Flamborough Head, Filey Brigg to South Bay: Prediction of 50-Year Cliff Recession Distances

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1 Introduction

This short report has been prepared in response to the request from Natural England for advice relating to the following coastal cliff sites:

- the Filey Brigg SSSI;
- the Gristhorpe Bay and Redcliff SSSI;
- the proposed SSSI extension between Filey Brigg and Gristhorpe Bay;
- the Cayton, Cornelian and South Bays SSSI.
- the Flamborough Head SSSI;
- the Flamborough Head and Bempton Cliffs SPA;

The specific casework question to be addressed relates to the expected 50-year cliff recession distance along these clifflines. These predictions are required to underpin the site notification.

The assessment has involved:

1. *Review of recession prediction methods;* this draws on recent research into the reliability of various prediction methods to estimate recession along the Holderness coast (Lee, 2011);
2. *Identification of cliff units*; these are lengths of cliffline with broadly consistent geological materials (bedrock and glacial deposits), exposure to wave attack and cliff types (Figure 1) and shoreline forms. Over the long-term, they can be expected to retreat at relatively uniform rates i.e. a single 50-year retreat prediction should apply for the whole unit.
3. *Assessment of historical recession rates for each cliff unit*, based on a review of available reports (e.g. Furureocast, SMP2 reports, NECAG monitoring reports).
4. *Development of 50-year predictions*, providing both upper and lower-bound estimates, taking account of the historical recession rates and the expected impact of relative sea-level rise (RSLR).

The stages are described in the following sections. For convenience, the various sites have been grouped together as the “Scarborough to Filey Cliffs” (Holbeck to Filey Brigg) and the “Flamborough Cliffs” (Sewerby to Reighton).

The following definitions are used in this Report:

Cliff Recession is the landward retreat of the cliff profile (from cliff foot - cliff top) in response to the cliff erosion process.

Cliff Behaviour Unit (Cliff Unit); the fundamental units for cliff investigation and management, reflecting the interrelationships between process and form over time. Cliff Units comprise three interrelated systems: cliff tops, cliffs and the foreshore.

Cliff Recession Categories; a broad classification of recession rates, based on the work of Cosgrove et al., (1997):

Class Range (m/year)	Category
0-0.1	Negligible
0.1-0.5	Moderate
0.5-1.0	Intense
1.0-1.5	Severe
>1.5	Very severe

Cliff Top; the junction of the cliff face and the un-displaced material adjacent to the cliff face.

Undercliff; an intermediate series of cliff faces and landslide benches between the rear cliff and the sea cliff.

Sea cliff; the most seaward cliff face within a landslide complex*.*

Rear cliff; the most landward cliff face within a landslide complex (i.e. the cliff top).

Relative sea level rise (RSLR) is the increase in the level of the sea relative to the land, taking account of both eustatic and tectonic/isostatic changes. RSLR can be associated with eustatic (global) sea-level rise or land subsidence, or a combination of both.

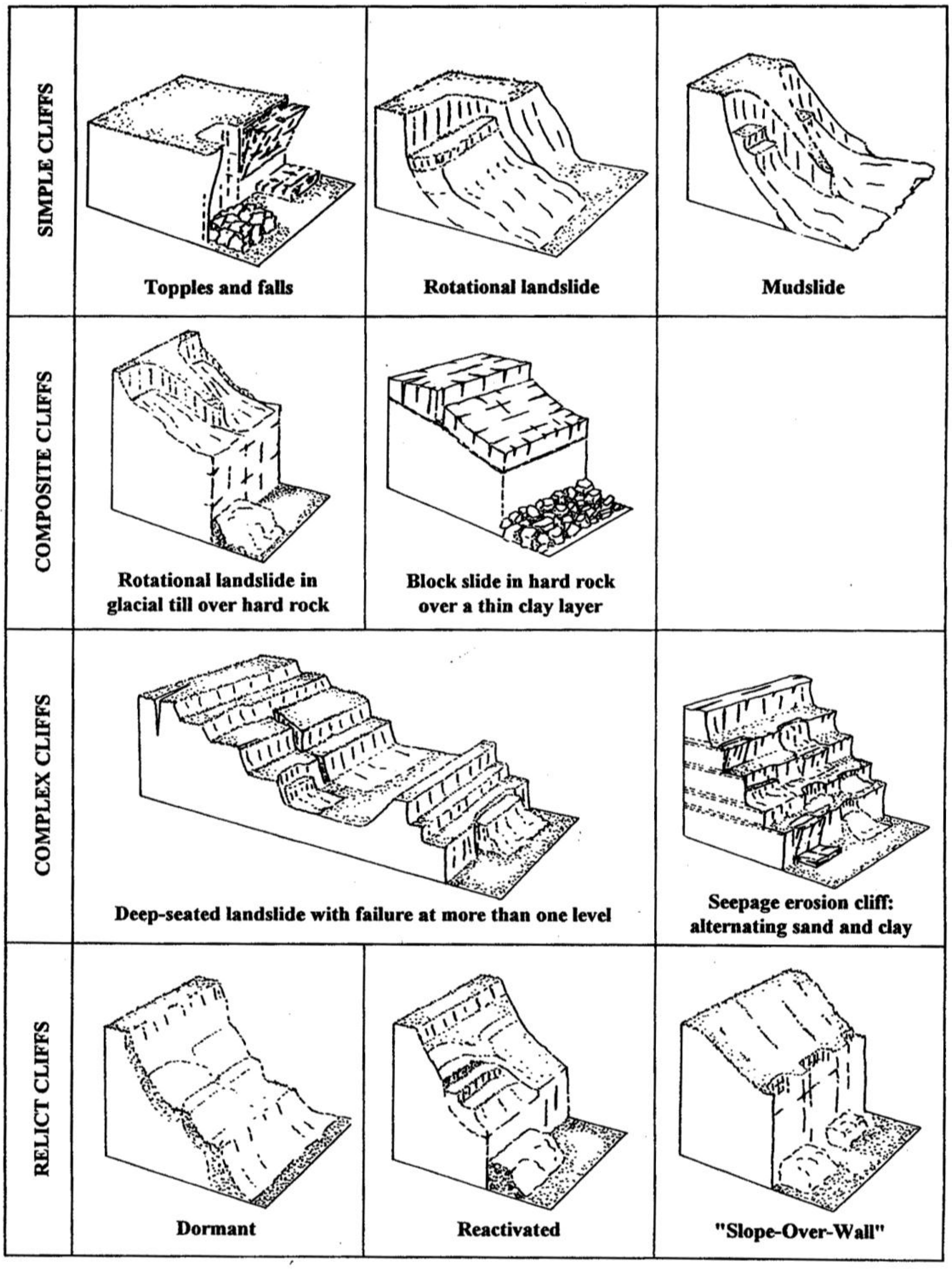

Figure 1 Cliff Types (from Lee and Clark, 2002)

