Understanding the recession of the Holderness Coast, east Yorkshire, UK: a new presentation of temporal and spatial patterns

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Abstract: The Holderness coastline is known to be one of the most rapidly retreating coastal regions in Europe. Previous studies on the recession of this coastline have often concentrated on providing a single annual value for the whole coast or for large subdivisions of it; however, relatively little attention has been given to the overall spatial and temporal variability. This paper summarizes and critically appraises the work previously undertaken in this region, presents the results of the former recession rate investigations and displays new interpretations of the data. This assessment found there to be a knowledge gap relating to the processes involved in the recession of this coastline, particularly with regard to frequency of high recession events, further knowledge of which could assist in the planning of the region. It is concluded that many of the former investigations are inadequate by today's standards, because of either the methods employed or the manner in which the results are displayed. Significant steps in gathering high-quality data relating to the erosion of this coastline have been made by the East Riding of Yorkshire Council with the initiation of their Erosion Post monitoring scheme and more recently by their dGPS monitoring. However, if further advancement is to be made in the understanding of the erosion of this region, this work will need to be supplemented with geomorphological monitoring of the cliff line, which will further resolve the processes occurring and aid the production of predictive models. These geomorphological data could be obtained through employment of traditional methods as well as new techniques such as laser scanning or digital photogrammetry.

Supplementary Material: A table giving the magnitude and variability in recession at each Erosion Post location and graphs showing the actual annual variations for each Erosion Post, calculated using a filtered version of the Erosion Post dataset, are available at http://www.geolsoc.org.uk/sup18345.

The Holderness coastline is located in the northeast of England and is a roughly 60 km, generally concave-shaped stretch of land extending between Flamborough Head in the north and Spurn Point in the south (Fig. 1). The coastline exhibits an undulating topography with cliff heights varying from 36 m to less than 5 m above Ordnance Datum (OD), and fluctuations within this range occur throughout the region. The area is predominantly composed of agricultural land together with several small towns and villages, oil and gas terminals, a windfarm and numerous caravan holiday parks.

The cliffs that make up this stretch of the coastline are almost entirely composed of glacial clays, which, since their deposition during the Devensian Glaciation (<*c.* 18 ka), have been rapidly eroding; the rate of erosion here is currently deemed to be among the fastest of any coastal areas in Europe (IECS 1994). The erosion has been the cause of great concern in this region and has triggered several investigations into its rate, particularly over the last 150 years (Reid & Mathews 1906; Sheppard 1913; Thompson 1923; Valentin 1971; Dosser 1955; East Riding of Yorkshire Council 2004).

The aim of this paper is to clearly present the pattern and rate of recession along this coastline to assist engineers and planners more accurately assess the amount of land loss to be expected during the life of current and future engineering projects, and better estimate the life expectancy of residential and commercial property. The data available from current and previous recession rate studies have been reviewed in light of the recommendations for assessing soft cliff recession in a recent research and development document published by DEFRA (Lee 2002). The latest erosion rate values are presented and recommendations are made regarding the treatment of the available data.

Geological background

The published solid geological maps for this region indicate that the entire area is underlain by chalk deposited between the Santonian (85.8 Ma) and Maastrichtian (65 Ma) stages of the Late Cretaceous Epoch. The main chalk units present are the Rowe Chalk Formation, which occupies the central section of the coastline, and the Flamborough Chalk Formation, which occupies the remainder.

The maps displaying the drift deposits indicate the majority of the region to be underlain by 'Till', dating from the Devensian Glaciation, locally interspersed with glacial sand, gravel and lacustrine clay, together with post-glacial alluvium and marine sand deposits.

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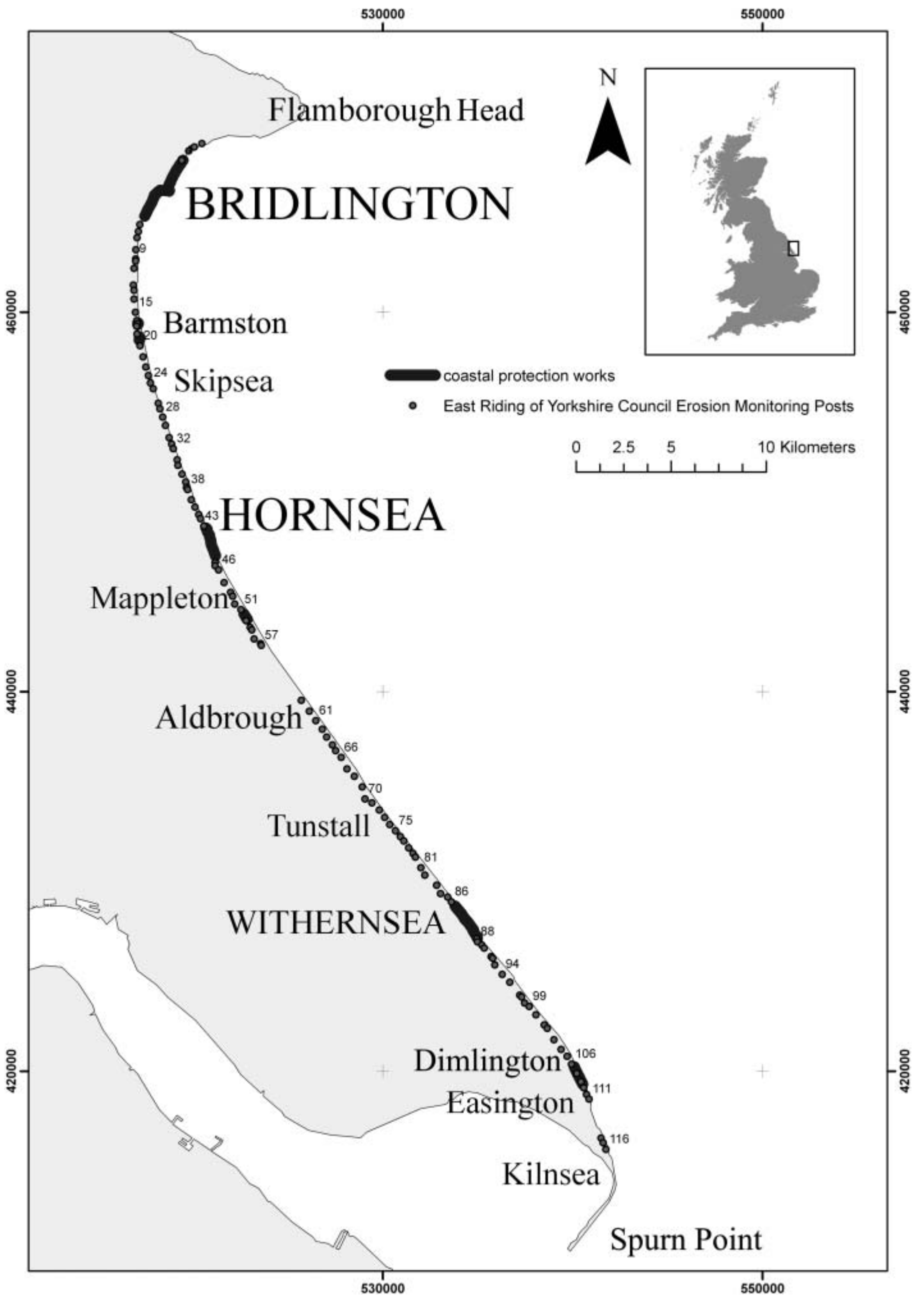

Fig. 1. Location plan for the Holderness coastline showing coastal protection works and the positions of the Erosion Posts of the East Riding of Yorkshire Council.

