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3.2.2. Shoreline Geometry: DSAS as a Tool for Historical Trend Analysis

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ABSTRACT: Shoreline geometry remains one of the key parameters in the detection of coastal erosion and deposition and the study of coastal morphodynamics. The Digital Shoreline Analysis System (DSAS) as a software extension within the Environmental System Research Institute (ESRI) ArcGIS© has been used by many researchers in measuring, quantifying, calculating and monitoring shoreline rate-of-change statistics from multiple historic shoreline positions and sources. The main application of DSAS is in utilisation of polyline layers as representation of a specific shoreline feature (e.g. mean high water mark, cliff top) at a particular point in time. A range of statistical change measures are derived within DSAS, based on the comparison of shoreline positions through time. These include Net Shoreline Movement (NSM), Shoreline Change Envelope (SCE), End Point Rate (EPR), Linear Regression Rate (LRR) and Weighted Linear Regression Rate (WLR). Despite the inability of this tool to determine the forcing of morphodynamics, it has been shown to be effective in facilitating an in-depth analysis of temporal and historical movement of shoreline positions and cliff geometry.

KEYWORDS: GIS, Historical Trend Analysis, DSAS, Shoreline Changes, transects.

Introduction

Coastal shorelines, the interface between land and sea, change variably in response to one or more factors, which may be morphological, climatological or geological in nature. Shoreline geometry depends on the interactions between and among waves, tides, rivers, storms, tectonic and physical processes. Erosion (landward retreat) and deposition (advance and growth through accretion) can both present challenges to coastal communities, coastal infrastructures and the adjacent estuarine systems (e.g. Benumof *et al*., 2000; Moore and Griggs, 2002; Collins and Sitar, 2008; Katz and Mushkin, 2013). Knowledge and assessment of the changes in shoreline position have proved crucial in the overall understanding of dynamics in coastal areas and the morphodynamic processes driving the change. Shorelines are vulnerable to change driven by sea-level rise, varying coastal climates including marine, astronomical or other meteorological factors (Lisitzin, 1974; Cowell and Thom, 1994; Pugh, 1996, 2004; Paskoff and Clus-Auby, 2007; Pardo-Pascual *et al*., 2012; Thébaudeau *et al*., 2013). Changes (whether short-term or long-term) in the position and geometry of shorelines are very important in the understanding of coastal dynamism and the management of coastal areas (Esteves *et al.,* 2009; Rio *et al*., 2013). Prompt and intensive short-term field research is mostly used to evaluate shoreline responses to the coastal forcings (Collins and Sitar, 2008; Young *et al*., 2009; Quinn *et al*., 2010; Brooks *et al*., 2012). However, the wider range of longer time marine or terrestrial events which drive shoreline responses may not be appropriately linked or accounted for. Therefore, quantitative analysis of shoreline changes at different timescales is very important in understanding and establishing the processes driving erosion and accretion (Sherman and Bauer, 1993; Esteves *et al.,* 2011; Katz and Mushkin, 2013), computing sediment budgets (Zuzek *et al.,* 2003), identification of hazard zones (Lawrence, 1994; Al Bakri, 1996), as a basis for modelling of morphodynamics (Maiti and Bhattacharya, 2009), and for coastal management and interventions (Esteves *et al*., 2009).

Shoreline geometry and position are perhaps the most basic indicators with which to evaluate changes in coastal regions. Digital Shoreline Analysis System (DSAS) has therefore been used in investigating the dynamics of shoreline movements and changes at both shorter (e.g. Brooks and Spencer, 2010) and longer / historical (e.g. González-Villanueva *et al*., 2013) time scales. However, it is only by including longer time periods (decades to centuries) of investigation that a wider range of past coastal events, magnitudes and frequencies can be linked with the shoreline morphodynamics (Wolman and Miller, 1960; Brooks *et al.,* 2012). Historical Trend Analysis (HTA henceforth) is, therefore, one of the key approaches used in the analysis of change over historical (decade to century) timescales (Blott *et al.*, 2006; HR Wallingford *et al.,* 2006). This ‘bottom-up’ approach is used to identify past behaviour in order to predict future trends. The focus of this article is the application of HTA to analyse changes in shoreline positions, channel morphology, identification of areas of ‘cut’ and ‘fill’, or erosion and deposition over historical time. Specifically the application of the GIS-based Digital Shoreline Analysis System to HTA is explored.