2 Recession Prediction Methods

Prediction of cliff recession rates over a period of accelerating relative sea-level rise (RSLR) remains a significant challenge. A variety of approaches are available, including (see Lee and Clark, 2002):

- *extrapolation of past trends*; this approach is based on the assumption that the historical recession rate provides a reliable indication of the future rate. The model was used to generate lower bound cliff recession estimates for the Flamborough Head to Gibraltar Point SMP2 (Scott Wilson, 2009). Problems arise if the rate of RSLR in the future is expected to be different from the rise over historical period.
- *the Bruun rule*; RSLR is assumed to result in the parallel retreat of the cliff profile, albeit with a corresponding rise in elevation of the cliff foot. This geometric relationship forms the basis of an empirical model (the Bruun rule) for deriving the shoreline response to sea level rise (Bruun 1962). The model was used to generate upper bound cliff recession estimates for the Flamborough Head to Gibraltar Point SMP2 (Scott Wilson, 2009).

  The Bruun Rule is not without its critics (e.g. Komar et al 1991), although overall validity of this approach appears to have been confirmed for the eroding cliff shores of Chesapeake Bay and the Great Lakes (Rosen 1978; Hands, 1983; Zurek et al 2003). Rising sea or lake levels have produced a transfer of material from the cliff to the nearshore bed resulting in recession rates that were very close to those predicted by the model.

- *historical projection*; this approach assumes that future changes in recession rate are directly proportional to the change in rate in RSLR. It involves multiplying the past rate by an adjustment factor derived from the ratio of future to past rates of RSLR (Leatherman, 1990). The approach was used in the River Tyne to Flamborough Head SMP2 (Haskoning 2007).
- *probabilistic methods*; a variety of models have been developed, ranging from quasi-empirical judgement-based models (e.g. Lee, 2005) to more complex process-response simulation models (e.g. Lee et al., 2001; Lee et al., 2002; Dickson et al., 2007). A version of the empirical judgement based model was used by Lee (2004) to predict recession rates for the Benacre to Easton Bavents SSSI. Probabilistic simulation models have been used as a component within the regional-scale "coastal simulator" developed by the Tyndall Centre (Pearson et al., 2005).

The problem with all these models has been validation of the results. Many predictions have been made for cliffline changes over the next 50-100 years. However, the future has not arrived yet and, hence, the results cannot be tested against what actually happens.

Lee (2011) attempted to provide some insight into the validity of model predictions by using the early 1990s as a start point for an analysis that took account of the RSLR advice from MAFF (1990). Recession rates and distances for a single Erosion Post on the Holderness coast (EP 59; Aldbrough) are shown in Table 1, for 3 prediction methods: extrapolation of historical trends, the historical projection approach and the Bruun Rule. The results indicate that the method that gives the best prediction for the period 1990-2004 would have been simple extrapolation of past recession rates. The historical projection approach and the Bruun Rule over-estimate the actual recession for this period by over 400% and 20%, respectively.

Part of the problem is that the rate of RSLR did not accelerate in the way that had been predicted (MAFF 1990 suggested an allowance of 5mm/year). There has been a consistent rise of around 1.7mm/year throughout the last century, with a high degree of fluctuation from decade to decade (the highest rates are probably around 2-2.5mm/year; e.g. Holgate 2007). Some 10-year periods show above average rise, others show lower rates of rise or RSL fall. The 2 decades since 1990 appear to fit this pattern, with no evidence of the significant acceleration in global sea levels that had been predicted. Holderness cliff recession rates have risen over the last 60 years, from around 1.2m/years in the early 1950s to around 1.5m/year by the year 2000. However, in the same way that there has been no significant acceleration in the rate of global sea level rise since 1990 there has been no rapid increase in the recession rate (Lee 2011).

Table 1 Holderness Erosion Post 59 recession predictions for the period 1990-2004 (from Lee 2011).

Prediction Method	Historical Recession Rate m/year (1951-1990)	Predicted Recession Rate m/year (1990-2004)	Predicted Recession Distance m (1990-2004)	Actual Recession Distance m (1990-2004)
Extrapolation[1]	2.16	2.16	32.4	33.85
Historical projection[2]		9.73	146	
Bruun Rule[3]		2.71	40.65	

Notes:

[1] Predicted Recession Rate = Historical Recession Rate

[2] Predicted Recession Rate = Historical Recession Rate x Predicted RSLR/Historical RSLR = 2.16 x (5/1.11)

The predicted RSLR is 5mm/year (MAFF 1990).

The nearest tide gauge to Holderness is at Immingham, on the Humber estuary. The historical RSLR rate at this gauge is 1.11mm per year (Immingham, 1960-1995; standard error of ± 0.52mm; Woodworth et al., 1999).

[3] Predicted Recession Rate= $R_1 + Sc \times \frac{L}{P(B+H)}$

R_1 = Historical recession rate (2.16m/year)

Sc = Change in rate of sea level rise (m) i.e. 0.005-0.0011 = 0.0039m

P = Sediment overfill (the proportion of sediment eroded that is sufficiently coarse to remain within the equilibrium profile) (P=0.25)

B = Cliff height (m) (B = 16.7m)

H = Closure depth (m) (H = 12)

L = Length of cliff profile (to the closure depth, m) (L = 1000m)

