Scarborough Climate Change Review

Beach response to sea level rise

Scarborough Borough Council

05 April 2010

Final Report

9V7827

A COMPANY OF

ROYAL HASKONING

HASKONING UK LTD.
COASTAL & RIVERS

Stratus House
Emperor Way
Exeter, Devon EX1 3QS
United Kingdom

+44 (0)1392 447999	Telephone
01392446148	Fax
info@exeter.royalhaskoning.com	E-mail
www.royalhaskoning.com	Internet

Document title	Scarborough Climate Change Review Beach response to sea level rise
Document short title	
Status	Final Report
Date	05 April 2010
Project name	Scarborough Spa
Project number	9V7827
Client	Scarborough Borough Council
Reference	9V7827/REC3-1/303948/Exet

Drafted by	Mike Walkden	
Checked by	Nick Cooper	
Date/initials check	23/11/2010.	N. J. Cooper
Approved by	Hamish Hall	
Date/initials approval	29/11/2010	

SUMMARY

Scarborough Borough Council has commissioned Royal Haskoning to study the response of beaches within the Scarborough bays to future sea level rise, over a timeframe of one hundred years. The requirement is for a first-order assessment, i.e. a relatively quick and simple analysis to gauge trend and likely sale of beach response.

Good coastal management depends on understanding how beaches may change in the future. In developing such understanding it is very important to account for sea level rise, which is believed to be accelerating due to global warming.

Although sea level rise is certain, its scale is not, and so three different scenarios of possible future change have been explored: (1) no acceleration in sea level rise, (2) guidance provided by Defra (2006), and (3) sea level rise following a trajectory based on the recent findings of the UK Climate Impacts Programme.

In general terms, beaches respond to sea level rise by redistributing sediment down their profile, away from their upper sections. The approach taken in this study was based on the work of Per Bruun, and involved identifying an average annual beach profile, and then assessing how it might translate with the changing sea level. These changes were quantified along contours of the beach, specifically the water lines of a Mean High Water Spring tide and a Mean Low Water Spring Tide.

The results show that the beaches will become narrower overall, and lower at the seawalls, leading to reduction of amenity beach area and more severe wave conditions at high tide.

All three scenarios of sea level rise cause the beaches in both bays to become narrower. The beach width (at low water) decreases by between 10 and 60 metres in South Bay, and by between 20 and 90 metres in North Bay.

In North Bay, under all scenarios, sea level rise coupled with beach reshaping results in the (average annual) beach being completely submerged at high tide (Mean High Water Spring). The resulting depth of water at the seawalls depends on the rate of sea level rise and location within the bay. The projections range from 1 metre (in the north of the bay, assuming that sea level rise does not increase) to 3.25 metres (in the south of the bay assuming that Defra sea level rise projection occurs).

In south bay the equivalent range of water depths at Mean High Water Spring are projected to be from 0 to 1.5 metres.

In addition to the clear loss of amenity beach, such reductions in beach width and increases in water depth at high tide would be accompanied by larger waves at the seawalls. These would intensify wave impact pressures, which would increase the likelihood of structural damage. In addition greater wave uprush velocities and overtopping volumes would occur. Such changes would be more marked in North Bay, but should also be expected in South Bay.

CONTENTS

1 INTRODUCTION

Sea level rise is expected to accelerate in the future because of global warming. This will affect coastlines throughout the world, generally causing them to retreat. The scale of this retreat is likely to be sufficiently large to influence coastal management practices and policies. Recognising this, Scarborough Borough Council has commissioned Royal Haskoning to undertake a first-order study of the response of the beaches within the Scarborough bays to future sea level rise.

This report describes the results of that assessment. Section 2 describes the composition and geomorphic setting of the bays. A set of possible future sea level rise scenarios are then derived in Section 3. Section 4 projects the nature and scale of possible response of the beach profiles, over a timeframe of 100 years. Finally the future planshapes of the bays are mapped, under the two limiting scenarios of sea level rise.

This study has been chiefly informed by a technical inspection of Scarborough's bays (made on the 5th and 6th October 2010) and by the summary of their geomorphology, geological and hydrodynamic setting presented in the region's Shoreline Management Plan (Royal Haskoning 2007).

The results show that the beaches will become narrower overall, and lower at the seawalls, leading to reduction of amenity beach area and more severe wave conditions at high tide.

2 THE SCARBOROUGH BAYS

The Scarborough bay beaches extend over a length of around 5 km, and are divided into two similar sized embayments by Castle Headland, which projects around 700 metres into the sea. Facing east into the North Sea they are exposed to a marine climate dominated by waves approaching from the northeast. The general character of the coast in this region is rocky and cliffed, with well developed shore platforms. The Scarborough bays are distinctive in this setting because of their substantial beaches, which overlie the rock.

2.1 Scarborough South Bay

The South Bay comprises a beach perched on rock platform, backed by continuous seawalls. The beach is around 1.5 km long and extends from Castle Headland to the raised shore platform at Black Rocks (see Figure 1, Figure 2 and Figure 3).

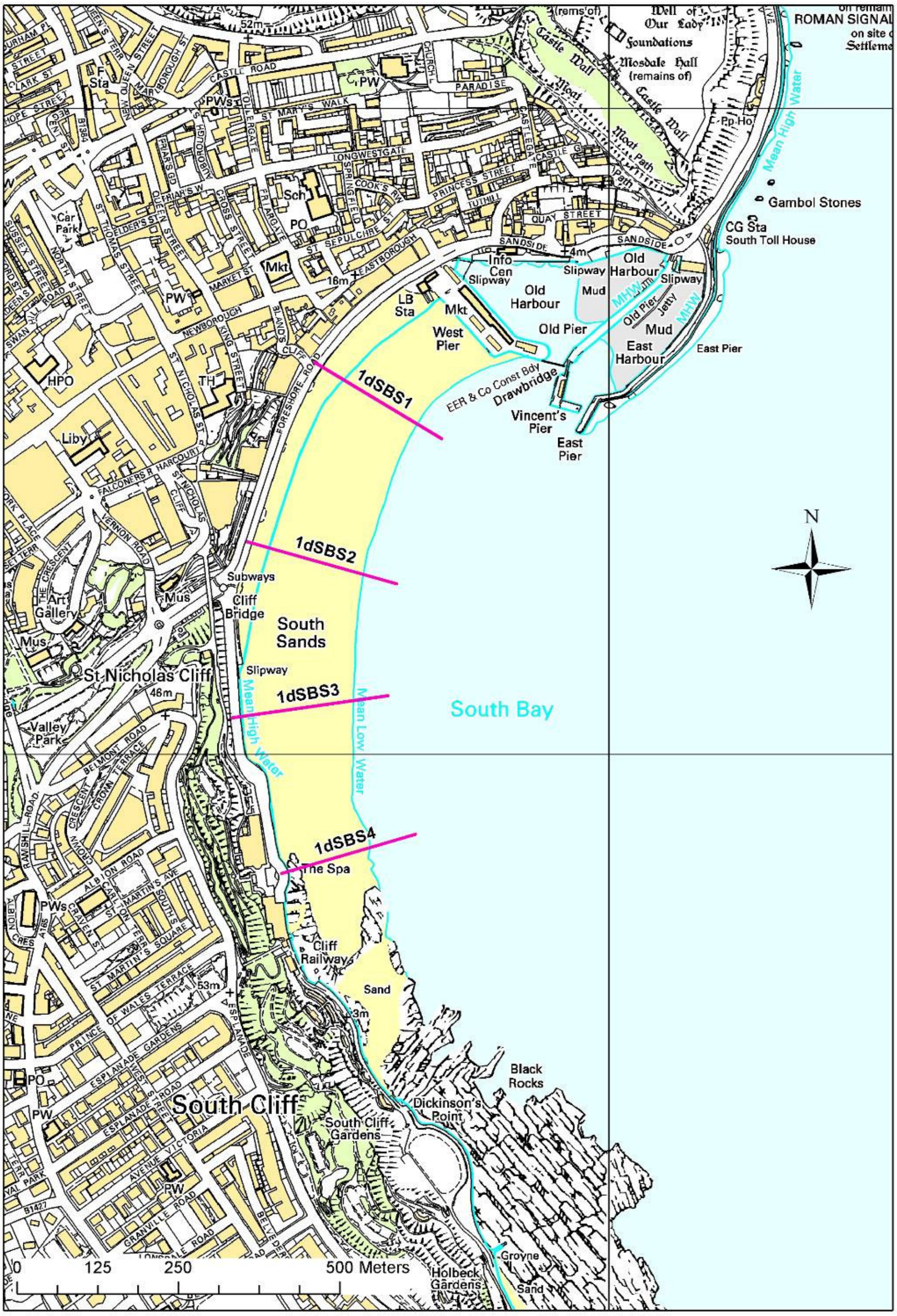


Figure 1. Scarborough South Bay showing locations of beach profiles provided by the North East Coastal Observatory