DSAS

The Digital Shoreline Analysis System (DSAS henceforth) is a GIS tool that can be used in HTA to examine past or present shoreline positions or geometry. One of the main benefits of using DSAS in coastal change analysis is its ability to compute the rate-of-change statistics for a time series of shoreline positions. The statistics allow the nature of shoreline dynamics and trends in change to be evaluated and addressed. DSAS has been developed as a freely available extension to Environmental System Research Institute (ESRI)’s ArcGIS (Thieler *et al.,* 2009). It has been updated and upgraded over time, so multiple versions exist allowing its use with ArcView 3.2 through to ArcGIS v10. In 2013, a web-based version (DSASweb) was released (USGS, 2013). Download and further information on the installation and use of DSAS can accessed at http://woodshole.er.usgs.gov/project-pages/dsas/. Instructions, usage of the software and the configuration of input and output parameters are well documented in Thieler and Danforth (1994a, 1994b) and Thieler *et al.* (2009).

There are numerous examples of the use of DSAS in the study of coastal behaviour and shoreline dynamics. Table 1 reviews examples of recent studies that have utilised DSAS in Historical Trend Analysis, coastal system dynamics, shorter time shoreline changes, cliff geometry modelling and estimations. More broadly, DSAS in HTA can be used to undertake:

i. The mapping of historic configurations of shoreline position over the period covered by available spatial data (e.g. maps, aerial photographs);

ii. The evaluation of historic changes and trends of individual or selected transects (discrete alongshore positions). Within DSAS, shoreline change is calculated at specific transects, and the time-series of change at specific locations can be evaluated using the DSAS output;

iii. The analysis of shoreline geometry, including foreshore steepening (using the distance between mean high and low water marks (after Taylor *et al*., 2004) and orientation (for example, to examine rotational tendencies (e.g. Nebel *et al*., 2012);

iv. To predict patterns of shoreline behaviour using the derivation of historical rate of change trends as an indicator of future trends assuming continuity in the physical, natural or anthropogenic forcing which have forced the historical change observed at the site.

Table 1. Recent studies on shoreline geometry that made use of DSAS

Coastline feature studied	Articles
Historical record of coastline dynamics	Carrasco *et al.,* 2012; Montreuil and Bullard, 2012; González-Villanueva *et al*., 2013; Jabaloy-Sánchez *et al.*, 2014
Shoreline variation, shoreline erosion and short-time coastal changes	Houser *et al*., 2008; Brooks and Spencer, 2010; Houser and Mathew, 2011; Restrepo, 2012; Beetham and Kench, 2014; Hapke *et al.,* 2013; Rio *et al.*, 2013
Gully development and evolution	Leyland and Darby, 2008; Draut *et al.*, 2011
Cliff retreat and erosion	Rio and Gracia, 2009; Brooks *et al.*, 2012; Katz and Mushkin, 2013; Young *et al*., 2014
Shoreline / cliff measurement and modelling	Hackney *et al.*, 2013; Thébaudeau *et al*., 2013