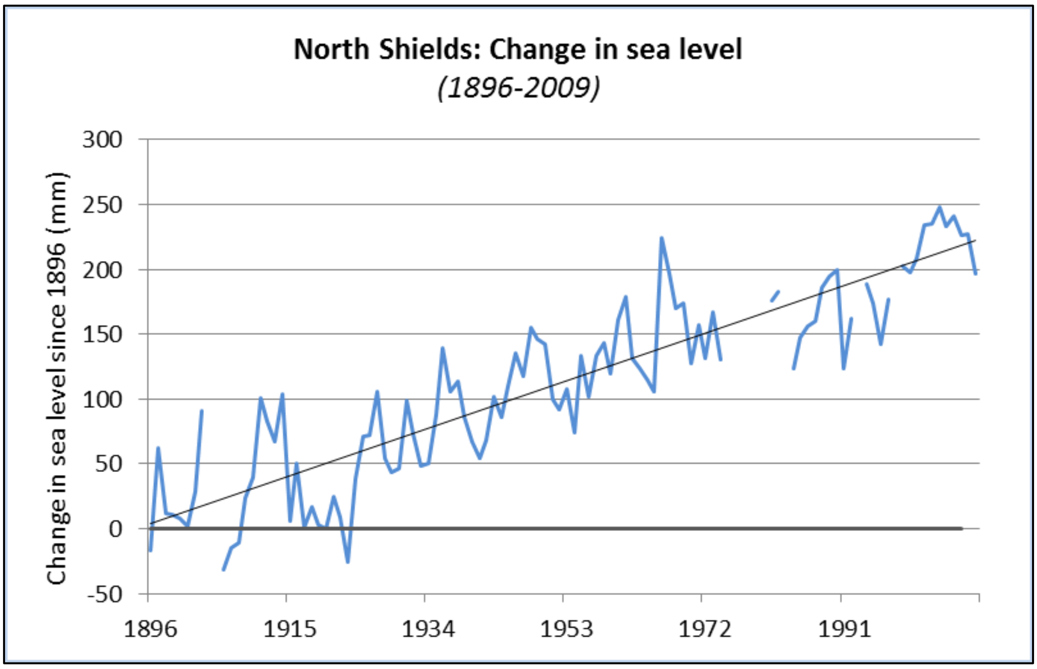

Figure 2 North Shields: changes in RSL (1896-2008) Source: Department of Energy and Climate Change
http://www.decc.gov.uk/assets/decc/Statistics/climate_change/1719-summary-report-on-sea-level-rise.pdf

It is quite possible that the acceleration in RSLR has been simply delayed and that it will be a driving factor in controlling cliff recession over the next 50-years. This, however, remains a considerable uncertainty and it seems unlikely that a single method can be used to predict recession rates with any degree of confidence. The better solution seems to be to provide predictions for contrasting scenarios:

1. Scenario 1 no acceleration of RSLR; this can be modelled by simple extrapolation of past trends;

2. Scenario 2 acceleration of RSLR at the predicted rates; assuming that future changes in recession rate are directly proportional to the change in rate in RSLR, this can be modelled with the historical projection approach:

   Predicted Recession Rate = Historical Recession Rate x Predicted RSLR/Historical RSLR

Recent analysis of tidal gauge data has demonstrated that over the last century sea-level has risen on the north east coast by up to 2.5mm/year (based on North Shields data, 1886-2008; Figure 2). If the sea level rises over the next 100 years at an average rate of 5mm/year, the above historical projection method suggests a factor of 2 increase in average annual recession rate.

Predicted Recession Rate = Historical Recession Rate x Predicted RSLR/Historical RSLR

= Historical Recession Rate x (5/2.5)

These 2 approaches will be used in this assessment (see Section 6). The extrapolation method is likely to result in a lower bound estimate, whereas the historical projection approach is likely to be very conservative. The reality may lie somewhere between.

3 Cliff Units: the Scarborough to Filey Cliffs

The cliffline is largely unprotected and has developed in Jurassic shales, sandstones, limestones and clays laid down between 140-180M BP. Two distinctive stratigraphic groups have been recognized (Table 2):

- the Upper Jurassic sediments associated with a marine transgression that commenced in the early Callovian and reached a peak around the Oxfordian/Kimmeridgian boundary. Mudrock deposition was widespread, along with shallow water oolitic limestones and sandstones of the so-called Corallian facies. Mudrocks were also the predominant lithology of the Kimmeridgian Age.
- the Middle Jurassic "Ravenscar Group" deposited in a vast river delta system. The deposits include a series of prograding deltaic sandstones and mudrocks of the Cloughton, Scarborough, and Scalby Formations. These rocks can be found on the coast between Scarborough and Osgodby Point, and between Yon's Nab and Lebberston Cliff.

Late Devensian age (around 18k BP) glacial tills have been emplaced across much of the landscape (the Filey Formation). These tills include stiff, silty sandy clays, sands and gravels and laminated stiff silty clays. They can be found either as a thin till-cap to many cliffs or represent a significant proportion of the cliff profile (e.g. Cornellian and Cayton Bays). In Cayton Bay, over 30m of till has been identified in boreholes drilled at Knipe Point (Halcrow, 2009).

Eleven main cliff units have been identified (Table 3):

1. Wheatcroft Cliff; composite cliffs developed in Scarborough Formation grits overlain by the Scalby Formation mudstones and sandstones which form the relatively gently sloping upper cliff section.
2. Cornelian Bay; vegetated coastal slopes developed in Scalby Formation mudstones and sandstones, overlain by considerable (>25m?) thicknesses of glacial till. The form of the cliff unit has been fashioned by a series of major elongate mudslides, probably seated within the till. The Cayton Bay fault brings the Cornbrash Formation, Osgodby Formation and Oxford Clay onto the shoreline in the south of the bay.
3. Cayton Cliff; vegetated coastal slopes developed in Osgodby Formation sandstone, Oxford Clay and Lower Calcareous Grit Formation, overlain by considerable (>30m) thicknesses of glacial till. The cliff is dominated by a large, deep-seated landslide with the basal shear surface in the Oxford Clay (Halcrow, 2009). Reactivation of this feature in 2008 has led to a series of rear cliff failures and the loss of property at Knipe Point.
4. Tenant's Cliff; a vegetated "undercliff" complex formed as a result of deep-seated landsliding possibly in the mid Holocene (Fish et al., 2006). The landslide comprises a series of shore-parallel ridges developed in Lower Calcareous Grit, in front of a high rear cliff. The basal shear surface is expected to be in the underlying Oxford Clay. A short section of blockwork wall protects the old water-works buildings.
5. Killerby Cliffs; vegetated cliffs developed in glacial till. These cliffs are actively eroding through a series of lobate mudslides.
6. Red Cliff; high, near-vertical rock cliffs developed in Cornbrash Formation limestone, Osgodby Formation (Red Cliff Rock Member), Oxford Clay and Lower Calcareous Grit sandstones. Towards Yon's Nab, the Red Cliff fault brings Scarborough and Scalby Formation sandstones and mudstone into the clifline, overlain by Cornbrash limestone and Osgodby Formation sandstones and mudstones.
7. Lebberston Cliff; composite cliffs developed in Scarborough Formation grits overlain by the Scalby Formation mudstones and sandstones capped by variable thicknesses of glacial till. Mudslides occur on the relatively gently sloping upper sections, formed within the till and weathered bedrock.

