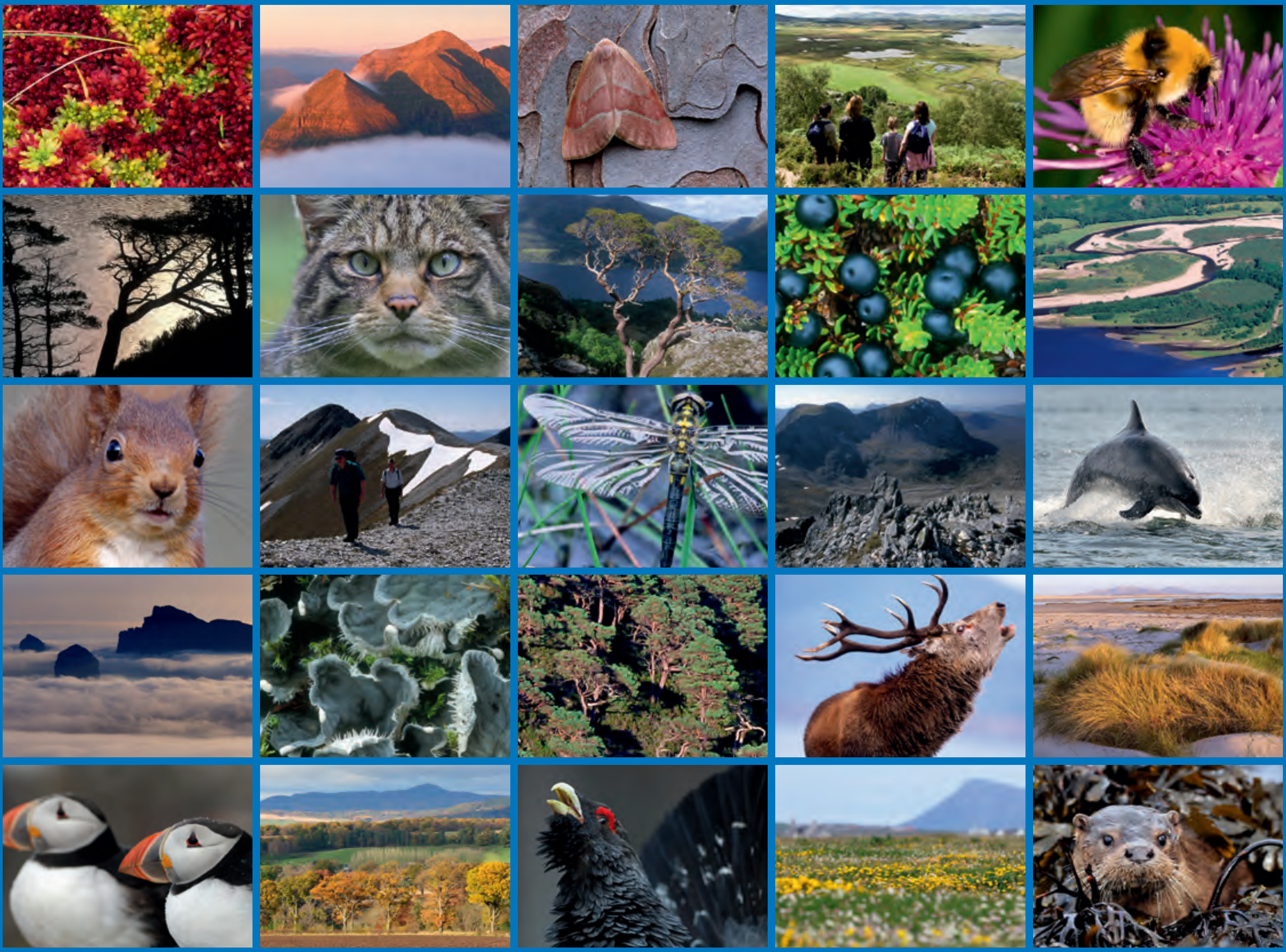
Scottish Natural Heritage
Commissioned Report No. 635

Golspie dunes: Coastal erosion options appraisal



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For further information on this report please contact:

Alistair Rennie
Scottish Natural Heritage
Great Glen House
INVERNESS
IV3 8NW
Telephone: 01463 725231
E-mail: alistair.rennie@snh.gov.uk

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COMMISSIONED REPORT
Summary

Golspie dunes: Coastal erosion options appraisal

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Background

- The coastal frontage of Golspie kart track is experiencing coastal erosion partly as a function of natural factors such as storm waves, sea level rise and reduction in natural coastal sediment supply but also as a result of coastal erosion protection measures emplaced to the north (updrift) of the site which have reduced the southward supply of sediment to the coast (downdrift).