Figure 2. Central and northern areas of Scarborough South Bay

Figure 3. Southern areas of the Scarborough South Bay beach

The SMP (Royal Haskoning 2007) found:

> *Drift over this frontage might be expected to be to the south, but to a degree the low foreshore is retained by the outcropping Black Rocks. The fact that beach levels are maintained, and may even be increasing does suggest a significant input from the nearshore area. Furthermore, the Spa defences may actually be retaining material to the north which might otherwise be lost to this short bay system.*

Both the Castle Headland and the harbour structures provide shelter from the dominant north-easterly waves. Beach sediments moving into the lee of the Headland along the face of Foreshore Road to the north, tend to be held by the West Pier. This movement of material is clearly demonstrated by both the need for the Council to remove material from along the northern section of the beach and by the harbour dredging, which amounts to the removal of some 4000 cubic metres of sand every year.

2.2 Scarborough North Bay

North Bay is around 1.7km long, and is bounded at its southern end by Castle Headland, and in the north by the hard rocky headland and platform of Scalby Ness, and Scalby Beck, which drains into the northern limit of the bay (Figure 4).

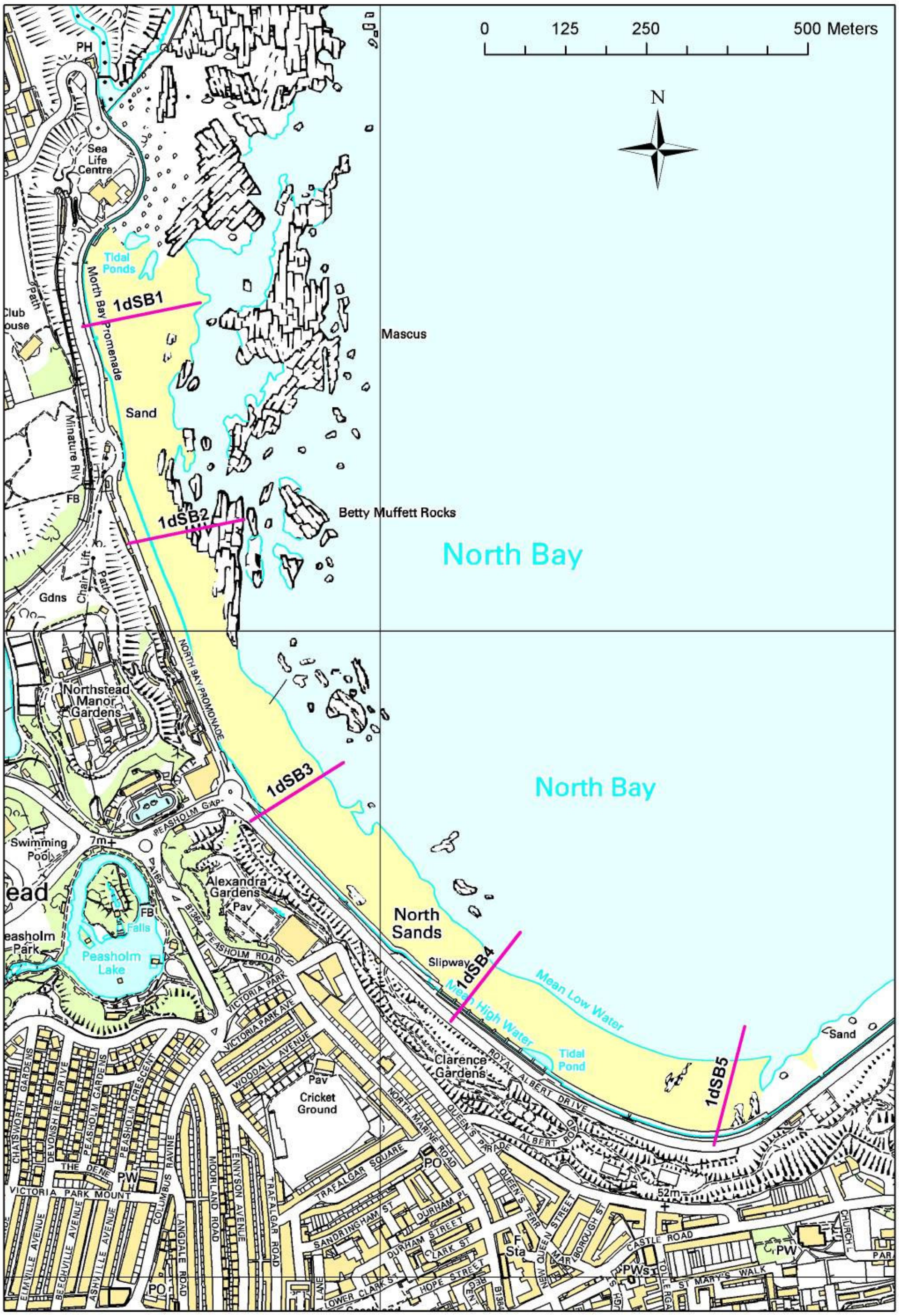


Figure 4. Scarborough North Bay, showing intertidal rock exposures and locations of beach profiles provided by the North East Coastal Observatory

Rocks emerge through the intertidal beach along the whole length of the bay, but their surface dips towards the south. The Scalby Ness rock platform grades into the narrower rock exposures of Mascus, which in turn grade into the less pronounced Betty Muffett

Rocks (see also Figure 5). In the southern third of the bay a small number of exposures can be found through the beach, for example along the seawall when the beach surface is depressed by scour (as shown in Figure 6).

Figure 5. The northern areas of North Bay

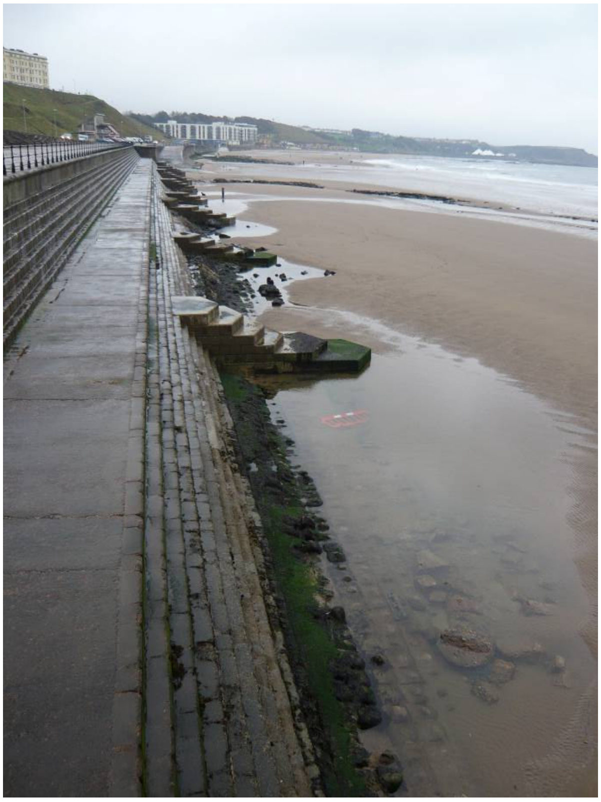


Figure 6. Steep seawalls towards the south of North Bay, showing shore platform outcrops through the beach