Shoreline digitisation and data quality consideration

The main stages in the shoreline analysis workflow, as undertaken using DSAS within ArcGIS, are detailed in Thieler *et al.,* 2009. Shoreline positions are important features defined in DSAS analysis. Specific features of interest should be extracted through digitisation, and these may include the Mean Low Water (MLW) and Mean High Water (MHW) marks. These shoreline positions are explicitly indicated on Ordnance Survey (OS) and other national mapping agency publications which make for simple digitisation and analysis within a GIS, thereby reducing some complications associated with automatic shoreline detections in other sources (Ryu *et al.*, 2002; Loos and Niemann, 2002; Maiti and Bhattacharya, 2009). Other sources from which shoreline positions can be derived include satellite imageries, digital orthophotos, aerial photographs, global positioning-system field surveys (GPS/ and dGPS), historical coastal-survey maps, or extracted from LiDAR surveys (e.g. Stockdon *et al.,* 2002; Weber *et al.,* 2005; Himmelstoss *et al.,* 2011; Hapke *et al.,* 2011; Hapke *et al.,* 2013). Accurate and careful digitisation of shoreline position, possibly with constant reference to the same feature, is however, recommended when digitising from these other sources. DSAS form of analysis is not immune to the usual limitations associated with digitisation and synthesisation of variable quality and resolution data derived from various sources as a result of irregular time sampling interval. For example, reliance on Ordnance Survey (OS) mapping relies on the accurate and consistent interpretation of surveyors and cartographers over decades and centuries (Fenster *et al.*, 1993; Burningham and French, 2006). Older surveys were usually land-based whilst later ones are often derived from aerial photography (Fenster *et al.*, 1993). Care must therefore be undertaken to ensure that accurate digitisation and critical review of features are considered in these source materials. The calculated measures of change provided by DSAS are only as reliable as the sampling and measurement accuracy associated with the source materials. For example, mapping errors can be estimated as +/- 10m for the pre-2000 data and +/-5m for post-2000 data (Anders and Byrnes, 1991; Crowel *et al.*, 1991; Thieler and Danforth, 1994; and, Moore, 2000).

Any form of spatial or laboratory analysis is always aimed at finding solutions to certain spatial problems or to understand certain processes (Uluocha, 2007). In order to achieve this focus, the significance of data quality cannot be over-stressed. The issue of data quality must therefore be given prominence. Care should be taken to determine the integrity, quality and relevance of any data to be used in any analyses (Uluocha, 2007). Data quality must not be compromised in shoreline analysis using DSAS. The indices which can be used in data quality check include logical consistency, completeness, positional accuracy and precision, scale, spatial resolution and currency (temporal accuracy and precision), (Faiz and Boursier, 1996; Jones, 1997; Dobson, 1992; Uluocha, 2007). It is therefore important that mapping uncertainties introduced and associated with shoreline mapping procedures be identified and included in shoreline change analysis so as to reflect the long-term trend which are not based on short-term variability (Romine *et al*., 2009).

Shoreline analysis and interpretation

The DSAS approach calculates shoreline rates of change based on the measured differences between the shoreline positions associated with specific time periods. The following statistical measures (from Thieler *et al.*, 2009) are possible in DSAS:

(i) Shoreline Change Envelope (SCE): a measure of the total change in shoreline movement considering all available shoreline positions and reporting their distances, without reference to their specific dates.

(ii) Net Shoreline Movement (NSM): reports the distance between the oldest and the youngest shorelines.

(iii) End Point Rate (EPR): derived by dividing the distance of shoreline movement by the time elapsed between the oldest and the youngest shoreline positions.

(iv) Linear Regression Rate (LRR): determines a rate-of-change statistic by fitting a least square regression to all shorelines at a specific transects. Further statistics associated with LRR include Standard Error of Linear Regression (LSE), Confidence Interval of Linear Regression (LCI) and R-Squared of Linear Regression).

Other standard DSAS statistical parameters are Weighted Linear Regression Rate (WLR) and associated measures (Standard Error of Weighted Linear Regression (WSE), Confidence Interval of Weighted Linear Regression (WCI), R-squared of Linear Regression (WR2)) and Least Median of Squares (LMS). All parameters can be illustrated to show the spatial patterns of change in shoreline change statistics. The objectives of the analysis to be investigated and the characteristics of the datasets are major determinants of the choice of statistical method.

Case Study: Shoreline morphodynamics at Crantock Beach, southwest England

Crantock Beach lies between Pentire Point East and Pentire Point West cliffs, on the north coast of Cornwall, southwest England (Figure 1). The coastline is macrotidal (mean spring tide range 6.4 m), and is exposed to a predominantly westerly wave climate with a 10% annual exceedance wave height of 2.5-3m, and a 1 in 50 year extreme offshore wave height of 20m. The beach lies at the seaward extent of the Gannel estuary, a ria estuarine system comprising sandy intertidal flats (c.70% of the valley is intertidal Davidson *et al.,* 1991). The estuarine valley is widest at the mouth where the large sandy beach-dune system of Crantock Beach lies. Saltmarshes have infilled the estuary at the landward extent (Oyedotun *et al.,* 2012). Previous research on the system has focused mainly on the Gannel estuary, on the impacts of mining on sediments / sedimentation (Reid and Scrivenor, 1906; Bryan *et al*., 1980; Pirrie *et al*., 2000; Pirrie *et al.*, 2002) and sedimentary environments and sedimentology (Oyedotun *et al*., 2012). The case study presented here describes the changes in shorelines at Crantock Beach, and low tide channel position within the inlet of the Gannel estuary through the analysis of historical maps using DSAS in ArcGIS. Temporal and spatial variability in coastal change, the geomorphic sensitivity and likely processes forcing the morphological behaviour are explored.