The glacial Till material has received a great deal of attention from researchers since 1825, when Sedgwick realized that the material could be divided into distinct layers, all of which contain rocks exotic to the region (Melmore 1935). Subsequent work in the 19th century by Wood & Rome (1868) and Reid (1885) resulted in the use of the terms Basement Till, Purple Till and Hessle Till to identify the different layers within the clay. This nomenclature was adapted by the work of Bisat in the 1930s and 1950s to include the term Drab Till for the upper sections of the Basement Till (Catt & Madgett 1981).

The Till nomenclature in this region was redefined by the work of Madgett (1975) and Madgett & Catt (1978) as a result of particle size distribution, mineralogical and petrographic analyses. These analyses showed the Drab and Purple Tills to be uniform and distinct, whereas the texture and composition of the Hessle Till varies and reflects that of its subjacent Till. As a consequence of this, the Drab and Purple Tills were renamed as Skipsea and Withernsea Tills, respectively, and the term Hessle Till was discontinued, with this unit acknowledged as being the weathered component of whichever Till unit it was observed to be overlying. The Skipsea and Withernsea Tills date from the Devensian Glaciation and the Basement Till is usually deemed to be Wolstonian in age; however, the age of the Basement Till is still subject to debate (Evans *et al.* 2005).

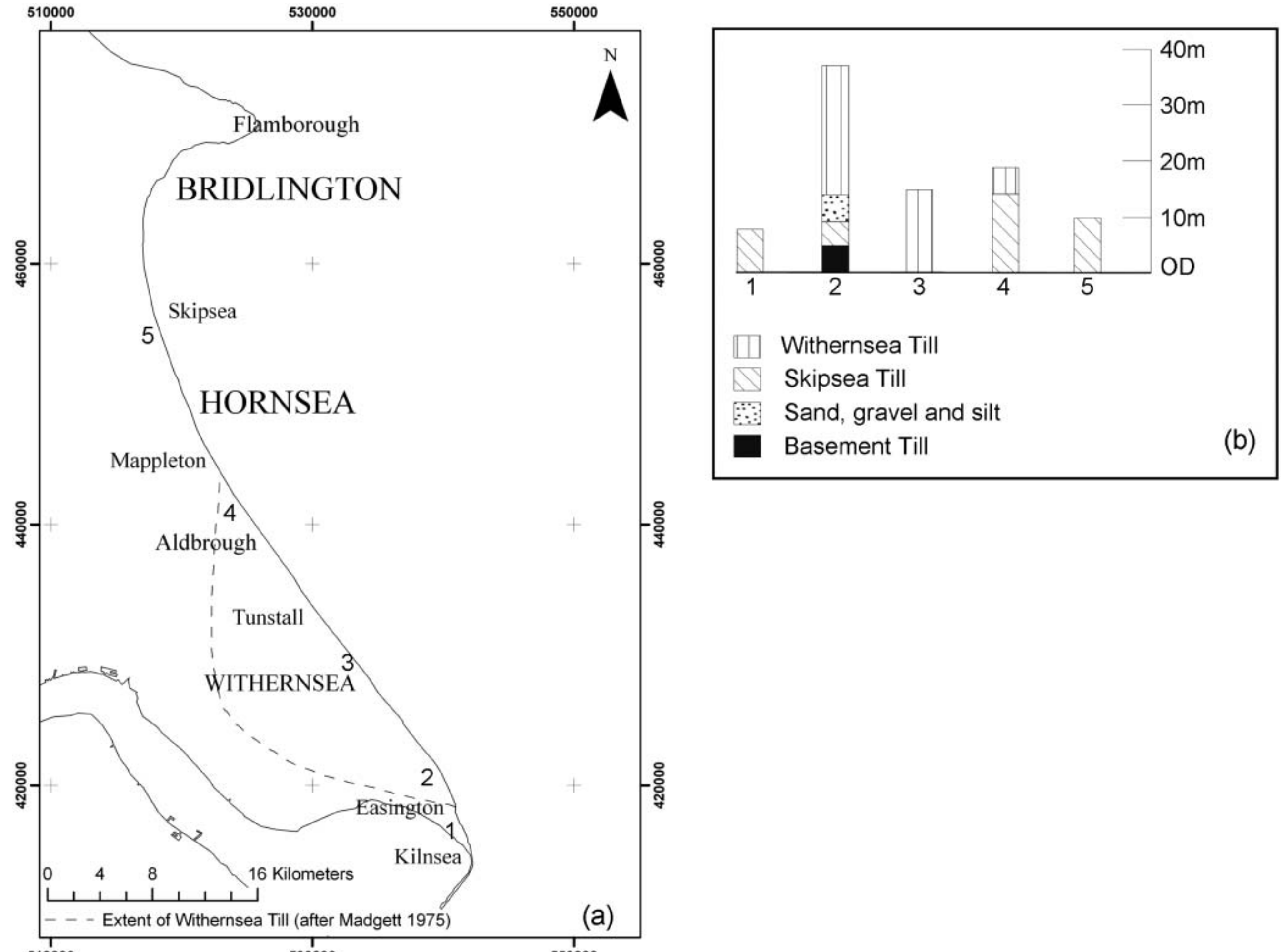

Fig. 2. (**a**) Plan view of the spatial distribution of the Withernsea Till, and (**b**) cliff face logs (after Catt & Madgett 1981; Berridge & Pattison 1994).

Further work on these units has indicated that the Withernsea Till occupies only an arcuate area extending from near Mappleton in the north and approaching Easington in the south (Catt 1991). The Skipsea Till underlies the Withernsea and is present across the majority of the coastline, and the Basement Till is understood to be present underlying the other Tills across the entire coast, but is visible above sea level only at locations near Dimlington and Bridlington (Catt & Digby 1988; Fig. 2).

The contact of the Basement Till with the underlying chalk is generally *c.* -30 m OD, but extends down to *c.* -70 m OD in a buried channel located in the south–central area of the coast (Markland & Powell 1985; Catt & Digby 1988; Berridge & Pattison 1994; Powell & Butcher 2003). The Till units also exhibit a gentle westerly or inland dip (Butcher 1991). Further details relating to the extent, deposition and composition of the Till units present along this coast have been presented by Catt (2007).

In addition to the many studies relating to the classification and origins of the Till units, which are of great interest to Quaternary scientists, extensive studies have been undertaken on their geotechnical properties. These geotechnical studies are likely to prove the most useful to the practising engineer, as they are often sufficiently detailed for preliminary design and feasibility study purposes. Also, these data could potentially be used in any numerical analyses of the cliffs that may be deemed necessary when assessing the cliff recession in accordance with the recommendations of Lee (2002). Sources of available data are given in Table 1.

