Cell 1 Regional Coastal Monitoring Programme
Update Report 6: 'Partial Measures' Survey 2014

Redcar and Cleveland Council
Final Report

July 2014

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Abbreviations and Acronyms

Acronym / Abbreviation	Definition
AONB	Area of Outstanding Natural Beauty
DGM	Digital Ground Model
HAT	Highest Astronomical Tide
LAT	Lowest Astronomical Tide
MHWN	Mean High Water Neap
MHWS	Mean High Water Spring
MLWS	Mean Low Water Neap
MLWS	Mean Low Water Spring
m	metres
ODN	Ordnance Datum Newlyn

Water Levels Used in Interpretation of Changes

Water Level Parameter	Water Level (m AOD) Hartlepool Headland to Saltburn Scar	Skinningrove	Hummersea Scar to Sandsend Ness	Sandsend Ness to Saltwick Nab
HAT	3.25	3.18	3.15	3.10
MHWS	2.65	2.68	2.65	2.60
MLWS	-1.95	-2.13	-2.15	-2.20
Water Level Parameter	**Water Level (m AOD) Saltwick Nab to Hundale Point**	**Hundale Point to White Nab**	**White Nab to Filey Brigg**	**Filey Brigg to Flamborough Head**
HAT	3.10	3.05	3.05	3.10
MHWS	2.60	2.45	2.45	2.50
MLWS	-2.20	-2.35	-2.35	-2.30

Source: *River Tyne to Flamborough Head Shoreline Management Plan 2*.
Royal Haskoning, February 2007.

Glossary of Terms

Term	Definition
Beach nourishment	Artificial process of replenishing a beach with material from another source.
Berm crest	Ridge of sand or gravel deposited by wave action on the shore just above the normal high water mark.
Breaker zone	Area in the sea where the waves break.
Coastal squeeze	The reduction in habitat area which can arise if the natural landward migration of a habitat under sea level rise is prevented by the fixing of the high water mark, e.g. a sea wall.
Downdrift	Direction of alongshore movement of beach materials.
Ebb-tide	The falling tide, part of the tidal cycle between high water and the next low water.
Fetch	Length of water over which a given wind has blown that determines the size of the waves produced.
Flood-tide	Rising tide, part of the tidal cycle between low water and the next high water.
Foreshore	Zone between the high water and low water marks, also known as the intertidal zone.
Geomorphology	The branch of physical geography/geology which deals with the form of the Earth, the general configuration of its surface, the distribution of the land, water, etc.
Groyne	Shore protection structure built perpendicular to the shore; designed to trap sediment.
Mean High Water (MHW)	The average of all high waters observed over a sufficiently long period.
Mean Low Water (MLW)	The average of all low waters observed over a sufficiently long period.
Mean Sea Level (MSL)	Average height of the sea surface over a 19-year period.
Offshore zone	Extends from the low water mark to a water depth of about 15 m and is permanently covered with water.
Storm surge	A rise in the sea surface on an open coast, resulting from a storm.
Swell	Waves that have travelled out of the area in which they were generated.
Tidal prism	The volume of water within the estuary between the level of high and low tide, typically taken for mean spring tides.
Tide	Periodic rising and falling of large bodies of water resulting from the gravitational attraction of the moon and sun acting on the rotating earth.
Topography	Configuration of a surface including its relief and the position of its natural and man-made features.
Transgression	The landward movement of the shoreline in response to a rise in relative sea level.
Updrift	Direction opposite to the predominant movement of longshore transport.
Wave direction	Direction from which a wave approaches.
Wave refraction	Process by which the direction of approach of a wave changes as it moves into shallow water.

Preamble

The Cell 1 Regional Coastal Monitoring Programme covers approximately 300km of the north east coastline, from the Scottish Border (just south of St. Abb's Head) to Flamborough Head in East Yorkshire. This coastline is often referred to as 'Coastal Sediment Cell 1' in England and Wales (Figure 1).

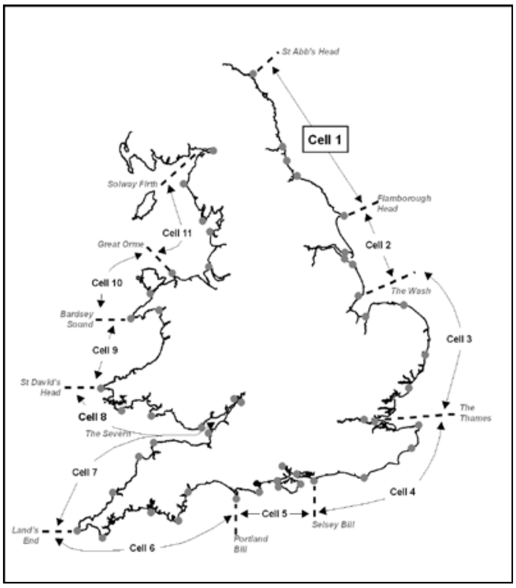


Figure 1 Sediment Cells in England and Wales

The main elements of the Cell 1 Regional Coastal Monitoring Programme involve:

- beach profile surveys
- topographic surveys
- cliff top recession surveys
- real-time wave data collection
- bathymetric and sea bed characterisation surveys
- aerial photography
- walk-over surveys

The beach profile surveys, topographic surveys and cliff top recession surveys are undertaken as a 'Full Measures' survey in autumn/early winter every year. Some of these surveys are then repeated the following spring as part of a 'Partial Measures' survey.

To date the following reports have been produced:

Table 1 Analytical, Update and Overview Reports Produced to Date

Year		Full Measures		Partial Measures		Cell 1 Overview Report
		Survey	Analytical Report	Survey	Update Report	
1	2008/09	Sep-Dec 08	May 09	Mar-May 09		
2	2009/10	Sep-Dec 09	Mar 10	Feb-Mar 10	Jul 10	
3	2010/11	Aug-Nov 10	Feb 11	Feb-Apr 11	Aug 11	Sep 11
4	2011/12	Sep-Oct 11	Oct 12	Mar-May 12	Feb 13	
5	2012/13	Sep 2012	Mar 13	Feb- Mar 13	May 13	
6	2013/14	Oct-Nov 13	Feb 14	Mar-April 14	Jul 14 (*)	

(*) The present report is **Update Report 6** and provides an analysis of the 2014 Partial Measures survey for Redcar and Cleveland Council's frontage.

1. Introduction

1.1 Study Area

South Gare Breakwater at the mouth of the River Tees estuary to Cowbar Nab at Staithes. For the purposes of this report, it has been sub-divided into six areas, namely:

- Coatham Sands
- Redcar Sands
- Marske Sands
- Saltburn Sands
- Cattersty Sands (Skinningrove)
- Staithes [1]

1.2 Methodology

Along Redcar & Cleveland Borough Council's frontage, the following surveying is undertaken:

- Full Measures survey annually each autumn/early winter comprising:
    - Beach profile surveys along nine transect lines
    - Topographic survey along Coatham Sands
    - Topographic survey along Redcar Sands
    - Topographic survey along Marske Sands
    - Topographic survey along Saltburn Sands
    - Topographic survey at Skinningrove along Cattersty Sands

- Partial Measures survey annually each spring comprising:
    - Beach profile surveys along nine transect lines
    - Topographic survey along Redcar Sands
    - Topographic survey along Saltburn Sands
    - Topographic survey at Skinningrove along Cattersty Sands

- Cliff top survey (biannually) at:
    - Staithes

The location of these surveys is shown in Figure 2. The Partial Measures survey was undertaken along this frontage between 31 March 2014 and 3 April 2014 (Coatham Sands, Redcar Sands, Markse Sands and Saltburn Sands), on 3 April 2014 (Cattersty Sands) and 9 April 2014 (Staithes). During the surveys the weather was varied; refer to the survey reports for specific details. The sea state was always calm.

On 5th December 2013 a significant storm surge, driven by strong northerly winds, coincided with one of the highest astronomical tides of the year. A comparison of the recorded water level data for the December 2013 storm surge at North Shields, Whitby and Scarborough has been provided in the second wave data analysis report covering the period 2013 to 2014. Recorded surge residuals from that report show a similar signature at the three sites, with the maximum surge height occurring before high water and the surge increasing in height as it progressed down the coast, from around 1.3m above predicted water level at North Shields to around 1.8m at Whitby and Scarborough. Based on the EA (2011) Coastal Flood Boundary Condition extreme water level data the surge had the follow chance of occurrence each year:

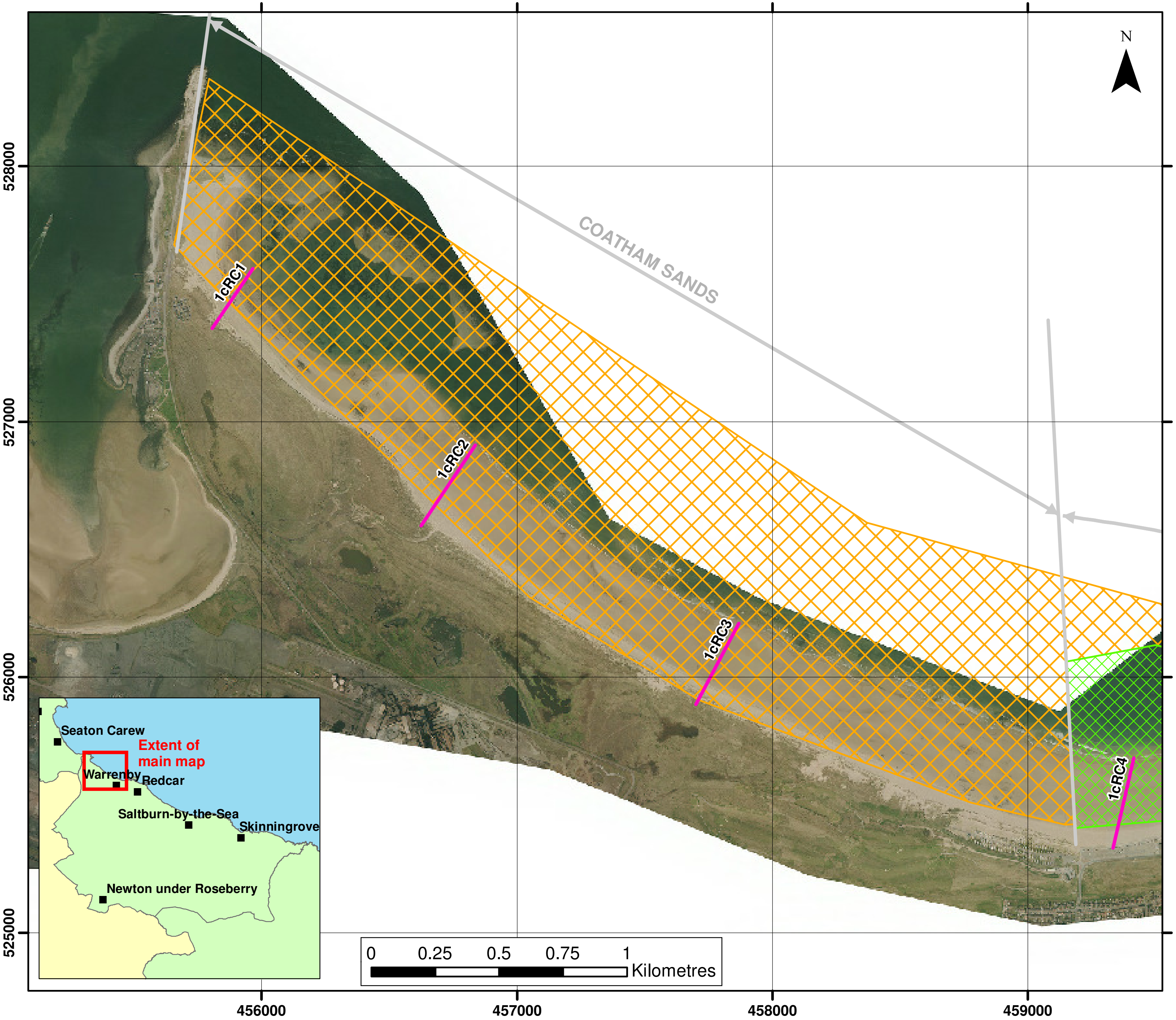
[1] The Staithes frontage straddles the boundary of jurisdiction of Redcar & Cleveland Borough Council and Scarborough Borough Council

- North Shields: between 1 in 200 and 1 in 500
- Whitby: between 1 in 100 and 1 in 500
- Scarborough: between 1 in 150 and 1 in 500

The Update Report presents the following:

- description of the changes observed since the previous survey and an interpretation of the drivers of these changes, including consideration of the impact of the storm surge (Section 2);
- documentation of any problems encountered during surveying or uncertainties inherent in the analysis (Section 3);
- recommendations for ‘fine-tuning’ the programme to enhance its outputs (Section 4); and
- providing key conclusions and highlighting any areas of concern (Section 5).

Processed data from the present survey are presented in the Appendices.



KEY

Topographic Profiles
- Annual
- 6 monthly

Topographic Surveys
- 6 monthly
- yearly
- 5 yearly

Cliff Top Monitoring Pegs
- 50m centres
- 100m centres
- 300m centres

(Indicative survey extents shown)

Client: North East Coastal Group

Project: Cell 1 Regional Coastal Monitoring Programme 2011 to 2016

Figure 2 - Map 1
Survey Locations
Coatham Sands
Redcar & Cleveland Borough Council

Update Report 6
Partial Measures Survey
Spring 2014

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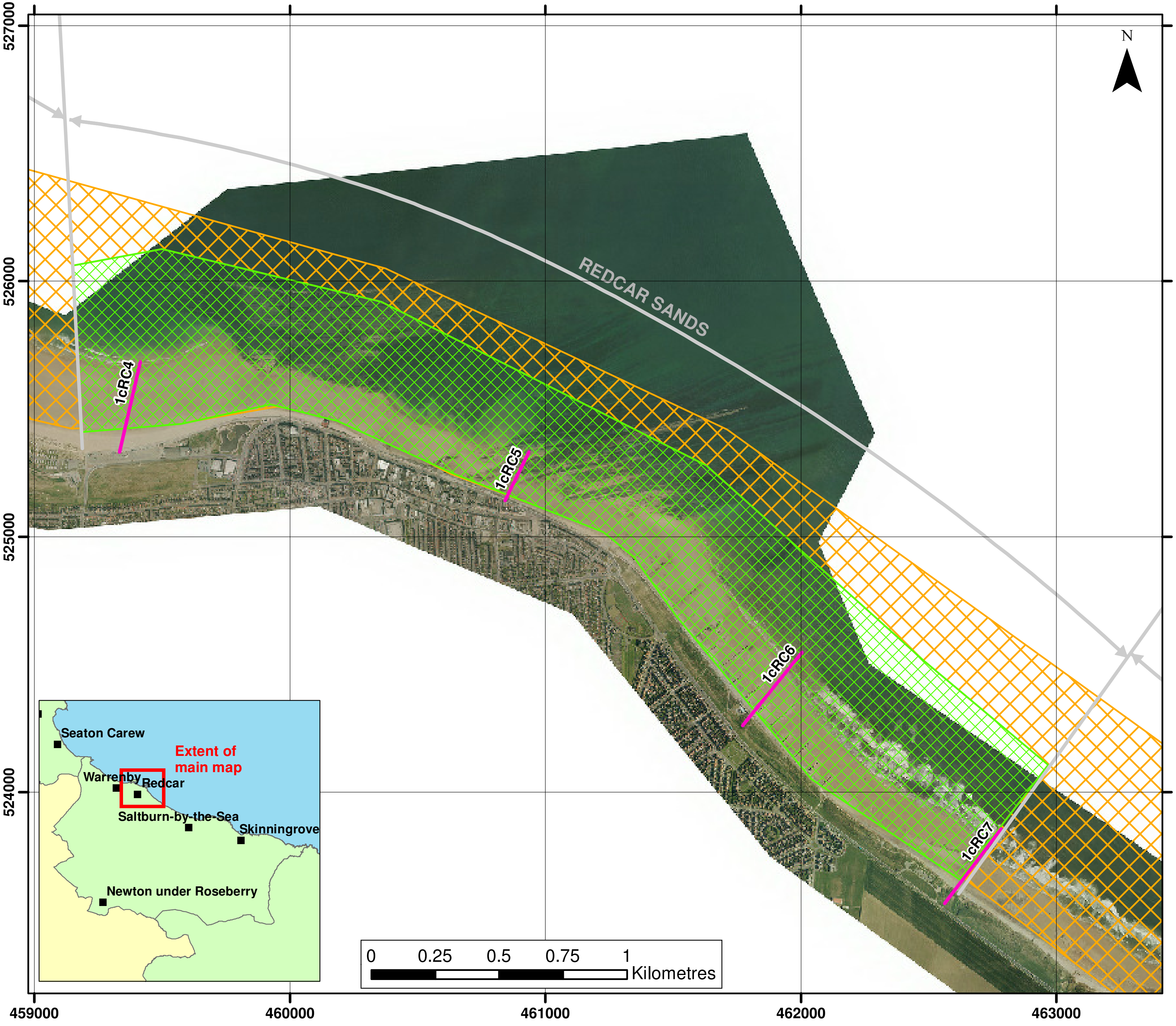

KEY

Topographic Profiles
- Annual
- 6 monthly

Topographic Surveys
- 6 monthly
- yearly
- 5 yearly

Cliff Top Monitoring Pegs
- 50m centres
- 100m centres
- 300m centres

(Indicative survey extents shown)

Client: North East Coastal Group

Project: Cell 1 Regional Coastal Monitoring Programme 2011 to 2016

Figure 2 - Map 2
Survey Locations
Redcar Sands
Redcar & Cleveland Borough Council

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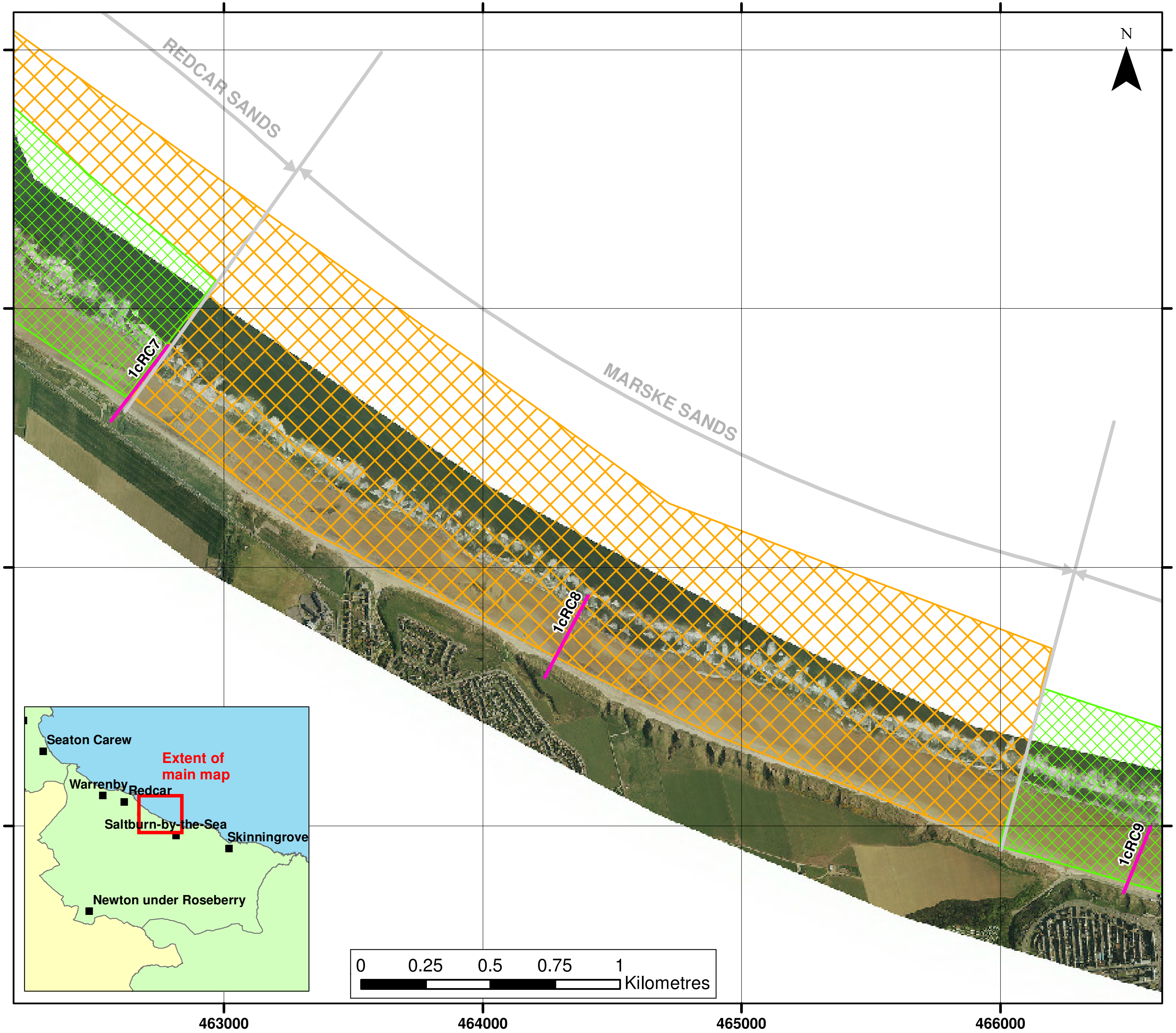