DSAS Method

The investigation of changes in shoreline positions in the vicinity of the sandy, macro-tidal Crantock Beach and Gannel estuary is carried out using the Ordnance Survey historical mapping archive, available for the period between 1888 and 2012 (Table 2). Movements of both the Mean Low Water (MLW) and Mean High Water (MHW) here are investigated in GIS using the DSAS extension developed by the USGS (Thieler *et al.,* 2009). The historical mapping is available as georeferenced GeoTiffs from Digimap. Shorelines were digitised from each map, and the standard DSAS shoreline change measures - Net Shoreline Movement (NSM) and End Point Rate (EPR) - were calculated. Net Shoreline Movement (NSM): reports the distance between the oldest (1888) and the youngest (2012) shorelines, which presents the overall change in shoreline position for the 124 year period. The End Point Rate (EPR) converts this net shoreline movement into an annual rate of shoreline change, i.e. dividing the distance of shoreline movement from the earliest to most recent shorelines by the time period passed.

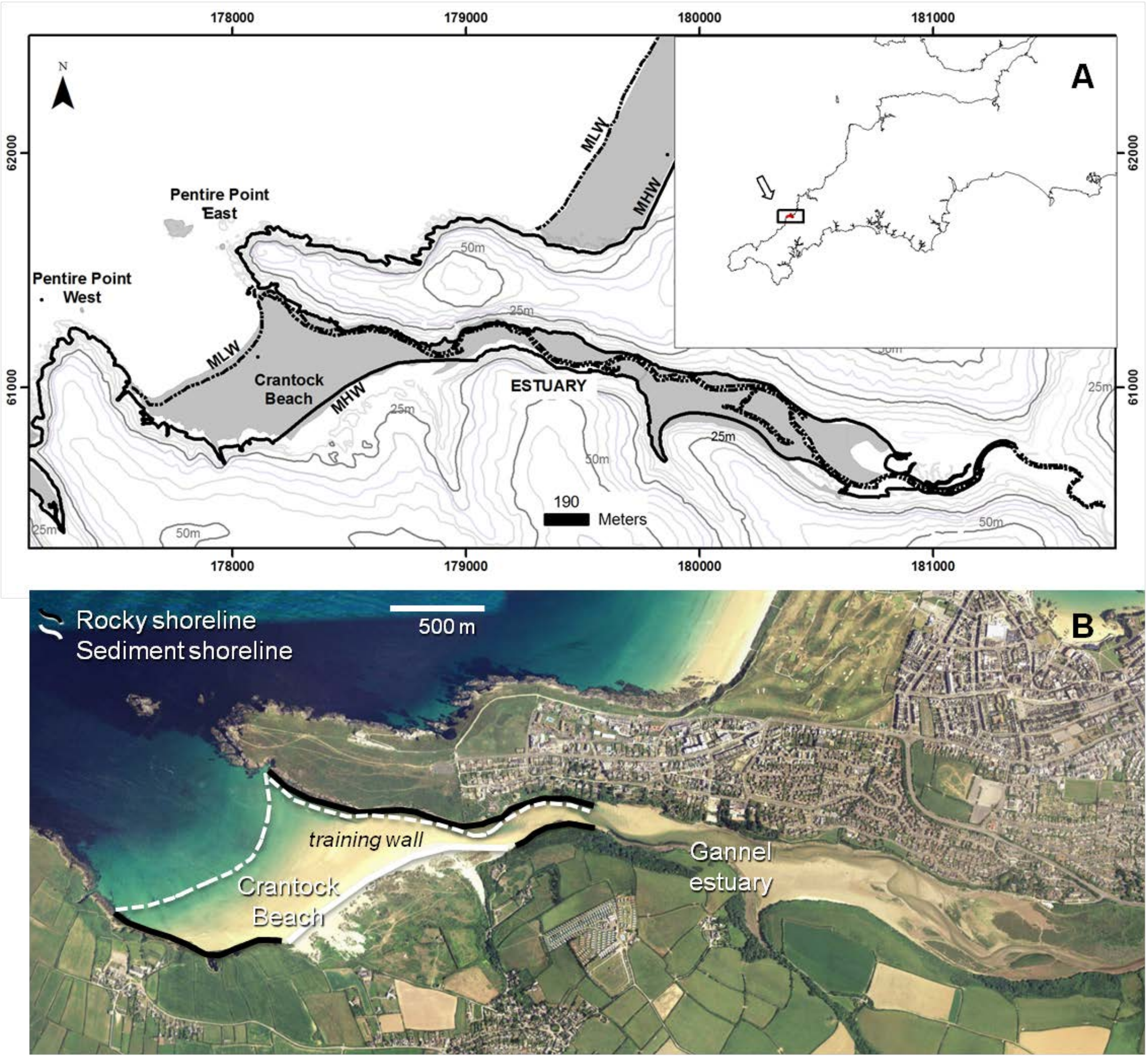

Figure 1: (A) Crantock Beach and the Gannel estuary, Cornwall, located in southwest England and (B) the area photograph showing the rocky and sediment shoreline.

Table 2. Ordnance Survey Data for this study.

Map date	Data	Scale	Resolution/accuracy
1888	County Series	1:10,560	+/-10m
1901	County Series	1:10,560	+/-10m
1977	National Survey	1:2,500	+/-10m
1996	1st Metric Edition	1:10,000	+/-10m
2012	MasterMap	1:2,000	+/-5m