In addition to the Till and cliffs, the beaches at Holderness have also received considerable attention from researchers. In normal circumstances the beaches generally display the form of shingle upper–sand lower (Mason & Hansom 1989; Simm *et al.* 1996). However, the beaches in this area are unstable, with sandbars and troughs forming in the intertidal zone (Gunn *et al.* 2006). These sandbars are formed as a consequence of stormy conditions and are often referred to as 'Ords' (Pringle 1981; Pethick 1996). Debate continues as to whether these features migrate along the coastline at 500 m a^{-1} (Pringle 1985), between roughly 100 and

Table 1. *Sources of geotechnical data for the Holderness Coast*

Data type	Reference
Atterberg limits, moisture content, bulk density and total/effective stress parameters	Eyles & Sladen (1981); Markland & Powell (1985); Russell & Eyles (1985); Butcher (1991); Bell (2002); Powell & Butcher (2003)
Stress path, shear moduli and cone penetration test (CPT) results	Markland & Powell (1985); Powell & Butcher (2003)
Hydraulic conductivity data	Bonell (1976); Markland & Powell (1985); Powell & Butcher (2003); Kilner (2004)

800 m a^{-1} (Moore *et al.* 1998), or are not migrating at all, but simply form and are destroyed as a result of storm events (Pethick 1996). Regardless of whether or not these 'Ords' migrate, it is apparent that they accelerate coastal erosion rates, as, because of their shape, they leave an area of the cliff more exposed to the sea with little or no beach cover (Pringle 1981, 1985; Pethick 1996).

Historical background to erosion monitoring and recession rates

The erosion of the Holderness coastline has long been considered to be problematic, with around 26 villages having been lost to the sea since the time of the *Domesday Book*, and studies of recession date back to the 14th century with the writing of *Chronica Monasterii De Melsa* (*The Chronicle of Meaux Abbey*) (Sheppard 1906). Reid (1885) presented a summary of the work undertaken by many of the early investigators of the erosion and combined them to produce an average annual value of erosion of 2¼ yards (2.1 m). However, Reid also criticized much of this historical work and deemed it untrustworthy. The limitations of these early studies were also recognized by the British Association for the Advancement of Science, which in 1852 considered that a more accurate assessment was necessary. The results of this work were published in 1895 and indicated a mean recession rate of 5 feet 10 inches (1.8 m) per year (Sheppard 1912). This assessment was based on map evidence.

Reid & Mathews (1906) presented the results of investigative work undertaken as a partial requirement for the design works for the Bridlington sea defences. The method of assessment was not described, but it was stated that the average annual recession of the coastline is 3 yards (2.7 m). However, Sheppard (1913), who was working contemporaneously with Reid & Mathews, did not share these opinions and instead believed that a value of 7 feet per annum (2.1 m a^{-1}) was more appropriate. Sheppard's value was arrived at by comparing maps dating from the reign of Henry VIII onwards with those of the 18th and 19th centuries, comparing quantities of arable land occupied by Yorkshire manors quoted within the *Domesday Book* (Anon. 1086) with the amount of land occupied by the same manor in 1800, and taking measurements from structures that contained plaques stating the distance from the cliff edge at time of construction and comparing them with distances in the early 1900s. This value of 7 feet per annum was used to claim that an area of land roughly 2.5 miles wide was lost to the sea since the Roman invasion (Sheppard 1913); far less than an estimate from Reid & Mathews (1906) of 3.33 miles.

Following from the work of Sheppard, Thompson (1923) obtained additional recession values by taking measurements on the ground and comparing them with first edition 1:10 560 Ordnance Survey maps. In this manner an erosion rate of 4.8 feet per annum (1.5 m a^{-1}) was calculated (Hobson 1924). This work was further developed by Dosser (1955) and Valentin (1971), who arrived at average erosion rates of 5 feet per annum (1.5 m a^{-1}) and 1.2 m a^{-1}, respectively. Dosser's value was based on three sets of measurements from seven structures located along the coastline, whereas Valentin's value was based on 307 observation points, comparing distances on the ground with those on the first edition Ordnance Survey maps and, where access was not available, comparing distances on the Ordnance Survey maps of 1951 with those on the first edition maps.

In 1951 the East Riding of Yorkshire Council initiated a programme of coastal monitoring using a similar method to that of Dosser (1955), measuring the distance to the coast from structures; 114 monitoring stations occupying positions at varying distances along the coastline were used, which have since been termed Erosion Posts. Measurements of the distance between these posts and the coastline were taken at an angle normal to the coastline and at roughly annual intervals, until 1993, when the measurement interval was increased to 6 months (East Riding of Yorkshire Council 2004). Posts were added at various times since the scheme began and the final number totalled 120. When combined, the results of the Erosion Post monitoring produce a mean erosion value of *c.* 1.5 m a^{-1} for the entire coastline between 1953 and March 2007.

In 2003 the East Riding of Yorkshire Council initiated a system of monitoring cliff recession through differential Global Positioning System (dGPS) surveys of the cliff line at 6 month intervals. These surveys are supplementary to the Erosion Post analysis and are being undertaken in conjunction with dGPS beach profile surveys. Use of the dGPS survey data obtained to date indicates a mean cliff line recession rate of roughly 1.7 m a^{-1} across the entire coastline; however, this currently (2007) covers a period of only 4 years. The results of these surveys can be viewed online at http://gofer.eastriding.gov.uk/coastalexplorer/.

In addition to the average annual values of erosion cited above, Pethick (1996) quoted a value of 1.82 m a^{-1}, calculated in 1993 based on 150 years of map record analysis; however, a detailed description of the method was not given.

Therefore, following roughly 150 years of research and the utilization of several different methods and measurement frequencies, mean recession rates of between 1.2 and 2.7 m a^{-1} have been calculated.

The various recession rates referred to above are summarized in Table 2.

Critical appraisal of methods used for estimating recession rate

Reid (1885) criticized the technique of comparing areas of land in the *Domesday Book* with those of the present time, stating that it is impossible to consider fully the parishes that have been completely destroyed, or know accurately where boundaries have been altered since the time of the *Domesday Book*.

The use of cartographic information dating prior to 1800 is not particularly useful for coastal change studies, as it usually has an inappropriately small scale and inadequate accuracy (de Boer & Carr 1969). Indeed, the use of cartographic information dating post-1800 is far from ideal; in the study by Valentin (1971) it was stated that the maps used were only accurate to ± 3 m, which results in an error of ± 6 m when comparing two maps. This error would average out to only ± 0.06 m a^{-1} over the 100 year study performed by Valentin (1971); however, if this study was to be performed on a shorter time period, for example to establish finer-scale trends, then the error in the average value would become significant.

In addition to the inaccuracies of using historical maps for estimating erosion rates, this method is also limited in that the data obtained are simply numbers representing land loss over a period of several years, which give no indication of the annual variations or processes occurring (Rosser *et al.* 2005).