8. Gristhorpe Cliff; near-vertical rock cliffs developed in Cornbrash Formation limestone, Osgodby Formation limestones and Oxford Clay. Cliff recession occurs mainly through rockfalls and topples.
9. Newbiggin Cliff; near-vertical rock cliffs developed in Osgodby Formation limestones, Oxford Clay and Lower Calcareous Grit Formation sandstones. Cliff recession occurs mainly through rockfalls, often forming steep talus cones at the base of the cliff.
10. North Cliff; composite cliffs developed in Lower Calcareous Grit sandstones and Coralline oolitic limestones, overlain by a thick sequence of glacial till. A series of distinctive mudslide embayments have developed in the till sequence. The unit extends along the north face of Filey Brigg.
11. Filey Cliff; composite cliffs developed in a thick sequence of glacial till above Lower Calcareous Grit sandstones and Coralline oolitic limestones. Mudslide embayments have developed in the till sequence. The unit extends along the south face of Filey Brigg

Table 2 Stratigraphy: the North Yorkshire Coast between Scarborough and Filey (source: Rawson and Wright 2000)

Age	Stage	Lithostratigraphic Division		Description	Maximum Thickness
150M	Middle Oxfordian	Coralline Oolite Formation		**Hambelton Oolite Member (Upper Leaf)**;	
				Birdsall Calcareous Grit Member;	
				Hambelton Oolite Member (Lower Leaf); A slightly weathered, medium to thickly bedded, , strong, oolitic limestone	0-2m
				Passage Beds Member; a slightly weathered, medium bedded, limestone with interbedded sandstone	10m
	Lower Oxfordian	Lower Calcareous Grit Formation		**Saintoft Member**; fine grained sandstone with calcareous concretions	2m
				Tenants' Cliff Member; thick bedded calcareous sandstone	13-15m
		Oxford Clay Formation		**Weymouth Member**; Grey silty clay	30m
				Scarburgense Subzone; Grey silty clay and black clay	
	Callovian	Osgodby Formation		**Hackness Rock Member;** fine-grained, poorly sorted sandy limestone and calcareous sandstone.	2m
				Langdale Member; fine-medium grained sandstone and siltstone, thin clay partings.	15m
				Red Cliff Rock Member; fine grained sandstone with beds of sandstone and limestone.	11.5m
		Cayton Clay Formation		Grey shaly, silty and sandy clay	3
		Cornbrash Formation		**Fleet Member;** limestones and sandy marl	1
160M	Bathonian	Ravenscar Group	Scalby Formation	**Long Nab Member**; clay and silt with thin sheets of fine sandstone.	52m
				Moor Grit Member; cross-bedded sandstone, overlain by rippled sandstone with mudflake conglomerate.	8m
	Upper Bajocian		Scarborough Formation	**Bogmire Gill Member**; siltstone passing up into fine grained sandstone (marginally marine). **White Nab Ironstone Member**; sulphurous grey sandy shales with iron-rich concretions. **Ravenscar Shale Member**; grey sandy shales	30m

Age	Stage	Lithostratigraphic Division		Description	Maximum Thickness
				Spindle Thorne Limestone Member; alternations of sandy shales and argillaceous limestone; **Hundale Sandstone Member**; massive sandstone over a thin-bedded flaggy, argillaceous sandstone, separated by a thin pink-weathering sideritic limestone resting on shale. **Hundale Shale Member**; silty sandstone passing up into argillaceous sandy limestone. **Helwath Beck Member**; shaly siltstones passing up to massive convoluted sandstone.	
	Lower Bajocian		Cloughton Formation	**Gristhorpe Member**; mudstone, siltstone and sheet sandstones.	30m
				Lebberston Member; sandstones and shale, ooidal limestone	9m
				Sycarham Member sandstones, siltstones, shales and low-grade coal.	50m
182M	Aalenian		Eller Beck Formation	Prominent sandstone units underlain by shales with ironstone.	8m
			Saltwick Formation	Sandstones, siltstones, shales and low-grade coal. (the **Lower Deltaic Series**).	57m
		Dogger Formation; hard ferruginous sandstone, limestone, laminated shale, pebble beds			12m

Table 3 Cliff Units: Holbeck to Filey Brigg (the Scarborough-Filey Cliffs)

Cliff Unit	Description
	**WHEATCROFT CLIFF** (Holbeck to White Nab) Photo: ML 6 January 2012 ***Bedrock;*** Scarborough Formation (White Nab Ironstone Member & Bogmire Grit Member) overlain by the Scalby Formation (Moor Grit Member & Long Nab Member) ***Superficial Deposits***; Filey Formation glacial tills of varying thickness **Cliff Activity (NECAG Slope Condition)**; Locally active to Partly active **Cliff Instability;** Vegetated high-angled debris slides in weathered bedrock and glacial till **Recession rates (SMP2);** 0.2-0.3m/year
	**CORNELIAN BAY** (White Nab to Osgodby Point) Photo: http://www.trekearth.com/gallery/ ***Bedrock;*** Scalby Formation (Moor Grit Member & Long Nab Member). Cayton Bay fault brings Cornbrash Formation, Osgodby Formation and Oxford Clay onto cliffline ***Superficial Deposits***; Filey Formation glacial tills of considerable thickness. **Cliff Activity (NECAG Slope Condition)** Totally active to Locally active **Cliff Instability;** Active elongate mudslides developed in glacial till **Recession rates (SMP2);** 0.2-0.3m/year

Cliff Unit	Description
	**CAYTON CLIFF** (Osgodby Point to Tenant's Cliff) Photo: ML 6 January 2012 ***Bedrock;*** Cornbrash Formation, Osgodby Formation, Oxford Clay and Lower Calcareous Grit Formation ***Superficial Deposits***; Filey Formation glacial tills of considerable thickness (>30m?). **Cliff Activity (NECAG Slope Condition)** Totally active to Partly active **Cliff Instability;** Active elongate mudslides developed in glacial till and Oxford Clay **Recession rates (SMP2);** 0.3-0.4m/year
	**Tenant's Cliff** (Cayton Cliff to Killerby Cliff) Photo: ML 6 January 2012 ***Bedrock;*** Oxford Clay overlain by Lower Calcareous Grit Formation (Tenant's Cliff Member) ***Superficial Deposits***; Thin capping of Filey Formation glacial tills. **Cliff Activity (NECAG Slope Condition)** Inactive **Cliff Instability;** Deep-seated non-rotational (compound) landslide (possibly mid Holocene) **Recession rates (SMP2);** 0.3-0.4m/year. Rear cliff recession probably minimal

<table>
<tr><th>Cliff Unit</th><th>Description</th></tr>
<tr><td></td><td>Killerby Cliff (Tenant’s Cliff to Red Cliff) Photo: ML 6 January 2012

Bedrock; not observed (probably on foreshore)
Superficial Deposits; Filey Formation glacial tills.