- In order to assess the past changes in the position of the coast south of Golspie over time, the position of Mean High Water Spring (MHWS) and Mean Low Water Spring (MLWS) was extracted from historical OS maps dating from 1879, 1907, 1971 and augmented by aerial photography and ground survey from 2013.

- The rate and extent of past coastal change was established via 2D analysis of time-series historical and present day MHWS and MLWS positions at 205 transects (spaced 25 m apart). This showed a landward movement in MHWS along much of the shoreface, Taking the period 1879-2013 as a whole then the underlying trend is of a low coast that is susceptible to erosion of around 0.5 m/yr in the north increasing to 1.5 m/yr in the south.

- As is often the case the rate of movement of MLWS is more variable than MHWS. Over the period 1879-1907 MLWS accreted seaward at Golspie by up to 8 m/yr. South of this the MLWS largely accretes seaward at an average rate of about 1 m/yr over this period. The period 1907-1971 shows a change in the balance toward an erosion rate of 0.5-1 m/yr in the north and accretion in the south. This is reversed over the period 1971-2013 with erosion in the south of up to 7 m/yr. The trend over the last 40 years is of erosion and landward movement of MLWS in the south. Summary maps are also shown in the Annex.

- The likely causes of coastal erosion at the kart track are outlined and categorised into two groups; the underlying causes (such as sea level and sediment deficits) and the immediate causes (such as storm wave activity and human modification of the shoreline). Having considered the situation at Golspie kart track the potential management options available are: 1. do nothing, 2. extend or elevate the rock armour revetment, 3. beach nourishment, reprofiling and recycling, and 4. re-evaluation of land-use priorities.

- The authors' recommendations centre on a beach recharge scheme to reinstate a natural gravel beach ridge targeted on the key areas at risk from erosion and wave overwash leading to flooding. The targeted areas for recharge commence in the north at the golf course 6th tee and extend alongshore to join the kart track embankment in the south. A second area of recharge commences at the south end of the kart track embankment and extends approximately 100 m to the south.

For further information on this project contact:
Alistair Rennie, Scottish Natural Heritage, Great Glen House, Inverness, IV3 8NW.
Tel: 01463 725231 or alistair.rennie@snh.gov.uk
For further information on the SNH Research & Technical Support Programme contact:
Knowledge & Information Unit, Scottish Natural Heritage, Great Glen House, Inverness, IV3 8NW.
Tel: 01463 725000 or research@snh.gov.uk

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1. INTRODUCTION AND CONTEXT

Scotland's 600 sandy beach and dune systems comprise approximately 7% of the Scottish coast (Ritchie and Mather, 1984) and represent very dynamic components of the coastline, with the ability to adjust rapidly both to individual events and to longer term trends such as changes in sediment supply and sea level. However, beach response to the impact of individual events is constrained by a range of factors related to beach condition, such as the amount and calibre of beach sediment, beach profile geometry and the planimetric position of the beach and these factors are the result of trends that have affected the beach over the short, medium and long term. It follows that erosion, such as that which occurs at the Golspie Kart Track, is unlikely to be a recent phenomenon (although the rate at which the coastal edge recedes may be increasing) and it is unlikely to be restricted to the Kart Track frontage. As a result any proposed management of the Kart Track frontage needs to also consider the wider management of the beaches at Golspie.

1.1 Aims of the Project

1. To undertake an appraisal of the options for the management of coastal erosion at the site in order to inform discussions aimed at safeguarding both the activities of the Kart Track and the Natural Heritage interests of the neighbouring site.
2. Review the past and present rate of coastal change along the Kart Track frontage and wider coast.
3. Establish the likely cause of coastal erosion at the site.
4. Undertake an options appraisal of the alternative forms of management and their associated costs.