There are also similar drawbacks to measuring erosion by recording the distance between the cliff line and fixed points inland, as unless the measurements are made at spatial and temporal frequencies commensurate with the frequency of cliff failures then this method will also not provide any information regarding process. This point was raised by Pethick (1996) who, when criticizing the Erosion Post system of the East Riding of Yorkshire Council, stated that the temporal and spatial scale is too small and that the assumption that the measurements are being made normal to the coastline is not necessarily true, because if the section of coast being measured has recently incurred a failure then its orientation may well have changed relative to the fixed point.

The use of dGPS surveys of the top of the cliff line, currently being undertaken by the Council, goes some way to redressing the points raised regarding the Erosion Post system. This method, however, does have practical difficulties, in that it is difficult to traverse accurately the top of a notoriously unstable cliff line whilst maintaining verticality and stability of a GPS antenna and ensuring the safety of the operator. Therefore, although the accuracy of high-end dGPS systems is potentially centimetric, there will be significant variation in the precision of the measurements made along the coast depending on factors such as the stability of the cliff, amount of vegetation at the top of the cliff (which could potentially obscure the cliff line's true location) and weather conditions at the time of surveying. Furthermore, the measurement of the cliff top without also assessing the remainder of the cliff once again makes it difficult to infer processes from the results. However, in practice, the surveying of the base of the entire cliff line with a GPS would not only be potentially dangerous for the operator, but also impractical because of the repeated losses of satellite lock caused by the proximity of the cliff.

Therefore, all of the methods of calculating erosion along this stretch of coastline are limited because of insufficient accuracy, inappropriate spatial or temporal frequency of measurements, or the fact that it is difficult to determine the processes that are occurring. Alternative methods that could potentially resolve these issues include the inclusion of traditional geomorphological mapping in the GPS surveys, digital photogrammetry and laser scanning (Lim *et al.* 2005). The British Geological Survey (BGS) is currently conducting terrestrial laser scanning on a section of this coastline limited to the area around Aldbrough, and laser scanning and digital photogrammetry have been used to produce useful results at neighbouring coastal stretches (Hobbs *et al.* 2002; Lim *et al.* 2005; Rosser *et al.* 2005). In response to this and because of the potential accuracy and volume of data generated, a move towards one of these methods would appear to be the next logical step in the evolution of the monitoring of this coastline.

Variability of the recession

Regardless of which method of analysis is used, if the data obtained are reduced to a single number intended to characterize the recession of the coastline, this will mask the local spatial and temporal variability that is

Table 2. *Summary of the rates of recession calculated using various techniques*

Investigator	Recession rate (m a^{-1})	No. of measurement points	No. of measurements taken	Time period of study	Method	Limitations
Reid (1885)	2.1	Obtained from assessment of various early studies of recession				Low accuracy
British Association for the Advancement of Science (1895) (Sheppard 1912)	1.8	31	2	1852–1889 (37 years)	Comparison of maps	Low accuracy, difficult to infer process, and low spatial and temporal resolution
Reid & Mathews (1906)	2.7	19	Not stated	Pre-1906	Not stated	Uncertain
Sheppard (1913)	2.1	Varies depending on the method used		1086–1895	Various	Low accuracy, difficult to infer process, and low spatial and temporal resolution
Thompson (1923)*	1.5	66	2	1852–1922 (70 years)	Comparison of field measurements with points on the 1852 Ordnance Survey map	Low accuracy, low spatial and temporal resolution, and difficult to infer process
Valentin (1971)	1.2	307	2	1852–1952 (100 years)	Comparison of maps and field measurements with points on the 1852 Ordnance Survey map	Difficult to infer process, and low spatial and temporal resolution
Dosser (1955)	1.5	7	3	1876–1951 (75 years)	Comparison of distances of structures from the cliff face	Difficult to infer process, and low spatial and temporal resolution
Pethick (1996)	1.8	Uncertain		150 years	Map evidence	Probably similar limitations to other map studies detailed above
East Riding of Yorkshire Council*	1.5	120	Different for each post	1953–2007 (54 years)	Annual measurement of distance of structures from the cliff edge	Low spatial resolution
East Riding of Yorkshire Council*	1.7	Continuous	9	2003–2007 (4 years)	Traversing the cliff edge with a differential GPS receiver	Difficult to infer process

* Recession values were not presented for the entire coastline by the original investigators, as they believed that this would provide a misleading value for many areas of the coast.
All studies were undertaken at various locations along the coastline and attempted to collect sufficient data to represent the recession of the entire coast.

present (Reid 1885; Thompson 1923; Cambers 1976; Pethick 1996). Figure 3, which was created using mean values of recession for the entire coast, illustrates the danger of using an average value. In this instance the erosion in this area is lower than that of the coast as a whole, which leads to a large overestimation of the amount of land that would be lost over the 50 years between 1956 and 2006 when the average rate for the whole coast is used. Also, because of the episodic nature of the cliff retreat, apparent from the undulating cliff line, the use of any average derived from a large area or long time period could produce misleading results on a local scale or over a short time period.

Spatial variability of recession has been recognized by the East Riding of Yorkshire Council (2004), which has divided the area south of Bridlington into six regions and detailed the current erosion rate and possible future location of the coastline in these regions. The region

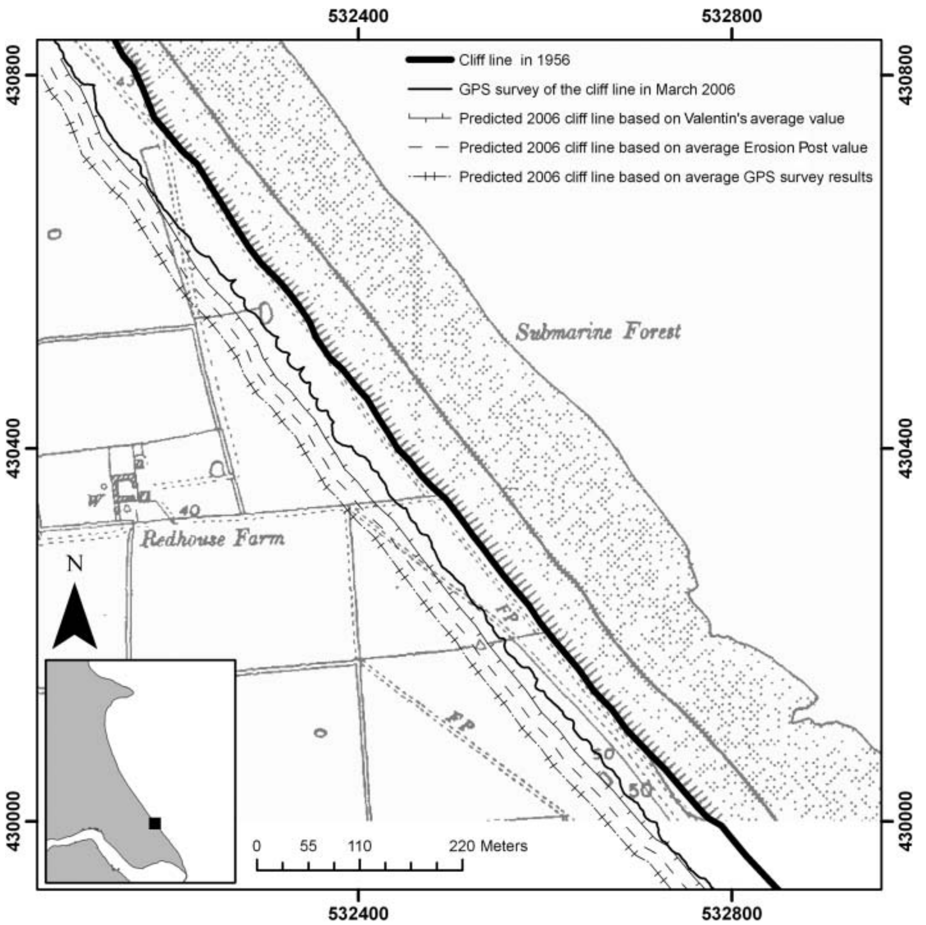

Fig. 3. Map showing the cliff line in 1956 and 2006, and the position of the predicted cliff face using mean annual values of recession.