KEY

Topographic Profiles
- Annual
- 6 monthly

Topographic Surveys
- 6 monthly
- yearly
- 5 yearly

Cliff Top Monitoring Pegs
- 50m centres
- 100m centres
- 300m centres

(Indicative survey extents shown)

Client: North East Coastal Group

Project: Cell 1 Regional Coastal Monitoring Programme 2011 to 2016

Figure 2 - Map 3
Survey Locations
Marske Sands
Redcar & Cleveland
Borough Council

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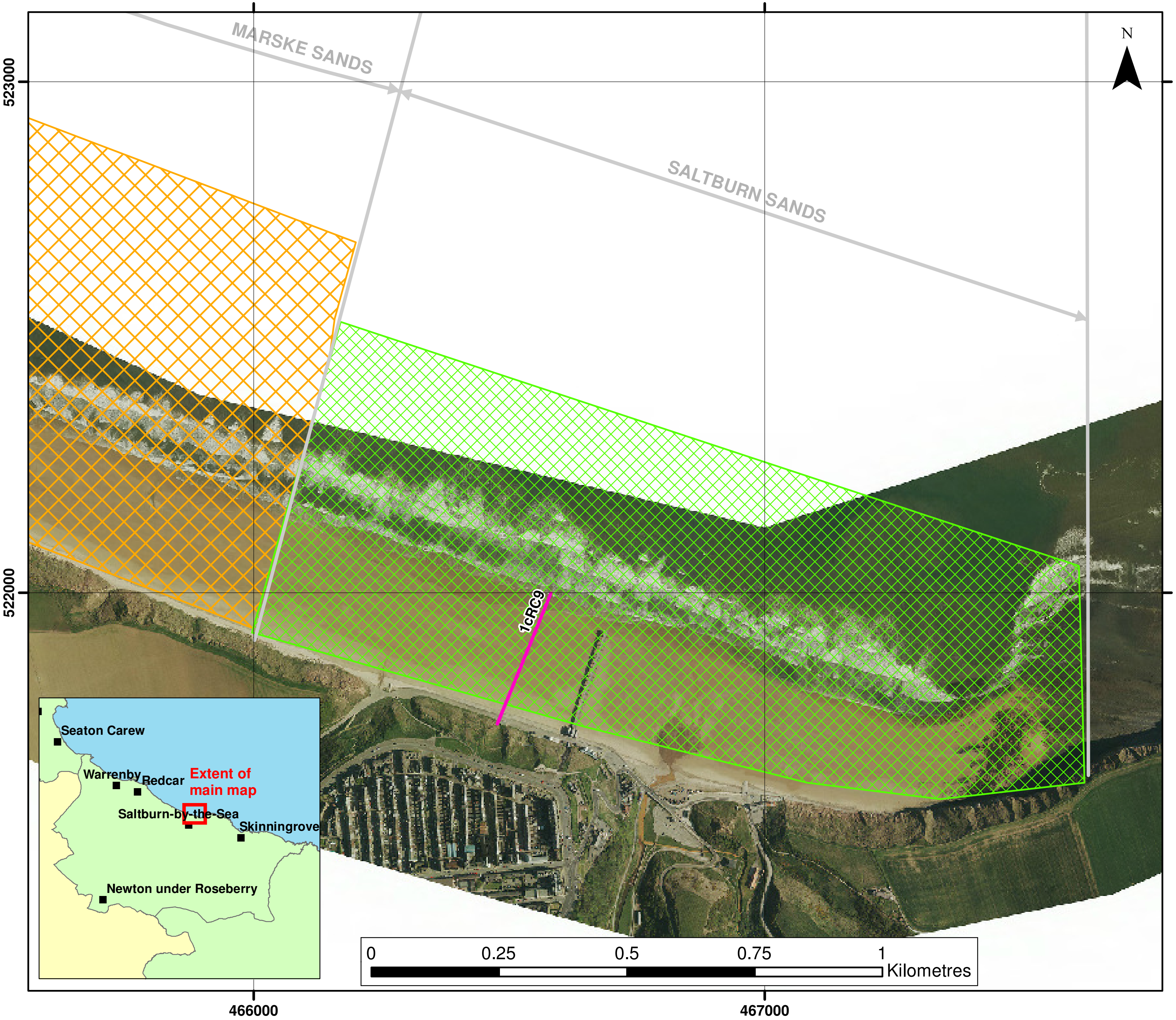

KEY

Topographic Profiles
- Annual
- 6 monthly

Topographic Surveys
- 6 monthly
- yearly
- 5 yearly

Cliff Top Monitoring Pegs
- 50m centres
- 100m centres
- 300m centres

(Indicative survey extents shown)

Client: North East Coastal Group

Project: Cell 1 Regional Coastal Monitoring Programme 2011 to 2016

Figure 2- Map 4
Survey Locations
Saltburn Sands
Redcar & Cleveland Borough Council

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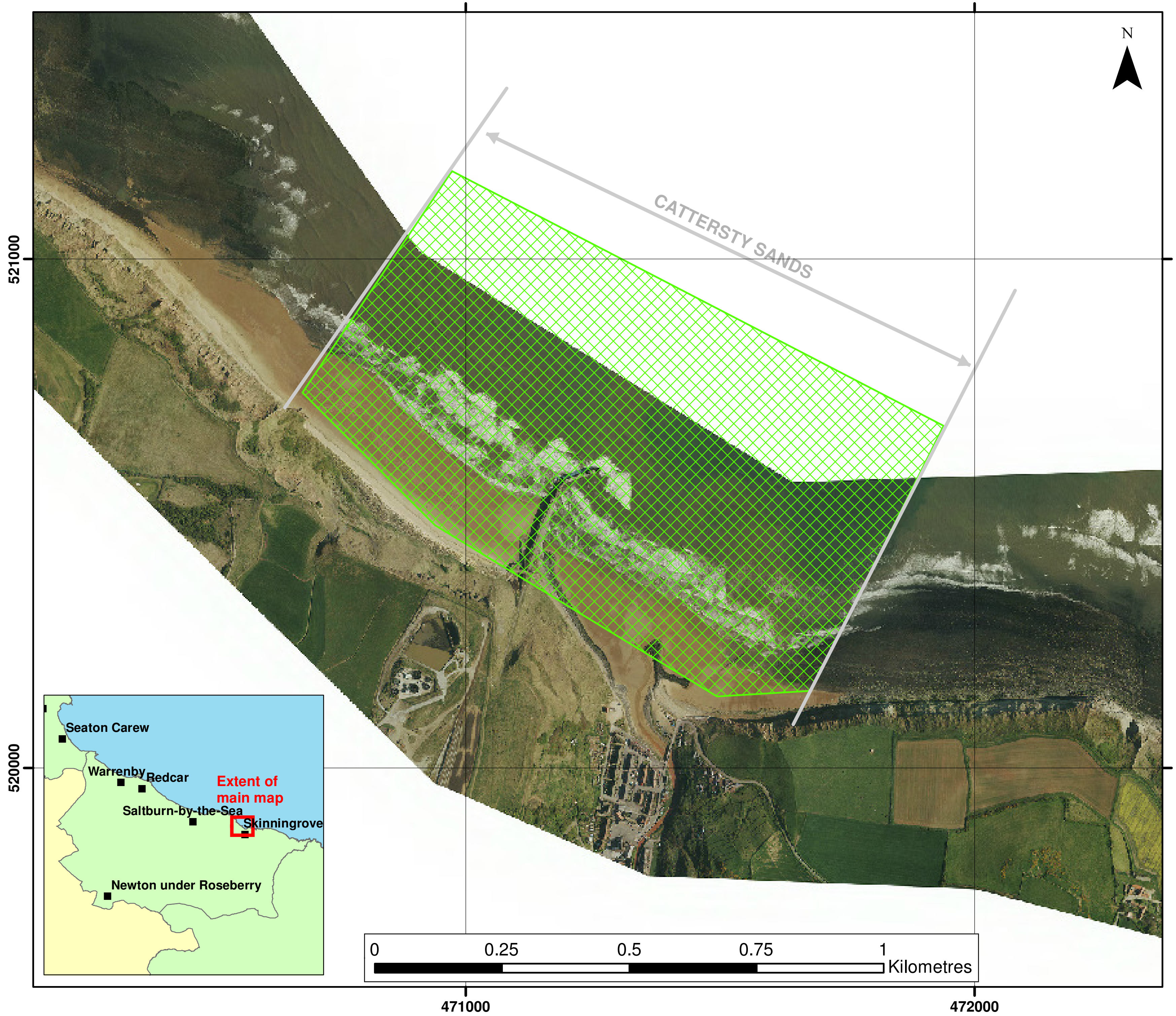

KEY

Topographic Profiles
- Annual
- 6 monthly

Topographic Surveys
- 6 monthly
- yearly
- 5 yearly

Cliff Top Monitoring Pegs
- 50m centres
- 100m centres
- 300m centres

(Indicative survey extents shown)

Client: North East Coastal Group

Project: Cell 1 Regional Coastal Monitoring Programme 2011 to 2016

Figure 2 - Map 5
Survey Locations
Cattersty Sands
Redcar & Cleveland
Borough Council

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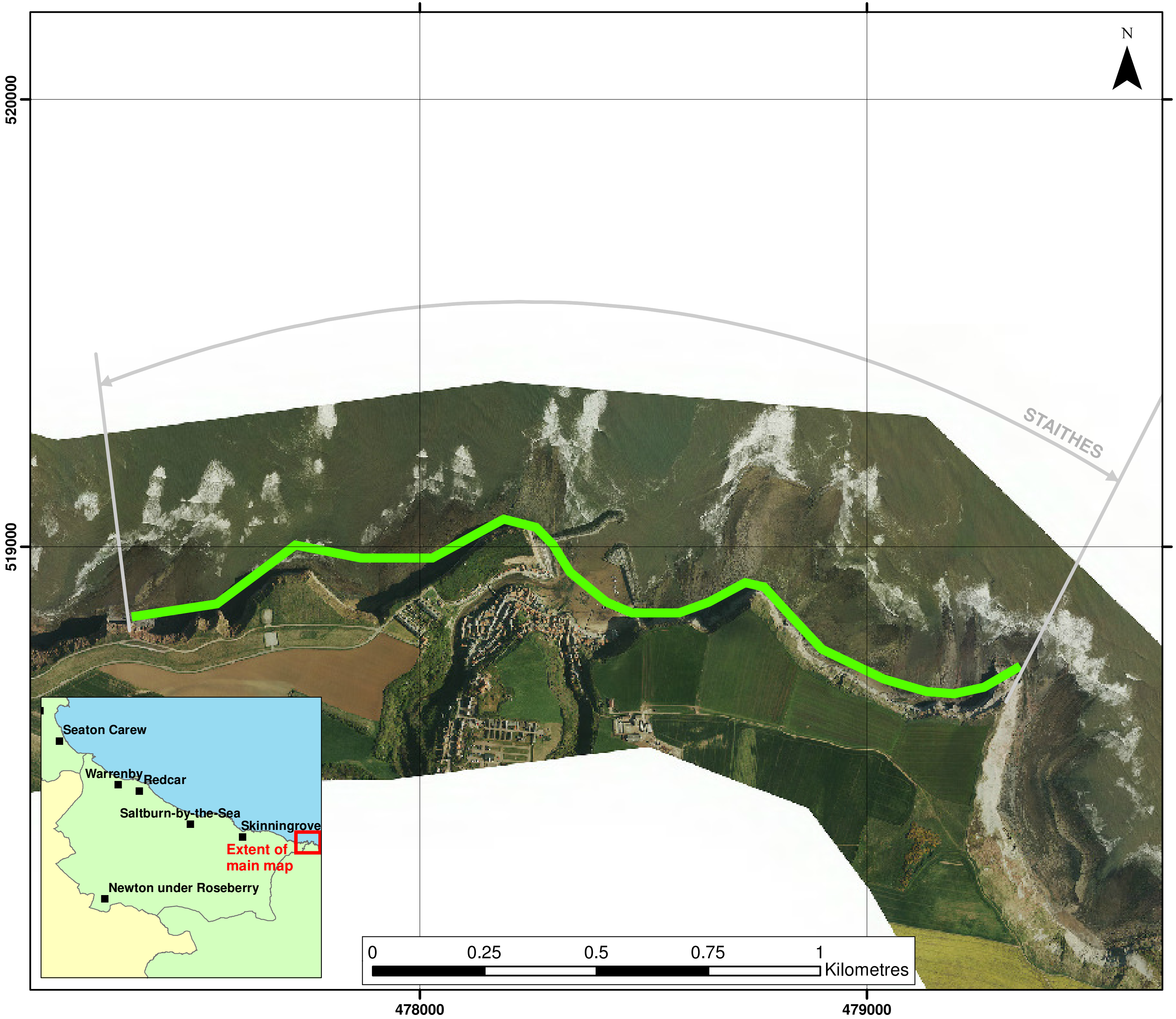

KEY

Topographic Profiles
- Annual
- 6 monthly

Topographic Surveys
- 6 monthly
- yearly
- 5 yearly

Cliff Top Monitoring Pegs
- 50m centres
- 100m centres
- 300m centres

(Indicative survey extents shown)

Client: North East Coastal Group

Project: Cell 1 Regional Coastal Monitoring Programme 2011 to 2016

Figure 2 - Map 6
Survey Locations
Staithes
Redcar & Cleveland
Borough Council

Update Report 6
Partial Measures Survey
Spring 2014

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2. Analysis of Survey Data

2.1 Coatham Sands

Survey Date	Description of Changes Since Last Survey	Interpretation
3rd April 2014	**Beach Profiles:** Coatham Sands is covered by four beach profiles during the Partial Measures survey (1cRC1 to 1cRC4; Appendix A) that were last surveyed in October 2013. **Profile 1cRC1** is located approximately 300m southeast of the South Gare Breakwater, in the lee of the German Charlies slag banks. The upper profile is dominated by dune ridges that have remained stable since 2009. Minor erosion and accretion (±0.2m) has occurred since the last survey from the dune front to 100m chainage. Marginally greater erosion of c. 0.4m has occurred between 100m and 130m chainage and the beach has accreted by 0.2m between 130m and 200m chainage. Little change has occurred below this point, although the end of the survey stops around 30m short of the October 2013 survey. Along **profile 1cRC2** dune levels and the majority of the profile have remained high relative to earlier survey. The crest of the foredune at 65m chainage has increased by 0.3m but there has been limited recession (<1m) of the dune front since the last survey. The beach has accreted slightly (up to 0.4m but generally around 0.1m) between the foredune toe at 75m chainage and 2010m chainage. Between 210m and 275m chainage a significant trough present in the October 2013 survey has been filled, raising the level of the beach by up to 1m. A berm that had formed in the October 2013 survey between 260m and 340m chainage has been eroded. The very lowest part of the profile between 340m and 420m chainage was not surveyed in October 2013 but is similar to that recorded in March 2013. **Profile 1cRC3** showed no change to 50m chainage, with the main dune and foredune crests both remaining stable since the last survey. However the dune front has experienced c. 8m of recession and the upper beach to c. 95m chainage has been lowered by 0.4m. Little change has occurred since the last survey between 95m and 150m chainage, but a berm has accreted between 150m and 200m chainage, raising the level of the beach by 0.6m. This corresponds with the erosion of a berm seen lower down the profile in the last survey between 200m and 260m chainage. The lowest part of the profile between 260m and 320m chainage is low compared to October 2013 but similar to profiles in	Profiles 1cRC1 and 1cRC4 show little change between the October 2013 and April 2014 surveys, with stable dunes and comparatively minor redistributions in the beach profile. 1cRC2 shows limited erosion of the dune front and 1cRC3 shows more substantial change with significant recession and steepening of the dune front and lowering of the upper beach. These changes are likely to have occurred during the December 2013 storm surge, with the greatest impacts seen at undefended coastlines that are not sheltered by the South Gare breakwater. **Longer term trends:** The pattern of accretion in the north of the bay with erosion or limited accretion in the central bay is consistent with previous observations of a northwards net transfer of material at Coatham sands. However, the erosion of the dune front and upper beach experienced at profile 1cRC3 in the central part of the bay has substantially interrupted a longer term pattern of dune accretion since 2008 and requires monitoring to determine longer-term impacts.

Survey Date	Description of Changes Since Last Survey	Interpretation
	earlier surveys. **Profile 1cRC4** is located at the beginning of the defended section at Coatham and Redcar. No change has occurred landward of the base of the seawall, against which the level of the beach has increased by up to 0.4m between 14m and 26m chainage. Between 26m and 80m chainage there has been slight lowering of the beach (0.1 – 0.2m). Accretion has taken place between 80m and 190m chainage, with a berm crest forming at the point of maximum accretion (0.4m) at 170m chainage. A small trough has formed between 190m and 220m chainage through the lowering of the beach by up to 0.2m and a corresponding bar has formed between 220m chainage and the end of the profile at 370m chainage through the accretion of up to 0.6m of sand. Compared to earlier surveys, the beach profile is within the range of those previously experienced, with the upper beach being in the lower end of the range and the lower beach in the higher end of the range.	

2.2 Redcar Sands

Survey Date	Description of Changes Since Last Survey	Interpretation
3rd April 2014	**Beach Profiles:** Redcar Sands is covered by three beach profiles (RC5 to RC7; Appendix A), with RC7 being approximately on the boundary with the Marske Sands area. They were last surveyed in October 2013. At **profile 1cRC5** the sea defences constructed in 2012 remain unchanged as far as 15m chainage. However, an accumulation of material present at their base in October 2013 has been eroded and the profile of the upper beach between 15m and 28m chainage lowered by a maximum of 0.8m to expose more of the sea defence toe. Limited erosion (0.2m lowering) has occurred between 40m and 60m chainage and between 100m and 115m chainage, but overall the profile to this point is very similar to the October 2013 survey with the exception of the erosion at the base of the sea wall. The foreshore rock platform continues to be exposed in the central section of the profile between 110m and 170m chainage but between 170m and 210m chainage the foreshore has accreted by around 0.3m. Lowering of the profile by around 0.4m has occurred between 210m chainage and the end of the profile at 0.1m. Whilst slightly lower than the previous survey, the beach level is generally higher than in the majority of previous surveys and significantly higher than immediately post-construction of the new sea defences in 2012. The **profile at 1cRC6** has not changed landward of 50m chainage since the last survey due to the presence of the sea defence. At the base of the sea defence, the beach has accreted by 0.4m due to the accumulation of gravel (evident in the survey photos). Between 60m and 80m chainage (around HAT and MHWS), the beach has been lowered by 0.2m, a berm has formed and steepening has occurred seaward of the berm crest. Between 90m and 230m the beach has accreted by 0.3m but significant lowering of the beach by up to 1m has taken place to create a trough between 240m and 330m chainage. A berm has formed in the most seaward part of the profile, but this is beyond the extent of the previous survey. Overall, the change is mostly with the past range, with the exception of the trough that has occurred around MLW which has taken the profile to its lowest surveyed level at this point. **Profile 1cRC7** is undefended. The profile has not changed landward of 50m chainage, however, the toe of the till cliff and upper beach between 50m chainage and MHW have seen significant change, with up to 8m of cliff recession and 0.5m lowering of the upper beach. Between 70m and 130m up to 0.4m of	The profiles and topographic survey difference plots indicate that there has been a trend of erosion of the upper beach, accretion in the central beach, and erosion of the lower beach. The profiles tend to have been smoothed, with berms being absent or more subdued. The most notable change is 8m erosion of the cliff toe and lowering of the upper beach at 1cRC7, which most likely resulted from the December 2013 storm surge. **Longer term trends:** No progressive long term trends have been noted from the latest survey. However, attention should be given in future surveys to the response of 1cRC7 to the erosion of the cliff toe and whether this initiates recession of the cliff top and its progressive retreat or whether a new, stable cliff profile is achieved. At the location of the most substantial erosion noted from the topographic survey at Coatham Rocks, accretion of a similar magnitude had taken place between Autumn 2012 and Spring 2013, suggesting that the winter storms and particularly the storm surge in December may have reversed the pattern of accretion here.

Survey Date	Description of Changes Since Last Survey	Interpretation
	gravel and sand have accreted. Between 130m and 180m a trough has been infilled with around 0.4m of sand but the substantial berm present in the October 2013 survey from 180m chainage to 300m chainage has been eroded by around 0.6m. Comparison to earlier surveys indicates that the cliff toe is at its most landward and the uppermost part of the beach at its lowest since monitoring began. The rest of the profile is comparable to, or higher than, previous levels.	
3rd April 2014	**Topographic Survey:** Redcar Sands is covered by a 6-monthly topographic survey. Data have been used to create a DGM (Appendix B – Map 1a) using a GIS. The DGM shows that the beach topography broadly parallel to the shore, although there is a slight embayment with a slightly steeper beach between the two headlands at Coatham Rocks and Redcar Rocks. The GIS has also been used to calculate the differences between the current topographic survey (Spring 2014) and the most recent (Autumn 2013) topographic survey, as shown in Appendix B – Map2a, to identify areas of erosion and accretion. The difference plot of the DGMs show that most changes along Redcar Sands between Autumn 2013 and Spring 2014 are within a range of ±1m. The largest change was over 1m of erosion close to Coatham Rocks on the west side of the Redcar frontage. Whilst not wholly consistent throughout Redcar sands, there is a pattern of erosion of the uppermost parts of the beach and accumulation in the central parts. Larger areas of erosion are also concentrated around Coatham Rocks, the lower foreshore in the embayment between Coatham Rocks and Redcar Rocks and at several points in the lower foreshore to the west of Redcar Rocks.	