Figure 7. Defences in the northern section of North Bay

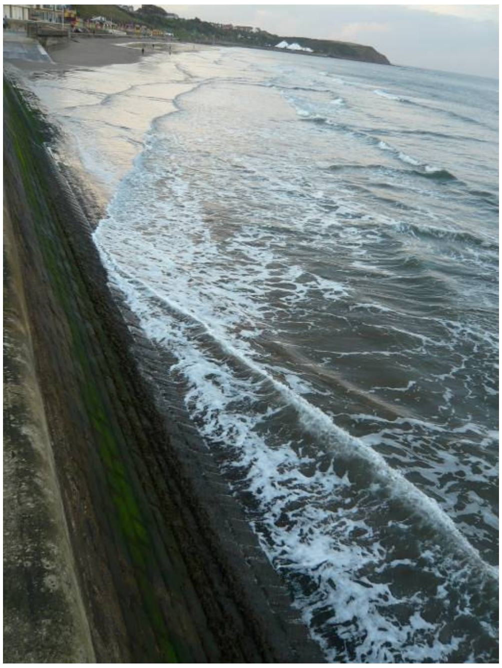


Figure 8. Wave reflection at the face of the North Bay seawall

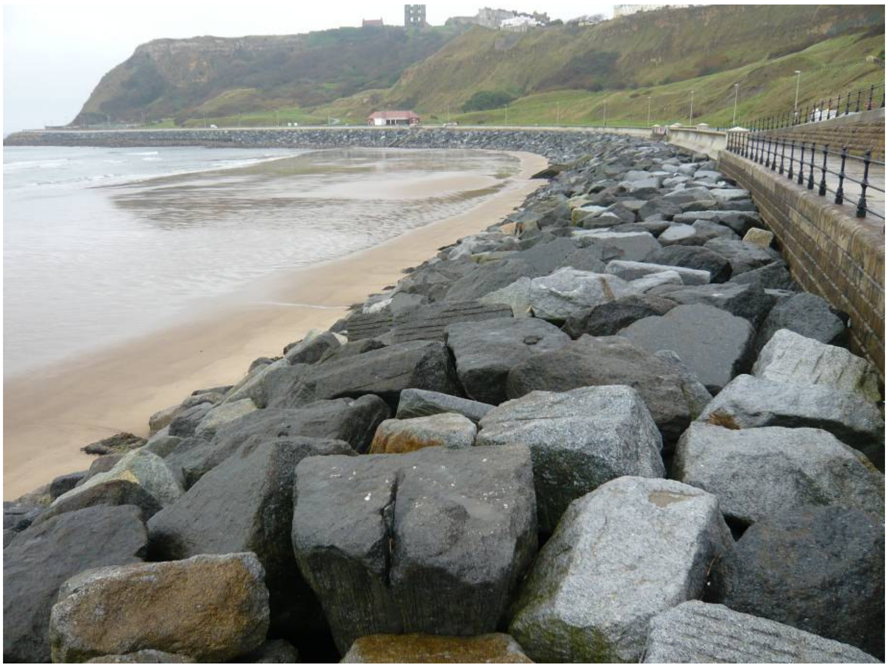


Figure 9. Rock armour revetment backing low beach at the southern limit of North Bay

The profile of the northern bay beach varies, becoming less steep in the south. It is backed by coast protection structures throughout its length. These mostly comprise reflective near-vertical seawalls originally dating to the 19th century (e.g. Figure 7 and Figure 8), but in its southern section a more recent rock revetment has been constructed (Figure 9). This is contiguous with the Castle Headland revetment.

The beach is believed to be retreating, and the rate at which this occurs has been estimated by the recent Shoreline Management Plan (Royal Haskoning 2007) as 20 metres per century. The SMP also found:

> *The evidence of earlier beach change, particularly within North Bay does suggest that the construction of the sea walls along the north beach may have resulted in significant loss of sediment. This, given the orientation and nature of North Bay would be sensible. North Bay is very open to the dominant wave directions. The extent of indent of the bay would very much dictate the ability of the bay to retain an upper beach.*

The North Bay beach therefore differs from South Bay in that the underlying rock is shallower and it is subject to loss of volume. Because platform level influences sediment redistribution following a change in sea level, the response of the two bays to sea level rise should be expected to differ.

3 SEA LEVEL RISE

Sea levels have been rising for thousands of years, since the end of the last ice age, and this has driven shoreline retreat. The current tendency for retreat in the North Bay is due, in part, to this. The Proudman Oceanographic Laboratory has analysed historic tide gauge data and estimated the recent historic rate of sea level rise to be around 2.45 mm/year in the Scarborough area. This rate was derived as part of a national scale assessment of extreme water levels and sea level rise, and included hourly water level data from the class A gauges at Immingham (from 1963) and Whitby (from 1981).

3.1 Potential future sea level rise

Climate scientists believe that sea level rise will accelerate, but there is considerable uncertainty about the scale of the change. To recognize that uncertainty in this study, projections of shore change have been made under three different possible scenarios of sea level rise, which are illustrated in Figure 10.

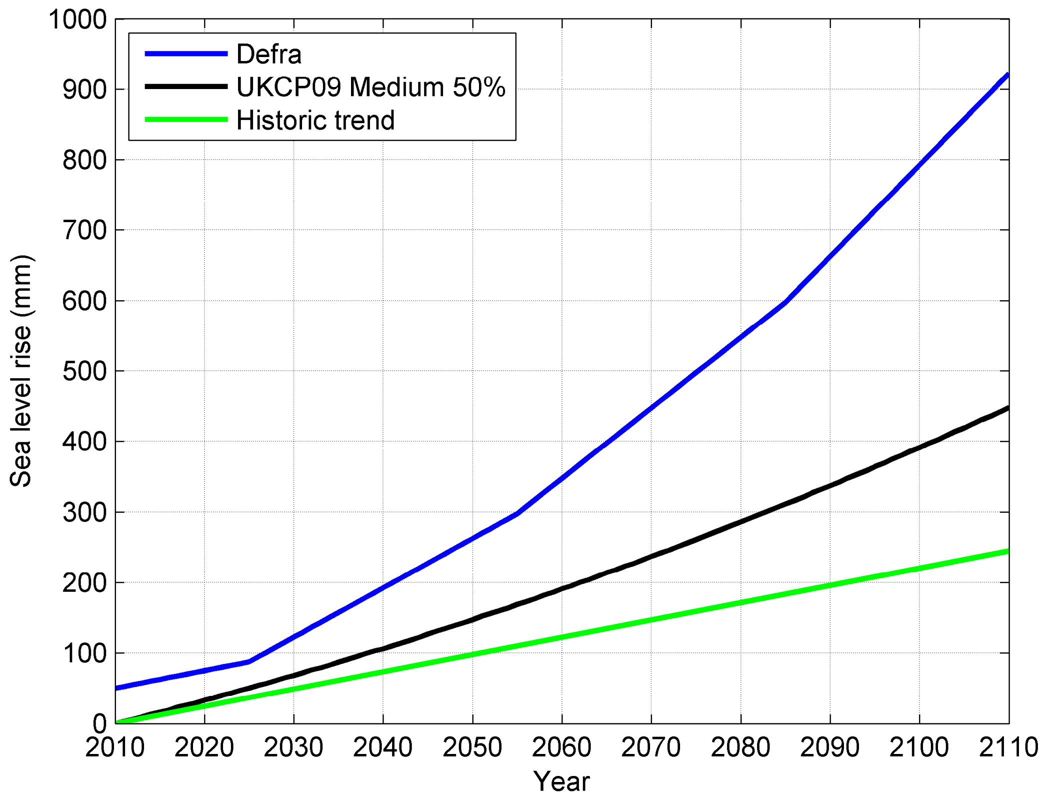


Figure 10. Three sea level rise trajectories adopted within this study

The most recent authoritative description of future sea level around the UK was provided by the UK Climate Impacts Programme, within their 2009 UK Climate Projections (UKCP09), and so these were utilised within this study.

The UKCP09 sea level rise trajectories have not yet been formally adopted by Defra, who instead provide their own sea level rise trajectory (Defra 2006). This is shown in Figure 10, and was adopted as the second scenario in this study.

The third scenario chosen was a continuation of historic rates of sea level rise. Although this scenario is considered highly unlikely, it is useful in interpreting historic beach retreat and in illustrating a lower limit of possible future change.

The UKCP09 projections are probabilistic and dependent on scenarios representing low, medium and high greenhouse gas emissions. In order to proceed with the analysis these were translated into one deterministic sea level rise trajectory. Given that the

Defra scenario represents quite a high future sea level trajectory, and that a continuation of historic rates represents a very low condition, it was decided to select a trajectory from UKCP09 to represent a middle condition. Consequently the 50th percentile of the medium emissions scenario was adopted.

The UKCP09 projections include two elements, absolute sea level rise and local isostatic land movement. The isostatic data model used by UKCP09 shows isostatic adjustment at Scarborough of -0.5 mm/y (relative land fall). This has been added to the UKCP09 projection to provide the trajectory shown in Figure 10.

