	Minor Channel B: from Patty's farm	5.3	3.4	1.6	meandering
	Minor Channel C: between Millhouse and Gulf Farm	4.6	3.2	1.4	sinuous
	Minor Channel D: near Damside and Pilling	5.0	3.0	1.6	meandering

9.2 Appendix B: additional figures

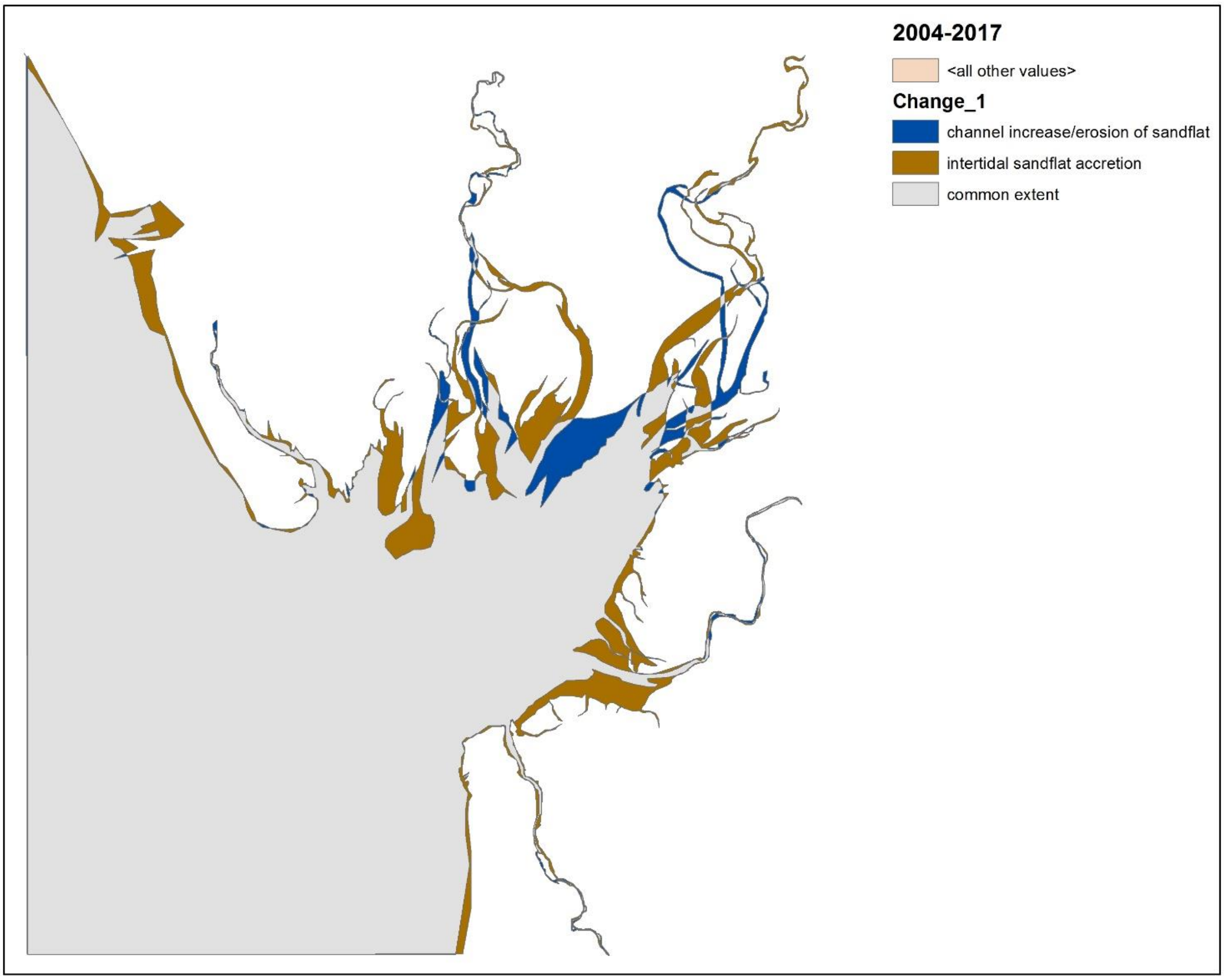


Figure 18: Channel movement between 2004 and 2017 in Morecambe Bay