2.3 Marske Sands

Survey Date	Description of Changes Since Last Survey	Interpretation
3rd April 2014	**Beach Profiles:** Marske Sands is covered by two beach profiles during the Partial Measures survey (RC7 to RC8; Appendix A), with RC7 being approximately on the boundary with the Redcar Sands area. **Profile 1cRC7** is located along The Stray and has been discussed in Section 2.2. **Profile 1cRC8** has not changed as far as 50m chainage, However, between 50m and 70m chainage the upper beach has lowered by around 0.3m and the cliff toe has eroded by 10m since October 2013. Between 100m and 150m chainage the profile has been lowered by around 0.5m, while a similar amount of accretion has occurred between 150m and 190m chainage. The lower foreshore has accreted between 240m and 340m chainage by around 0.6m to form a 100m-wide berm. Overall the beach is at its lowest level at many points since monitoring began in 2008 and the cliff toe is substantially further landward than in any previous survey.	Both 1cRC7 and 1cRC8 show that the December 2014 storm surge has caused lowering of the upper beach and recession of the cliff toe. **Longer term trends:** The April 2014 profiles are amongst the lowest seen at 1cRC8, but are the majority of profile 1cRC7 is more consistent with the range of profiles established in earlier surveys. The cliff toe recession at both locations is unprecedented and future surveys may demonstrate the longer term response of the cliff to changes at its toe.

2.4 Saltburn Sands

Survey Date	Description of Changes Since Last Survey	Interpretation
3rd April 2014	**Beach Profiles:** Saltburn Sands is covered by one beach profile (RC9; Appendix A). Overall **Profile 1cRC 9** has experienced no change over the section covered by the sea defence as far as 20m chainage. A small accumulation of gravel has increased the level of the beach at the base of the sea defence, but between 20m and 160m chainage the beach profile has lowered by up to 0.4m at 40m chainage and is at its lowest recoded level since 2008. Between 170m and MLW at 270m chainage the beach has accreted by up to 0.5m creating a more consistent gradient to the end of the survey than was evident in the October 2013 survey.	1cRC9 shows limited erosion from the upper beach and accretion in the lower beach, probably representing a seasonal transfer of material towards the lower foreshore that may have been accelerated by the storm surge. Coarse material has accumulated against the sea defence, also likely transported during the surge. **Longer term trends:** The upper beach is at its lowest since monitoring began, which continues a recent trend.
3rd April 2014	**Topographic Survey:** Saltburn Sands is covered by a 6-monthly topographic survey. Data have been used to create a DGM (Appendix B – Map 2a).The beach topography consists of shore parallel contours, with a small change at the mouth of the channel. This DGM has been compared against the previous (Autumn 2013) survey in Appendix B – Map 2b. The difference plot comparing the DGMs shows that since Autumn 2013 that all erosion on the beach is between ±1m, except at the mouth of the stream channel where the elevation of the beach has increased by more than 1m. For the most part, there appears to have been sediment accumulation at the very back of the beach against sea defences, with the exception of areas immediately adjacent to the channel mouth where erosion has taken place. Erosion is predominant across most of the rest of the beach with particular in the central to upper beach except in the area beyond the western extent of the sea defences where erosion and accretion are more equally balanced.	The difference plot indicates a pattern of widespread erosion with small accumulations of sediment against the sea defences. This pattern is the same as that indicated by profiles. The localised increase in elevation at the channel mouth relates to migration of the stream. The data indicate a net movement of beach material offshore and towards the west, which was probably been accelerated by the storm surge.

2.5 Cattersty Sands

3rd April 2014	**Topographic Survey:** Cattersty Sands is covered by a 6-monthly topographic survey. Data have been used to create a DGM (Appendix B – Map 3a). For the most part the beach contours are shore-parallel, and steeper east of the breakwater than west of it. Two deviations from the shore parallel pattern occur where the channel outflow crosses the beach and in the furthest east part of the survey where the contours indicate an embayment. The April 2014 DGM has been compared against the previous (autumn 2013) survey in Appendix B – Map 3b.The comparison between DGMs shows that over the winter erosion dominated the bay to the east of the breakwater and that deposition was predominant west of the breakwater. Changes were generally between ±1m, with only localised areas of more significant change.	The pattern of change suggests a west to east movement of material since November 2013. East of the breakwater, sediment has been eroded from central part of the bay and driven in a westwards direction against the breakwater. To the west of the breakwater, material has been eroded from the upper beach, particularly adjacent to the breakwater, drawn down to the central part of the beach.. **Longer term trends:** Changes between 2012 and 2013 show the opposite pattern to that observed between 2013 and 2014, suggesting the current data show an atypical pattern of change caused by the storm surge.

2.6 Staithes

9th April 2014	**Cliff-top Survey:** Twenty ground control points have been established at Staithes for the purposes of cliff top monitoring. The separation between any two points is a nominal 100 m. The cliff top surveys at Staithes are undertaken bi-annually. Data collection involves a distance offset measurement from the ground control point to the cliff edge along a fixed bearing. Appendix C provides results from the April 2014 survey, showing the distance from the ground control point to the edge of the cliff top along the defined bearing and changes in position since the November 2008 baseline survey and the previous September 2012 survey. The results provided in Appendix C show that none of the profiles have experienced erosion greater than the assumed error of ±0.1m between November 2013 and April 2014. Some profiles indicate cliff advance, which reflects difficulties precisely determining the edge of the cliff top. Calculation of longer-term erosion rates based on the recorded change indicates that 19 of the cliff top survey points recorded changes less than ±0.1m/yr or advances. These data are either statistically insignificant or erroneous. Only location No.13, which is situated above the eastern harbour arm, shows long-term recession, at a rate of 0.4m/yr.	The recorded changes to the cliff top between November 2013 and April 2014 are small. There have been no large failures which have affected the cliff top. **Longer term trends:** Table C1 in Appendix C presents the erosion rates calculated from the data collected since 2008. Only Point 13 profile shows a reliable average recession rate, which is 0.4m/yr since Nov 2008.
March 2013 to March 2014	**Durham University Laser Scanning:** The Cowbar Nab cliff is subject to monthly high-resolution laser scanning surveys by Durham University that are used to precisely monitor the locations and rates of erosion. An update on their work between March 2013 and March 2014 is provided here. Twelve surveys at one-monthly intervals have been undertaken over the last year, allowing difference models to be calculated over the period and for comparison to previous periods dating back to January 2011. The data indicate that: - The maximum recession of the cliff face during any one event was 2.80m, which occurred 6.7m above the cliff toe at a point that had previously experienced undercutting. - Greatest erosion of the cliff face is concentrated in areas not protected by rock armour, although	**Longer Term Trends** Laser scanning surveys suggest an increase in the number of rock falls between 2012-13 and 2013-14 but that no recession of the cliff top occurred. This is consistent with the cliff top monitoring data.

	smaller falls do occur in the protected cliff. - Despite the numerous rock falls, no retreat of the cliff top occurred. However, losses below the cliff line indicate a steepening of the cliff that will eventually lead to cliff top failure.	

3. Problems Encountered and Uncertainty in Analysis

Topographic Survey

No significant problems were reported with the topographic surveys but the following points were highlighted in the survey report:

- A large gravel bank had accreted in front of Saltburn promenade.
- Railings and ramps at Saltburn were being repaired following storm surge damage.
- Tarmac in front of Saltburn Pier had been broken due to sea water being 'forced up the sea defence beneath the pier'.
- More rock was exposed at the southern end of Cattersty Sands. This is concurrent with observations from the data that erosion was predominant to the east of the breakwater.
- Sections 1cRC3, 1cRC7 and 1cRC8 displayed vertical faces at the toe of the dune or cliff several metres landward of the previous survey (these are discussed Section 2 above).

Cliff Top Surveys

The cliff top surveys at Staithes are assumed to have a limit of accuracy of ± 0.1 m due to the methodology. Erosion can reliably be measured at only one location but as monitoring progresses, underlying patterns in erosion will become more evident.

4. Recommendations for 'Fine-tuning' the Monitoring Programme

No further recommendations are made at this stage for the fine-tuning of the monitoring programme.

5. Conclusions and Areas of Concern

- At Coatham Sands, the recorded profiles show relative stability in the northern part of the bay and in the defended section towards Redcar. However, the central and more southerly undefended parts of the bay show notable recession of the dune front and lowering of the upper beach following the December 2013 storm surge.
- At Redcar Sands, the profiles and the topographic survey show removal of material from the upper beach and its deposition in the middle beach, as well as lowering or erosion of troughs in the lower foreshore. As at Coatham Sands, the undefended section has experienced recession at the toe of the cliff above MHW resulting from the December 2013 storm surge.
- At Marske Sands, the recorded profiles show recession of the cliff toe and lowering of the upper beach in response to the December 2013 storm surge.
- At Saltburn Sands, the upper beach is at its lowest since monitoring began, continuing the pattern seen in the previous few surveys and likely to have been exacerbated by the storm surge conditions in December 2013. The topographic survey shows erosion to be more predominant than deposition for the most part.
- At Cattersty Sands, the topographic survey shows that the pattern of erosion and deposition differs between the east and west side of the breakwater, with erosion being predominant on the eastern side of the breakwater and deposition predominant on the western side of the breakwater, in contrast with the long term trend shown at the last full measures survey.
- At Staithes, the records from cliff top monitoring show no recent erosion. Work by Durham University at Cowbar Nab indicates a successive pattern of smaller failures of the cliff that tend to progressively move up the cliff face. No recession of the cliff top has occurred, which is consistent with observations from the cliff top monitoring.

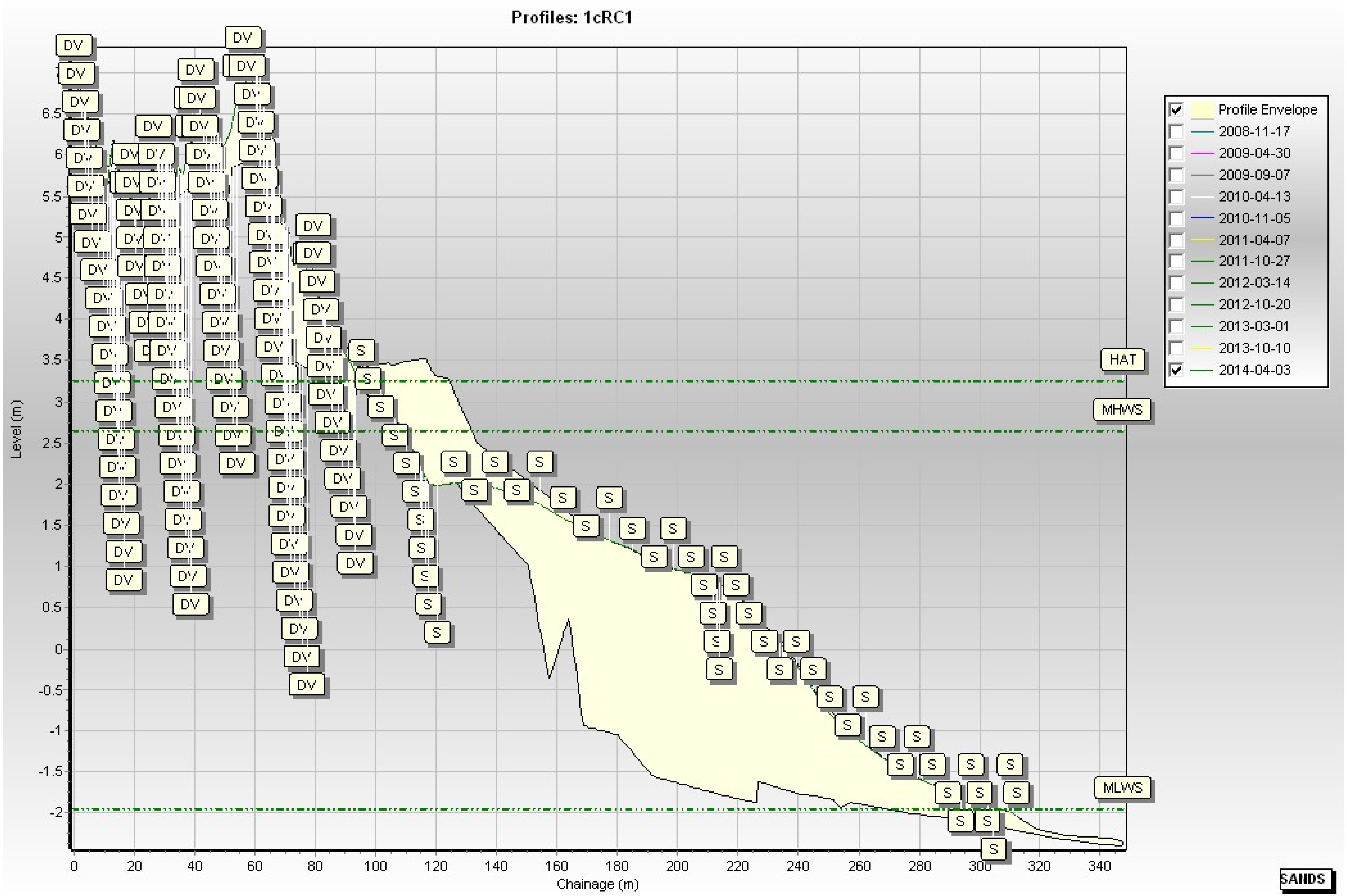
Appendices

Appendix A

Beach Profiles

The following sediment feature codes are used on some profile plots:

Code	Description
S	Sand
M	Mud
G	Gravel
GS	Gravel & Sand
MS	Mud & Sand
B	Boulders
R	Rock
SD	Sea Defence
SM	Saltmarsh
W	Water Body
GM	Gravel & Mud
GR	Grass
D	Dune (non-vegetated)
DV	Dune (vegetated)
F	Forested
X	Mixture
FB	Obstruction
CT	Cliff Top
CE	Cliff Edge
CF	Cliff Face
SH	Shell
ZZ	Unknown


Profiles: 1cRC1
Level (m)
Chainage (m)
Profile Envelope
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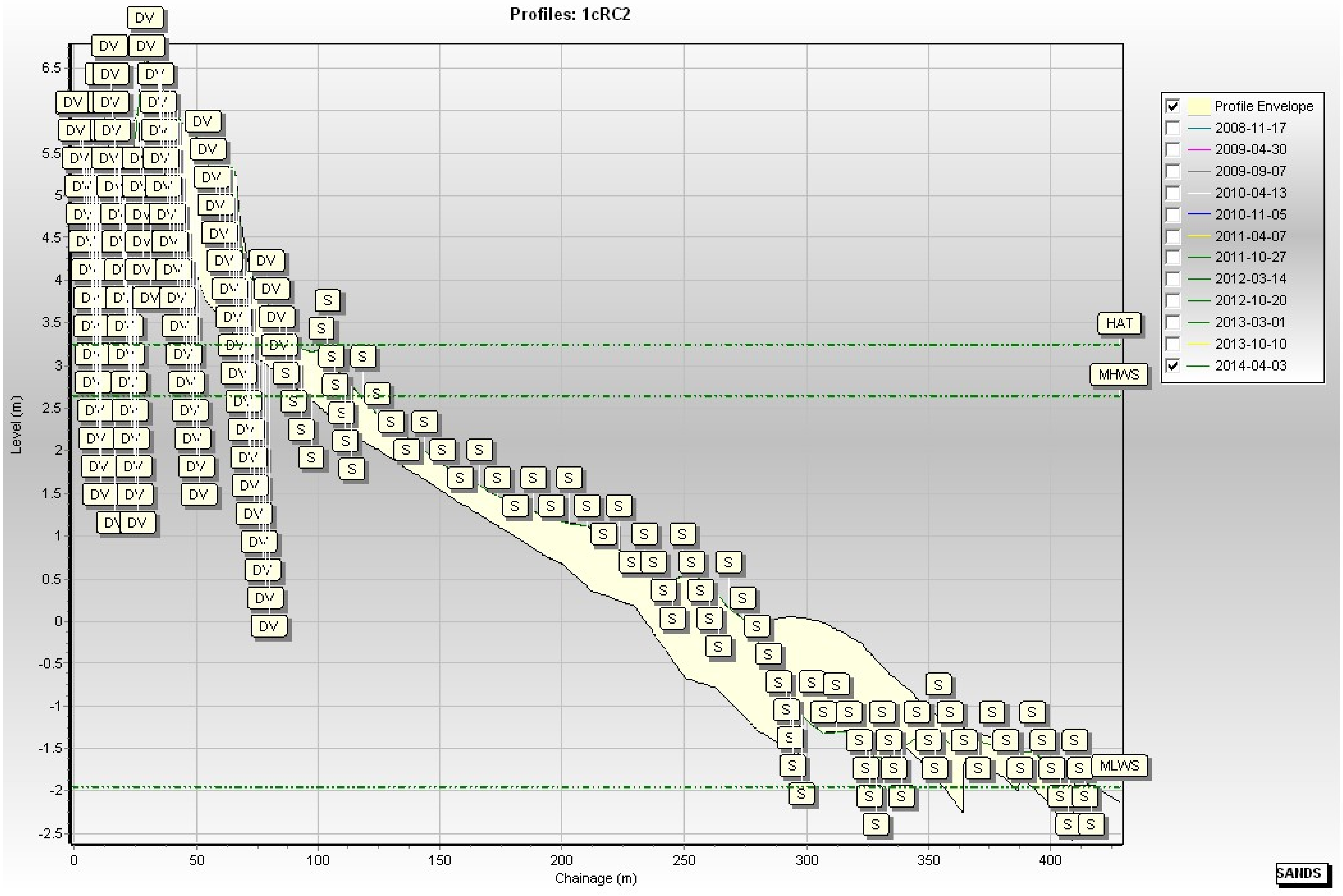
2009-09-07
2010-04-13
2010-11-05
2011-04-07
2011-10-27
2012-03-14
2012-10-20
2013-03-01
2013-10-10
2014-04-03
HAT
MHWS
MLWS
SANDS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2009-09-07
2010-04-13
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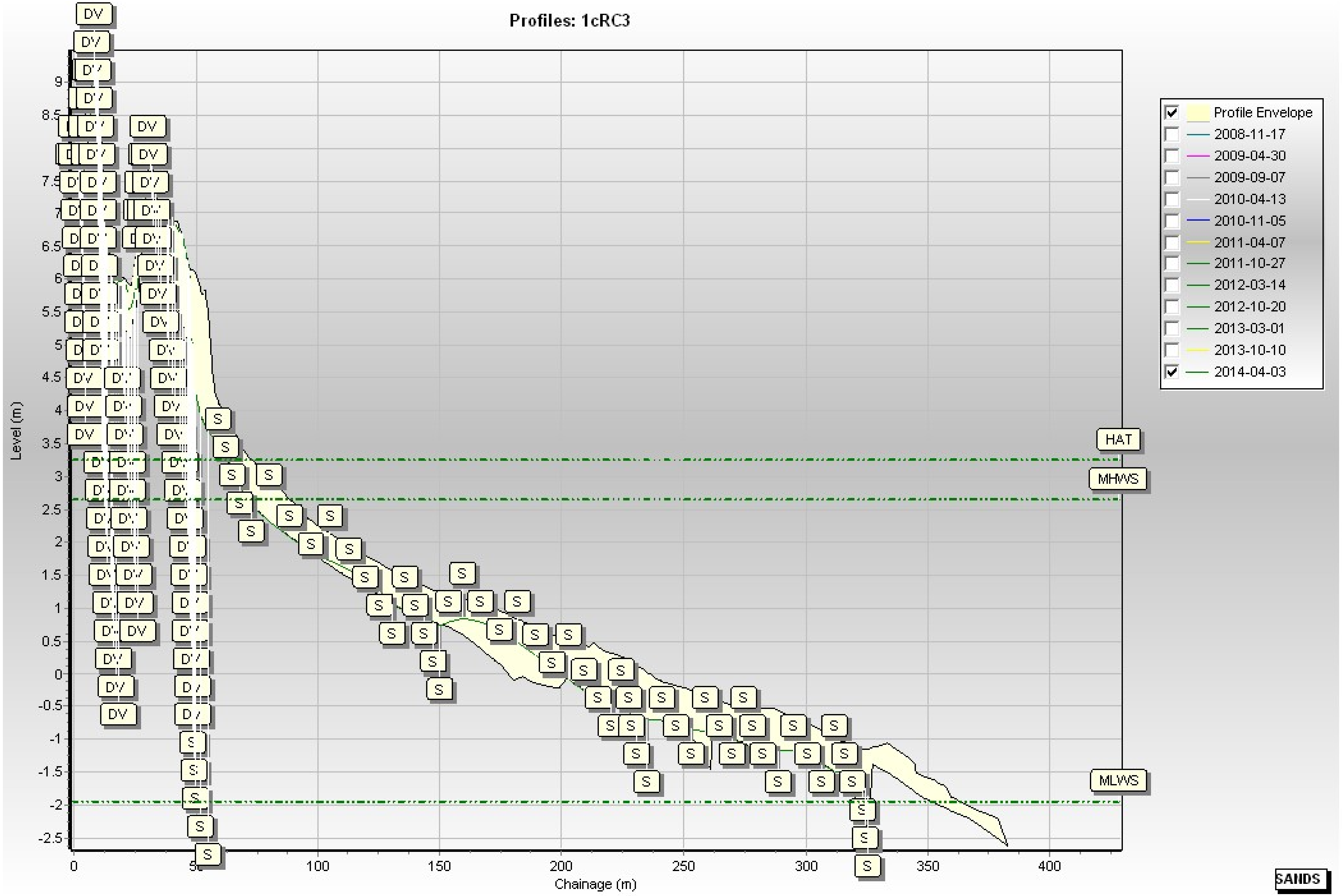
2011-04-07
2011-10-27
2012-03-14
2012-10-20
2013-03-01
2013-10-10
2014-04-03
HAT
MHWS
MLWS
SANDS