4 BEACH RESPONSE TO SEA LEVEL RISE

Beaches are highly dynamic, they respond to the action of the sea at all timescales, from individual waves to long term trends in sea level. Beaches exist because they tend to build at the shoreline. The height to which they build depends on, amongst other things, the height that waves reach, and the availability of beach material. A beach profile is also limited by its own stability under wave action; it cannot be too steep.

A full, unfettered sandy beach is able to rise with the sea level, but it must also retreat, cutting into its own backshore to release sand to deposit on its lower profile, to maintain a stable slope. A beach constrained by a seawall is not free to rise and retreat in this way because material can not be released from the backshore. Instead water levels increase at the seawall, raising wave energy levels across the beach face. These raised energy levels destabilise the beach, causing it to move material down its profile. This can further expose the sea wall leading to failure if the wall was not designed for lowered foreshore levels and the associated increase in wave energy.

First order assessments of beach response to sea level rise are strongly based on the shore profile shape. The normal approach is to consider how this profile will translate vertically and horizontally as the sea level rises, in the context of the broader geomorphic setting. The rock substrate is assumed not to lower, or if it does so the effect on the redistribution of beach sediments is assumed to be negligible.

In this study, LiDAR data was first used to get an impression of the general three-dimensional form of the beach. LiDAR provides an excellent 'snapshot' perspective of the beach at one moment in time, but this is not ideal for understanding beach profiles, which tend to fluctuate from season to season. For this reason a set of profile surveys was used to view the fluctuating form of the beaches, and to determine their time-averaged shape. These were provided by the North East Coastal Observatory, and were recorded twice per year (spring and autumn) from 2008. The locations of the available profiles are shown in Figure 1 and Figure 4. Single bathymetric profiles were also available, and these were joined to the beach data. Not all the beach profiles were used, instead one was selected to represent the South Bay beach, and a further two were identified to represent the North Bay beach.

The data at these locations were analysed to identify average profiles. This process made use of a semi-empirical model of beach profile shape known as the 'Bruun profile' (Bruun 1954).

Once each representative profile was established, it was then translated to simulate beach response to sea level rise. First it was displaced upwards by a distance equal to the expected sea level rise, and then moved landward, which had the effect of 'eroding' the beach surface close to the seawall and 'accreting' it lower down the profile. The translation continued until the volume of erosion matched the accretion volume, and this condition was deemed to represent the future equilibrium form of the beach.

4.1 South Bay profile change

Profile 1dSBS2 was used to represent the South Bay beach. This was selected because it is close to the centre of the bay (as can be seen in Figure 1), and passes through a relatively full area of the beach. The shore profile data for this section are shown as thin blue lines in Figure 11, along with the available bathymetric information.

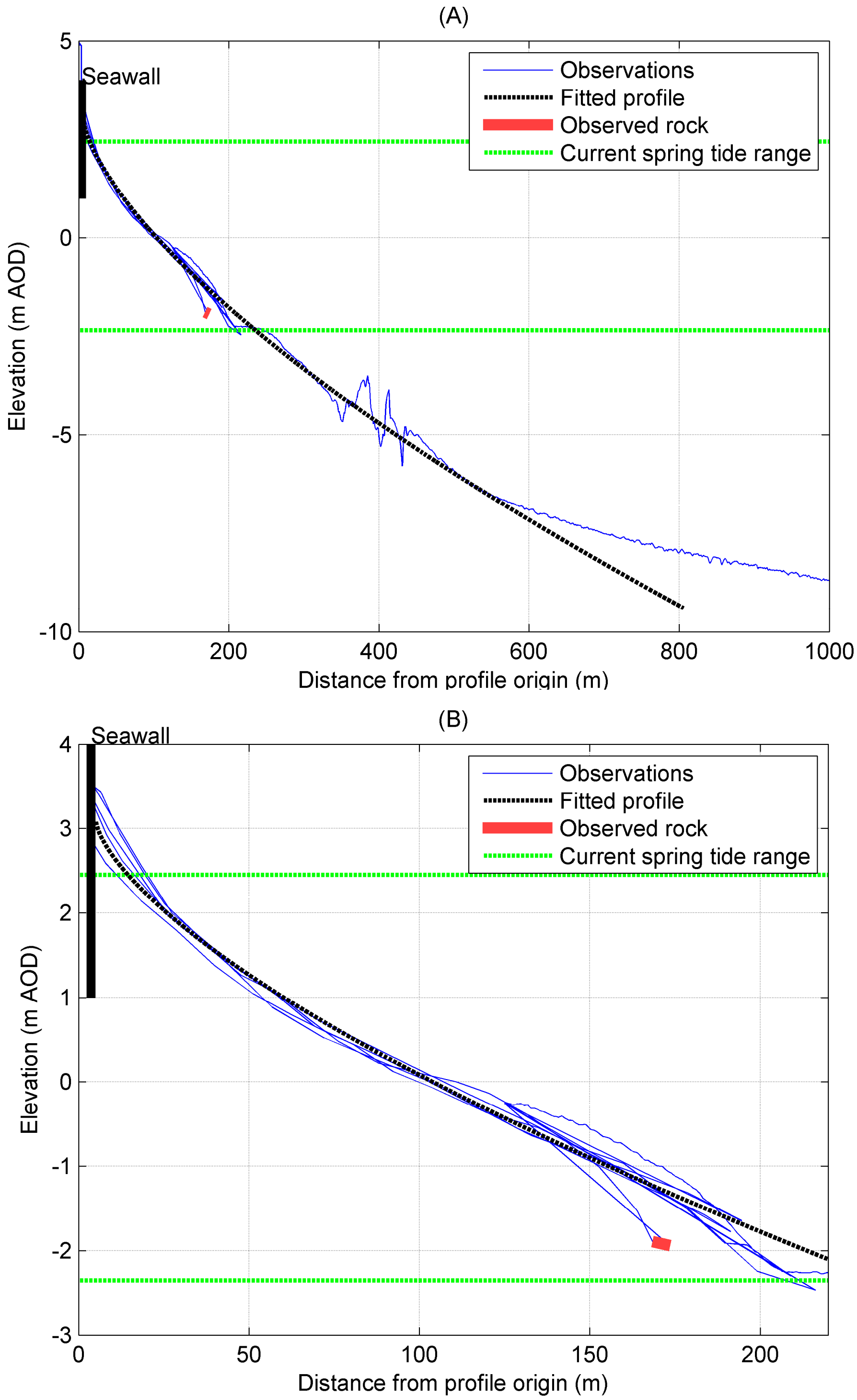


Figure 11. Observed beach profiles in South Bay (section 1dSBS2), with bathymetric data, shown at two scales.

The observations indicate that the beach profiles have been relatively stable during the monitoring period. The vertical fluctuations observed amount to around 0.6 metres at the seawall, with a maximum of around 0.9 metres at a distance of approximately 180 metres from the seawall. The changes at the seawall have revealed rock which underlies the beach in this area. Further evidence of rock can be found in the bathymetric data at distances from around 350 metres to 450 metres across the profile.

A Bruun curve was fitted to these profiles, and this is shown as a black dotted line in Figure 11. The beach profiles follow the fitted curve well. The natural profile deviates from this form at a depth of around 6.6 mODN, and this is taken to be the 'closure depth' of the beach, i.e. the point at which littoral processes no longer dominate the morphology.

To assess the response of this profile to a continuation of the historic rate of sea level rise, the fitted Bruun curve was raised by 0.245 metres, and then translated landward until a negligible change in overall beach volume was achieved between the seawall and the closure depth. This was found, through iteration, to be 14 metres, resulting in the same retreat of the mean low water spring contour. The mean high water spring contour was projected to retreat to the seawall, marginally above the top of the beach profile. The same process was repeated for the UKCP09 and Defra sea level rise projections and the results are shown in Figure 12 and summarised in Table 1.