Cliff Activity (NECAG Slope Condition)
Totally active to Partly active

Cliff Instability;
High-angled lobate mudslides

Recession rates (SMP2);
0.3-0.4m/year.</td></tr>
<tr><td></td><td>Red Cliff (Killerby Cliff to Yon’s Nab) Photo: ML 6 January 2012

Bedrock; Cornbrash Formation, Osgodby Formation (Red Cliff Rock Member), Oxford Clay and Lower Calcareous Grit Formation
South of Red Cliff fault: Scarborough Formation overlain by the Scalby Formation, Cornbrash and Osgodby Formation
Superficial Deposits; Thin capping of Filey Formation glacial tills.

Cliff Activity (NECAG Slope Condition)
Totally active to Locally active

Cliff Instability;
Rockfalls, topples and lobate mudslides

Recession rates (SMP2);
0.3-0.4m/year.</td></tr>
</table>

Cliff Unit	Description
	**Lebberston Cliff** (Yon's Nab to Castle Rocks) Photo: ML 6 January 2012 ***Bedrock;*** Scarborough Formation overlain by the Scalby Formation, Cornbrash and Osgodby Formation ***Superficial Deposits***; Thin capping of Filey Formation glacial tills. **Cliff Activity (NECAG Slope Condition)** Totally active to Locally active **Cliff Instability;** Lobate mudslides developed in glacial till and weathered bedrock **Recession rates (SMP2);** 0.1-0.2m/year.
	**Gristhorpe Cliff** (Castle Rocks to The Wyke) Photo: ML 6 January 2012 ***Bedrock;*** Scalby Formation overlain by Cornbrash (Fleet Member), Osgodby Formation and Oxford Clay ***Superficial Deposits***; Thin capping of Filey Formation glacial tills. **Cliff Activity (NECAG Slope Condition)** Partly active to Locally active **Cliff Instability;** Rockfalls and topples **Recession rates (SMP2);** 0.1-0.2m/year.

Cliff Unit	Description
	**Newbiggin Cliff** (The Wyke to Club Point) Photo: ML 6 January 2012 ***Bedrock;*** Osgodby Formation, Oxford Clay and Lower Calcareous Grit Formation ***Superficial Deposits***; Thin capping of Filey Formation glacial tills. **Cliff Activity (NECAG Slope Condition)** Partly active to Locally active **Cliff Instability;** Rockfalls and topples **Recession rates (SMP2);** 0.2m/year.
	**North Cliff** (Club Point to Filey Brigg) Photo: ML 6 January 2012 ***Bedrock;*** Lower Calcareous Grit Formation overlain by Coralline Oolite Formation (Hambelton Oolite Members) ***Superficial Deposits***; Thick mantle of Filey Formation glacial tills (>10m). **Cliff Activity (NECAG Slope Condition)** Totally active to Locally active **Cliff Instability;** High-angled lobate mudslides **Recession rates (SMP2);** 0.2m/year.

Cliff Unit	Description
	**Filey Cliffs** (Filey Brigg to Wool Dale) Photo: ML 6 January 2012 ***Bedrock;*** Lower Calcareous Grit Formation overlain by Coralline Oolite Formation (Hambelton Oolite Members) ***Superficial Deposits***; Thick mantle of Filey Formation glacial tills (>10m). **Cliff Activity (NECAG Slope Condition)** Totally active to Locally active **Cliff Instability;** High-angled lobate mudslides **Recession rates (SMP2);** 0.2m/year.

4 Cliff Units: the Flamborough Cliffs

The cliffline between Reighton and Sewerby is developed in Cretaceous chalk and softer Upper Jurassic sedimentary rocks (Table 4). The cliffs expose a continuous Northern Province Chalk succession from the base of the Upper Cretaceous Series, in the Hunstanton Red Chalk Formation at Speeton Cliff, up to the lower part of the Lower Campanian succession, at the top of the Flamborough Chalk Formation at Sewerby Steps. The Upper Jurassic Speeton Clay and Kimmeridge Clay are exposed along the Speeton cliffs.

Table 4 Stratigraphy: the Flamborough Cliffs (source: Rawson and Wright 2000)

Age		Stage	Lithostratigraphic Division	Maximum Thickness (m)
75M	Upper Cretaceous	Campanian	Flamborough Chalk Formation	>300m
		Santonian		
			Burnham Chalk Formation	150m
		Coniacian		
		Turonian		
			Welton Chalk Formation	53m
		Cenomanian		
			Ferriby Chalk Formation	44m
95M	Lower Cretaceous	Albian	Hunstanton Red Chalk Formation	18m
		Aptian	Speeton Clay Formation	>100m
		Barremian		
		Hauterivian		
		Valanginian		
		Ryazanian		
	Upper Jurassic	Volgian	Kimmeridge Clay	

The cliffs are capped by a variable thickness of late Devensian (c18k BP) till associated with the Flamborough Head Moraine (Eyles et al., 1994).

Five main unprotected cliff units have been identified (Table 5):

1. Speeton Cliff; simple cliffs developed in Upper Jurassic and Lower Cretaceous clays, the Red Chalk and overlying glacial till. The cliffs are fronted by a broad sand and gravel beach. They are actively eroding through a sequence of high-angled debris slides and mudslides;
2. Buckton Cliff; near-vertical simple rock cliffs developed in Upper Cretaceous Chalk units (Ferriby, Welton and Burnham Chalk Formations), with a narrow platform and beach. Cliff recession occurs mainly through rockfalls, often forming steep talus cones at the base of the cliff;
3. Bempton Cliff; near-vertical simple rock cliffs developed in Upper Cretaceous Chalk units (Welton and Burnham Chalk Formations). Cliff recession occurs mainly through rockfalls and topples. The shoreline comprises a narrow platform and gravel/cobble beach;
4. Flamborough Cliff; composite rock/till cliffs developed in the Burnham and Flamborough Chalk Formations, mantled by variable thicknesses of glacial till which forms the relatively gently sloping upper cliff section. The cliff-platform is cut by numerous small faults, resulting in a complex planform, with caves, narrow steep-sided inlets and blowholes.
5. Sewerby Cliff; composite rock/till cliffs developed in the Burnham and Flamborough Chalk Formations, mantled by variable thicknesses of glacial till which forms the relatively gently sloping vegetated upper cliff section. The shoreline comprises a narrow platform and gravel/cobble beach.