Profiles: 1cRC3
Level (m)
Chainage (m)
Profile Envelope
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2009-04-30
2009-09-07
2010-04-13
2010-11-05
2011-04-07
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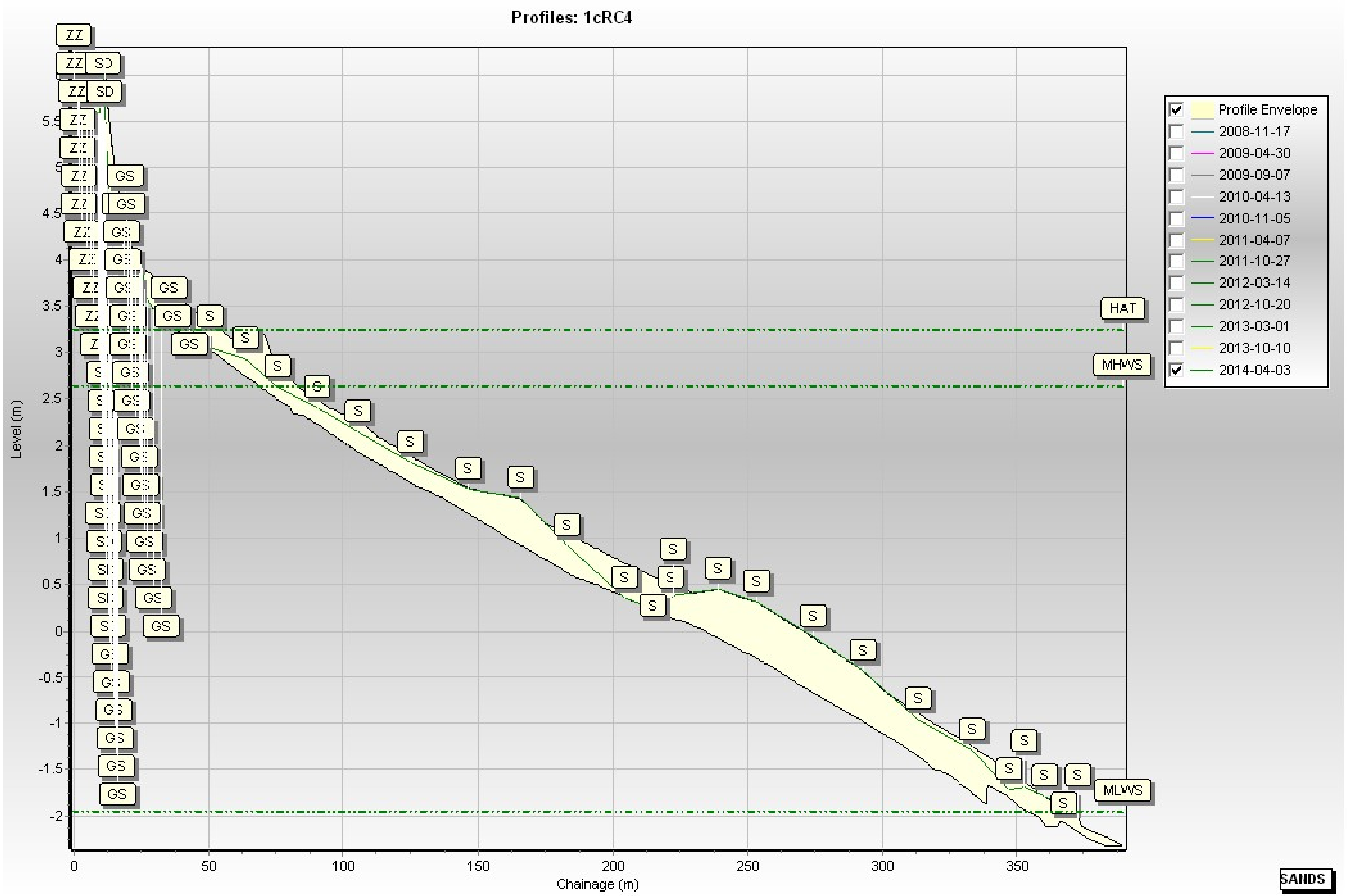
2012-10-20
2013-03-01
2013-10-10
2014-04-03
HAT
MHWS
MLWS
SANDS



Profiles: 1cRC4
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Chainage (m)
Profile Envelope
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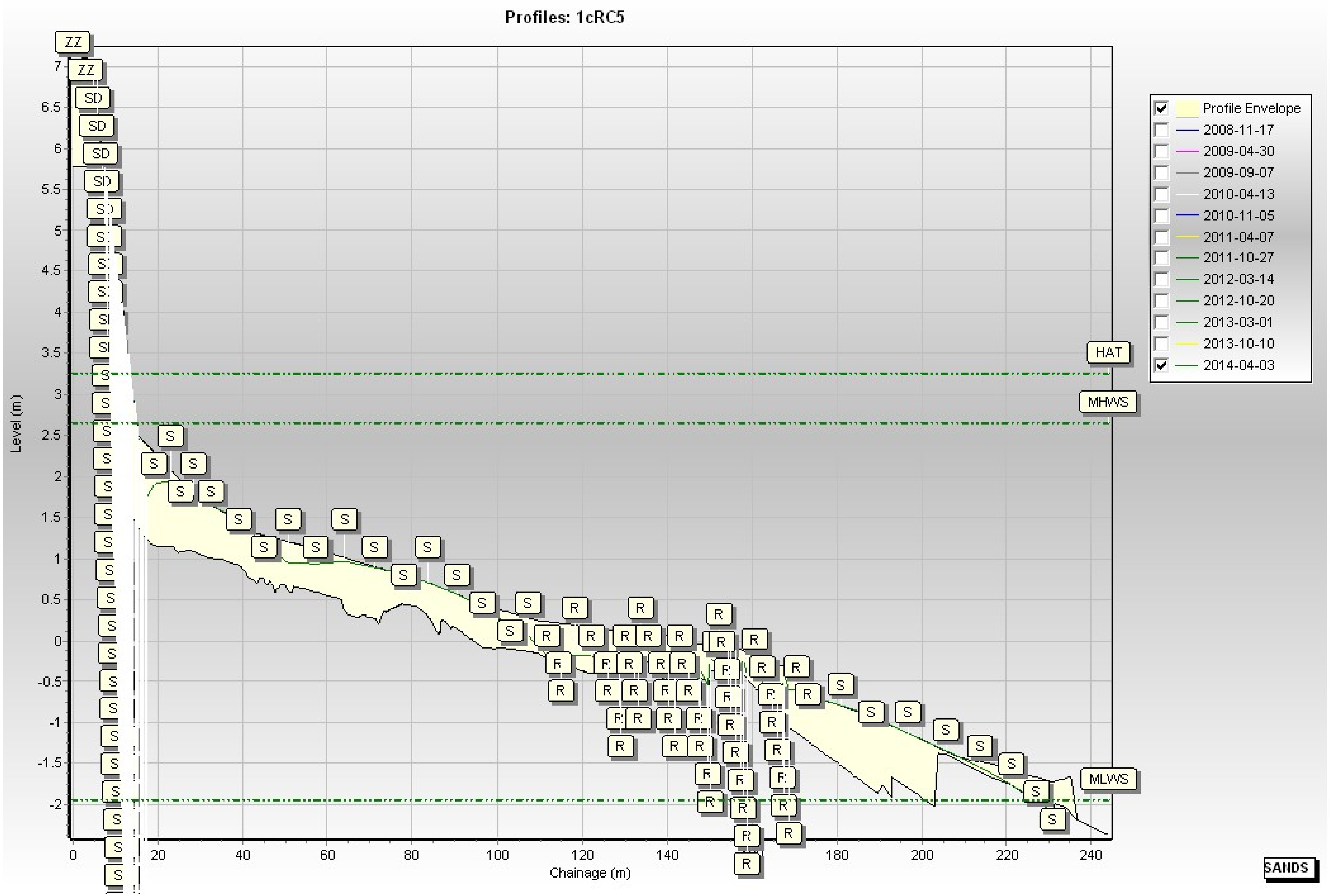
2009-04-30
2009-09-07
2010-04-13
2010-11-05
2011-04-07
2011-10-27
2012-03-14
2012-10-20
2013-03-01
2013-10-10
2014-04-03
HAT
MHWS
MLWS
SANDS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Level (m)
Chainage (m)
Profile Envelope
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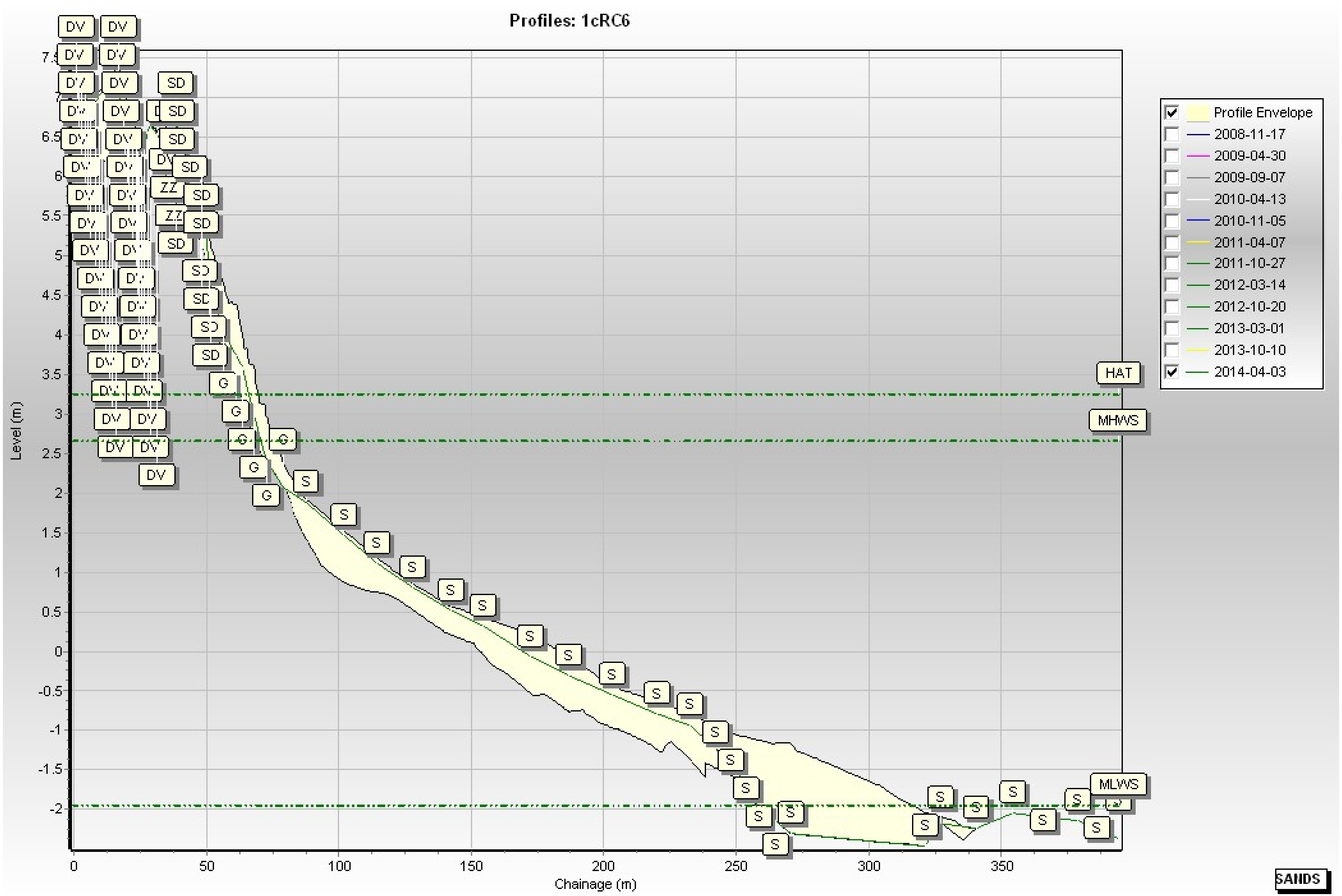
2009-04-30
2009-09-07
2010-04-13
2010-11-05
2011-04-07
2011-10-27
2012-03-14
2012-10-20
2013-03-01
2013-10-10
2014-04-03
HAT
MHWS
MLWS
ZZ
SD
S
R
SANDS



Profiles: 1cRC6
Level (m)
Chainage (m)
Profile Envelope
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2009-04-30
2009-09-07
2010-04-13
2010-11-05
2011-04-07
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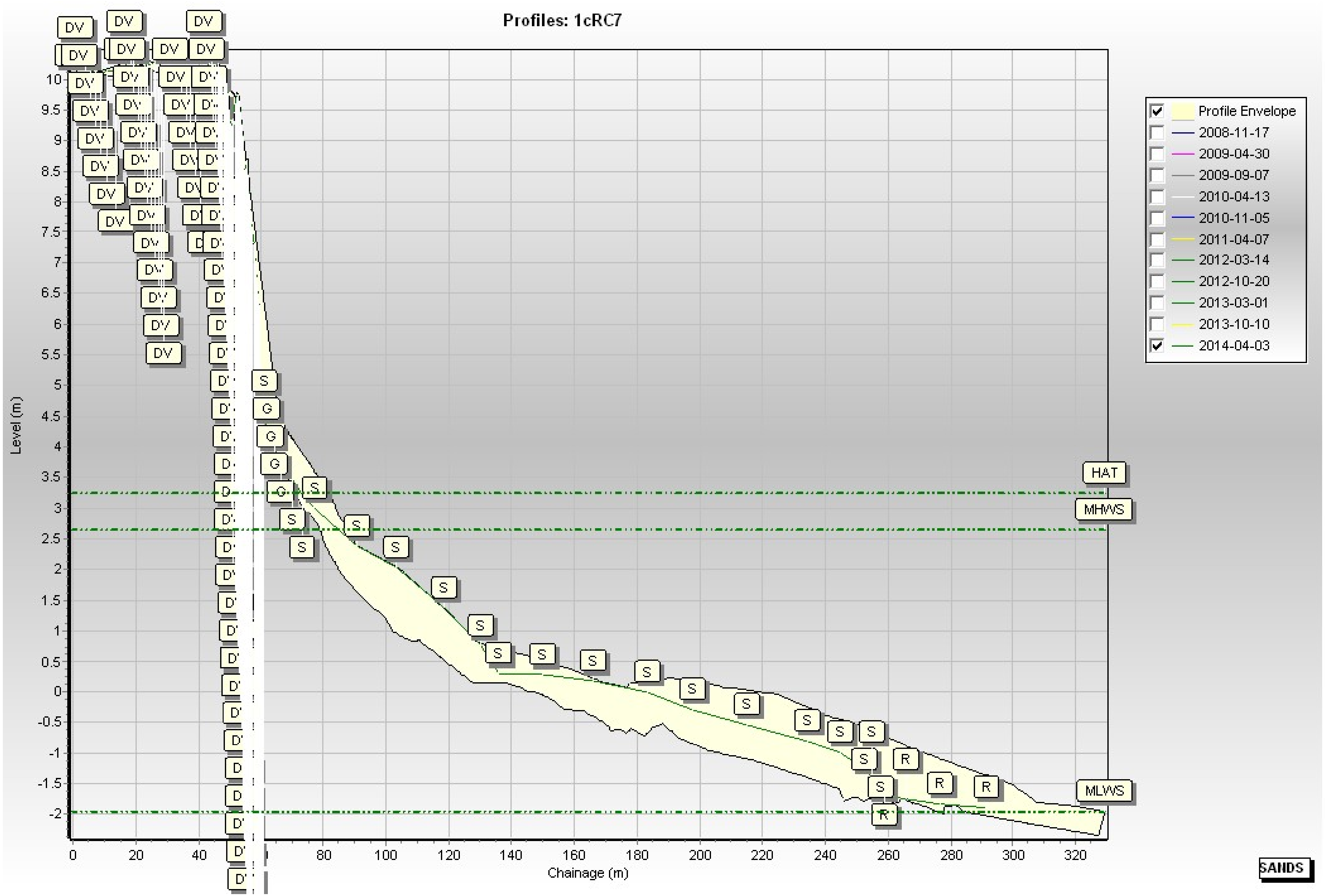
2014-04-03
HAT
MHWS
MLWS
SANDS