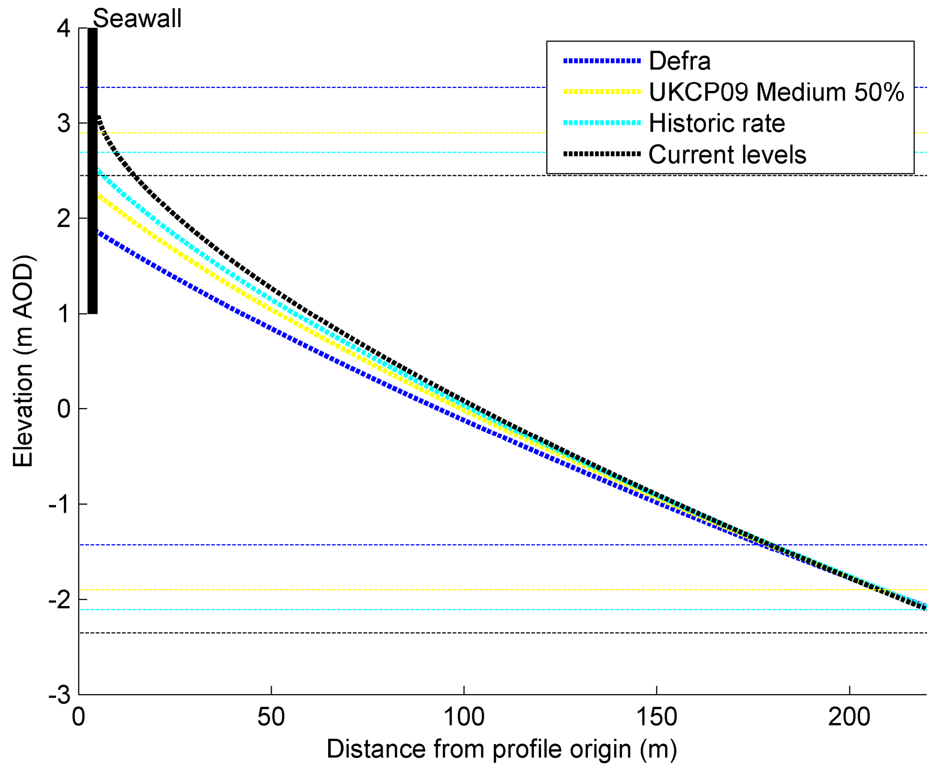


Figure 12. South Bay, current and projected elevations of MHWS and MLWS (horizontal lines) and beach profile form (thick dotted lines) under three sea level rise projections over 100 years: (1) continuation of historic rates of sea level rise, (2) the 50th percentile of the UKCP09 medium emissions scenario and (3) Defra (2006) guidance.

As would be expected, the retreat of the beach profile necessary to balance the redistribution of sediment above the closure depth is significantly greater for the UKCP09 and Defra based projections than was seen under the assumption of a continuation of historic rates. The resulting retreat of the MLWS contour was found to be 27 metres (UKCP09) and 58 metres (Defra). In each case the MHWS contour retreated to the face of the seawall. The coupled effect of sea level rise and beach lowering at the structure is projected to result in water depths (at MHWS) of approximately 0.6 metres (UKCP09) and 1.5 metres (Defra). These results, and others calculated for the South Bay beach are summarised in Table 1.

4.2 North Bay profile change

Two profiles were selected for analysis in the North Bay. This was necessary because of the changing gradient of the beach, which becomes progressively steeper with distance north.

Beach levels are higher in the northern part of the bay, and profile 1dSB2 was chosen to represent this area. As in the southern bay, observed beach profiles were joined to the available bathymetric profile. The origin of the bathymetric profile is around 380 metres to the south, and apparently passes through an area with a slightly lower rock surface than would be found directly seaward of 1dSB2. This does not, however, influence the analysis.

4.2.1 Retreat of the northern part of North Bay

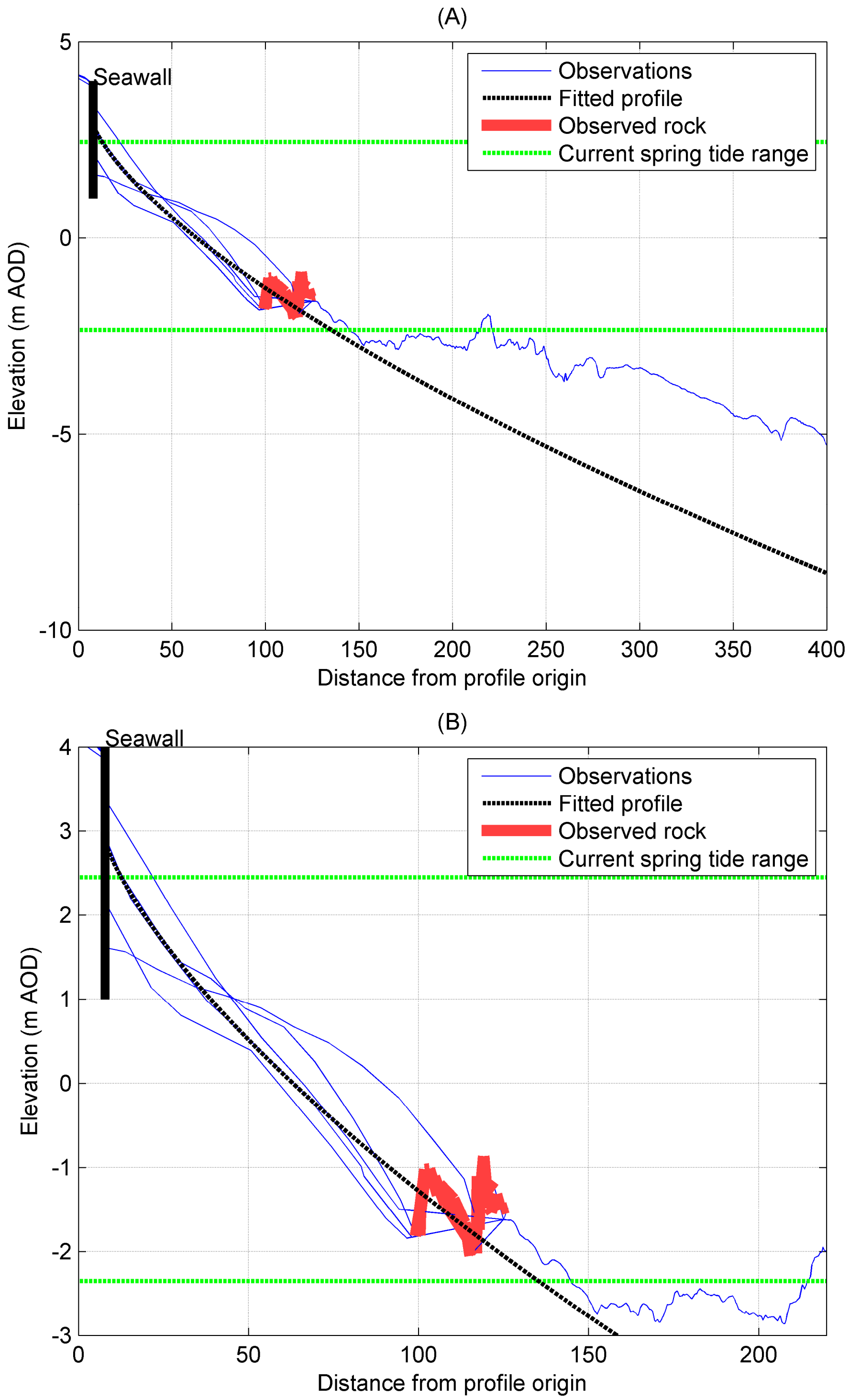


Figure 13. Observed beach profiles in the northern part of North Bay (section 1dSB2), with bathymetric data, shown at two scales.

As can be seen in Figure 13, the beach surface here is more variable than was observed in the South Bay. The beach level varies by about 1.8 metres at the seawall, and between around 0.6 m and 1.6 m elsewhere. This may be attributed to the reduced availability of sediment and the influence of reflected wave energy. A Bruun curve was fitted to the beach profiles (as shown in Figure 13), and a closure depth of 2.1 mODN was identified, which was defined by the level of the rocky foreshore.

As noted above, the North Bay beach is subject to a recessive trend, which is estimated to be 20 metres per century (Royal Haskoning, 2007). This is due, at least in part, to historic sea level rise, which is estimated to be 2.45 mm/year. Translation of the fitted Bruun profile indicates that 6 metres of beach rollback is required to accommodate 100 years of sea level rise at this rate. This information allows the general retreat trend in the bay to be divided into two elements, a sea level rise component of around 6 m/century and an erosion trend of around 14 m/century.

The future retreat of the northern section of the North Bay, if the current rate of sea level rise were to continue, is therefore estimated to be 20 metres over the next 100 years, and this translation is illustrated in Figure 14. Under this condition the mean high water spring contour retreats to the seawall, creating a water depth above the top of the beach of approximately 1 metre.

The profile change projected under the higher (UKCP09 and Defra) projections of sea level rise are also shown in Figure 14. It can be seen that the projected beach profile is relatively insensitive to the sea level rise scenario, although, naturally, the water depth is.