1.2 Methodology

1. The rate and extent of past coastal change was established via 2D analysis of time-series historical OS maps. This was done by comparing Mean High Water Springs (MHWS) and Mean Low Water Springs (MLWS) positions from OS maps in a geographic information system (ArcGIS). At 205 beach locations spaced at 25 m intervals along the coastal frontage, the change in distance between sequential positions of MHWS and MLWS was calculated using the Digital Shoreline Analysis System (DSAS) software. This programme computes rate-of-change statistics from multiple historic shoreline positions residing within a geographic information system (http://csc.noaa.gov/digitalcoast/tools/dsas).
2. The present configuration and altitude of 4.5 km of coastal frontage between Golspie town and Loch Fleet was established by obtaining ground altitudes via GNSS[1] survey and using these as height control for a Digital Terrain Model (DTM) produced by photogrammetry based on aerial photographs flown on 19th February 2013 by Caledonian Air Surveys Limited.
3. Results to be supported by a GIS.
4. Alternative management approaches to be considered as part of a cost-benefit appraisal.

1.3 Output

1. A succinct report and GIS outlining the analysis, results and management options.

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[1] GPS, the United States' Global Positioning System, is not the only satellite navigation system available. The term 'Global Navigation Satellite System' (GNSS) encompasses not only GPS but also GLONASS (Russia) and the developing Compass (China) and Galileo (Europe) satellite navigation systems.

1.4 Reporting

1. Final report delivery, 31 August 2013 supplied in Word for Windows format.

2. NATURE OF THE COASTLINE BETWEEN GOLSPIE AND LOCH FLEET

South of the bedrock and boulder outcrops at the north end of Golspie beach at Dunrobin, the entire coastline as far as Loch Fleet is of low altitude and backed by emerged marine sands and gravels deposited over a period of higher relative sea level some 6,500 years ago. Until recently, relative sea levels were falling in this part of Scotland and this has resulted in the deposition of a series of gravel beach ridges that lie at an altitude of about 10 mOD along most of the spine of the peninsula that extends from Golspie to the Loch Fleet exit. To the east (seaward) these gravel beach ridges also underlie the topography and in the northern part decline in altitude to a gravel-based platform at 5 m which underlies much of the Golspie golf course. In the southern part, the platform is absent and the emerged ridges are fronted by low-lying gravels at 1-2 mOD before merging with recent beach ridges at ca 2 mOD which are sometimes capped by low dunes the highest of which reach 4 mOD. The long term coastal development of this part of the coast is directly related to the net southward and alongshore sediment drift direction (Ramsey and Brampton, 2000). The (now emerged) gravel beach ridges progressively extended southward as an emerged spit composed of a series of ridges and recurves to progressively enclose a pre-existing wide inlet, This resulted in the enclosure of Loch Fleet and its fringing low-lying carseland (Figure 1).

This process continues at the present sea level with sands and gravels extending in a short stubby spit at the south end of Golspie Sands, their southward extension being arrested by the tidal outflow from Loch Fleet and which itself has formed a substantial ebb tidal delta. A key point is that spits often develop by updrift erosion at their proximal ends which then feeds sediment down-drift towards their distal ends (in the Golspie case erosion in the north feeds deposition in the south), a process that continues today.