Table 5 Cliff Units: Reighton to Sewerby (the Flamborough Cliffs)

Cliff Unit	Description
	**SPEETON CLIFF** (Reighton to Dulcey Dock) Photo: http://www.speeton.ukfossils.co.uk/ ***Bedrock;*** Speeton Clay Formation overlain by the Red Chalk and Ferriby Chalk Formation ***Superficial Deposits***; Flamborough Head moraine glacial tills of varying thickness. **Cliff Activity (NECAG Slope Condition)**; Locally active to Partly active **Cliff Instability;** High-angled debris slides and mudslides in weathered bedrock and glacial till **Recession rates (SMP2);** 0.25m/year
	**BUCKTON CLIFF** (Dulcey Dock to Standard Hill) Photo: www.commons.wikimedia.org/ ***Bedrock;*** Ferriby Chalk Formation, Welton Chalk Formation and Burrnham Chalk Formation ***Superficial Deposits***; Thin cap of Flamborough Head moraine glacial tills **Cliff Profile** Near-vertical cliff and narrow shore platform **Cliff Instability;** Rockfalls and topples **Recession rates (SMP2);** 0.1m/year

Cliff Unit	Description
	**BEMPTON CLIFF** (Standard Hill to Long Ness) Photo: http://place.uk.com/2011/08/ ***Bedrock;*** Welton Chalk Formation and Burnham Chalk Formation ***Superficial Deposits***; Thin cap of Flamborough Head moraine glacial tills **Cliff Profile** Near-vertical cliff and narrow shore platform **Cliff Instability;** Rockfalls and topples **Recession rates (SMP2);** 0.1m/year
	**FLAMBOROUGH CLIFF** (Long Ness to Cattlemere Hole) Photo: http://shatasm.blogspot.co.uk/2011/06/ ***Bedrock;*** Burnham Chalk Formation and Flamborough Chalk Formation. Numerous small faults. ***Superficial Deposits***; Variable thickness of Flamborough Head moraine glacial tills **Cliff Profile** Near-vertical cliff and structurally controlled shore platform; numerous caves, arches and stacks, several blowholes. **Cliff Instability;** Rockfalls and topples; mudslides in the glacial till on upper slopes **Recession rates (SMP2);** 0.1m/year

Cliff Unit	Description
	**SEWERBY CLIFF** (Cattlemere Hole to Sewerby) Photo: http://commons.wikimedia.org/wiki/ ***Bedrock;*** Burnham Chalk Formation and Flamborough Chalk Formation ***Superficial Deposits***; Variable thickness of Flamborough Head moraine glacial tills **Cliff Profile** Composite cliff (till over bedrock) and shore platform with narrow gravel/cobble beach **Cliff Instability;** Rockfalls and topples; mudslides in the glacial till on upper slopes **Recession rates (HECAG SMP2);** 0.1 – 0.4m/year

5 Historical Cliff Recession Rates

Little appears to have been published on cliff recession rates between Flamborough and Scarborough. This is in contrast to Holderness (south of Flamborough) where the local authority has monitored cliff recession since 1952 (e.g. Lee 2011) and further north where Agar (1960) presented cliff recession data for the cliffline between Ravenscar and Staithes, for the period 1862 to 1960.

Information on historical recession is limited to the generalised statements made in Futurecoast (Halcrow 2002) and in the SMP2 documents. This information is summarised in Table 6.

Table 6 Estimated cliff recession rates: Scarborough to Filey (from: Futurecoast and the SMP2)

Cliff Unit	Futurecoast		SMP2*	Recession Rate Category (Cosgrove et al., 1997)
	Recession Potential	Average Annual Recession Rate (m/year)	Average Annual Recession Rate (m/year)	
Wheatcroft Cliff	Medium	0.5 - 1	0.2 – 0.3	Moderate/Intense
Cornellian Bay	Medium	0.5 - 1	0.2 – 0.3	Moderate/Intense
Cayton Bay	Medium	0.5 - 1	0.3 – 0.4	Moderate/Intense
Tenant's Cliff	Medium	0.5 - 1	0.3 – 0.4	Moderate/Intense
Killerby Cliff	Medium	0.5 - 1	0.3 – 0.4	Moderate/Intense
Red Cliff	Medium	0.5 - 1	0.3 – 0.4	Moderate/Intense
Lebberston Cliff	Low	0.1 – 0.5	0.1 – 0.2	Moderate
Gristhorpe Cliff	Low	0.1 – 0.5	0.1 – 0.2	Moderate
Newbiggin Cliff	Low	0.1 – 0.5	0.2	Moderate
North Cliff	Low	0.1 – 0.5	0.2	Moderate
Filey Cliff	Medium	0.5 - 1	0.2	Moderate/Intense
Speeton Cliff	Medium	0.5 - 1	0.25	Moderate/Intense
Buckton Cliff	Low	0.1 – 0.5	0.1	Negligible/Moderate
Bempton Bay	Low	0.1 – 0.5	0.1	Negligible/Moderate
Flamborough Cliff	Low	0.1 – 0.5	0.1	Negligible/Moderate
Sewerby Cliff	Low	0.1 – 0.5	0.1 – 0.4	Moderate

Note: * The 2nd generation Shoreline Management Plans for:
River Tyne to Flamborough Head SMP2 (Royal Haskoning, 2007)
Flamborough Head to Gibraltar Point SMP2 (Scott Wilson, 2009)

The recession estimates presented in Futurecoast are generally higher than those reported in the SMP2 documents. However, it is understood that the Futurecoast rates are high-level predictions based on cliff types and materials. The SMP2 rates are likely to have been supported by some historical map analysis.