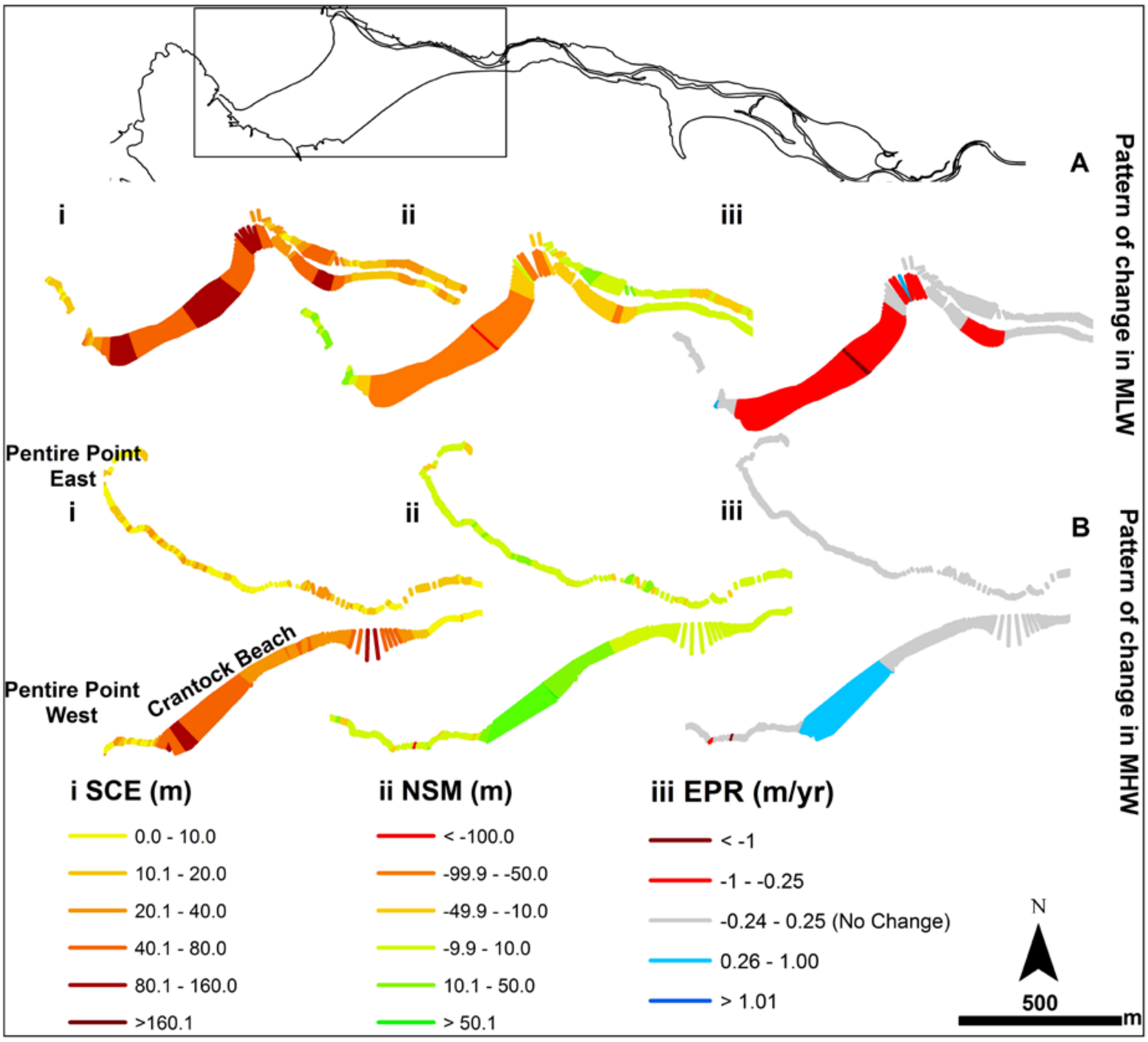

Figure 2. Shoreline Change Envelope (SCE), annual rate of change (EPR) and Net Shoreline Movement (NSM) for Mean Low Water (MLW) and Mean High Water (MHW) at Crantock Beach

Historical Shoreline Changes

Figure 2 summarises the scales and rates of change in shoreline position at Crantock Beach. Scales of change in the position of MLW are maximum in the centre of the bay and minimum in the inlet (Figure 2Ai). These changes are almost entirely the consequence of recession (landward movement) of the low water shoreline at a rate of 0.1-0.8 myr^{-1} (Figure 2Aii). The only place in the lower foreshore where significant erosion is not taking place is along the ebb channel margins within the inlet. Comparison of the SCE with NSM shows that the majority of change in the position of MLW change exhibited here is equivalent to the difference between the earliest (1888) and most recent (2012) shorelines.

The scales of change in the position of high water are somewhat reduced by comparison. First, it is clear that the rock-dominated shorelines along Pentire Points West and East have changed very little (<20 m) over this 124 year period (Figure 2B). Second, the high water shoreline of Crantock Beach has shifted in position by up to around 140 m, but is largely characterised by change of the order of 30-60m. Interestingly, shifts in MHW are the product of shoreline advance (deposition), and there is evidence that gross change (SCE) is greater than net change (NSM). In the absence of significant change in tidal regime, the product of a retreating low water and advancing high water is steepening of the intertidal profile.

Sites of specific change can be explored in detail through the examination of discrete transect data (Figure 3). Comparison of the time series of changing shoreline position shows how important it is to consider both the envelope of variability (SCE) and the net change (NSM and EPR). Transects at Pentire Points West (Figure 3A) and East (Figure 3D) show consistency in shoreline positions, principally because they represent the rocky shorelines (indicated in aerial photograph of Figure 1). Changes along the Pentire Points are small, but the inlet shoreline shows the minimum change across the system, and these changes are likely well within the accuracy margin (Figure 3C). At Crantock Beach (Figure 3B) however, the high water shoreline has advanced substantially (c. 25 m), but during the entire 124 year period, also experienced an episode of erosion during the late 19th century. All the plots show that the most recent shoreline is a significant departure from those from previous years. In most cases, the change between the late 1990s and 2012 is greater than change at any other time.