with the highest rate is between Hornsea and Mappleton (2.74 m a^{-1}) and the one with the lowest rate is between Bridlington and Barmston (0.43 m a^{-1}). However, the general rule presented in the East Riding of Yorkshire Council's documents on the relocation, or 'roll back', of properties along the coast is that the northern region is receding between 1 and 1.5 m a^{-1} and the southern region between 1.5 and 2 m a^{-1} (David Tyldesley & Associates 2003; East Riding of Yorkshire Council 2005).

This spatial variation is demonstrated most clearly when attention is given to the frequency distribution of the annualized erosion rates along the coast. Figure 4 shows considerable variation around the peak values and also shows that the erosion rates along the coastline follow a positively skewed distribution. The skewed distribution is not particularly evident in the results of Valentin (1971) but the distributions from the Council's datasets show a clear positive skew. The skewed nature of the results would imply that a median value would be a more appropriate gauge of central tendency than a mean. Therefore, if it is necessary to produce a single value for the entire coast, or for discrete regions of it, the median should be used in preference to the mean; an alteration which has a small but noticeable effect.

The spatial variations in recession rates may be more clearly illustrated through the use of maps, in which the point values of recession are taken and used to interpolate values for the intervening sections. Figure 5 indicates that the spatial distribution of recession rates produced by Valentin (1971) differs considerably from that of the Erosion Post dataset. This difference is deemed to reflect changes in land usage: Valentin's study covered a period during which sand was extracted from beaches, a practice that ceased in 1910 (Dosser 1955), and since Valentin's study many alterations have also occurred to the coastal defences in the region (East Riding of Yorkshire Council 2004), an example of the effects of which is illustrated in Figure 6. This figure shows that the construction of the defences at Mappleton in 1991 reduced the rate of land loss to the north over the *c*. 3 km stretch of coast between the Mappleton and Hornsea sea defences. The rate also decreased immediately to the south of the defences, which is thought to be a consequence of waves being deflected from this area because of the protruding form of the defences. South of this area of reduced recession the cliff line showed a marked increase in recession rate following the construction of the defences; however, it can also be seen that the recession rate following construction is

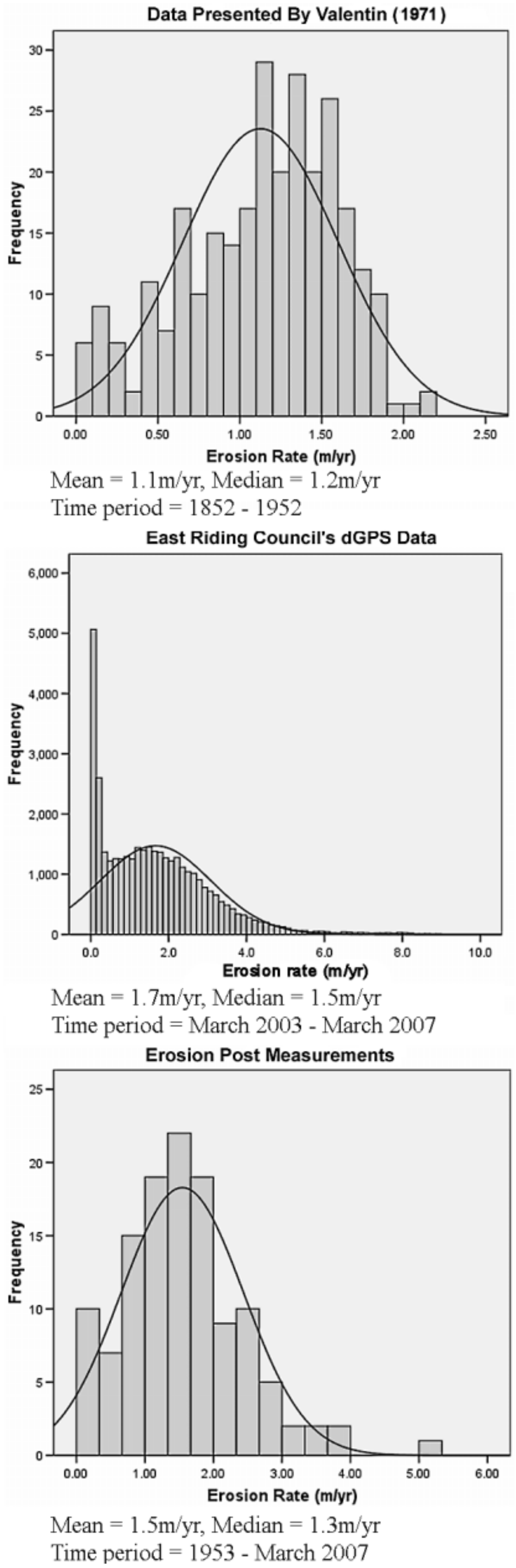

Fig. 4. Distributions of the average values of recession derived by the authors using data presented by Valentin (1971) and using the East Riding of Yorkshire Council's Erosion Post and GPS data. It should be noted that the Erosion Post data have been filtered to include only values taken from datasets with >10 annual records, to be representative of medium-term trends.

higher than before for the entire stretch of coast between Mappleton and Withernsea. Therefore it is difficult to determine the extent of any possible negative impact from these defences, as this effect is masked by the naturally higher recession rates in the region since their construction. The effect of the Hornsea and Withernsea sea defences was assessed by Maddrell *et al.* (2003) using a combination of Ordnance Survey maps, recent aerial photography and the Erosion Post dataset. The findings of that study were that the installation of the sea defences at these areas caused an increase in the recession rate to the south because they starved the beaches of sediment, but that the region of influence was limited to *c.* 1.5 km. However, because that study made use of old maps to assess recession rates it is subject to the same errors as discussed above. Nonetheless, even though the negative impact of the defences may be of limited extent, the reduction in recession rates in the region protected by, and north of, the defences would cause the findings of Valentin's study to differ from more recent assessments.