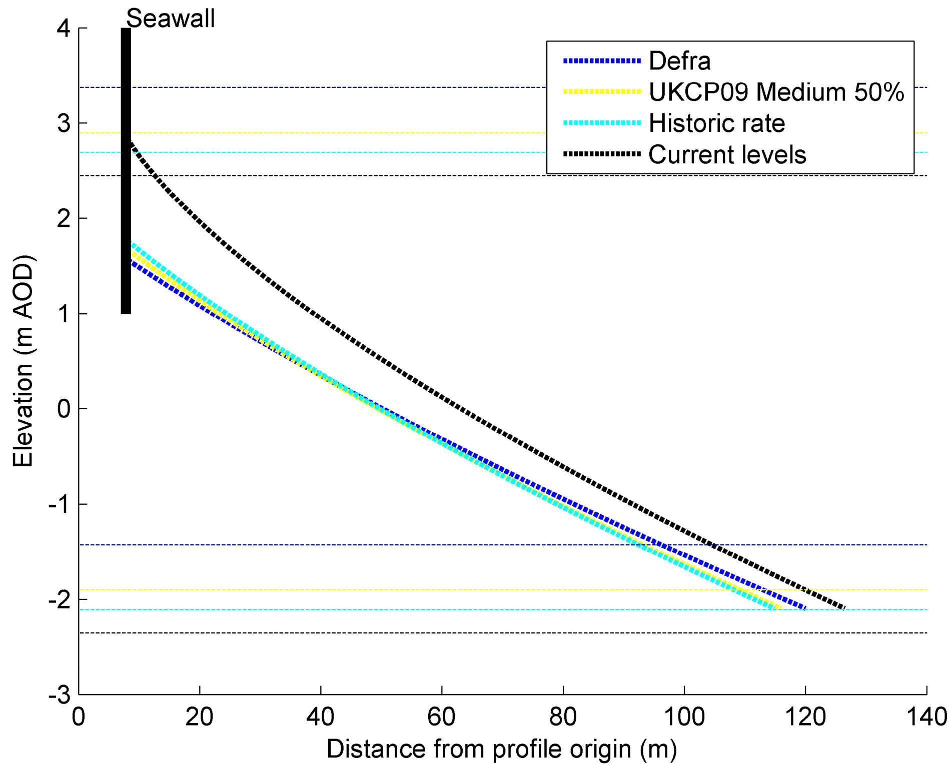
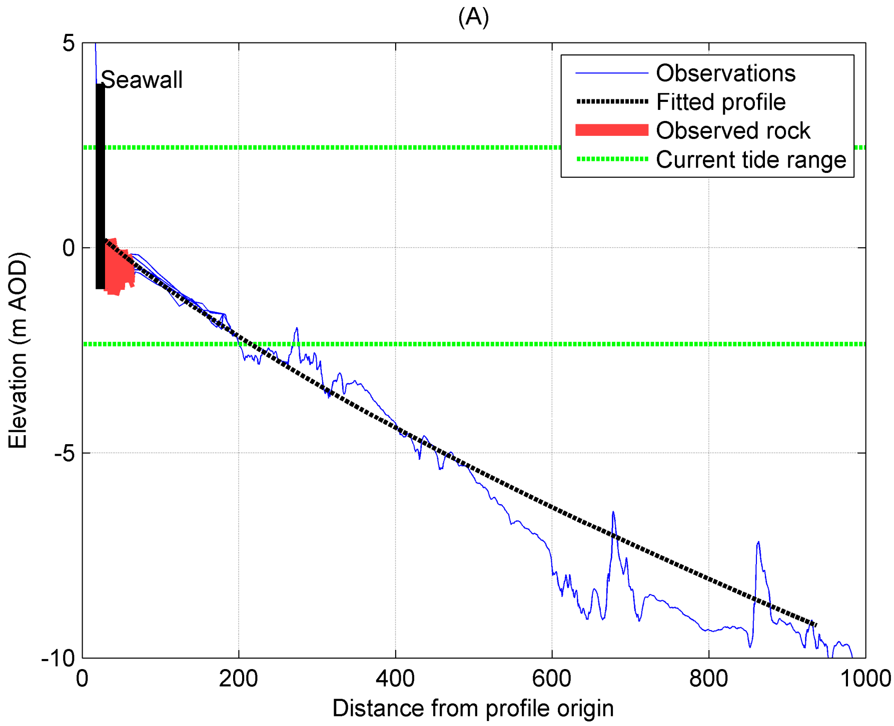


Figure 14. Northern section of North Bay, current and projected elevations of MHWS and MLWS (horizontal lines) and beach profile form (thick dotted lines) under three sea level rise projections over 100 years: (1) continuation of historic rates of sea level rise, (2) the 50th percentile of the UKCP09 medium emissions scenario and (3) Defra (2006) guidance.

The recession necessary to balance the redistribution of sediment across the beach profile under a rise in sea level of 0.925 metres is 25 metres. When this is coupled with the erosion trend of 14 metres (per century), a total retreat of 39 metres is obtained. The equivalent distance associated with the UKCP09 projection is 26 metres.

4.2.2 Retreat of the southern part of North Bay

The southern profile of the North Bay (1dSB4) also passes over both sand and rock. Here the beach is low, close to the seawall it is currently around 2 m below Mean High Water Spring (Figure 15). At the seawall the profiles reveal that rock is often exposed in a scour pit caused by reflection at the seawall face. Given the low level of the beach and its very gentle gradient, a Bruun-based approach is not appropriate for the assessment of response to sea level rise. A better approach is simply to track the landward translation of the tide level contours along the very gentle gradients.



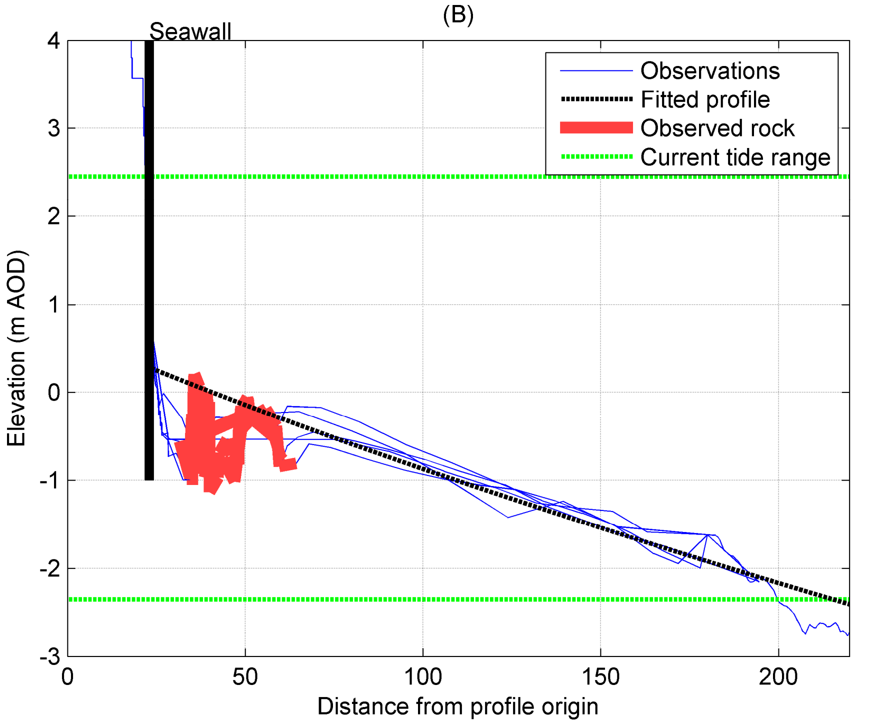


Figure 15. Observed beach profiles in the southern part of North Bay (section 1dSB4), with bathymetric data, shown at two scales.

In Figure 15 a generic curve is fitted to the beach profiles. This curve is reproduced in Figure 16, and translated 14 metres landward, to represent the recession trend believed to affect this bay.

The figure also shows projected future tide levels, and illustrates increasing water depths at the seawall and narrowing intertidal zone. The metrics of these changes are summarised in Table 1.