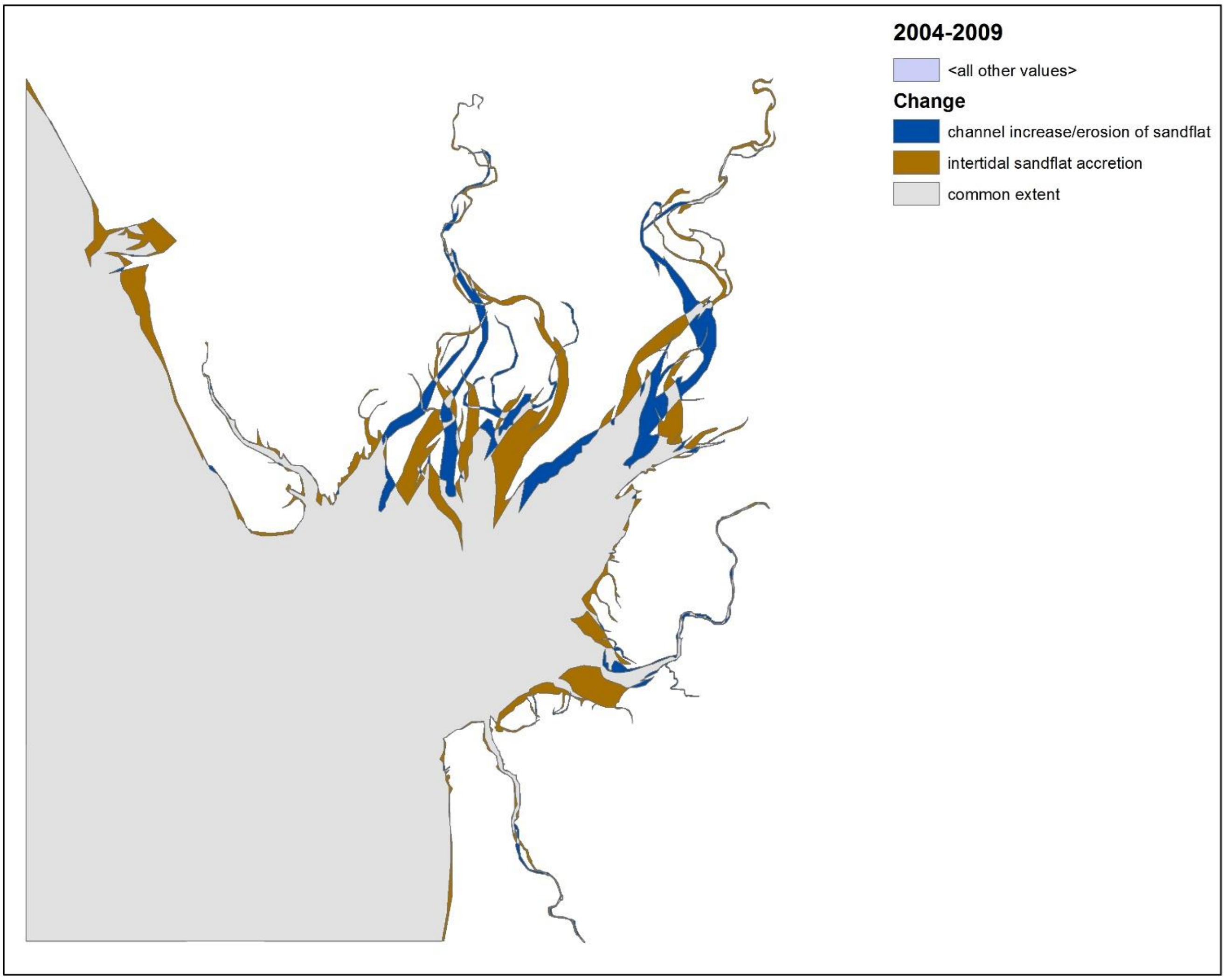


Figure 19: Channel movement between 2004 and 2009 in Morecambe Bay

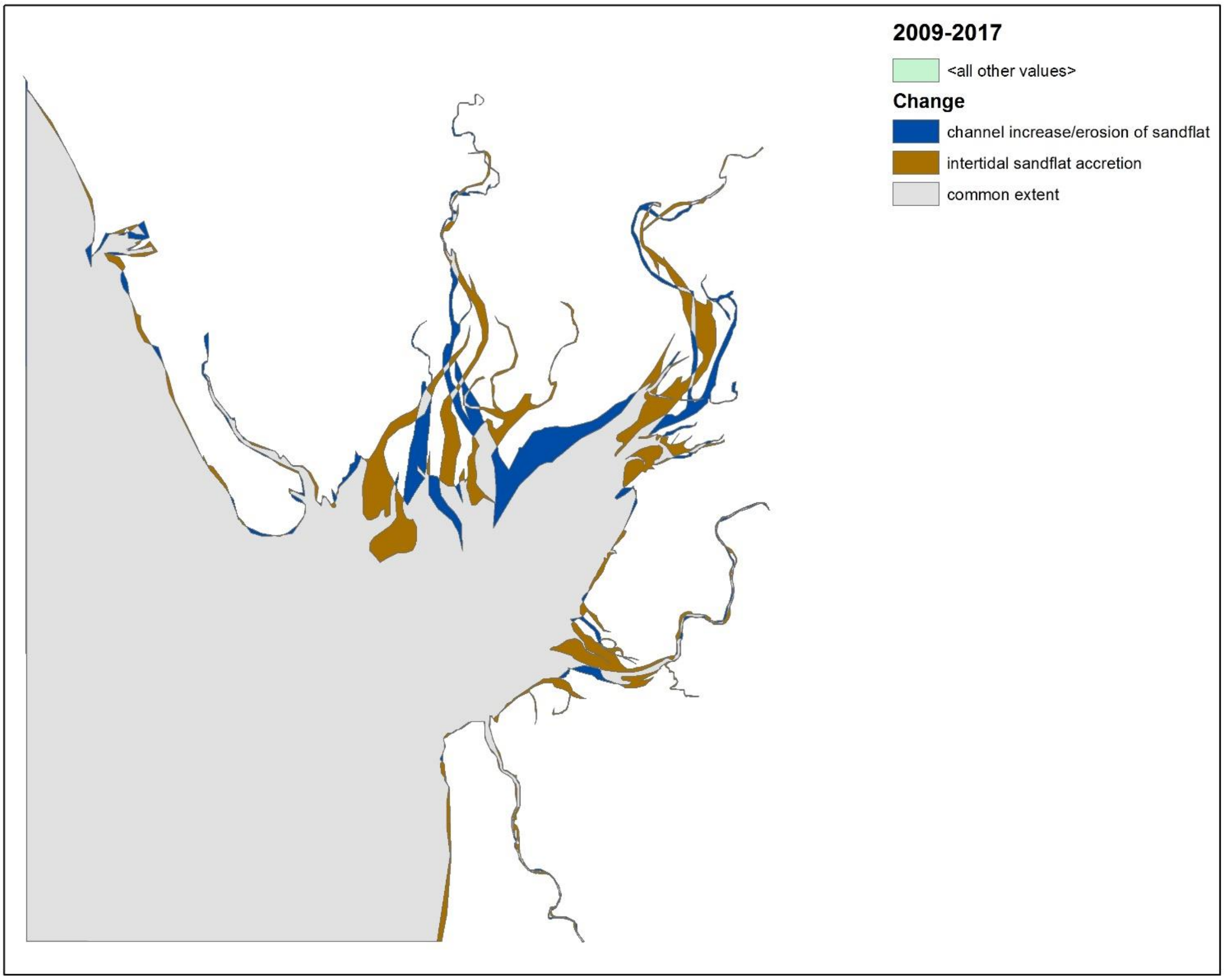


Figure 20: Channel movement between 