The spatial distributions indicated by the Erosion Post and GPS methods are broadly similar; however, as the GPS dataset illustrates a small temporal 'slice' the single values are not representative of medium-term trends. Therefore, currently the Erosion Post dataset is the most representative of medium-term spatial trends, but the GPS dataset is useful if it is necessary to ascertain the rate of erosion in the very recent past. However, because of the superior spatial resolution of the GPS dataset this method will prove far more useful than the Erosion Post system once sufficient measurements have been obtained. The use of the historical data from Valentin (1971) should be discontinued, as they are outdated and are no longer representative of the current pattern of erosion along the coastline.

As indicated above, the recession rates along this stretch of coastline are extremely variable with time (Reid 1885; Pethick 1996; David Tyldesley & Associates 2003). The temporal distributions of land loss along the coast also exhibit skewed forms, with many annual records indicating a relatively low value of land loss and few years having a large value of recession. The temporal skewness of single Erosion Post results follows a spatial trend that is effectively the inverse of the Erosion Post average erosion rate trend displayed in Figure 5, with regions of high average erosion rates displaying low temporal skewness and areas with low erosion rates displaying greater skewness. This is due to the Erosion Posts with low average values displaying many very low annual losses, often registering zero; therefore the few years with any erosion will skew the distribution considerably. This contrasts with the areas of very high erosion rates, which ordinarily experience considerable land loss, so that the few years of extremely high land loss will not overtly skew the distribution.

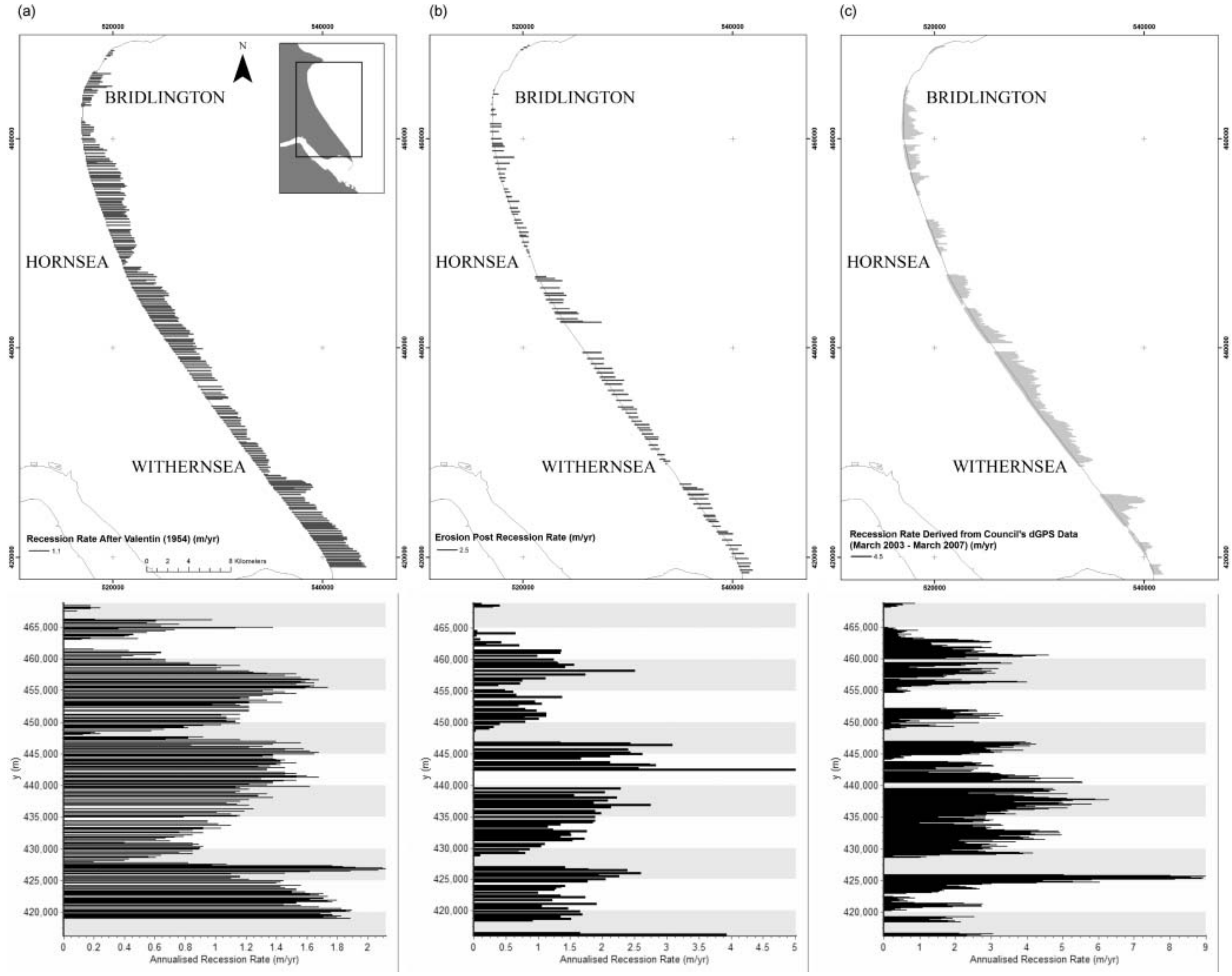

Fig. 5. Spatial distribution of recession rates using (**a**) data from Valentin (1971), (**b**) data from the Erosion Post dataset and (**c**) data from the East Riding of Yorkshire Council's GPS surveys.

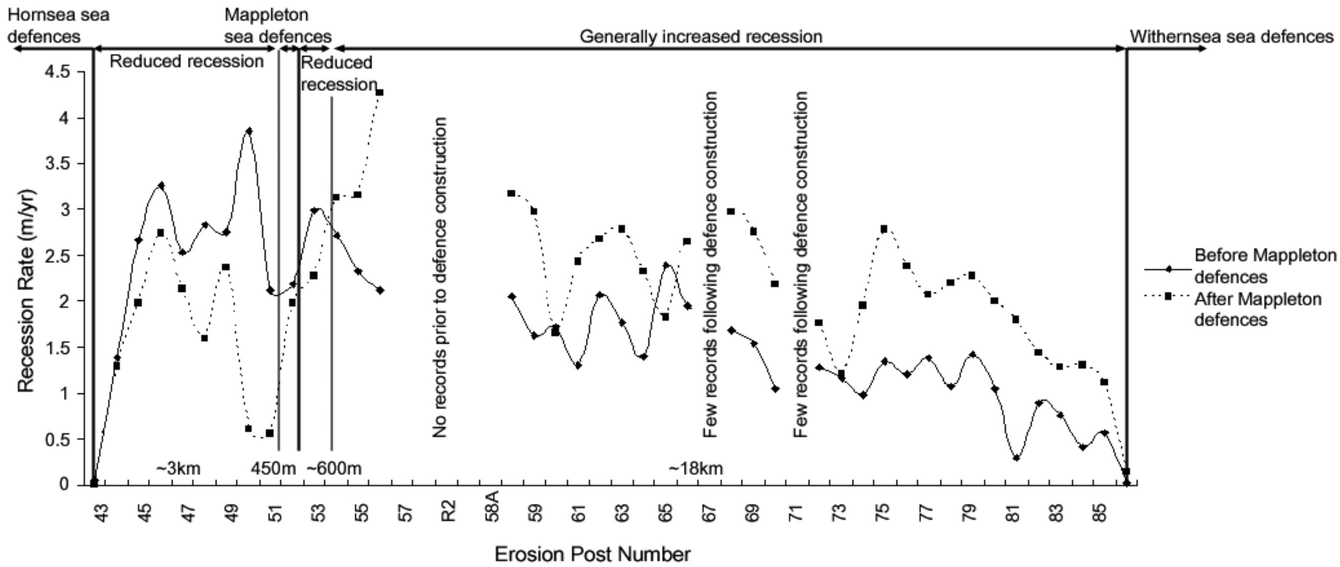

Fig. 6. Comparison of the mean recession rate values for the Erosion Posts in the vicinity of Mappleton for before and after sea defences were constructed in this region in 1991.