Annual rates of change in MHW and MLW at each transect are summarised in Table 3. The analyses show that 42% of MHW transects and 71% of MLW transects are erosion-dominated (i.e. these have experienced a net landward retreat in position). Furthermore, 10% of MHW transects remained unchanged (with no appreciable change in MHW position). Rates of change in MLW are significantly greater than rates of change in MHW. Fewer transects show evidence of deposition, with only 27% experiencing advance in the MLW and 48% showing seaward shifts in the MHW.

The scenario observed here can be compared to what Taylor *et al.* (2004) referred to as “lateral landward retreat through non equilibrium profile” (Page 181). The patterns of change shown indicate an overall dominance of erosion, and rates of retreat and advancement are occurring at unequal levels between MHW and MLW. This leads to a change in foreshore geometry. Here, the landward shift in MLW, and seaward advance in MHW has produced a narrower and steeper intertidal zone. This has occurred at some locations in the tidal inlet, but mainly along Crantock Beach. Where MLW and MHW both retreat or advance at similar rates, the foreshore is maintaining a consistent intertidal profile. The shifts in shoreline positions vary throughout the bay, and regions of stability can be found in close proximity to areas of significant change.

Shoreline change statistics (SCE, NSM and EPR) presented for the case study has been able to show the large-scale patterns of retreat and growth of the case study’s shorelines. Other statistical methods are also effective in indicating the pattern of spatial and temporal movements. However, the choice of SCE is because of its capacity is providing the envelope of variability and it is the only measure which take into account all shorelines. The NSM and EPR only reflect change between the first and the most recent surveys. The choice of DSAS statistical parameters in the case study has been able to explore the temporal and spatial dynamics of the coastal change and the geomorphic variability along the beach because of their ability in making use of all shoreline positions (SCE), the cumulative shoreline movement (NSM) and the time variations (EPR) which encapsulate the rate-range of the historical dataset.

The consideration of utilising five historical maps in the case study underlies the importance of the availability and accessibility of archival datasets in HTA. The maps utilised here are the five complete historical dataset accessible at the Ordnance Survey. Full and detailed opportunities for decadal and annual scale analyses are mostly infrequent in many analyses because the complete and up-to-date archival records have to exist for such analyses in being able to: better understand process drivers, determine barriers to recession and conditions for erosion / deposition etc. (Bray and Hooke, 1997; Brooks *et al.*, 2012). More archival data can, therefore, be sourced from other sources like area photographs and other imagery, to add further understanding of the contemporary morphodynamics of the case study (which is not the focus of this current article). However, the sampled analysis executed using only the Ordnance Survey data has shown that DSAS can yield valuable information on shoreline dynamics at both historical and non-historical timescale.