Profiles: 1cRC7
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Chainage (m)
Profile Envelope
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2009-04-30
2009-09-07
2010-04-13
2010-11-05
2011-04-07
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2012-10-20
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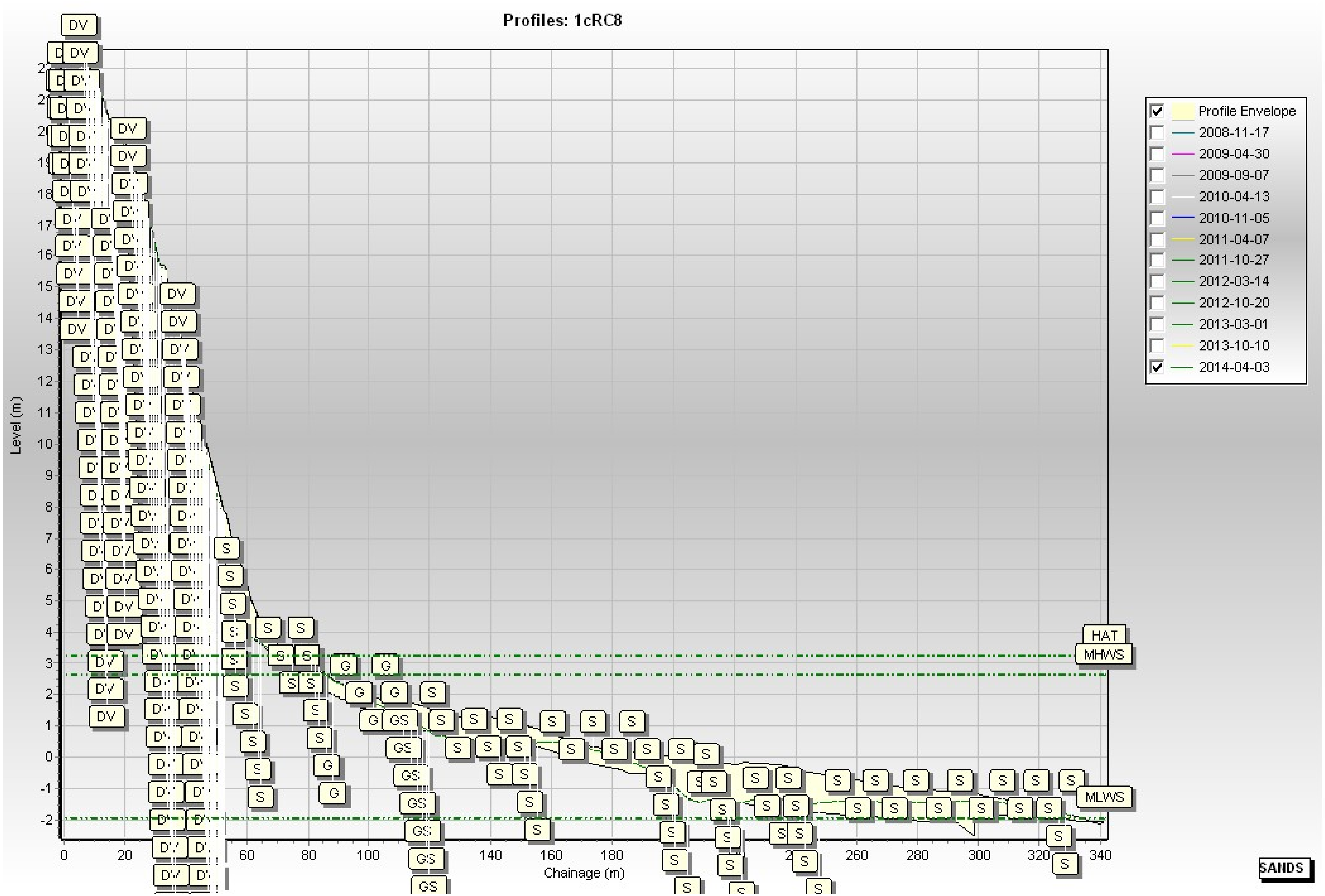
2013-10-10
2014-04-03
HAT
MHWS
MLWS
SANDS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2010-04-13
2010-11-05
2011-04-07
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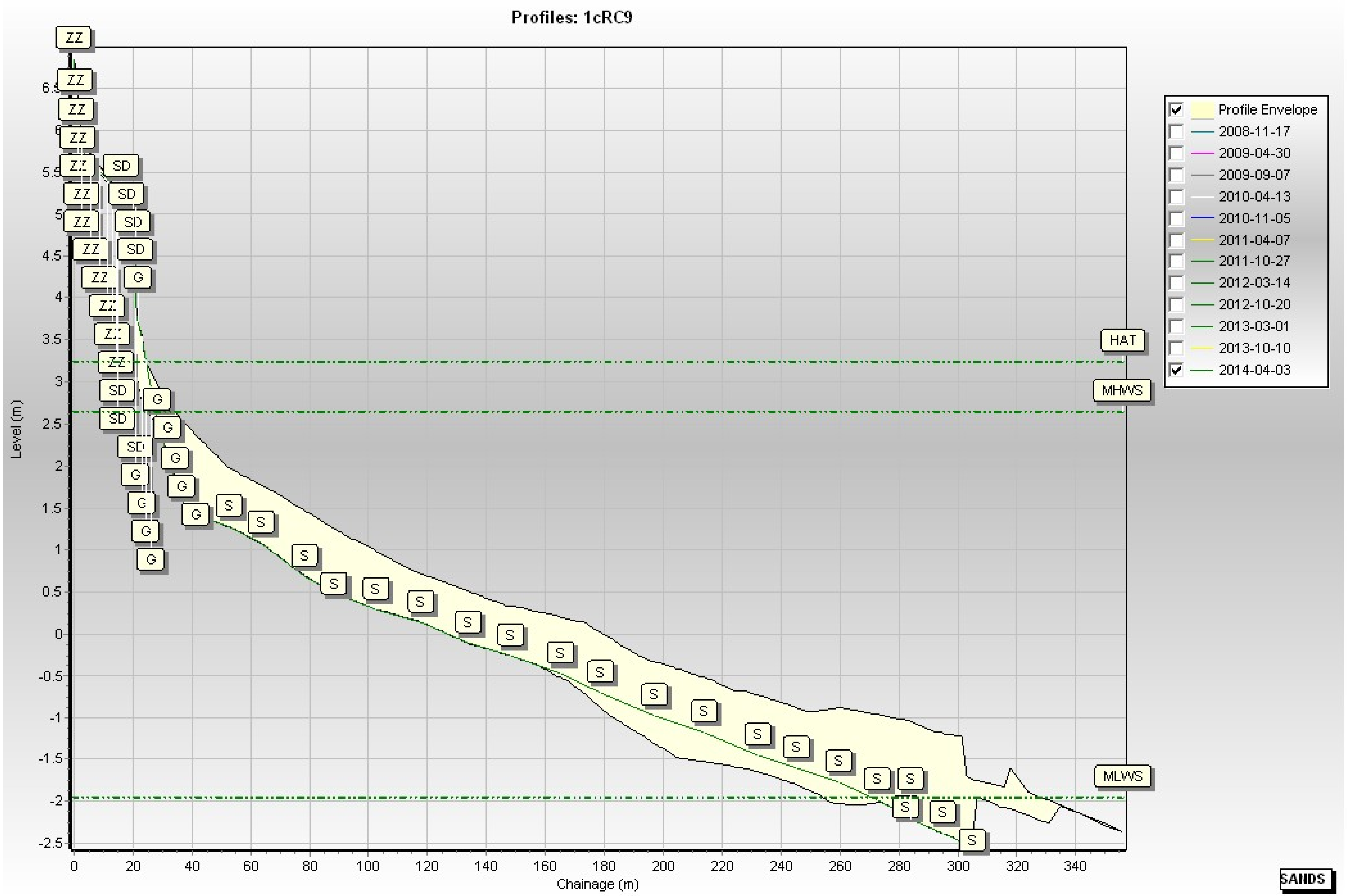
2014-04-03
HAT
MHWS
MLWS
SANDS



Profiles: 1cRC9
Level (m)
Chainage (m)
Profile Envelope
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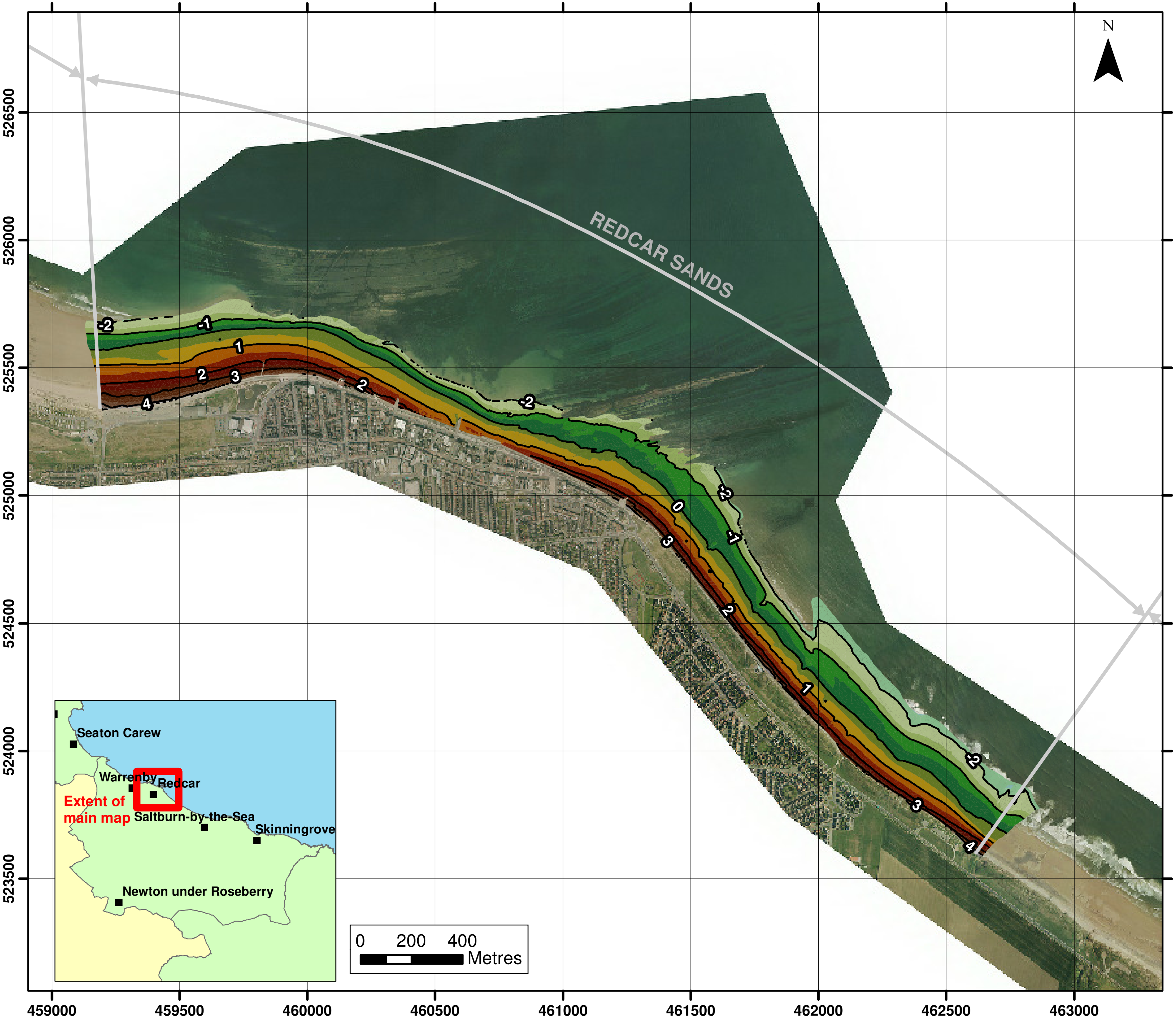
2009-04-30
2009-09-07
2010-04-13
2010-11-05
2011-04-07
2011-10-27
2012-03-14
2012-10-20
2013-03-01
2013-10-10
2014-04-03
HAT
MHWS
MLWS
SANDS

Appendix B

Topographic Survey



KEY

Elevation (m OD)

- 5.5 - 6
- 5 - 5.5
- 4.5 - 5
- 4 - 4.5
- 3.5 - 4
- 3 - 3.5
- 2.5 - 3
- 2 - 2.5
- 1.5 - 2
- 1 - 1.5
- 0.5 - 1
- 0 - 0.5
- -0.5 - 0
- -1 - -0.5
- -1.5 - -1
- -2 - -1.5
- -2.5 - -2
- -3.0 - -2.5
- Contour 1m

Client: North East Coastal Group

Project: Cell 1 Regional Coastal Monitoring Programme 2011 to 2016

Appendix B - Map 1a
Topographic Survey
Redcar Sands
Redcar & Cleveland
Borough Council

Update Report 6
Partial Measures Survey
Spring 2014

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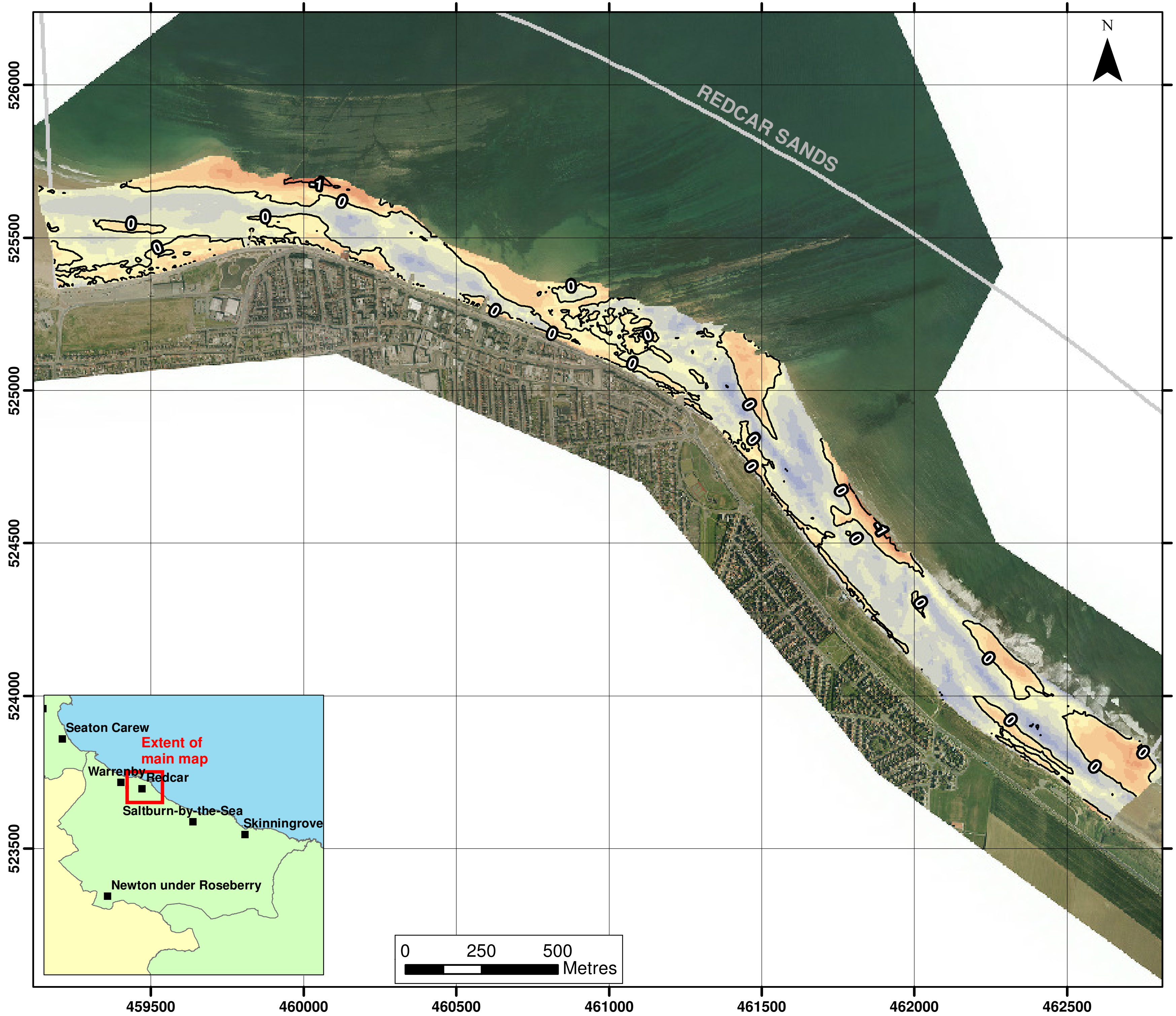

KEY Autumn 2013 and Spring 2014
Change in elevation (m)

- <-2
- -2 - -1.75
- -1.75 - -1.5
- -1.5- -1.25
- -1.25 - -1
- -1 - -0.75
- -0.75 - -0.5
- -0.5 - -0.25
- -0.25 - -0.1
- -0.1 - 0
- 0 - 0.1
- 0.1 - 0.25
- 0.25 - 0.5
- 0.5 - 0.75
- 0.75 - 1
- 1 - 1.25
- 1.25 - 1.5
- 1.5 - 1.75
- 1.75 - 2
- >2

Loss

Change < 0.1 m

Gain

Contours of change

Client: North East Coastal Group
Project: Cell 1 Regional Coastal Monitoring Programme 2011 to 2016

Appendix B- Map 1b
Short-term Elevation Change Redcar Sands Redcar & Cleveland Borough Council

Update Report 6
Partial Measures Survey
Spring 2014

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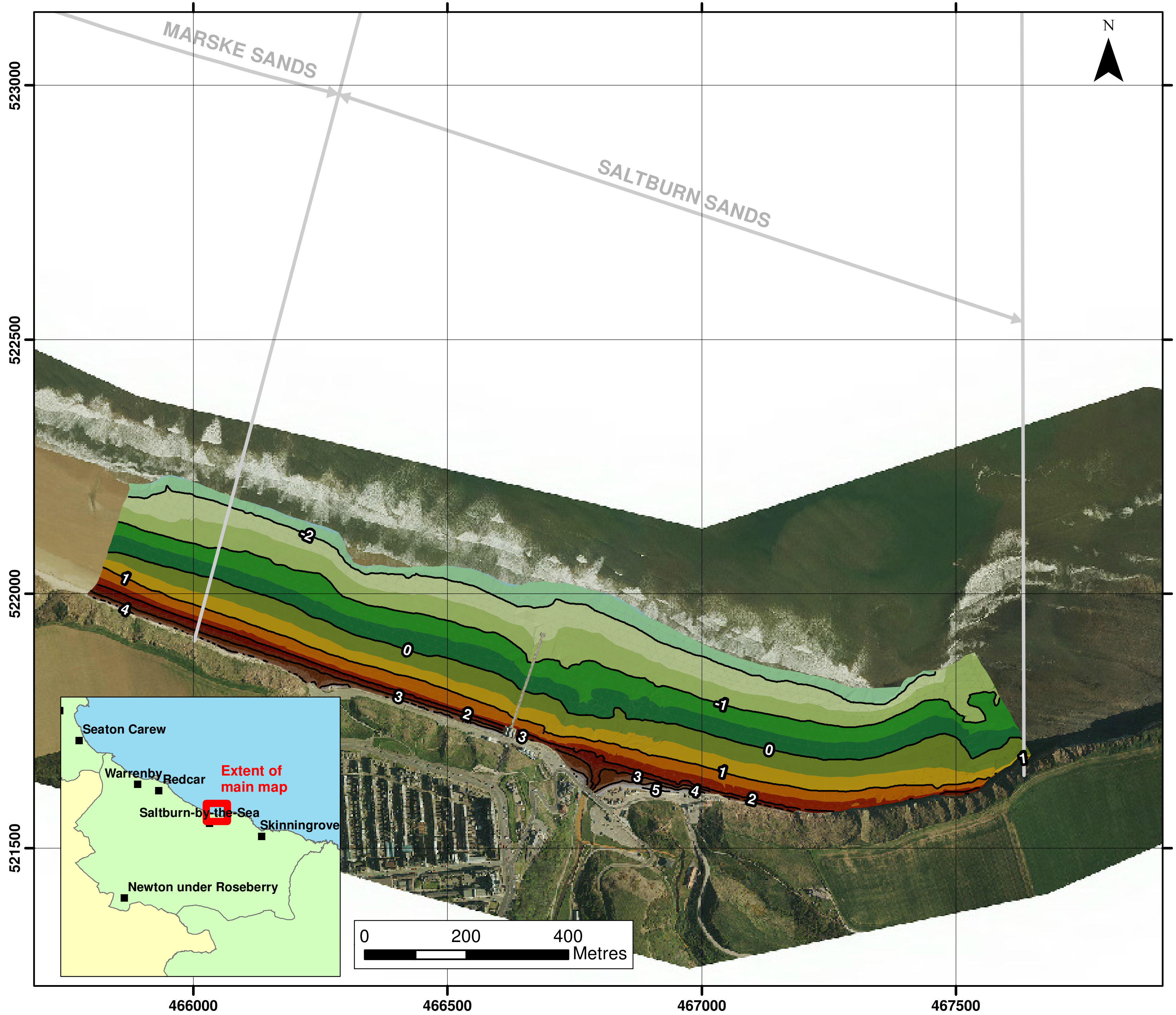

KEY

Elevation (m AOD)

- 5.5 - 6
- 5 - 5.5
- 4.5 - 5
- 4 - 4.5
- 3.5 - 4
- 3 - 3.5
- 2.5 - 3
- 2 - 2.5
- 1.5 - 2
- 1 - 1.5
- 0.5 - 1
- 0 - 0.5
- -0.5 - 0
- -1 - -0.5
- -1.5 - -1
- -2 - -1.5
- -2.5 - -2
- -3 - -2.5
- Contour 1m

Client: North East Coastal Group

Project: Cell 1 Regional Coastal Monitoring Programme 2011 to 2016

Appendix B - Map 2a
Topographic Survey
Saltburn Sands
Redcar & Cleveland
Borough Council

Update Report 6
Partial Measures Survey
Spring 2014

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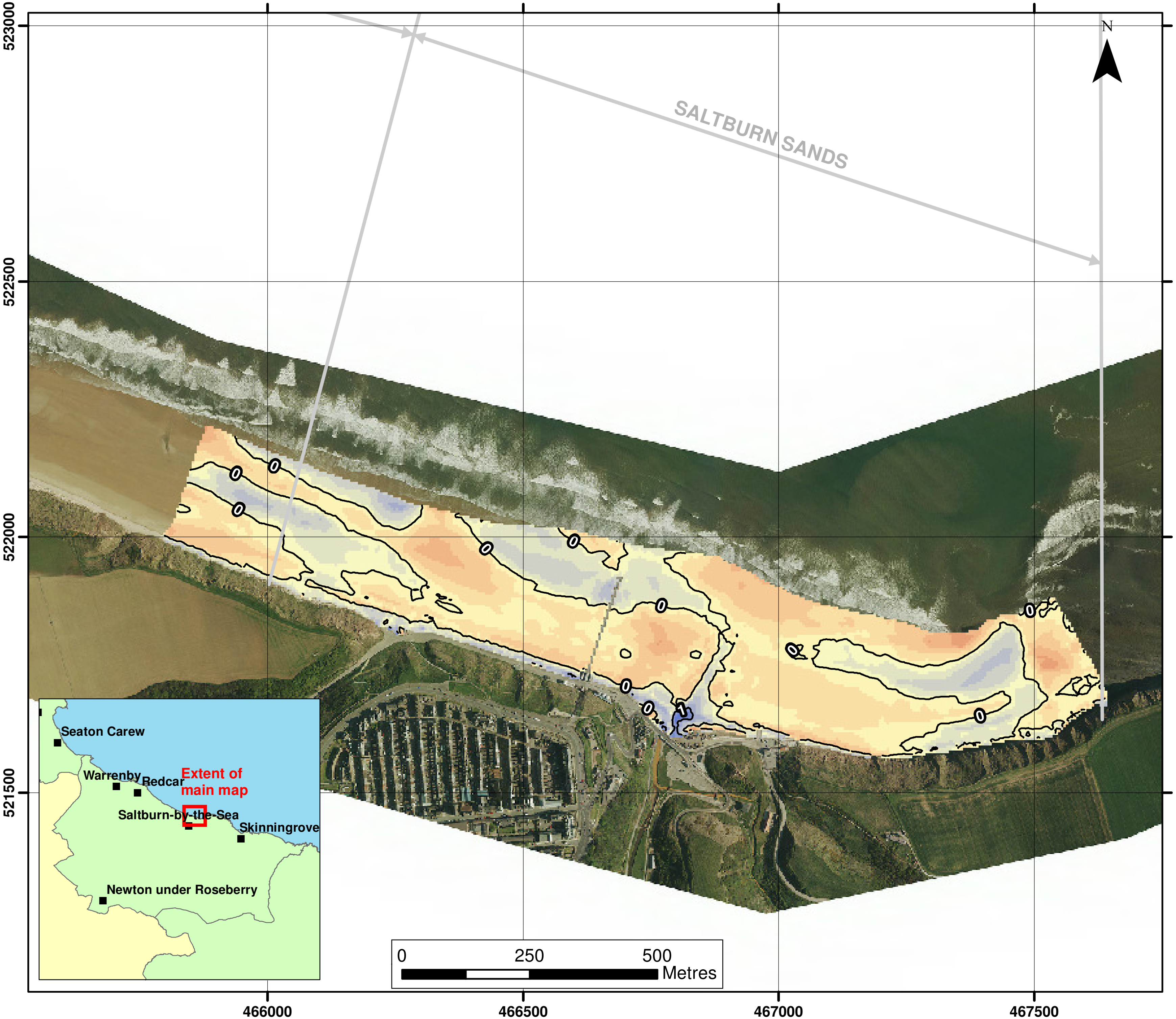