Since 2008, Scarborough Borough Council (as part of NECAG) have monitored cliff recession rates at a series of Ground Control Points between Staithes and Filey Bay. These control points are typically at 300m centres along selected clifflines. Data collection involves a bi-annual survey, measuring the distance from the control point to the cliff edge along a fixed bearing. A total of 27 points lie within the cliff units between Scarborough and Speeton Cliff; there has been no monitoring of the Flamborough Cliffs. The various monitoring reports produced since 2008 are available from the North East Coastal Observatory website: http://www.northeastcoastalobservatory.org.uk/

Table 7 North East Coastal Group cliff recession measurements: Scarborough to Filey (from Haskoning and Halcrow, 2011)

Cliff Unit	Ground Control Points	Measurement Period	Cliff Top Recession	Cliff Top Recession Rate
Wheatcroft Cliff	South Bay 5	March 2010 – February 2011	0.2m	0.2m/year
	South Bay 6		0.2m	0.2m/year
	South Bay 7		0m	None recorded
	South Bay 8		0m	None recorded
Cornelian Bay	South Bay 9		0m	None recorded
	South Bay 10		0m	None recorded
	South Bay 11		0.4m	0.4m/year
	South Bay 12		0.2m	0.2m/year
	South Bay 13		0.9m	0.9m/year
Cayton Cliff	No Ground Control Points			
Tenant's Cliff	Cayton 1*	November 2008 – March 2011	0.5m	0.2m/year
	Cayton 2*		5.1m	2m/year
	Cayton 3*		0m	None recorded
Killerby Cliff	Cayton 4		0m	None recorded
	Cayton 5		0m	None recorded
	Cayton 6		0.1m	<0.1m/year
	Cayton 7		0m	None recorded
Red Cliff	Cayton 8		0m	None recorded
Lebberston Cliff	No Ground Control Points			
Gristhorpe Cliff	No Ground Control Points			
Newbiggin Cliff	No Ground Control Points			
North Cliff	Filey Bay 24**	September 2010		None recorded
	Filey Bay 25**	September 2010		None recorded
	Filey Bay 26**	March 2011		None recorded
	Filey Bay 27**	March 2011		None recorded
Filey Cliff	Filey Bay 1	November 2008 – March 2011	0m	None recorded
	Filey Bay 2		0m	None recorded
Speeton Cliff	Filey Bay 20	November 2008 – February 2011	0.3m	0.1m/year
	Filey Bay 21		0m	None recorded
	Filey Bay 22		0.2m	0.1m/year
	Filey Bay 23		0m	None recorded

Notes:
* Ground Control Points sited within the landslide complex, not on the rear cliffline.
** Ground Control Points only recently established – no available measurements to date.

The cliff monitoring results are summarised in Table 7. The only clifflines where recession has been recorded are: Wheatcroft Cliff, Cornelian Bay, Cayton Bay, Killerby Cliff and Speeton Cliff (note that the control points at Tenant's Cliff are sited within the undercliff and the monitoring does not record rear cliff retreat).

The results are consistent with the SMP2 estimated recession rates and generally fall within the Moderate category. Only at Cornelian Bay (South Bay point 13; 0.9m/year) has the recorded recession fallen within the Intense category. The fact that many sites have shown no recession merely indicates the episodic nature of cliff retreat, rather than that the cliffs in question are stable; the monitoring period (often less than 1 year) has simply been too short.

Given the limited data available on recession rates, it remains something of a challenge to define a baseline recession rate for each cliff unit that can be used as the basis for future predictions. The expected long-term recession rates presented in Table 8 have been based on the information discussed above, plus the author's experience of recession rates elsewhere on the North Yorkshire-Humberside coast. As suggested by Agar (1960), the recession rate is usually a reflection of strength of the cliff materials, the exposure to wave attack and the protection provided by the presence of a beach. It follows that:

- cliffs developed in weak glacial till or weak rock (e.g. the Oxford or Kimmeridge Clay) are expected to erode at a faster rate than cliffs developed in strong rock (e.g. sandstones and limestones);
- the rate of recession of composite cliffs developed in glacial till over strong rock will, in the long-term, be controlled by the erodibility of the rock cliff. However, there could be significant landslide activity on the till slopes, causing episodic loss of cliff top land;
- the cliff top recession behind major landslide complexes developed in glacial till (e.g. Cayton Cliff and Cornelian Bay) is likely to be markedly episodic and could involve the significant loss of land over relatively short periods of time (at Holbeck Hall, over 90m of cliff top land was lost over the course of several days in June 1993; Lee 1999).
- the cliff top recession behind major landslide complexes developed in rock (i.e. Tenant's Cliff) is likely to be constrained by the stabilising effect of large detached blocks within the undercliff. The long-term rear cliff retreat rates are likely to have been Negligible.

Table 8 Estimated baseline cliff recession rates

Cliff Unit	**Dominant Cliff Type and Materials**	**Assumed Baseline Recession Rate (m/year)**
Wheatcroft Cliff	Composite cliff: Moderately Strong Rock	0.3
Cornellian Bay	Coastal slope: Glacial Till	0.5
Cayton Bay	Coastal slope: Glacial Till	0.5
Tenant's Cliff	Undercliff: Strong Rock	0.1
Killerby Cliff	Simple cliff: Glacial Till	0.5
Red Cliff	Simple cliff: Moderately Strong Rock	0.3
Lebberston Cliff	Composite cliff: Strong Rock	0.2
Gristhorpe Cliff	Simple cliff: Strong Rock	0.2
Newbiggin Cliff	Simple cliff: Strong Rock	0.2
North Cliff	Composite cliff: Glacial till and Strong Rock	0.2
Filey Cliff	Composite cliff: Glacial till and Strong Rock	0.2
Speeton Cliff	Simple cliff: Weak rock/Glacial Till	0.5
Buckton Cliff	Simple cliff: Strong Rock	0.1
Bempton Bay	Simple cliff: Strong Rock	0.1
Flamborough Cliff	Composite cliff: Glacial till and Strong Rock	0.2
Sewerby Cliff	Composite cliff: Glacial till and Strong Rock	0.3

6 50-Year Cliff Recession Predictions

As discussed in Section 2, lower and upper bound estimates of the recession distance at each of the cliff units have been generated using simple models:

- lower bound estimate; this has involved simply extrapolating the assumed baseline rate over 50-years:

  50-Year Distance = Baseline Rate x 50

- upper bound estimate; this is based on the use of the "historical projection" method, and involves multiplying the baseline rate by an adjustment factor calculated from the ratio of the historical and future rates of relative sea-level rise (RSLR):

  50-Year Distance = Baseline Rate x (Future RSLR/Historical RSLR)

  = Baseline Rate x (5mm/2.5mm)

The results are presented in Table 9. Even for the very conservative "Historical Projection" approach, the predicted recession distances are not great. The highest losses (up to 50m) should be expected along the glacial till/weak rock dominated sections at Cornelian Bay, Cayton Cliff, Killerby Cliff and Speeton Cliff. Up to 30m loss of cliff top land could occur at Wheatcroft Cliff, Red Cliff and Sewerby Cliff. Elsewhere, recession distances of 20m or less might be expected.