2009 and 2017 in Morecambe Bay

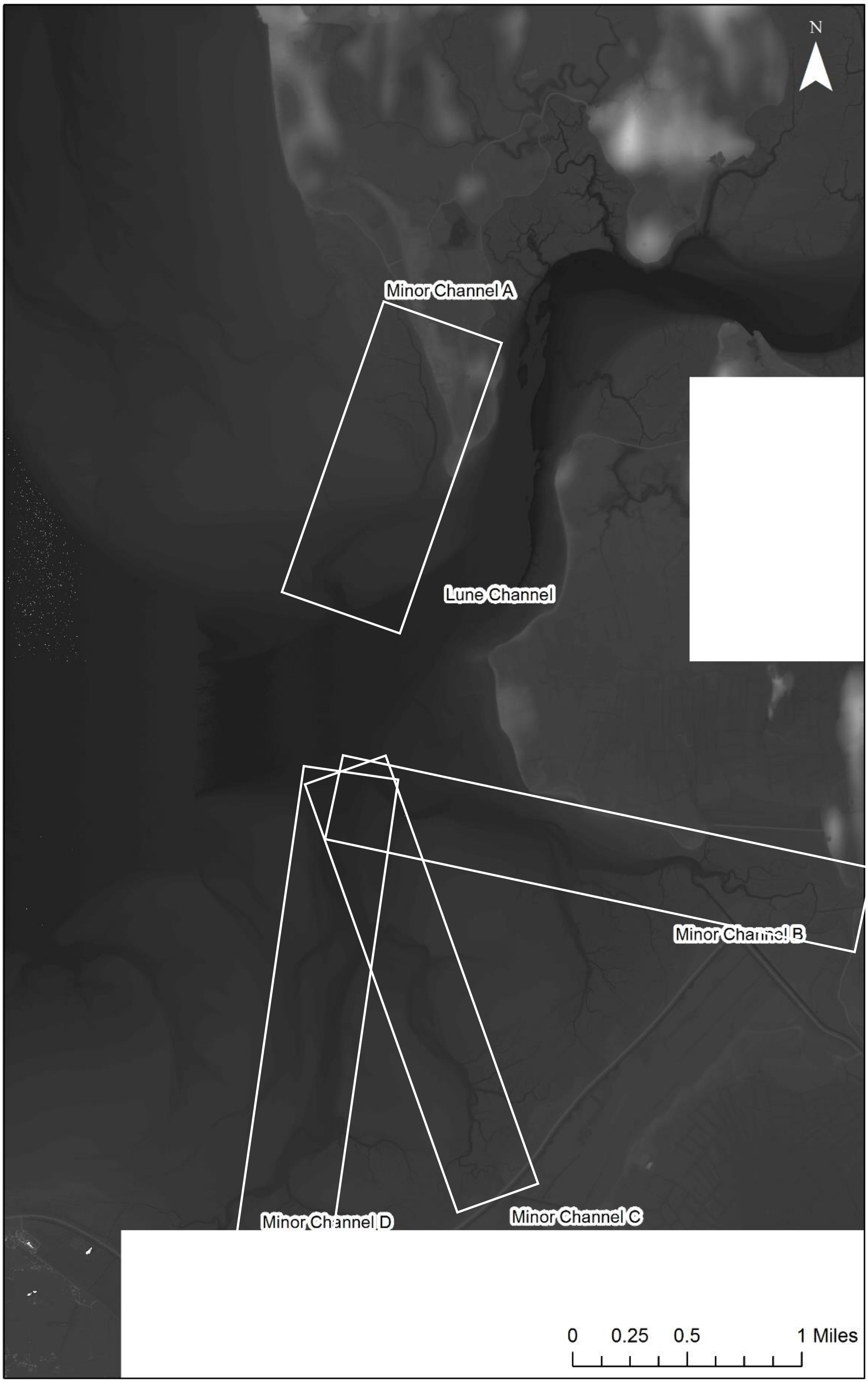


Figure 21: The LiDAR images from which sinuosity of minor drainage channels was calculated for 2004