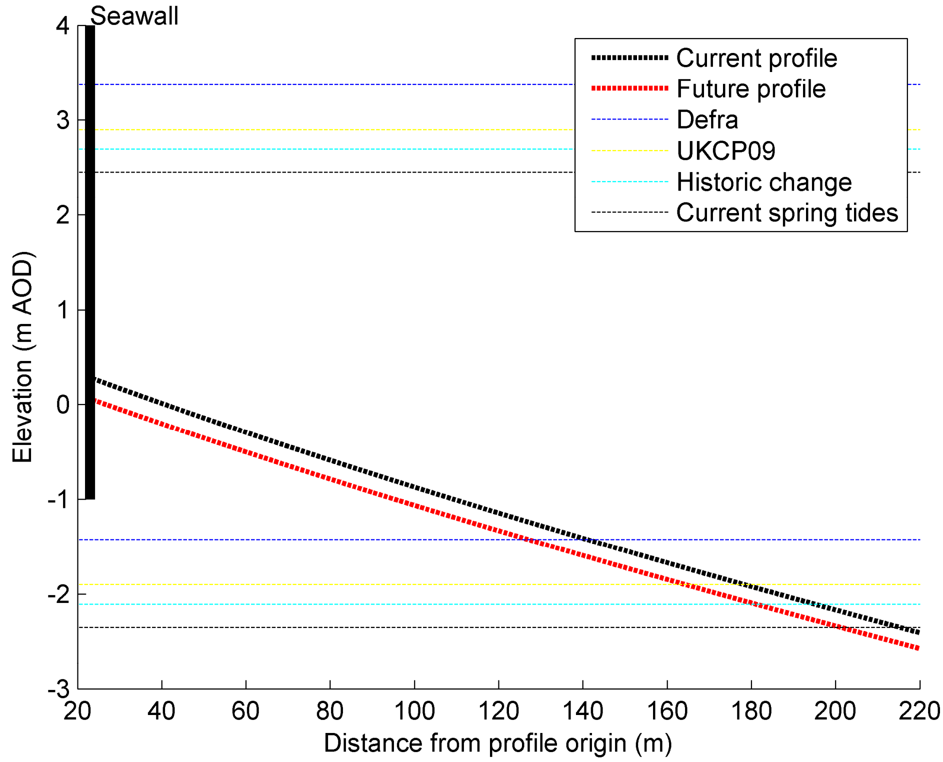


Figure 16. Projected future beach profile in the south of North Bay after 100 years, with tide levels.

4.3 Planshape changes

Planshape changes were estimated using the following sources of information: (1) LiDAR survey data were used to reveal the 'present day' three-dimensional beach topography, (2) beach profiles provided cross-shore detail and (3) the fitted and translated Bruun beach profiles were used to indicate future relative locations of beach contours. The interpretation of this data to provide each contour is described below. The UKCP09 projections were not mapped, as these were encompassed by the envelope created by the other two sea level rise scenarios.

4.3.1 South Bay

Current MLWS and MHWS
These contours were best estimated by the LiDAR topographic data. Spatial coverage of MLWS is incomplete, and so some interpolation and extrapolation was necessary, informed by the beach profile survey data.

MLWS + 0.245m (continuation of historic sea level rise)
The beach profile translation indicated very little change in the beach topography at this level, and so this contour was estimated using the LiDAR topography. This contour currently contains details (undulations and a meander at the north of the bay) which may not be present in the future, and so some smoothing was introduced.

MHWS + 0.245m (continuation of historic sea level rise)
Profile translation indicated that MHWS would be slightly above the top of the average form of the beach along Foreshore Road. Consequently this contour is positioned along the seawall face.

MLWS + 0.925 (Defra sea level rise)
The beach profile translation indicated very little change in the beach topography at this level, and so this contour is best estimated using the LiDAR topography. This contour currently exhibits undulations which may not be present in the future, and so some smoothing was introduced.

MHWS + 0.925 (Defra sea level rise)
The beach profile translation indicated that the top of the beach would be submerged at MHWS, and so this contour is positioned along the seawall.

The resulting tidal contours are shown in Figure 17.

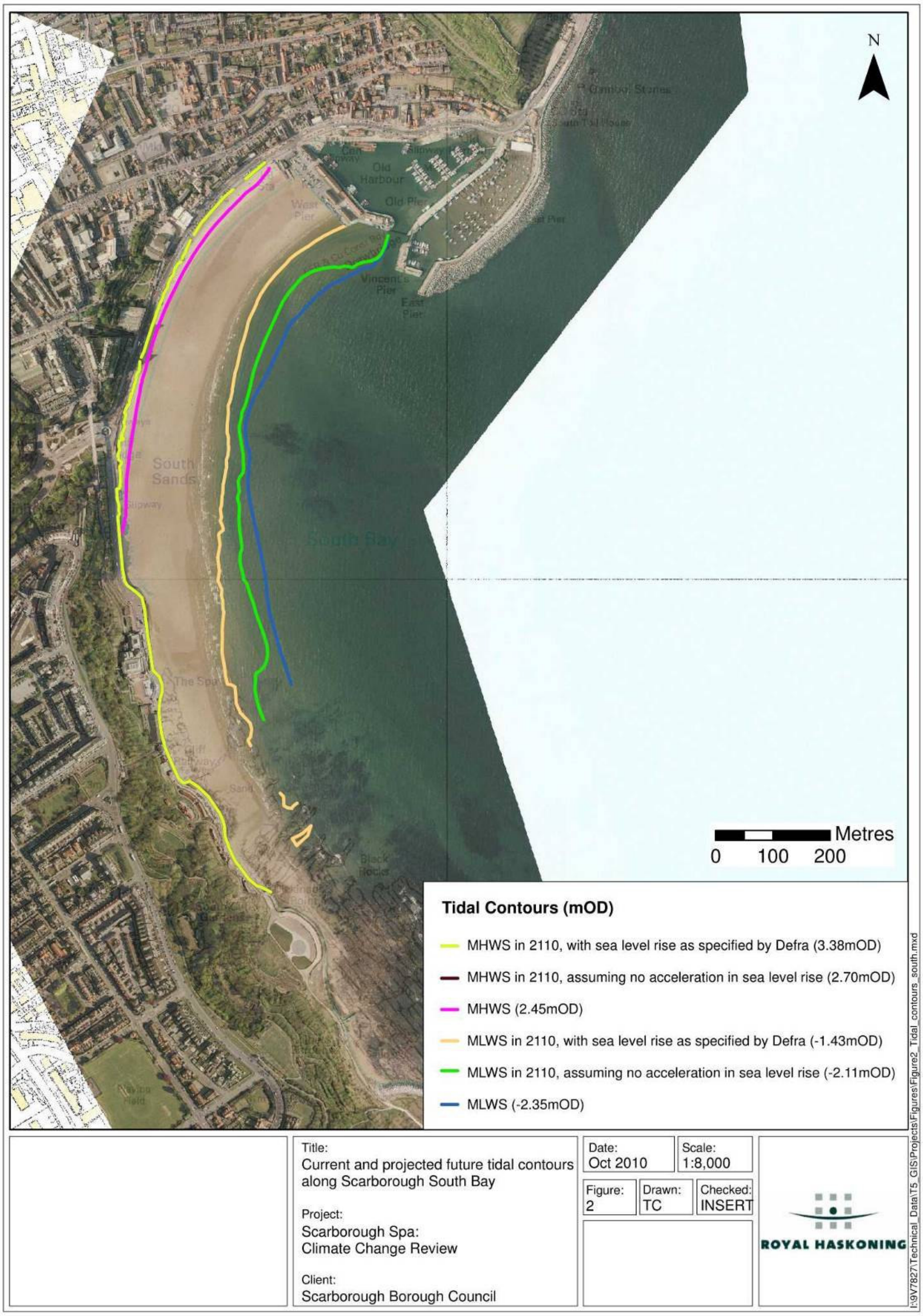


Figure 17. Projected tidal contours in the South Bay, note that the MHWS contours are in the same location (at the face of the seawall) and so hidden for most of their length

4.3.2 North Bay

Current MLWS and MHWS

These contours are best estimated by the LiDAR topographic data because of their large spatial coverage. Detail along MLWS is incomplete, and so some interpolation and extrapolation is necessary, informed by the beach profile survey data. Rock outcrops make this process unreliable in the north of the bay, and so the contour is curtailed in this area.

MLWS + 0.245m (continuation of historic sea level rise)

This contour is best estimated using the LiDAR topography. This contour currently contains undulations that may not persist, and so some smoothing was introduced. In the north, rock outcrops and a lack of survey data make the contour impossible to locate, and so it is curtailed in this area.

MHWS + 0.245m (continuation of historic sea level rise)

Profile translation indicated that MHWS would be above the top of the average form of the beach. Consequently this contour is positioned along the seawall face.