Table 3. *Average periodicities of values higher or lower than percentile values for the frequency distributions of annual measurements of erosion for Erosion Post datasets*

Percentile	Average periodicity of values greater than the percentile (years)	Average periodicity of values less than the percentile (years)
10	1.6	0
15	1.6	0
25	1.6	0
50	2.1	2.0
75	4.1	1.3
85	7.3	1.2
90	11	1.1

The average 25th percentile value for each dataset is 0 m; therefore results below this value are identical.

Every Erosion Post dataset recorded displays a minimum value of erosion of 0 m for at least one year, however, the median maximum land loss in any given year for the Erosion Post dataset is 9.1 m, with 25% of posts having experienced losses in excess of 11.6 m in a single year.

The periodic nature of the recession events is displayed in Table 3, which indicates a pattern of events that should be expected. The extremely high magnitude events occur on average once every 11 years, land loss in excess of the 75th percentile values occurs on average once every 4 years, whereas values just above or below the median occur on an average of a 2 year frequency. The general pattern of events indicated by the Erosion Post dataset is that an extremely high recession year will often be preceded by a period of above-average recession and will be succeeded by 1–3 years of above-average, but progressively decreasing land loss (Fig. 7). This sequence will then often be followed by a period of low to zero cliff top recession. However, the pattern varies depending on the Erosion Post being considered. The pattern described above was explained by Pethick (1996) as a consequence of the Erosion Post system being incapable of representing the manner of cliff recession in this area, which Pethick claimed to be through the longshore migration of a series of embayments. However, other geomorphological explanations are also possible, for example, that the cliff is destabilized through the first moderate recession event, which triggers a large failure that subsequently destabilizes the upper cliff region and causes accelerated recession for the following year(s) (Fig. 8). Variations on the idealized pattern outlined in Figure 8 could be expected depending on the rate of marine erosion and the drainage conditions throughout the slope, which will dictate the time needed for negative pore pressures resulting from the removal of land to be equalized. If the marine erosion is slow and the drainage good then the stage shown in Figure 8b may well be omitted; however, if the contrary is true then the stage shown in Figure 8c may never exist. Also, depending on these conditions, situations may exist where two or more of these stages occur within a single year. It should also be noted that this pattern of events can take place only in regions where mass failures (Fig. 8c) can occur, which is unlikely in areas of low cliff height. The actual sequence of events can only be determined through geomorphological surveying; however, it is possible that a provisional geomorphological explanation of the Erosion Post data could be made by assessing the morphology of the cliff at the time that past Erosion Post measurements were made, using historical aerial photography in line with the techniques outlined by Newsham *et al.* (2003) and Walstra *et al.* (2007), although the dates on which past aerial photographs were taken will be too infrequent for a full geomorphological explanation to be obtained with this technique.

The value of understanding the recession processes is evident when consideration is given to the current planning policy in this region, which is to relocate, or ‘roll back’, properties wherever possible (East Riding of Yorkshire Council 2002). Detailed knowledge of the processes occurring during cliff retreat, together with knowledge of the medium- and short-term cycles of recession, should result in the best use being made of the available land. Furthermore, if the sequence of events leading to and following a year of high erosion was properly understood, the long-term response of this cliff line to factors such as sea-level rise or increased precipitation could be predicted with a greater degree of confidence.

As the coastline extends for only 60 km, the whole area will be affected similarly by tidal and climatic influences, with the exception of the north of the region, which is protected from the tides by Flamborough Head and the Smithic Sands, and localized regions that may receive some protection from offshore sand bars. Therefore, it could be expected that a year with especially high tides, waves or rainfall would cause the cliff line of the whole region to move at an above-average rate. However, an assessment of the Erosion Post dataset clearly illustrates that the high values of recession for single Erosion Posts do not all occur within the same year. It is also evident that one post may experience values of recession well above average, whereas other posts located nearby will experience much lower values. These temporal fluctuations could be explained by the migration of ords (Pringle 1985) or the longshore progression of embayments (Pethick 1996). However, these explanations are not fully representative of the modes of recession along the entire coastline, which displays a variety of types of slope failure, resulting from and triggered by different influencing factors.

With new knowledge of the frequency distributions for erosion at various points along the coast, it would appear logical that use should be made of probabilistic

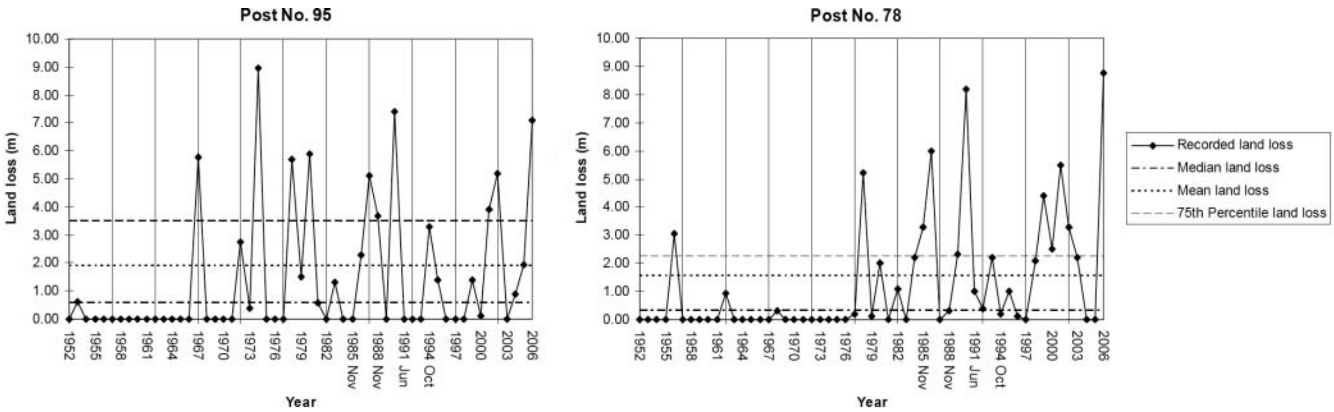

Fig. 7. Example Erosion Post records. It should be noted that sub-annual results have been merged to facilitate comparison with earlier records, and years in which no records have been taken have been assigned the value zero land loss. The years with no records have been omitted from the calculation of the statistical parameters displayed.