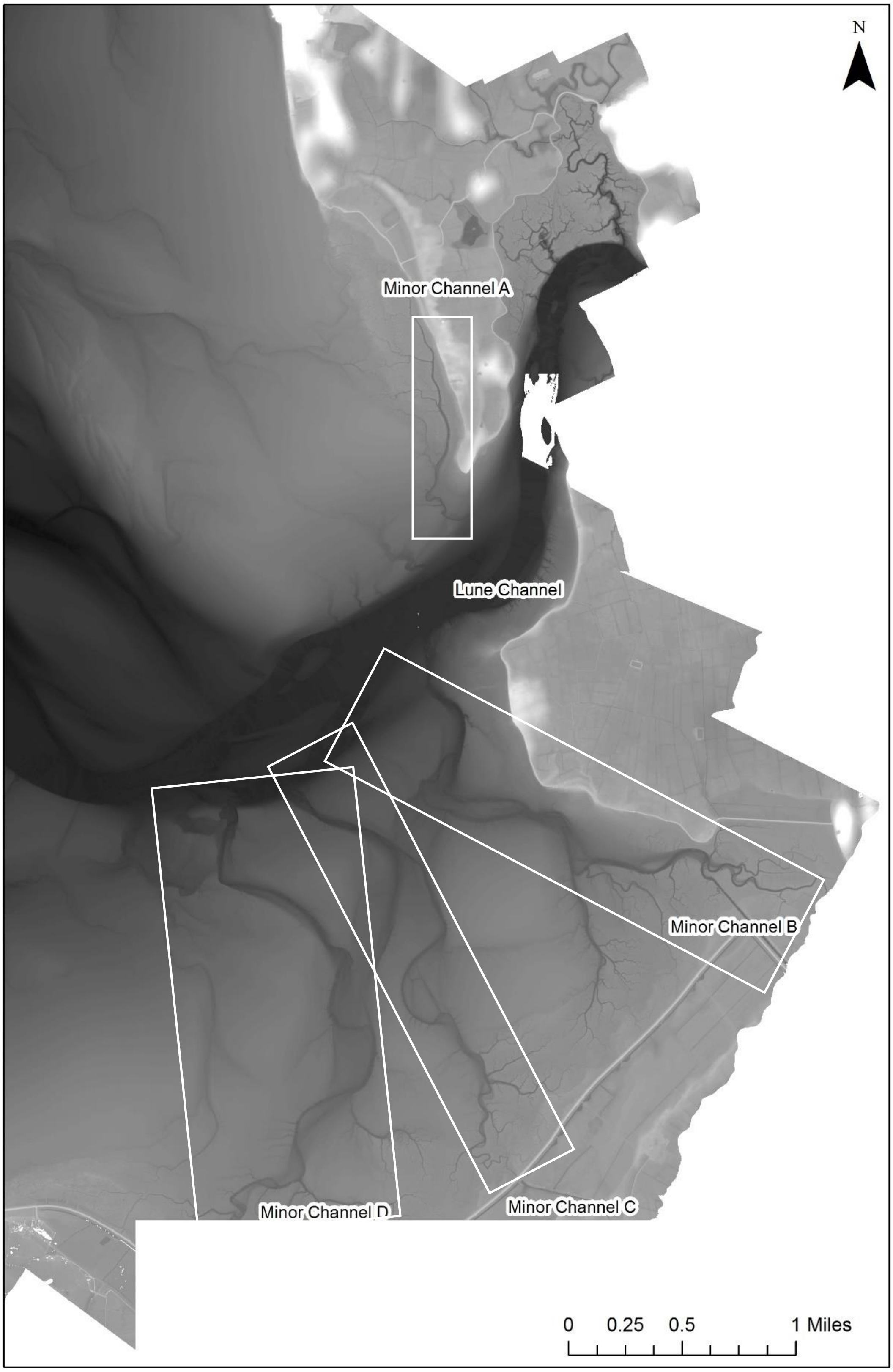


Figure 22: The LiDAR images from which sinuosity of minor drainage channels was calculated for 2010.

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