KEY Autumn 2013 and Spring 2014
Change in elevation (m)

Change in elevation (m)	
<-2	Loss
-2 - -1.75	
-1.75 - -1.5	
-1.5- -1.25	
-1.25 - -1	
-1 - -0.75	
-0.75 - -0.5	
-0.5 - -0.25	
-0.25 - -0.1	
-0.1 - 0	Change < 0.1 m
0 - 0.1	
0.1 - 0.25	Gain
0.25 - 0.5	
0.5 - 0.75	
0.75 - 1	
1 - 1.25	
1.25 - 1.5	
1.5 - 1.75	
1.75 - 2	
>2	

Contours of change

Client: North East Coastal Group
Project: Cell 1 Regional Coastal Monitoring Programme 2011 to 2016

Appendix B- Map 2b
Short-term Elevation Change Saltburn Sands Redcar & Cleveland Borough Council

Update Report 6
Partial Measures Survey
Spring 2014

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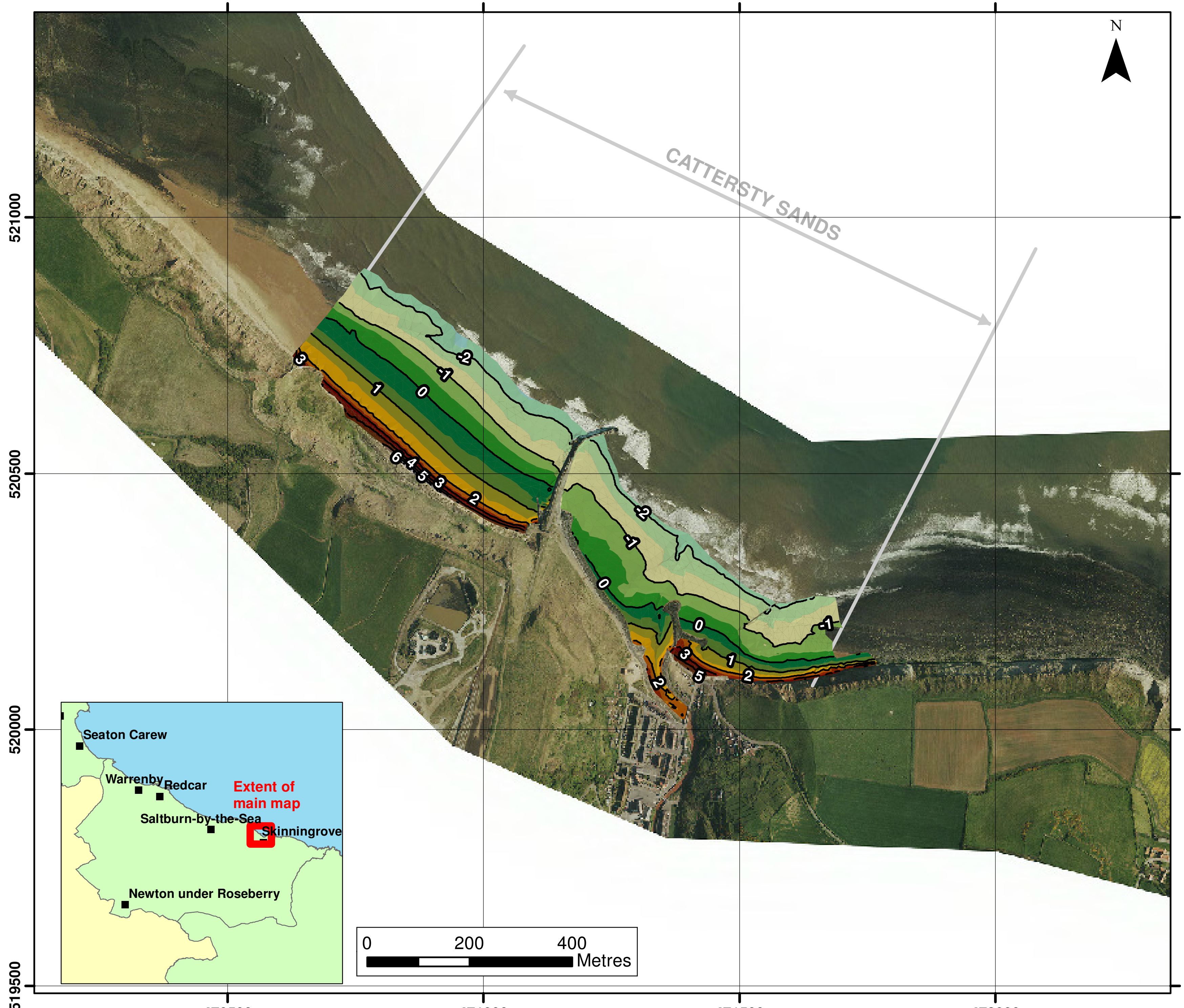

KEY

Elevation (m AOD)

- 7.5 - 8
- 7 - 7.5
- 6.5 - 7
- 6 - 6.5
- 5.5 - 6
- 5 - 5.5
- 4.5 - 5
- 4 - 4.5
- 3.5 - 4
- 3 - 3.5
- 2.5 - 3
- 2 - 2.5
- 1.5 - 2
- 1 - 1.5
- 0.5 - 1
- 0 - 0.5
- -0.5 - 0
- -1 - -0.5
- -1.5 - -1
- -2 - -1.5
- -2.5 - -2
- -3 - -2.5
- Contour 1m

Client: North East Coastal Group

Project: Cell 1 Regional Coastal Monitoring Programme 2011 to 2016

Appendix B- Map 3a
Topographic Survey
Cattersty Sands
Redcar & Cleveland
Borough Council

Update Report 6
Partial Measures Survey
Spring 2014

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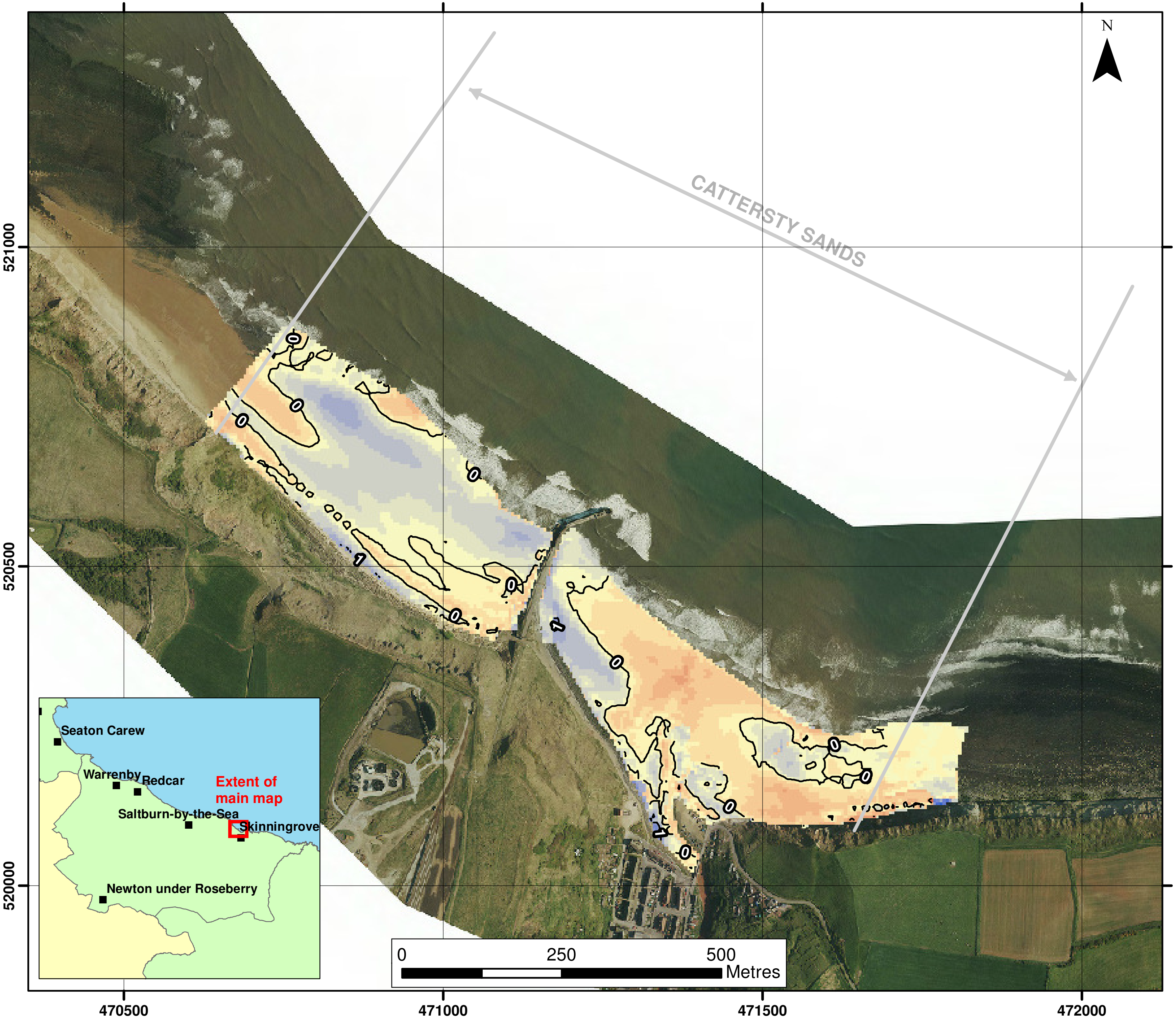

KEY Autumn 13 and Spring 14
Change in elevation (m)

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- -2 - -1.75
- -1.75 - -1.5
- -1.5- -1.25
- -1.25 - -1
- -1 - -0.75
- -0.75 - -0.5
- -0.5 - -0.25
- -0.25 - -0.1
- -0.1 - 0
- 0 - 0.1
- 0.1 - 0.25
- 0.25 - 0.5
- 0.5 - 0.75
- 0.75 - 1
- 1 - 1.25
- 1.25 - 1.5
- 1.5 - 1.75
- 1.75 - 2
- >2

Loss
Change < 0.1 m
Gain

Contours of change

Client: North East Coastal Group
Project: Cell 1 Regional Coastal Monitoring Programme 2011 to 2016

Appendix B - Map 3b Short-term Elevation Change Cattersty Sands Redcar & Cleveland Borough Council

Update Report 6
Partial Measures Survey
Spring 2014

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Appendix C

Cliff Top Survey

Cliff Top Survey

Staithes

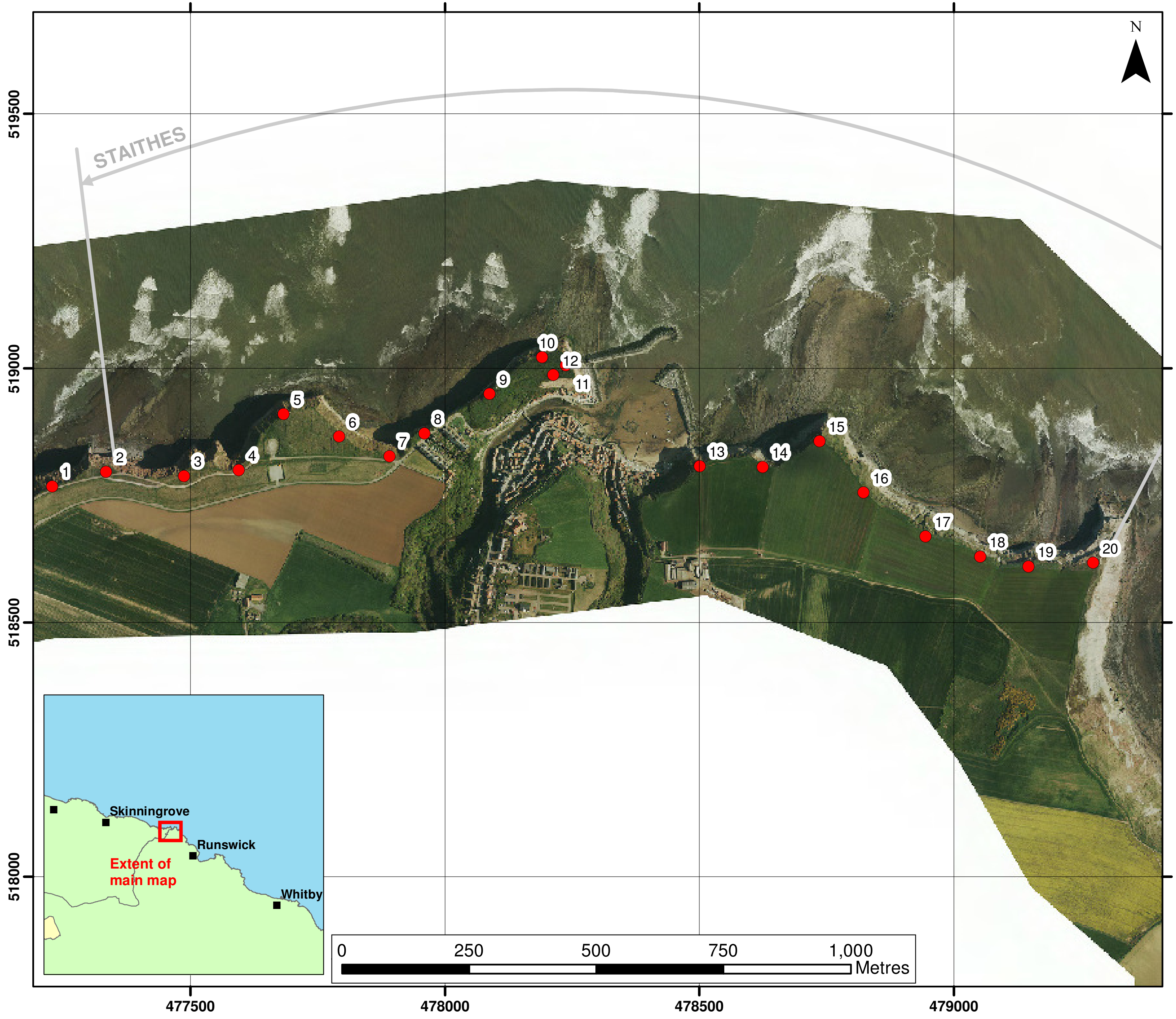
Twenty ground control points have been established at Staithes (Figure C1). The maximum separation between any two points varies along the coast, reflecting the degree of risk from the erosion.

The cliff top surveys at Staithes are undertaken bi-annually. Measurements are taken from a fixed ground control point along a fixed bearing to the edge of the cliff top.

Table C1 provides baseline information about these ground control points and results from the November 2008 (baseline) survey showing the position from the ground control point to the edge of the cliff top along the defined bearing. Future reports will show results from subsequent surveys and provide a means of assessing erosion since the baseline survey.

Table C1 – Cliff Top Surveys at Staithes

Ground Control Point Details				Distance to Cliff Top (m)			Total Erosion (m)		Erosion Rate (m/year)
Ref	Easting	Northing	Bearing (º)	Baseline Survey (Nov 2008)	Previous Survey (Oct 2013)	Present Survey (April 2014)	Baseline (Nov 2008) to Present (April 2014)	Previous (Oct 2013) to Present (April 2014)	Baseline (Nov 2008) to Present (April 2014)
1	477228	518769	320	1.9	1.7	1.7	-0.2	0.0	0.0
2	477334	518798	0	10.9	10.8	10.9	-0.1	0.1	0.0
3	477487	518789	350	7.1	8.5	8.4	1.3	-0.1	0.2
4	477594	518801	340	5.9	5.2	5.1	-0.8	0.0	-0.1
5	477683	518911	350	8.4	8.9	9.4	1.0	0.5	0.2
6	477792	518867	30	8.6	8.5	8.6	0.0	0.0	0.0
7	477891	518828	60	7.7	7.5	7.5	-0.2	0.0	0.0
8	477959	518873	350	8.7	9.9	9.9	1.2	0.0	0.2
9	478088	518950	350	7.6	8.3	8.3	0.7	0.0	0.1
10	478191	519023	340	8.4	8.8	8.8	0.4	0.0	0.1
11	478237	519007	60	6.9	6.7	6.8	-0.2	0.0	0.0
12	478213	518988	150	6.1	6.2	6.7	0.6	0.5	0.1
13	478501	518809	15	11.4	9.2	9.2	-2.2	0.1	-0.4
14	478624	518807	20	7.5	7.5	7.5	0.0	0.0	0.0
15	478737	518858	60	6.1	6.4	6.5	0.4	0.0	0.1
16	478823	518757	60	8	9.3	9.2	1.2	0.0	0.2
17	478944	518671	30	9.3	9.4	9.4	0.1	0.0	0.0
18	479052	518630	20	9.2	9.4	9.4	0.2	0.0	0.0
19	479147	518610	0	14.2	14.4	14.4	0.2	0.0	0.0
20	479274	518618	20	11.4	11.4	11.4	0.0	0.0	0.0



KEY

● Ground Control Points

Client: North East Coastal Group

Project: Cell 1 Regional Coastal Monitoring Programme 2011 to 2016

Appendix C - Map 1
Ground Control Points
Staithes
Redcar & Cleveland Borough Council

Update Report 6
Partial Measures Survey
Spring 2014

CH2MHILL
Halcrow

Halcrow Group Ltd, Lyndon House, 62 Hagley Road, Edgbaston, Birmingham, B16 8PE

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Photography courtesy of North East Coastal Observatory
www.northeastcoastalobservatory.org.uk

Appendix D

Durham University Laser Scans of Cowbar Nab

COWBAR COASTAL CLIFF MONITORING
STAITHES, N. YORKSHIRE

April 2014

Dr N Rosser

University of Durham

Prepared for and on behalf of:

Redcar and Cleveland Borough Council

c/o Steve Dunning

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1. CONTEXT

- This report summarizes the Year 3 results from an ongoing monitoring program at Cowbar Nab, Staithes, North Yorkshire.
- The monthly monitoring program began in January 2011, and aims to build up a high resolution dataset on cliff face erosion.
- This report considers the results of the study up until March 2014.
- This report establishes the rate of erosion using the best attainable data, and uses this to highlight features observed in the nature of erosion as and when they arise.
- The monitoring program is being undertaken for and on behalf of Redcar and Cleveland Borough Council.

2. EXECUTIVE SUMMARY

The following tasks have been completed as part of this project in Year 3:

- Monthly high-resolution terrestrial laser scans of the cliff at Cowbar Nab have been undertaken, ongoing since January 2011, from a single position on the foreshore during low tides. Twelve (12) approximately monthly surveys were conducted during this period when tidal conditions allowed.

- Constant monitoring of the site is undertaken using a 3-axis seismometer, and a cliff face environmental monitoring system, allowing environment conditions and the timing of failure to be identified to explain the erosion data presented herein.

- The instrumentation is complemented by an innovative permanent terrestrial laser scanning system to observed changes to the cliff on a daily basis to locate rockfall on a day-to-day timescale. The installation of this equipment is now subject to removal upon request of the landowner.

The following data have been calculated for Year 3:

- A total volume of 460.53 m^3 in 4,815 discrete rockfall events occurred during this period.

- **The area averaged rate of retreat observed in the period March 2013 – March 2014 was 0.519 x 10^{-3} myr^{-1}**.

- **The modeled rate of retreat in the period March 2013 and March 2014 was 0.804 x 10^{-3} myr^{-1}**.

- The lowest monthly volume of rockfall was observed in October 2013 (0.284 m^3).

- The highest monthly volume of rockfall occurred in April 2013 (366.760 m^3).

- The maximum depth (relative to the cliff face) of any single rockfall observed on the cliff face during this period was 2.80 m, which occurred 6.7 m above the cliff toe above a previously undercut section.

- A notable rockfall sequence occurred during the early months of this monitoring period, contiguous with an area of previous failure. In total, this area lost 325.52 m^3 during this monitoring period (equivalent to a cube of dimensions 6.879 m, and 70.68 % of the total rock volume lost during this year). Note that some of the 'event' was captured in the Year 2 report.