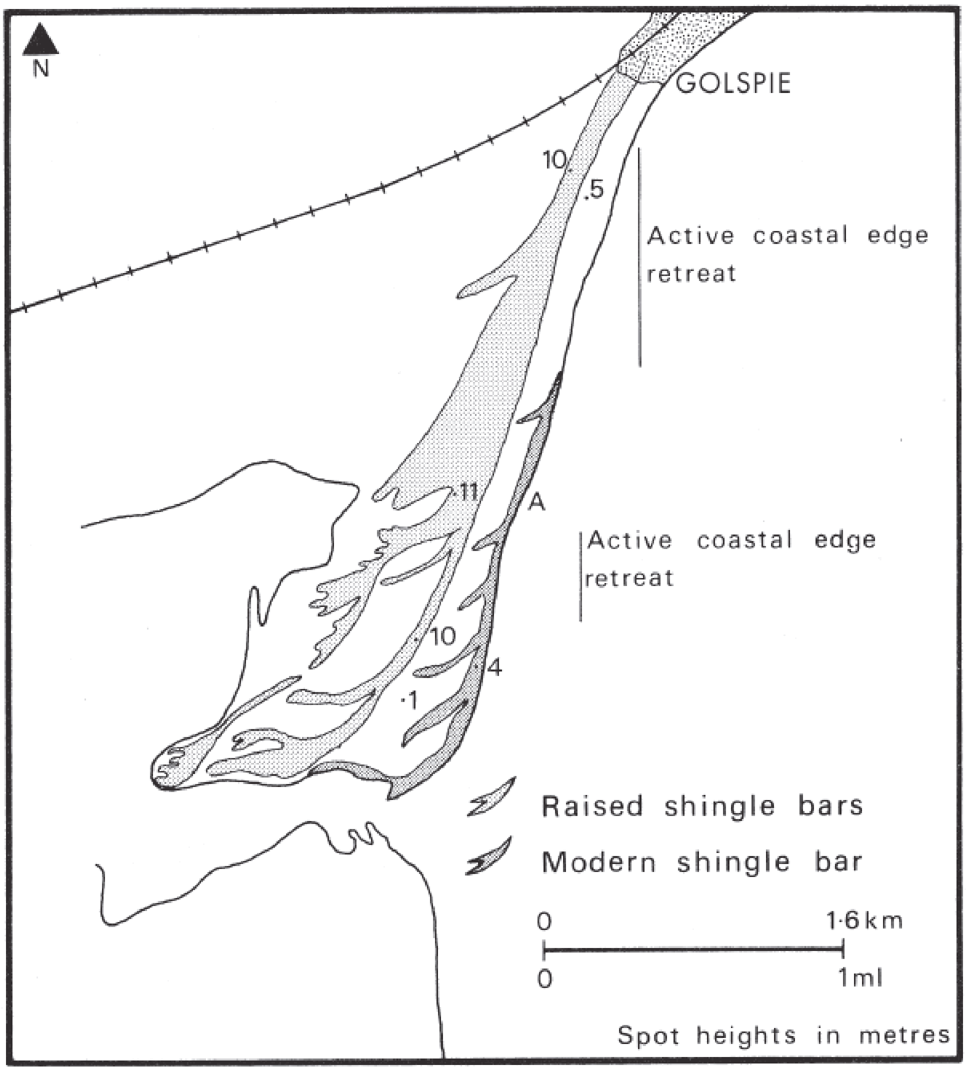

Figure 1: The southward-extending emerged gravel spit enclosing Loch Fleet and its carselands and fronted by an eroding Golspie beach (Smith and Mather, 1973).

The present day beach configuration reflects these trends with a net southward movement of sediment over a low beach composed of mixed sand and gravels, although substantial areas of the lower beach are composed of coarser gravels and boulders that move only infrequently with the coarsest boulders showing only limited signs of movement during recent storms. The maximum present day beach altitude is about 2 mOD, but it is occasionally marginally higher. The intertidal beach width varies between 100 m in the north at Golspie to well in excess of 200 m in the south at the Loch Fleet exit. Immediately landward of the beach, the coastal edge is characterised by a series of low sand dunes composed of sands that have been blown landward from the beach. These sand dunes are more than likely several thousand years old (although they will have been subject to more recent change and human modification) and veneer much of the area comprising the present day golf course, caravan park and Kart Track as well as the Loch Fleet National Nature Reserve (referred to for the remainder of the report as ‘the NNR’) to the south. However, the only area where the sand dune development can be described as recent and active is in the extreme south of the NNR toward the Loch Fleet exit where, in spite of evidence of landward migration of the shoreline (i.e. erosion), the availability of intertidal beach sand remains sufficient to comprise a healthy sediment source for dune growth. To the north of this the development of a fringe of dunes at the rear of the beach has led to elevations along the coastal edge that are higher than parts of the land inland, particularly southward from the vicinity of the golf course clubhouse. This situation is often described as having a ‘negative gradient’ where elevations briefly decrease landward of the MHWS ridge (Figure 2). Such areas are particularly vulnerable to erosion and flooding. Typically along much of the northern part of the golf course frontage the dune and undulating ground surface to the rear is of the order of 5 mOD. At the golf course southern boundary (the 6th and 7th tees) and at the adjoining caravan park and Kart Track, the dune cordon along the coastal edge is lower and narrower at ca. 3-4 mOD, with the ground behind lying at ca. 2-3 mOD. This creates the potential for extensive flooding if the narrow dune coastal edge is overtopped or breached during storm wave activity. In places elsewhere, erosion has removed the dune cordon.