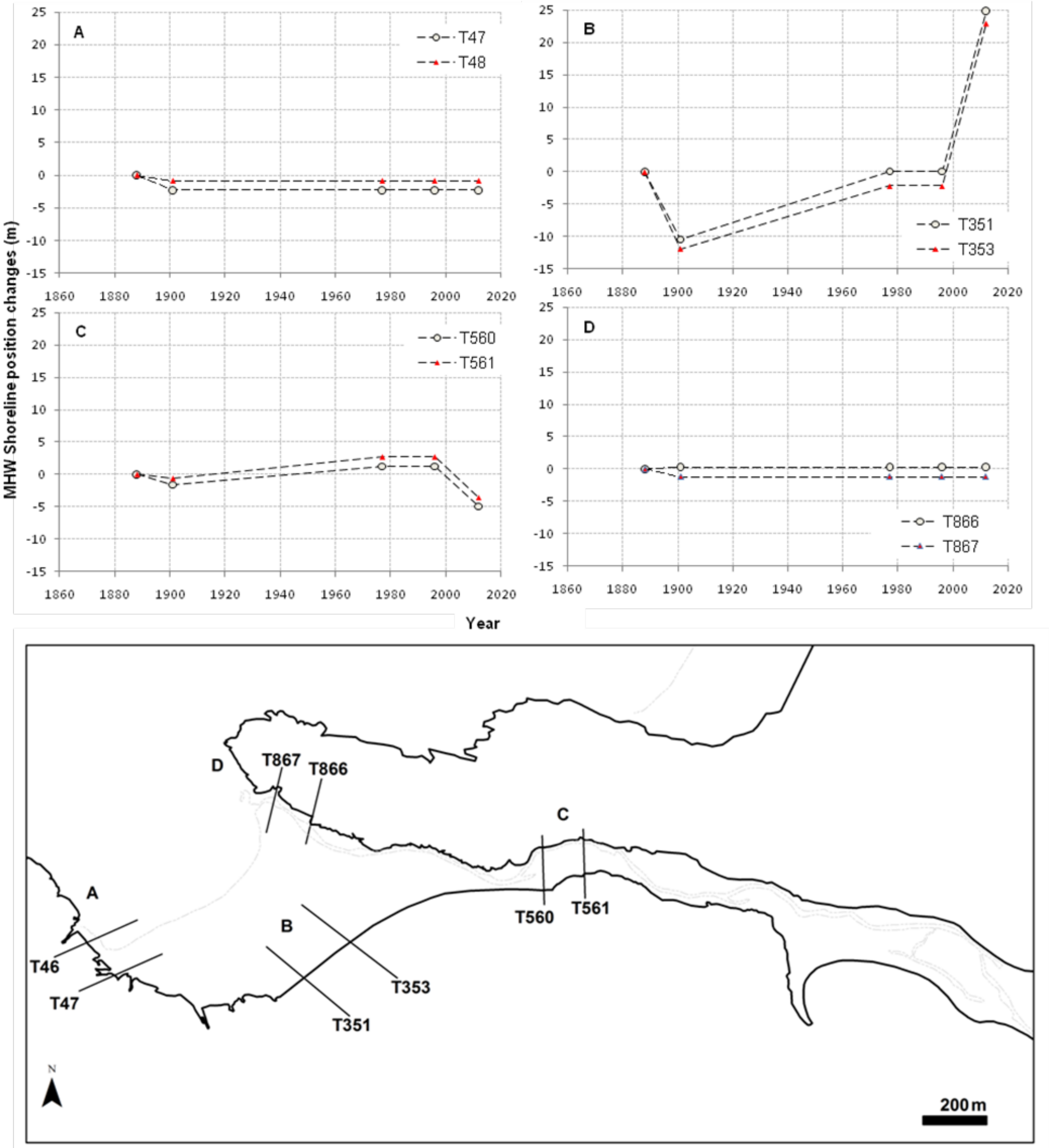

Figure 3. Cumulative change in shoreline position at example transects (A) Pentire Point West, (B) Crantock Beach, (C) Inlet and (D) Pentire Point East.

Table 3 Summary of MHW and MLW movements and trends in the beach

Shoreline	No of Transects	% of Transects	Change rate (m yr^{-1})	Total Erosion Change (m) Minimum to Maximum
MLW Retreat	.1.1 411	71	-0.01 to -5.96	-0.17 to -738.67
MLW Advance	157	27	+0.01 to +6.51	+0.1 to +707.7
No MLW Movement	8	1.4	-	-
MHW Retreat	382	42	-0.01 to -0.75	-0.01 to -93.64
MHW Advance	437	48	+01.01 to +1.99	+0.01 to +248.26
No MHW Movement	87	10	-	-

Conclusion

The historical evolution and temporal morphodynamics of shoreline position and geometry are of significant importance in evaluating the spatial dynamics of the coastal system behaviour. The ability of DSAS within ArcGIS not only enhances the functionality of the software but also enables the calculation of scales and rates of change statistics from multiple historic shoreline positions and sources. The potential and application of the DSAS extension has been explored in this article. DSAS, however, is only useful to address features that can be represented as lines at a particular point in time, with the accuracy of the results being dependent on the accuracy of the input data. Despite the inability of the DSAS extension to indicate the forcing driving the observed dynamics and changes in coastal environment, it is effective in (i) historic measurement of movement of shoreline geometry, and, (ii) the mapping and identification of coastline erosion and accretion on the coastal environment. Changes at the annual, decadal and historical time scale on the coastal environment are easily and simply measurable in GIS through the DSAS extension within the ArcGIS environment.

The case study presented here has shown that DSAS can yield valuable information on the morphodynamic behaviour of shorelines in terms of shifting shoreline position and changes in foreshore geometry, in the identification of areas of erosion and deposition, and in the variation of planimetric properties of the coastal environment.

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