- In response to the occurrence of this event, the monitoring frequency was increased to weekly intervals for a period of 4 weeks to mid-May, and then reduced after analysis of this data showed a reduction in the rate of rock loss from this section of the cliff face. Whilst there is no evidence in the monitoring data of the development of a deeper-seated failure, which would threaten the road and / or houses, the area that has experienced the largest rockfall beneath Cowbar Lane has undergone a sequence of change since the start of monitoring, and this is likely to continue. The general trajectory of the development of this failure is up- and across-cliff. The cliff profile in this location is overhanging. Failure depths up to 2.8 m upon this near-vertical cliff have been observed. As this area develops it is likely that failures will continue to this depth and magnitude.

- More widely, failure has been concentrated upon the rock cliff face itself, and no discernable change in the position of the cliff line above was observed during this period.

- Considerable month-on-month variability was observed (standard deviation in monthly total rockfall volumes = 103.9 m^3), with some months (October 2013) showing almost no discernible change.

- The spatial pattern of erosion is commensurate with marine driven erosion at the toe of the cliff, in addition to the continued failure of previously active areas of the cliff expanding. Work on the nature of this process, included outputs from monitoring at Cowbar has been published in Rosser et al., 2013.

- Propagation of existing failure scars, both vertically and laterally, is observed, and such features are likely to continue to develop in this manner in the future. We note that failures from previous years now coalesce, identifying areas of potential future failure.

- The widely jointed sandstone close to the crest of the cliff remains relatively intact compared to the shales and limestone beneath. Failure of the sandstone is likely to be less frequent but of larger magnitude, based upon our observations, which may lead to retreat of the cliff line.

- We observe minimal rockfall directly above the section of rock armor.

In comparison to Year 2, we observe:

- **Area average erosion rates was 37% of that in Year 2.** This decrease is significantly influenced by both the single rockfall reported above, in addition to an extended period of relative quiescence in rockfall activity since, in addition to overprint of interannual variability.

- **Modelled erosion rates show a 107% increase.** This increase represents interannual variability and accounts for the occurrence of the single rockfall reported above.

- The location of erosion in Year 3 is contiguous with areas of the cliff face that experienced erosion in Years 1 & 2, suggesting continued failure, propagation of rockfall scars and erosion of these areas during this most recent period.

The long-term (Year 1 to Year 3 end) erosion rates are as follows for the 39 months of monitoring at this site:

- **39 month area averaged erosion rate is 1.339 x 10^{-3} myr^{-1}.** This rate is based purely on the rockfalls we observe at site.

- **39 month modeled erosion rate is 1.293 x 10^{-3} myr^{-1}.** This rate considers the full range of possible rockfall sizes at this site, and will stabilize over time as a more complete range of event sizes is recorded. This approach overcomes the limitations of monitoring only a small area / non representative sample, during a limited time period (see: Barlow *et al.*, (2012) for methodology).

- Since the start of monitoring we observe a total of 906.542 m^3 of rockfall, sourced from 38,925 discrete rockfall events identified from monthly sequential monitoring. Note that the number of discrete areas of rockfall will reduce through time, as failure scars coalesce. Note also that figures provided in interim reports disaggregated volumes by weekly scan intervals, and so effectively double count volumes as compared to monthly scans.

- On average 1,156 discrete rockfall events occur at this site each month (in volumes > 2.5 x 10^{-4} m^3).

- The average monthly volume of rockfall is now 38.22 m^3, equating to 0.17 m^3 / month / m of coastline (equivalent to a cube of dimensions 0.55 m).

- The monthly volume of rockfall for this section of cliff remains on average lower than that observed elsewhere along this coastline (see: Rosser *et al.*, 2013), most likely due to the relatively low (< 30 m) cliff height. Retreat rates per unit area between this site and other monitored elsewhere on this coastline remain comparable in proportion to the cliff height / available rockfall source area.

The following conclusions have been drawn based upon our analysis of monitoring to date:

- There is no indication that the erosion of the cliff at Cowbar is accelerating or deviating away from behavior observed at this site previously. The reduction in rates of erosion reported here represents variability widely observed on such cliffs. This monitoring period demonstrates the possibility for larger-scale rockfall at this site.

- The rates of erosion observed at this site within each month are heavily influence by a low number (commonly < 3) of larger (> 1 m^3) rockfall. Where no such event occurs in any given month, the retreat rates are accordingly low. This year periods with no large events showed very low rates of averaged erosion.

- Continued analysis of the environment data shows limited correlation between environmental forcing and the erosion rates derived. The smallest events show some relationship; the largest events do not. The dominance of largest event on the mean erosion rates will continue to limited such correlation until a longer data set has been established, but in this monitoring period the contribution of the largest rockfall was countered by 8 months of relatively low rockfall activity.

- The concentration of erosion remains focused away from the 'pinch points' at this site, although a focus of activity is developing to the East of the rock armor. We also note that there were only a small number of rockfalls sourced on the section of cliff protected by the rock armour.

- No loss of cliff line was observed during this period, although critically this indicates cliff steepening via rockfall beneath, which will in time result in failure of the cliff top in future. We observe a sequence of larger failures, the development of which should be considered over the coming monitoring period.

- We will continue to refine the monitoring approach at the site, which in the forthcoming period will include real-time processing of the permanent scanning data, and a numerical analysis of the micro-seismic monitoring data.

3. MONITORING RESULTS

a. MONITORING RESULTS YEAR 3

- Table 1 summarizes the survey results from monitoring between January 2011 and March 2014, and reports the results from March 2013 to March 2014. Months since the beginning of the monitoring program (January 2011) are named 1, 2, 3 . . . to 39, with the corresponding date of the survey. The length of each survey epoch is calculated in days since the previous survey, and days since the first survey. For each month the total number of rockfalls and the cumulative total volume of rockfalls measured during this period are calculated, using the method described in previous reports.

- Total change between March 2013 and March 2014 is shown in Figure 1.

- Total change since the start of monitoring (January 2011) is show in Figure 2.

- The following erosion rates are calculated in two ways: (1) The total rockfall volume is averaged across the survey area. This is the conventional and widely used approach, but does not consider the limitations of small sample size, duration or survey area, and hence how representative the observations are of longer term behavior. (2) The modeling approach considers all possible rockfall sizes and overcomes the limitations of a small sample size and monitoring area, and therefore is considered to be more representative of long term behavior. We expect the area average and the modeled erosion rates to converge over time as a wider range of event sizes are included in the analysis.

- The total number of measured rockfalls between March 2013 and March 2014 was 4,815, with a total volume of 460.53 m^3. This equates to an area averaged erosion rate of **<u>0.519x 10^{-3} myr^{-1}</u>** over this period.

- The maximum monthly area averaged erosion rate was 4.979 x 10^{-3} myr^{-1} (April, 2013), and the minimum 0.004 x 10^{-3} myr^{-1} (October, 2013).

- The modelled erosion rate for this period is **<u>0.804 x 10^{-3} myr^{-1}</u>**, with a monthly maximum of 2.459 x 10^{-3} myr^{-1} (May 2013) and a minimum of 0.205 x 10^{-3} myr^{-1} (January, 2014). Note that in the modeling we assume a maximum event volume of 2,500 m^3, during a 100-year return period, which has not been exceeded to date.

- We highlight key features of the erosion observed between March 2013 and March 2014 in Figure 1, numbered (1) to (3), and discussed below:

- We observe several areas indicative of the continued development (failure) of rockfall scars that have previously experienced collapse (e.g. Figure 1 (1 – 3)). These are normally vertically and horizontally extensive (> 1 m), but in general shallow in depth relative to the cliff face (< 0.15 m), often associated with release along face-parallel joints or stress relief features.

- Several areas which underwent larger scale (> 1 m^3) failure in Years 1 & 2 continue to show quiescence, with minimal change on the now-exposed intact failure scar rock (e.g. area up and right of (1) in Figure 1). Whilst the fresh face of such areas remains unchanged, such features commonly are seen to extend laterally across the cliff (vertically and horizontally) albeit to a limited extent, as shown in the month by month expansion of rockfall scars (Figure 3).

- Clear evidence of marine driven toe-cut erosion via abrasion and wave hammer is visible (e.g. beneath (1) in Figure 1). This is shown in small-scale change (< *c.* 0.0001 m^3), concentrated in a zone < 2 m from the break in slope at the toe of the cliff. In certain locations, such as Figure 1(1), this abrasion is then seen to propagate vertically up the cliff, resulting in rockfall of a larger magnitude in volume.

- There is a minimal number of rockfall sourced from the section of cliff face directly above the rock armor, labelled in Figure 2, as opposed to those sections of cliff not protected by the rock armor (Figure 2(4)). Those rockfall which have occurred are relatively shallow in depth (< 0.25 m).

- Some change is observed in isolated patches on the surface of the glacial till cap at the top of the cliff. On the Eastern section of the monitored section (Figure 1 - left), much of this change is associated with vegetation growth, rather than mass movements.

- A new rockfall was noted during student fieldwork on the coast on 14th April 2013, triggering further more frequency monitoring and analysis. This data was collected after the submission of the first draft of the Year 2 report to RCBC, but was reported on in the interim due to the failure size. The key features were as follows:

  i. Approximately 27 m in cross-shore width, up to 17 m in height and up to 2.8 m in depth was released from the cliff between March 12th and April 14th (Figure 1(1), & Figures 4 – 6).

  ii. The rockfall occurred directly above an area which has been previously been observed to have experience marine undercutting, and was identified above as a potential location for future loss of material. The position of the rockfall relative to the location of Cowbar Lane is provided in Figure 7 for context.

  iii. The rockfall did not result in the loss of the cliff top at this location, although it is likely that this area will continue to fail, and rockfall scars will coalesce, in the future. The cliff is now undercut and retains a steeper angle and should be continued to be monitoring on a regular monthly basis. There is no visible evidence of a deterioration in the stability of the cliff above the location of this rockfall. Events (1) and (2) in Figure 2 have removed lateral and basal support for the rock mass above, which may in time increase the probability of failure of this section of the cliff. Failure depths to date have been up to 2.8 m, and it is likely that this magnitude of failure depth with continue.

iv. The initial volume of material lost during as a result of this rockfall was identified as 687.1 m^3. Further subsequent analysis revealed that this event multiple failures which span the 2012 – 2013 and this monitoring period as shown in Figure 3 and 6 which describe the evolution of this failure. The failure reported here was 325.5 m^3.

v. The period since this event has been quiet, with fewer rockfalls than have been observed in previous months. As a result the monitored erosion rate for years 1 – 3 is reduced as compared to that for years 1 – 2. The modelled rate is more stable as this accounts for the possibility of larger events such as this.

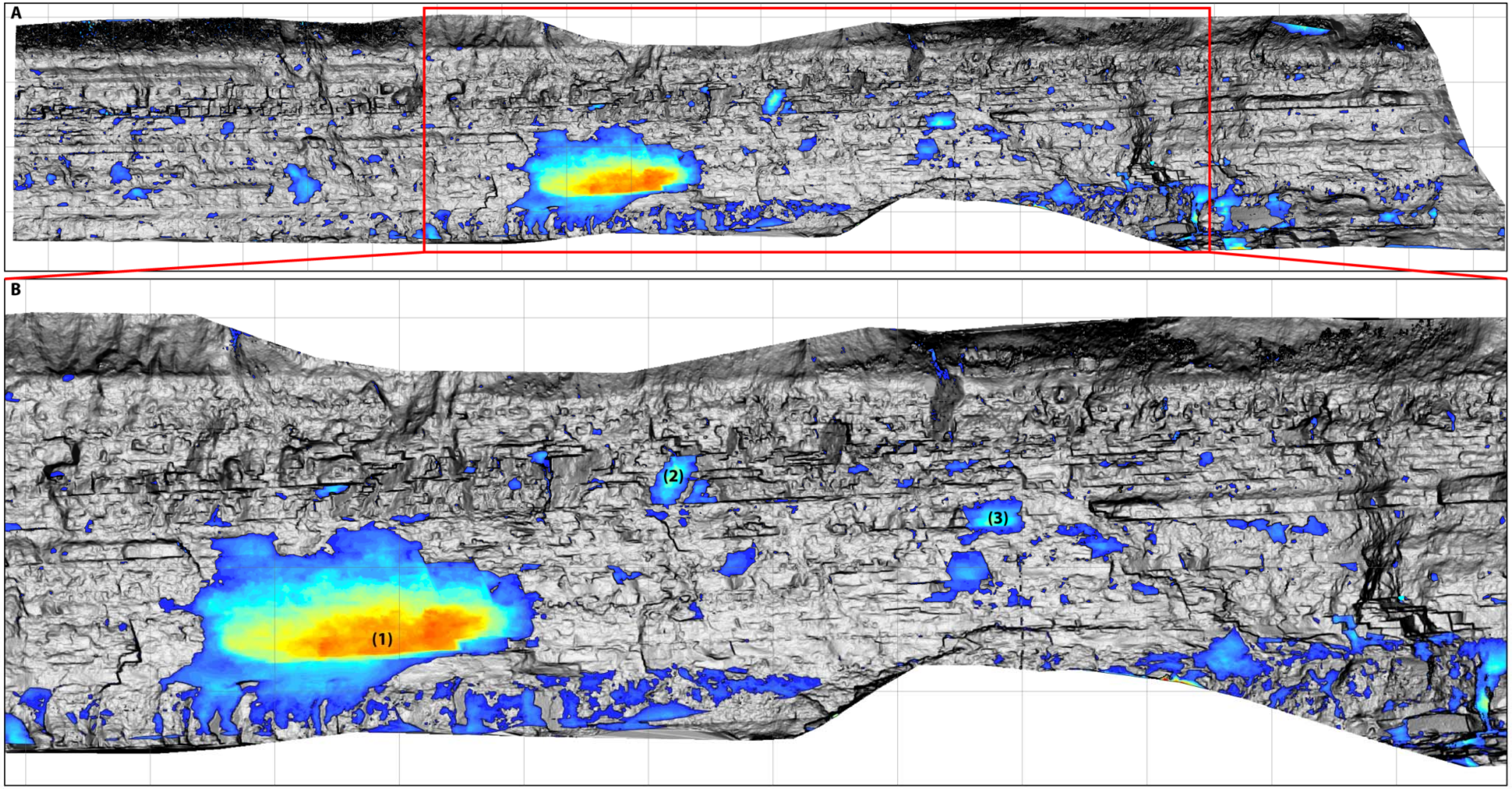

Figure 1. Monitoring erosion at Cowbar Nab between March 2013 and March 2014. **(A)** shows an elevation view of the rock cliff at Cowbar, displayed as if viewed from a point 100 m seaward from the cliff toe on the foreshore. The greyscale image is the slope of the cliff face, to provide indicative topography (hillshade), and the colours show erosion depth normal to the cliff face. Cold colours (blues) show erosion >= 0.1 m (the lower threshold of the change detection), and warm colours (orange to red) show erosion up to 3.5 m relative to the cliff face. The grid interval is 10 m in both horizontal and vertical axis. The red square delimits the extent of the area shown in B. **(B)** shows a close up view of the cliff directly beneath Cowbar Lane. The numerical labels are referred to in the body of the text.

Erosion depth
3.5 m
0.1 m

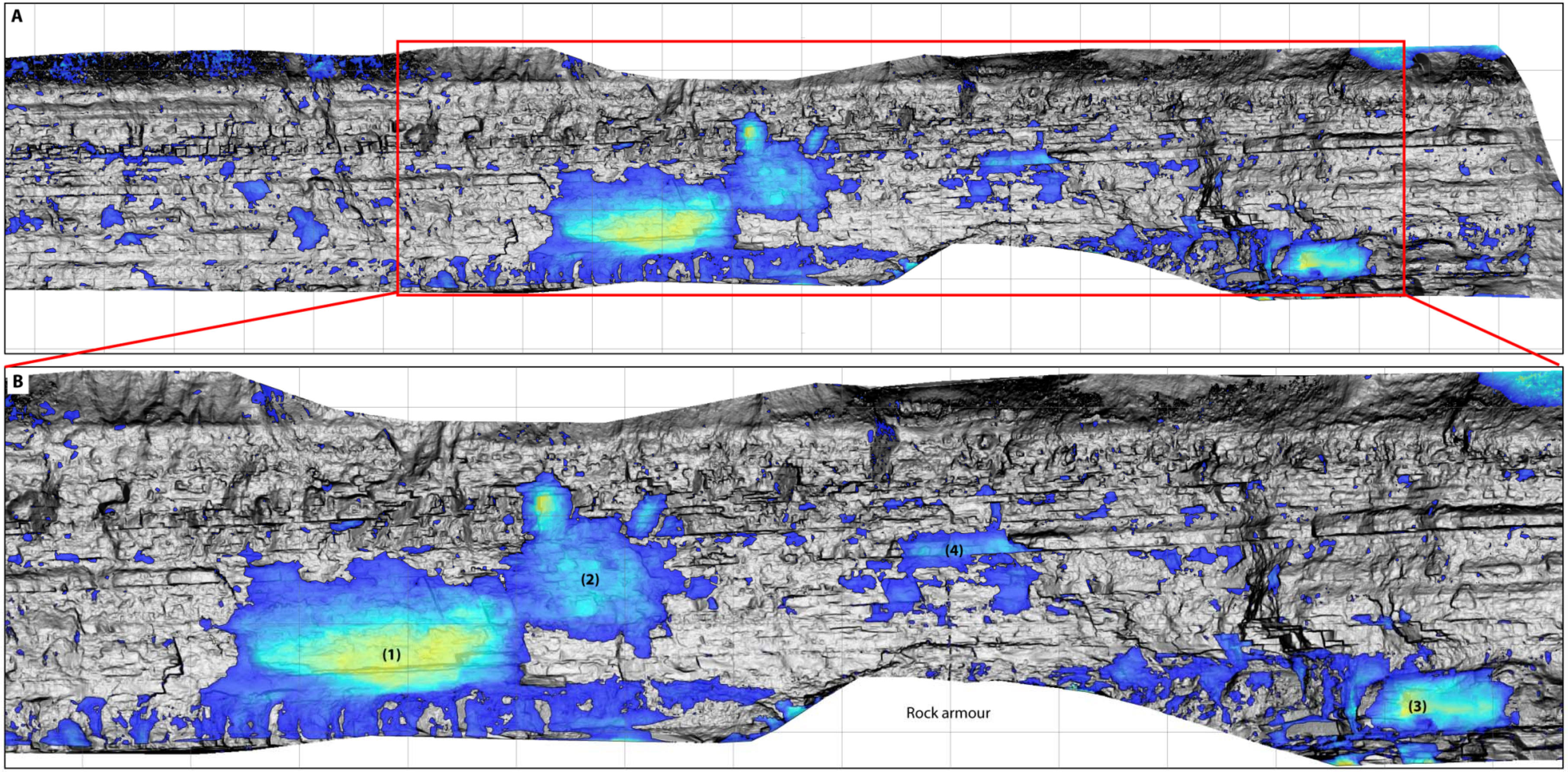

Figure 2. Monitoring erosion at Cowbar Nab between January 2011 and March 2014. **(A)** shows an elevation view of the rock cliff at Cowbar, displayed as if viewed from a point 100 m seaward from the cliff toe on the foreshore. The greyscale image is the slope of the cliff face, to provide indicative topography (hillshade), and the colours show erosion depth normal to the cliff face. Cold colours (blues) show erosion >= 0.1 m (the lower threshold of the change detection), and warm colours (orange to red) show erosion up to 3.5 m relative to the cliff face. The grid interval is 10 m in both horizontal and vertical axis. The red square delimits the extent of the srea shown in B. **(B)** shows a close up view of the cliff directly beneath Cowbar Lane. The numerical labels are referred to in the body of the text.

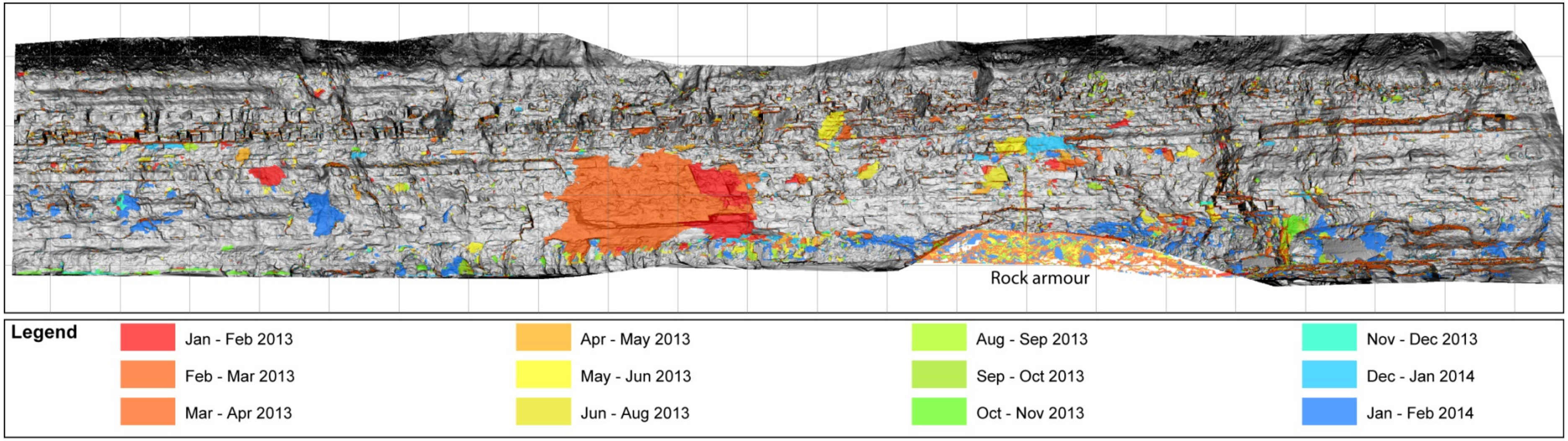

Figure 3. Monitoring erosion at Cowbar Nab between January 2013 and March 2014. The plot shows the the extent of recorded rockfalls for each month between January 2013 and the end of February 2014, each month with a unique colour. The grid interval is 10 m in both horizontal and vertical axis.