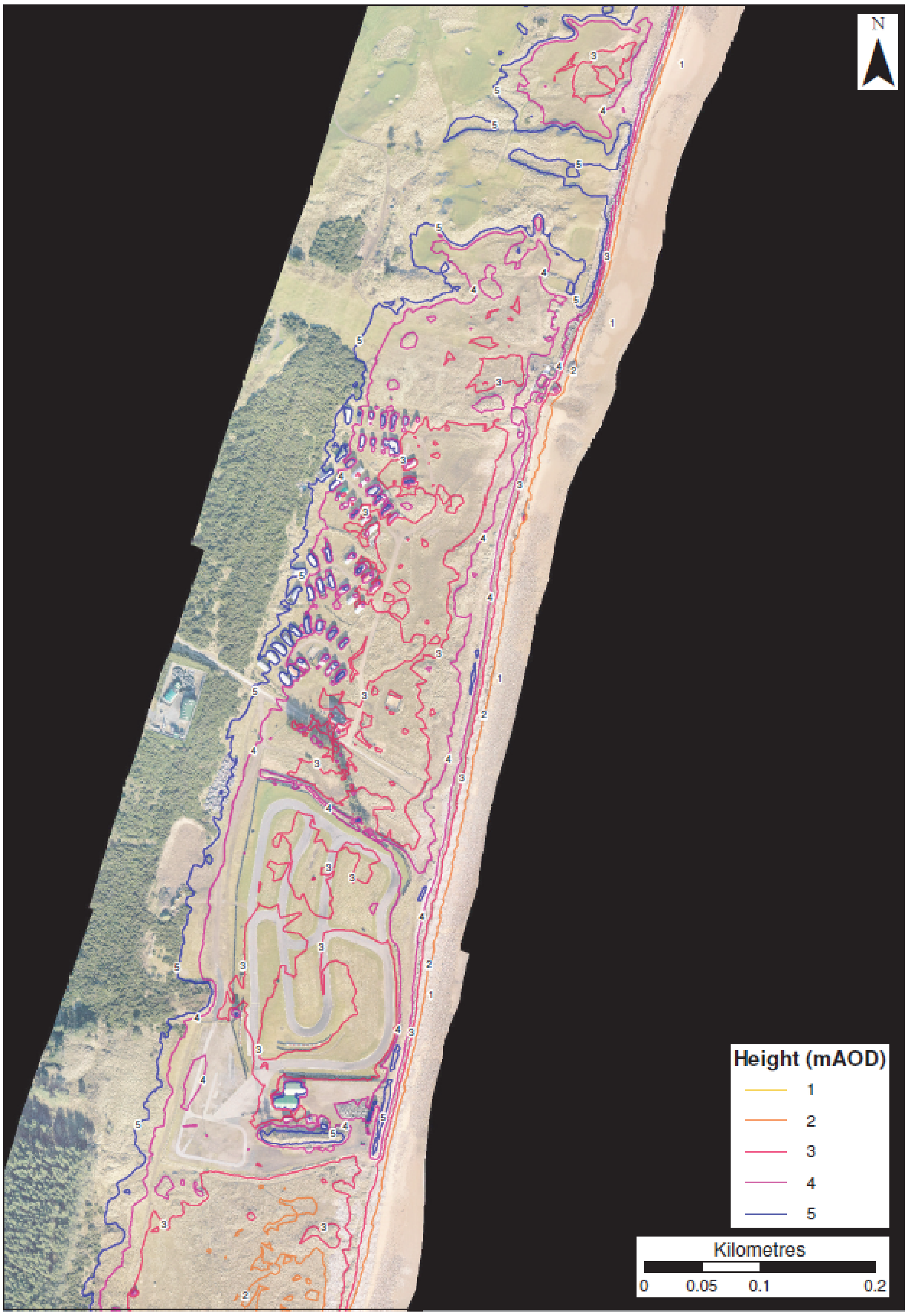

Figure 2: Aerial Photomap of part of Golspie Links from the southern end of the Golf course to the south end of the Kart Track with contours and spot heights in mOD (Photogrammetrically generated contours from photography flown on 19 Feb 2013 with GNSS ground control).

In view of the low altitude of the coastal edge and its sand and gravel composition, coastal erosion has been a feature of this coastline for many years, the rates and timing of which are detailed below. The response of both the Local Authority and golf course alike has been to favour hard engineering structures in an attempt to halt the loss of land. One of these structures is a masonry wall built in the late 1950's to replace earlier wooden structures in the north at Golspie town and a coast-parallel boulder breakwater of earlier but unknown age (Figure 3).

Figure 3: Golspie seawalls, pier and breakwater fronting the town and rock armour revetment fronting the northern part of the golf course.