MLWS + 0.925 (Defra sea level rise)

This contour is best estimated using the LiDAR topography, with some modification in the north. Here the profile translation analysis suggested that this contour would shift around ten metres landward. Some smoothing is appropriate to remove current transient undulations.

MHWS + 0.925 (Defra sea level rise)

The beach profile translation indicated that the top of the beach would be submerged at MHWS, and so this contour is positioned along the seawall.

The resulting tidal contours are shown in Figure 18.

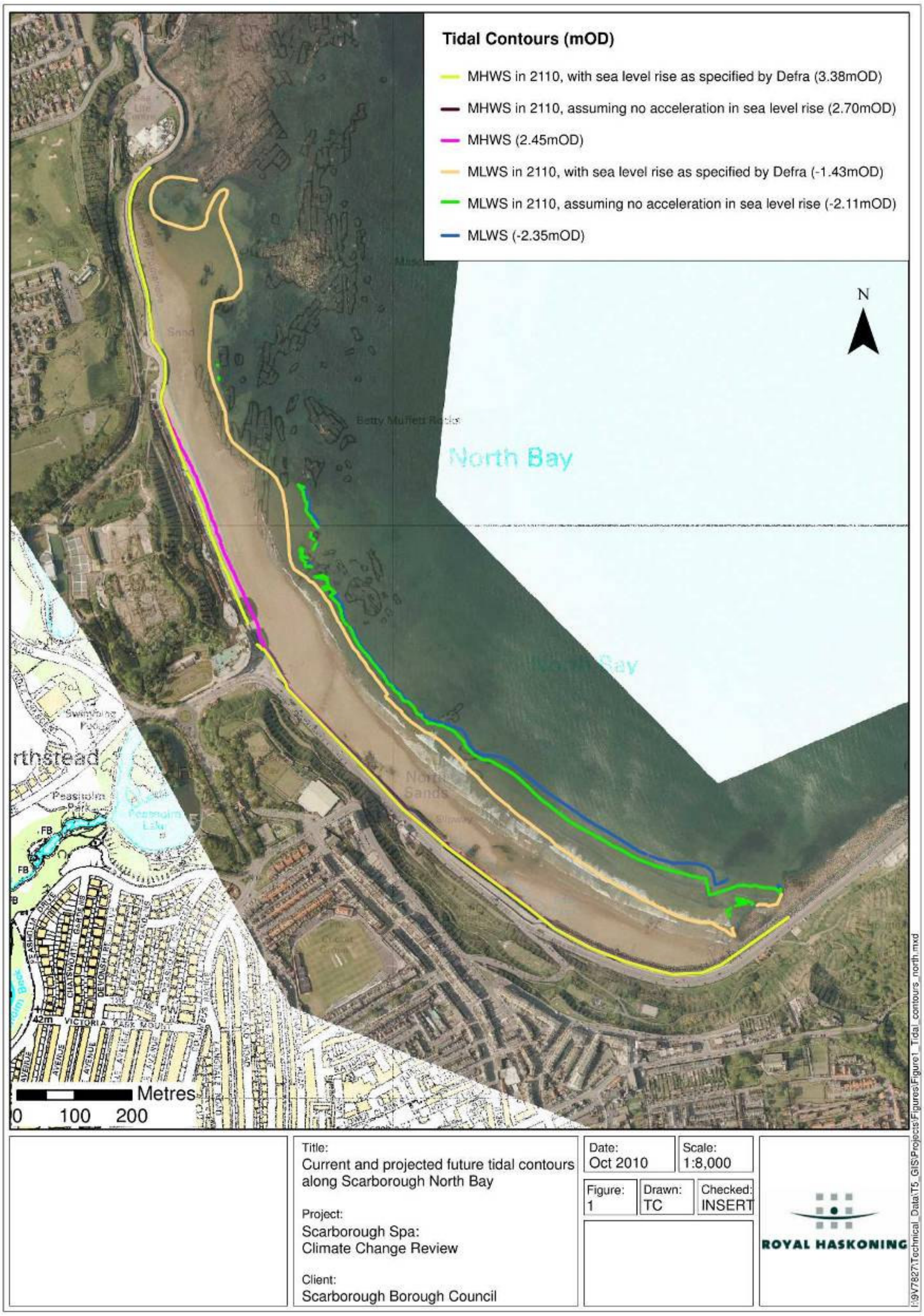


Figure 18. Projected tidal contours in the North Bay, note that the MHWS contours are in the same location (at the face of the seawall) and so hidden for most of their length

5 CONCLUSIONS

The Scarborough seafront includes two large sandy bays, resting on rock shore platforms and backed by continuous seawalls. This study has projected how they might respond to future sea level rise.

Future sea level rise is certain, but the scale of the increase is not. Consequently the behaviour of beach profiles within the bays has been projected under three different sea level rise scenarios (Figure 10): continuation of historic rates, the 50th percentile of the UKCP09 medium emissions projection, and the sea level guidance provided by Defra (2006).

Shore profile change has been assessed by first identifying an average annual beach profile. This is intended to represent an average form within the natural variation driven by changes in the weather and seasons.

With the exception of the beach in the southern part of North Bay (which are very low and flat) the response to sea level rise has been modelled using a 'Bruun rule' approach, involving quantification of sediment redistribution down the beach profile. The presence of the seawalls and rock platform were accounted for.

The future Mean High Water Spring (MHWS) and Mean Low Water Spring (MLWS) contours have been mapped across the bays for the highest and lowest of the sea level rise scenarios (Figure 10 and Figure 18).

The analysis shows loss of amenity beach under all scenarios, with none remaining at MHWS under any scenario. Given that Mean High Water Neap is 1.1 metres below MHWS, the projections indicate that there will be no amenity beach at MHWN in North Bay, unless sea level rise does not increase. It should be noted that these metrics relate to the annual average form, around which the beach would vary in response to changes in the weather and season.

The associated water depths range up to 1.5 metres in South Bay and 3.5 metres in the southern part of the North Bay (rounded to the nearest quarter metre). All the results are below included in Table 1.

location	Year	Sea Level Rise		Beach Width		Contour Change	
		Scenario	Increase	at MLWS	at MHWS	MLWS retreat	MHWS depth
			(m)	(m)	(m)	(m)	(m)
North Bay (N)	2110	Defra	0.93	90	0	40	1.75
	2110	UKCP09	0.45	100	0	30	1.25
	2110	Hist	0.25	110	0	20	1.0
	2010	~	0.00	130	5	~	~
North Bay (S)	2110	Defra	0.93	100	0	90	3.25
	2110	UKCP09	0.45	140	0	50	3.0
	2110	Hist	0.25	160	0	30	2.5
	2010	~	0.00	190	0	~	2.0
South Bay	2110	Defra	0.93	170	0	60	1.5
	2110	UKCP09	0.45	200	0	30	0.5
	2110	Hist	0.25	220	0	10	0.0
	2010	~	0.00	230	10	~	~

Table 1. Projected beach metrics under alternative scenarios of sea level rise (notes: 'Hist' indicates continuation of the historic rate of sea level rise, 2010 conditions have been included for comparative purposes, projected changes have been rounded to remove unrealistic precision, - depths to nearest quarter-metre, horizontal distances to nearest ten metres)

These are the results of a first order assessment of coastal change, i.e. one employing the simplest of a range of possible approaches. It is based on existing data, deterministic sea level scenarios and a simple behavioural model of shore change. As such the projections represent the first step of a potentially more detailed assessment of beach response and uncertainty. Further data and more detailed analysis would be required in order to associate probabilities with the predictions.

The projected reductions in beach width and increases in water depth at high tide would be accompanied by larger waves at the seawalls. These would intensify wave impact pressures, which would increase the likelihood of structural damage. Structure vulnerability would also be increased by the potential for undermining associated with the lower beach levels. In addition greater wave uprush velocities and overtopping volumes would occur. Such changes would be more marked in North Bay, but should also be expected in South Bay.

References

Bruun, P., (1954), Coast erosion and the development of beach profiles, Beach erosion board technical memorandum. No. 44. U.S. Army Engineer Waterways Experiment Station. Vicksburg, MS.

Royal Haskoning (2007). North East Shoreline Management Plan 2, North East Coast, River Tyne to Flamborough Head.

Defra (2006) Flood and Coastal Defence Appraisal Guidance FCDPAG3 Economic Appraisal Supplementary Note to Operating Authorities – Climate Change Impacts October.