Figure 4: Photograph (14/04/13) showing the location and extent of the rockfall observed between 14th March and 14th April, with debris pile below. Note people for scale.

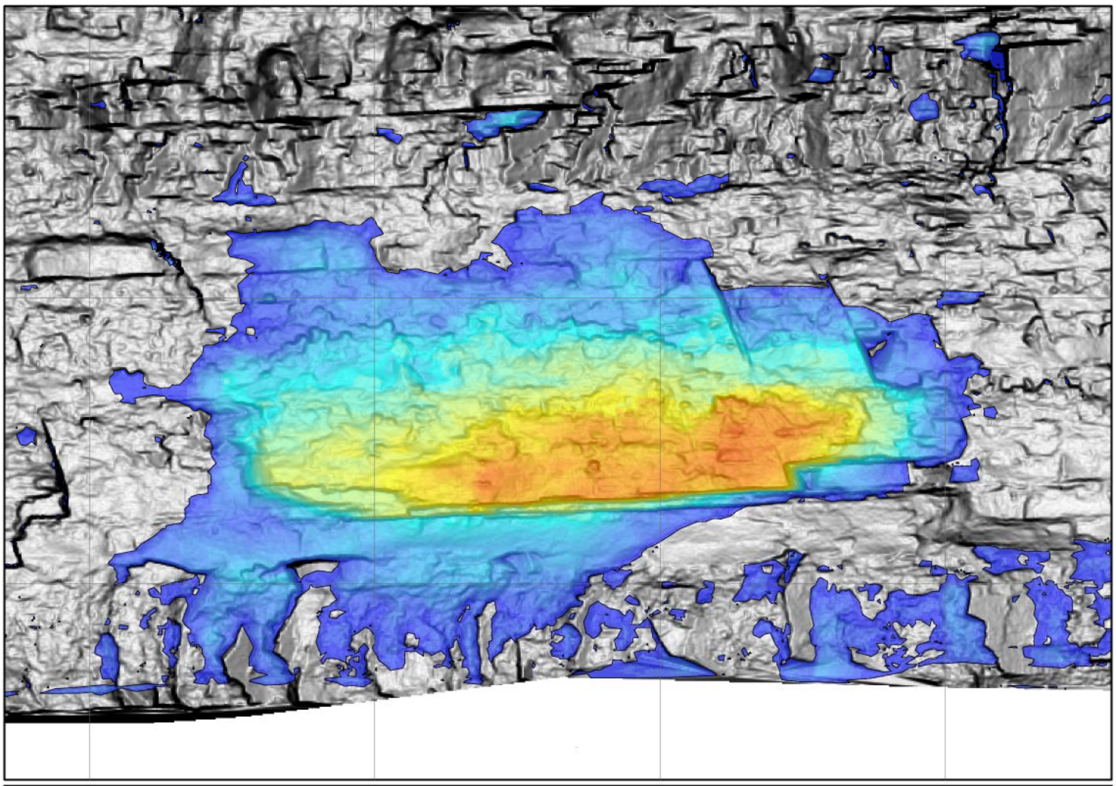

Figure 5: Close up view of rockfall scar recorded between March and April 2013. Image in greyscale shows hillshade for context of the slope topography. The warm colours show a greater depth of erosion, here up to 2.8 m, and cold colours (blues), show erosion greater than or equal to 0.1 m. Grid is 10 m interval in the horizontal and vertical axis.

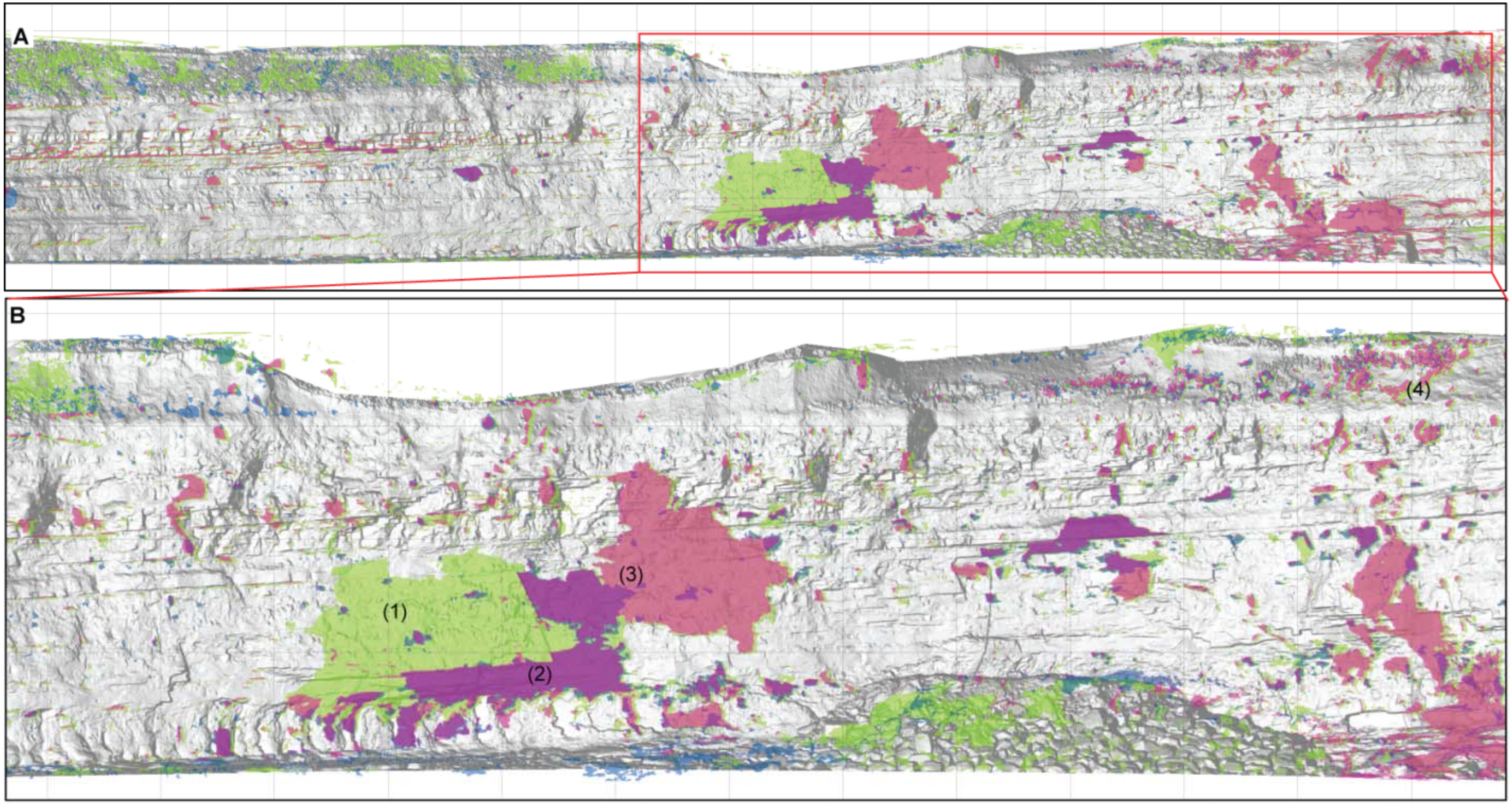

Figure 6. Areas of erosion > 0.1 m normal to the cliff face durign YEAR 1 (14th January 2011 and 26th March 2012) (BLUE), and during YEAR 2 (26th March 2012 and 12th March 2013) (RED), and during April 2013 (12th March to 25th April 2013) (GREEN). PURPLE areas change sections of the cliff face which changes in both Years 1 and 2. **(A)** shows elevation view of the rock cliff at Cowbar, as seen from a point 100 m seaward from the cliff toe on the foreshore. The grey-scale image gives indicative cliff face topography (hillshade). The grid interval is 10 m in bother horizontal and vertical axis. The red square delimits the extent of the section displayed in (B). **(B)** shows a close up view of the section of cliff directly beneath Cowbar Lane. Figure 7 gives the position of the rockfall shown above relative to Cowbar Lane.

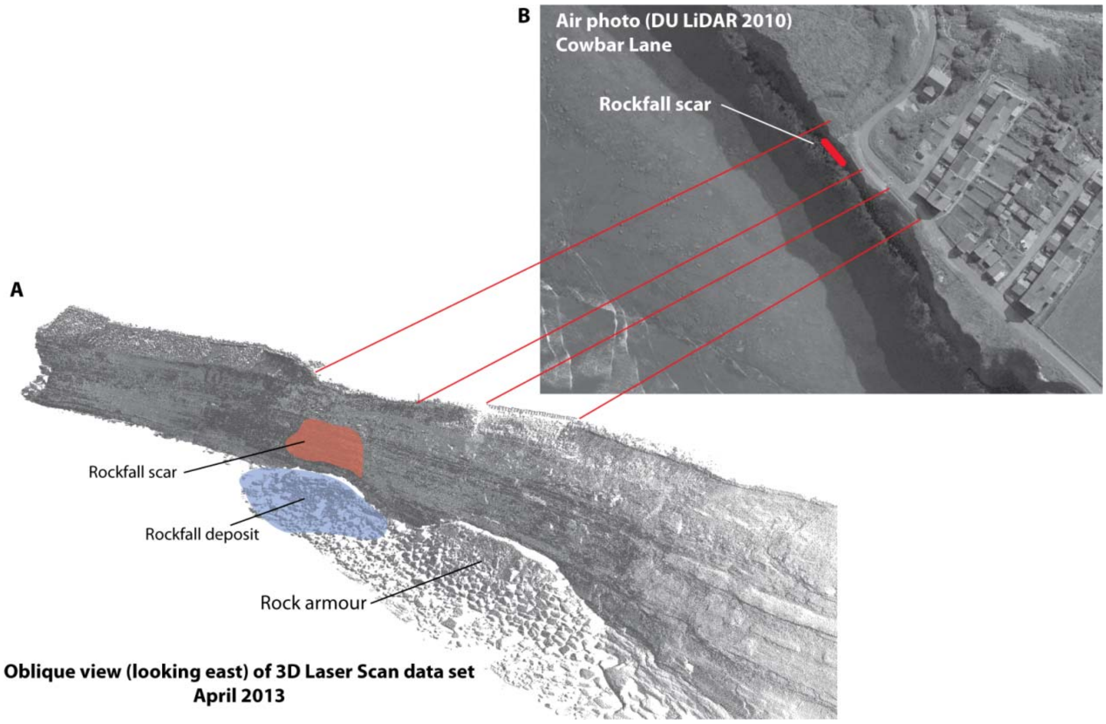

Figure 7. Location of the rockfall relative to Cowbar Lane. **(A)** shows a 3D point cloud collected from the terrestrial laser scanner, viewed obliquely. **(B)** Shows and air photo collected during a LiDAR survey in 2010.

b. Comparison of Years 2 to 3, and long-term erosion rates

- **Area average erosion rates in Year 3 have reduced to 37% during of the Year 2 rate.** This decrease is dominated by the single rockfall reported above, and the period of quiescence thereafter, in addition to the overprint of interannual variability.

- **Modeled erosion rates show a 136% increase during Year 3 and compared to Year 2.** This increase represents both interannual variability and the influence of the single rockfall event reported above, and the following period of relatively minimal erosion.

- With the exception of the rockfall event discussed above, the location of erosion in Year 3 is almost exclusively within the same areas of the cliff face that experience erosion in Years 1 & 2, suggesting continued failure and erosion of these areas.

- The long-term (Year 1 and to Year 3 end) erosion rates are as follows:

    - **39 month area averaged erosion rate is 1.339 x 10^{-3} myr^{-1}.** This rate is based purely on the rockfalls we observe at site.

    - **39 month modeled erosion rate is 1.293 x 10^{-3} myr^{-1}.** This rate considers the full range of possible rockfall sizes at this site, and overcomes the limitations of monitoring only a small area / non representative sampling duration.

- Since the start of monitoring we have observed 906.542 m^3 of rockfall.

- On average 1,156 rockfall occur at this site each month (in detectable volumes above 2.5 x 10^{-5} m^3).

- The average monthly volume of rockfall per month is 38.22 m^3.

- The monthly volume of rockfall for this section of cliff is, on average, lower than that observed elsewhere along this coastline, most likely due to the relatively low (< 30 m) cliff height and hence more limited rockfall source area.

- We highlight key features of the erosion observed between January 2011 and March 2014 in Figure 2, numbered (1) to (4), and discussed below:

    - The largest area of failure captured in Years 1 & 2 (Figure 2 (1, 2)), continues to grow, predominantly laterally across the cliff face. The depth of the failure also increases, suggesting continued failure at this site, to a greater extent compared to that observed in Years 1 & 2. The failure is both joint (structure) and rock-strength controlled as can be seen by the jointed-limited failure perimeter, and is therefore likely to continue developing in a similar manner over coming years. At present we see no indication of continued vertical propagation of this failure which would ultimately result in a failure of the cliff line above. It should however be noted that this failure is steepening this cliff section, which over time will readjust, resulting in failure of the cliff top in the area adjacent to Cowbar Lane. The timescale over which this process may occur is not known, but we note that the highest rates of change observed occur in this location. Other similar features of continued failure are seen in Figure 2(3, 4).

- We see some areas that experience large scale failure (> 1 m^3) in Year 1, but which stall and show no additional change in Year 2 (see overlaps in Figure 6, for example).

- Toe cutting leading to rockfall above, in seen in Figure 2(3), with some evidence of a continued processes of attrition of the toe and then release of material above, where kinematically permissible. At present it remains unlikely that the depth of toe cutting is sufficient to instigate a deeper-seated failure of the rock mass above that would threaten to result in step-back of the cliff line, although continued monitoring may help identify the development of such failures. Such a step back is not beyond what is possible at this site, but remains not probable at present.

- Some evidence of small-scale slumping is seen in the glacial till, but only in isolated positions. Such failures are located in positions of steep till, with sparse vegetation. At present areas that are experiencing this type of failure, are at sections of the cliff line at the greatest distance from Cowbar Lane.

Table 2. Combined erosion rates for Years 1 to 3 for the monitored cliff section.
Rates are derived using the methods outlined in the Appendix.

Year	Month	Month	Year	Survey date	Survey epoch length (days)	Running total of days	Number of rockfalls	Total volume of rockfalls (m^3)	Area average erosion rate (x 10 -3 myr^{-1})	m/f modelled erosion rate (x 10-3 myr^{-1})
1	1	January	2011	14/01/2011	0	0	0	0.000	0.000	0.000
	2	February	2011	18/02/2011	35	35	990	31.690	2.770	3.344
	3	March	2011	21/03/2011	31	66	969	31.000	2.710	2.816
	4	April	2011	28/04/2011	38	104	1036	33.150	2.900	1.716
	5	May	2011	20/05/2011	22	126	4	0.130	0.010	0.000
	6	June	2011	17/06/2011	28	154	21	0.680	0.060	0.022
	7	July	2011	21/07/2011	34	188	660	21.110	1.850	0.484
	8	August	2011	25/08/2011	35	223	560	17.930	1.570	2.684
	9	September	2011	27/09/2011	33	256	972	31.110	2.720	4.554
	10	October	2011	21/10/2011	24	280	802	25.660	2.240	4.642
	11	November	2011	17/11/2011	27	307	708	22.650	1.980	3.850
	12	December	2011	19/12/2011	32	339	207	6.620	0.580	0.176
	13	January	2012	17/01/2012	29	368	609	19.480	1.700	1.760
	14	February	2012	23/02/2012	37	405	1323	42.330	3.700	2.816
	15	March	2012	26/03/2012	32	437	1108	35.450	3.100	2.860
	Total after 1 year	-	-	-	-	**437**	**9969**	**318.990**		
	1 year average	-	-	-	**31**	-	**664.6**	**22.790**	**1.992**	**2.115**
2	16	April	2012	18/04/2012	23	460	2074	19.390	1.620	1.480
	17	May	2012	09/05/2012	21	481	1346	24.510	2.950	2.370
	18	June	2012	19/06/2012	41	522	356	3.090	0.360	0.220
	19	July	2012	14/07/2012	25	547	101	2.910	0.330	0.210
	20	August	2012	02/08/2012	19	566	334	2.540	0.390	0.210
	21	September	2012	08/09/2012	37	603	598	7.790	0.880	0.170
	22	October	2012	03/10/2012	25	628	5312	11.150	0.570	0.350
	23	November	2012	15/11/2012	43	671	3231	7.320	0.630	0.360
	24	December	2012	13/12/2012	28	699	227	12.230	0.650	0.450

	25	January	2013	06/01/2013	24	723	2891	2.850	0.510	0.140
	26	February	2013	11/02/2013	36	759	4379	20.240	5.290	1.090
	27	March	2013	12/03/2013	29	788	946	14.930	2.600	2.010
	Total	**-**	**-**	**-**	**-**	**328**	**24141**	**128.950**		
	Average	**-**	**-**	**-**	**29**	**-**	**2368**	**13.040**	**1.398**	**0.755**
	Total over 2 years	**-**	**-**	**-**	**-**	**765**	**34110**	**447.940**		
	2 year average	**-**	**-**	**-**	**31**	**-**	**1222**	**17.228**	**1.718**	**0.009**
3	28	April	2013	25/04/2013	44	832	160	366.760	4.979	1.500
	29	May	2013	23/05/2013	28	860	559	1.027	0.014	2.459
	30	June	2013	25/06/2013	33	893	251	7.225	0.098	0.234
	31	July	2013	22/07/2013	27	920	553	8.523	0.116	0.250
	32	August	2013	20/08/2013	29	949	349	6.828	0.093	0.229
	33	September	2013	17/09/2013	28	977	463	40.337	0.548	0.215
	34	October	2013	21/10/2013	34	1011	641	0.284	0.004	0.384
	35	November	2013	18/11/2013	28	1039	409	7.378	0.100	0.418
	36	December	2013	03/12/2013	15	1054	349	6.862	0.093	0.534
	37	January	2014	17/01/2014	45	1099	517	7.036	0.096	0.205
	38	Febraury	2014	18/02/2014	32	1131	309	1.743	0.024	1.127
	39	March	2014	15/03/2014	25	1156	255	4.600	0.062	2.096
	Total					**1156**	**4815**	**460.530**		
	Average				**30.7**		**401**	**38.217**	**0.519**	**0.010**
	Total over 39 months					**1156**	**38925**	**906.542**		
	39 month average				**30.4**		**963**	**23.856**	**1.339**	**1.293**

4. SUMMARY AND CONCLUSIONS – YEAR 3

The following conclusions have been drawn based upon this analysis:

- **The area averaged rate of retreat in Year 3 alone was 0.519 x 10^{-3} myr^{-1}**.
- **The modeled rate of retreat in Year 3 alone was 0.804 x 10^{-3} myr^{-1}**.
- **The 39 month area averaged erosion rate since the start of monitoring is 1.339 x 10^{-3} myr^{-1}.**
- **The 39 month modeled erosion rate since the start of monitoring is 1.293 x 10^{-3} myr^{-1}.**
- There is no indication that the erosion of the cliff at Cowbar is accelerating or deviating away from behavior observed at this site previously. The fluctuation of erosion rates reported above, both month-on-month and year-on-year, is commensurate with the variability in rockfall patterns observed more widely on this coastline, and beyond.
- This monitoring period has witnessed a rockfall of volume > 300 m^3. Failures of this size are a natural and expected component of coastal cliffs. We note that this area of the monitored cliff section has continued to evolve via a sequence of rockfall since the beginning of the monitoring campaign, and there is no reason to believe that this will cease in future. The trajectory of the rockfall scar appear to be both up- and across-cliff. Further monitoring and close scrutiny of the possible ways in which this failure may develop through time is recommended.
- The concentration of erosion is currently focused away from the 'pinch points' at this site. We observe continued erosion in Year 3 at areas of the cliff that underwent erosion in Years 1 and 2.
- No loss of cliff line was observed during this period, although continued rockfall at the site this indicates cliff steepening, which will in time result in failure of the cliff top. Continued monitoring will help identify where and when this may occur.
- There is no evidence in the monitoring data of the development of a deeper-seated failure which would threaten the road and / or houses above, but we do identify a pattern of rockfalls on the cliff face below.
- We recommend continuation of the monitoring to identify any deviation from the behavior experienced to date.

5. REFERENCES

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6. Document control sheet

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