The stepped and top-curved seawall extends southward parallel to the Main Street (the A9 trunk road) for ca. 450 m and is replaced by a 400 m long sand and dune beach that widens to 90 m wide in the south where it builds against, and is truncated by, a 120 m long coast-normal concrete pier (that parallels an older and now derelict counterpart). Smith and Mather (1973) show the area adjacent to the northern landfall of the pier to be artificially made ground that incorporates a waste tip fronted by the beach, both of which sit in the shelter of an older 900m coast-parallel boulder breakwater that emerges at MLWS (Figure 3). The coastal edge and MHWS deviates landward by 40 m before being replaced by a ca. 200 m concrete vertical sea wall that curves landward and further displacing the coastal edge by further 30 m inland beyond the beach line north of the breakwater. Abutting the southern end of the seawall, the coastal edge along the entire golf course frontage is protected by a substantial ca. 1.2 km long rock armour revetment constructed in phases in response to erosion which commenced at first in the north in the 1960's and early 1970's and led to rubble protection of the third hole being funded by the Manpower Services Commission. However the cumulative effect of erosion along the entire golf course frontage had resulted in lower-lying areas of the course being exposed to marine inundation and a storm in late

1977 submerged large areas of the 3rd, 4th and 5th fairways, as well as the 5th and 6th greens, with waves impinging on the embanked sides of the 18th green (http://www.golspie-golf-club.co.uk/chapter4.htm).

In 1979 rubble from a demolished railway bridge in Golspie was placed along the coastal edge below the golf course clubhouse and in 1980 funding from Highland Region saw the 3rd hole and most of the 4th hole given rock armour protection and four years later a similar scheme was effected around the 5th green and 6th tee. This led to a gravel storm ridge developing between the two lengths of rock armour revetment but this too has been subsequently replaced by a rock armour revetment so that the entire golf course frontage is artificially protected. Such a piecemeal down-coast extension of defences is typical where hard defences are installed on soft shorelines. It effectively exports the erosion ‘problem’ to adjacent sections of coast and fails to address the underlying cause. The most recent phase of coastal protection work along the golf course frontage occurred as a result of a storm in late 2012 when substantial lengths of the golf course rock armour revetment frontage was undermined, dropping in height to allow erosion of sediments behind the wall and overwash onto lower parts of the course itself. The remedial works focussed on reinstatement of the rock armour revetment to a slope of ca. 20-30^{O} and seated onto geotextile. Larger grade boulders were added together with a marginal increase in the rock armour revetment height and a gathering up of the coarser natural beach boulders harvested from the immediate foreshore. The planimetry of the reinstated rock armour revetment wall deviates into a series of mini headlands, particularly south from the Golf clubhouse, that follow the line of the erosional damage in the 2012 event whilst preserving the line of the holes and tees of the golf course. At the southern end of the rock armour revetment, at the 7th tee, the revetment is replaced by a rectilinear wall composed of over one hundred 1 m x 1 m gabion baskets that are seated directly onto geotextile over the natural beach material and fronted by rock armour revetment along the seaward face of the tee. The gabion wall takes an abrupt 90 degree turn inland for 4 m at the north and 11 m at the south of the tee before curving back toward an approximately coast-parallel orientation for 52 m (Figure 3).

This effectively creates a small headland on which the tee sits. The toe of the gabion baskets along this length are very steeply fronted by a 30^{O} slope over a 2m horizontal length of natural boulders that have been harvested from the adjacent fronting beach, contributing to its substantial lowering and boulder-free nature and increasing the vulnerability of this area of beach to wave impact. At the end of the gabion wall at the tee, the coastal edge moves inland by ca.11 m away from its natural orientation creating a small embayment backed by gabions and fronted by a depleted and lowered beach.

Immediately to the south of the gabion baskets at the southernmost end of the golf course land, the coastal dune fronts the ca. 430 m of caravan park. This area has undergone coastal erosion for many years but this has now increased to the point where only a narrow strip separates the upper beach from the lower lying land behind.

Figure 4: Position of the gabion baskets at the 7th tee and the erosional bight to the south.