Table 9 Predicted 50-Year Recession Distances

Cliff Unit	Assumed Baseline Recession Rate (m/year)	50 year Retreat: Extrapolation of Current Rate (m)	50 year Retreat: Historical Projection (m)
Wheatcroft Cliff	0.3	15	30
Cornelian Bay	0.5	25	50
Cayton Bay	0.5	25	50
Tenant's Cliff	0.1	5	10
Killerby Cliff	0.5	25	50
Red Cliff	0.3	15	30
Lebberston Cliff	0.2	10	20
Gristhorpe Cliff	0.2	10	20
Newbiggin Cliff	0.2	10	20
North Cliff	0.2	10	20
Filey Cliff	0.2	10	20
Speeton Cliff	0.5	25	50
Buckton Cliff	0.1	5	10
Bempton Bay	0.1	5	10
Flamborough Cliff	0.2	10	20
Sewerby Cliff	0.3	15	30

The predictions are presented in Figures 3 to 6, which show the extent of each cliff unit and the upper and lower bound estimates of cliff top loss over 50-years. How these estimates should be used to define the inland boundary of the SSSIs is a decision for Natural England. By way of guidance, the upper bound estimates are probably very conservative. If this recession distance is chosen, then there can be reasonable confidence that the estimates are unlikely to be exceeded. The upper bound estimate is also consistent with the SMP2 predicted changes for the Scarborough-Filey shoreline (Haskoning, 2007).

Figure 3 Cayton, Cornelian and South Bays SSSI: predicted 50-yrear recession rates of site boundaries (Image source: Google Earth). The coloured lines show the approximate cliff unit boundaries.

Figure 4 Filey Brigg SSSI, Gristhorpe and Redcliff SSSI and the proposed extension between Filey Brigg and Gristhorpe Bay: predicted 50-year recession rates of site boundaries (Image source: Google Earth). The coloured lines show the approximate cliff unit boundaries.

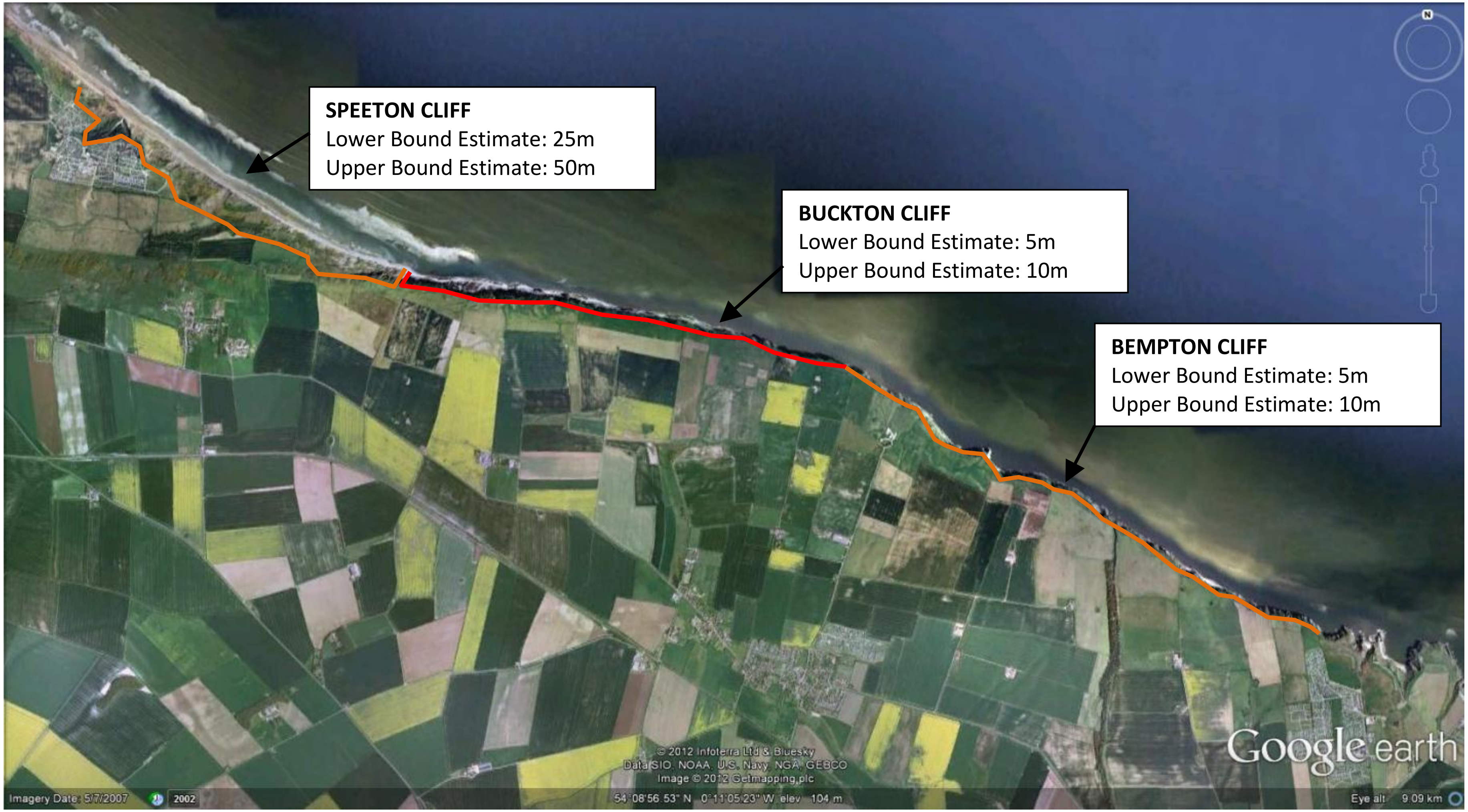

Figure 5 Flamborough Head SSSI (Reighton to Long Ness): predicted 50-yrear recession rates of site boundaries (Image source: Google Earth). The coloured lines show the approximate cliff unit boundaries.

Figure 6 Flamborough Head SSSI (Long Ness to Sewerby): predicted 50-yrear recession rates of site boundaries (Image source: Google Earth). The coloured lines show the approximate cliff unit boundaries.

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