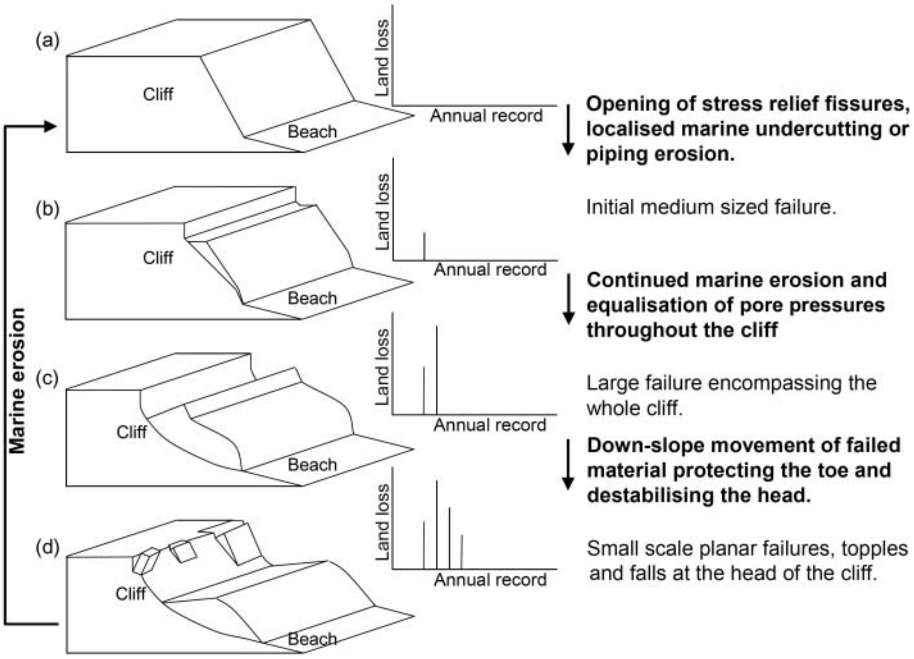

Fig. 8. Idealized schematic illustration of the episodic nature of cliff recession on the Holderness Coast.

methods of assessing the future recession of this coastline, in line with previously established methods (Lee *et al.* 2001; Lee 2002, 2005; Hennecke 2004). These methods would benefit from the relatively high temporal frequency of measurements (6 months) now being obtained (Dong & Guzzetti 2005), but would be much improved by the incorporation of geomorphological data such as those obtainable from laser scanning or digital photogrammetry (Rowlands *et al.* 2003; Lim *et al.* 2005; Rosser *et al.* 2005; Jones 2006).

Landslide geometry arising from coastal recession

According to published literature this coastline displays a wide variety of landslide types, which include rotational, Culmann wedge and planar failures, falls, topples and superficial earthflows (Pickwell 1878; Markland & Powell 1985; Richards & Lorriman 1987; Butcher 1991; Pethick 1996; Powell & Butcher 2003).

Following repeat visits to various sections of this coastline during 2007 it has become apparent that the landsliding is often the direct result of marine basal erosion, whereby a quantity of land is removed by the action of the sea, which oversteepens or undercuts the cliff, or lowers the beach level. This then significantly reduces the resisting forces in the landslide system and initiates deep-seated failures, earthfalls or topples. When deep-seated failures occur, earthflows occasionally initiate from them as a result of the addition of excess water from burst surface water pipes, the presence of sand lenses or a rapid rate of supply of earth from the weathered material above, thus initiating an undrained loading scenario (Bromhead 1979).

In many instances, however, the landsliding is not caused as a direct result of marine basal erosion. Often slides occur along lithostratigraphic boundaries as a result of variations in strength or permeability, which are made possible by removal of previously failed material by rain, waves or tides, but which are actually triggered by rainfall events.

Therefore, it is clear that the cliffs are influenced strongly by both marine and groundwater variations (Richards & Lorriman 1987; Pethick 1996), with some areas being influenced more strongly by one than the other, depending largely on the structural and material properties of the cliff and on the frequency with which the high tide level coincides with the base of the cliff.

The undulating topography of the coastline will have a strong influence on the observable pattern of landslide geometries and failure mechanisms. The topographic variability results in a highly changeable surface water flow direction, with areas existing where flow is in line with the cliff top, away from the cliff top or towards it. Therefore the role of surface water will differ along the coastline, in some areas having a strong impact, initiating mudflows and causing oversteepening by rilling erosion, and in other areas having no effect at all. Also, the undulating topography causes areas to exist where the cliff is of an insufficient height to generate the stresses necessary to initiate a mass failure throughout the cliff; these regions will then be susceptible only to smaller failures controlled by discontinuities.

The type of Till of which the cliffs are composed (Fig. 2) is not thought to have a significant impact on the variation in failure mechanism, as similar variations in failure type are evident throughout cliff sections composed mainly of Skipsea and/or Withernsea Till. Also, the regions containing Basement Till show no marked difference in failure mechanism from the adjacent stretches of land. This is believed to be a consequence of the fact that the difference in strength between each Till type is not especially great (Bell 2002).

To incorporate geomorphological data relating to landslide types and triggering mechanisms into predictive models of cliff recession, it would be necessary to map regions of change based on high-resolution data and ascertain whether the change was the consequence of climatic or marine influences. This would allow the predictive model to be customized by area depending on the dominant driving factor (Lee *et al.* 2001).

Conclusion

The level of past and current interest in the Holderness Coast by geologists, geographers, geomorphologists and coastal planners has been demonstrated. It is now clear that much of the previous work undertaken on assessing the rate of coastal recession is outdated because of the methods employed or can be misleading because of the presentation of results (i.e. the production of a single number to characterize the recession of the coast). The creation of the Erosion Post dataset represented a significant step forward in understanding the coastal processes, as it provided a method of assessing temporal variability, and the recent use of dGPS monitoring represents a further step forward, as it allows high-resolution characterization of the spatial variability. Through the use of these data it has been possible to analyse the frequency distributions of both the spatial and temporal fluctuations in land loss for various points along the coastline. From this analysis it has been established that the temporal distribution of recession in areas of low average recession rates exhibits a very much more skewed form than that in areas of high recession, and that the years of above-average recession tend to form clusters. Further understanding of the processes involved in the short-term fluctuations in recession could prove particularly useful throughout the implementation of the East Riding of Yorkshire's 'roll back' policy for properties on this coastline. This is because, when planning is undertaken, consideration of the cyclic nature of the recession and how this is represented geomorphologically should lead to the best use being made of the available land. Also, a proper understanding of the sequence of events surrounding a year of high erosion would aid the long-term planning of the region, as the response of the cliff to factors such as increasing precipitation or rising sea level could be estimated with greater confidence.

To advance further by fully understanding the cliff movements and therefore make useful predictions, understanding the type, nature and periodicity of the slope failures is important. Therefore it would be beneficial to combine the fine spatial- and temporal-scale monitoring data with geomorphological observations, which would greatly assist any predictive models generated for assessing the future recession of the coastline. The inclusion of these data could be aided to a large extent through use of laser scanning or digital photogrammetry, both of which have been used successfully in neighbouring regions albeit on a smaller scale.

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