Indeed there is a clear difference between the generally higher golf course land to the north of this point of 4-5 mOD (although there are a few lower parts) and the lower topography (2-3 mOD) of the caravan park, Kart Track and the northern part of the NNR (Figure 2). Along the caravan park frontage there is evidence of earlier work to reform the coastal edge to a height of ca. 3 mOD with sand and gravel taken from the upper beach, this strategy has been continued in the aftermath of the 2012 storm and augmented using gravel cleared from the overwash lobes that extended into the caravan park itself, mainly at its northern and lowest end where wave overtopping occurred in the 2012 storm, leading to marine flooding of the caravan park to a depth of 1-1.5 m. In spite of this the reformed coastal dune retains the characteristics of a natural ridge but it remains narrow and thus vulnerable to further wave erosion and overtopping to access lower land behind (Figure 4).

Figure 5: Reprofiled coastal ridge at the caravan park and lower land to the rear.

The ca. 320m Kart Track frontage has been eroding for many years and rubble has often been dumped along the beach frontage at, and south of, the access road end in an attempt to slow the rate of loss at this point. Concerns have been raised by the Kart Track managers over the altitude and narrowness of the frontal ridge well before the storm of 2012. The response to the 2012 storm has been the creation of a substantial sand and gravel embankment (or bund) along the Kart Track frontage (ca.4-5 mOD) that is positioned slightly seaward of the pre-existing natural line of the coast. Its seaward toe is faced with rock armour of similar grade to that used along the golf course frontage, augmented with large natural boulders harvested from the upper beach. The unsorted builder's rubble that was part of the earlier embankment (reflecting older development on the site) in this location was reused and remains visible in the reformed embankment along with substantial quantities of smaller gravels and sand beach material which may have been harvested from the upper beach or from a small sand and gravel quarry at the western end of the Kart Track land. As a result the embankment contains a mixture of calibres of material rather than the interlocked rock armour structure along the golf course frontage and so will be subject to more rapid erosion and undermining than is likely along the golf course frontage.

Another key point about the Kart Track embankment is its abrupt termination at the Kart Track boundary where it is replaced by a natural low gravel beach ridge whose altitude is a full 2-3 m lower than the crest of the embankment (Figure 6). Gravel overwash lobes at this point indicates that this area was overwashed during the 2012 storm with marine incursion onto the low-lying land behind.

Figure 6: The Kart Track embankment lies 2m vertically above the height of the adjacent coastal edge to the south.

The ca. 2.2 km coastline of the NNR to the south of the Kart Track is essentially a suite of natural sand and gravel beaches fronting a series of low gravel ridges before rising inland to the emerged gravel ridges that support woodland. Dune development, although sparse, increases to the south where the supply of beach sand becomes more plentiful. The low altitude of the fronting gravel beach ridge is such that wave overwashing appears to have been commonplace and not particularly restricted to the 2012 event and this is confirmed by pre-event aerial photography and on the ground by older gravel overwash lobes.

The beach and back beach to the immediate south of the Kart Track is composed mainly of medium sized gravels with a significant proportion of smaller concrete and brick rubble excavated from the eroding sections updrift. The upper and lower beach is dominated by a substantial gravel ridge (Figure 7) to just over 1km south of the Kart Track boundary where a substantial gravel and boulder bank extends seaward at MLWS and across which wave breaking can be observed. Smith and Mather (1973) note that these lower intertidal boulders appear to be immobile lag deposits and this appears to be currently the case. Although gravel ridges occur along the upper beach and gravel and boulders occur on the lower beach, to south of this point increasingly the lower beach becomes dominated by sand. Eventually the sand extends to include the upper beach with the low back beach ridges being replaced by low sand dunes that grow in height to the south and the Loch Fleet exit. It is clear that the greatest amount of planimetric change associated with the 2012 storm occurred within the NNR (particularly close to profile 81 with MHWS moving post-event by 70 m inland but this had stabilised at about 30-40 m inland by July 2013).


29.07.2013

Figure 7: To the south newly deposited gravels form substantial coastal parallel ridges.

3. COASTAL CHANGES AT THE KART TRACK AND ADJACENT COAST

Assessment of past changes in the position of the coast south of Golspie involves the collection of positional shoreline changes from historical Ordnance Survey maps, aerial photography of February 2013 and GNSS ground survey in August 2013. This was augmented by several visits to establish the site condition before and after the 2012 storm.

3.1 Selection of Time Steps

The data collection process included the plotting of positional shoreline changes as depicted on historical and present day OS maps at 1:10,250 and 1:10,000 scale and the use of these positional movements to infer movement within the beach profile. Taylor *et al*. (2004) used two map dates (oldest and latest). In order to assess whether two map dates effectively capture the changes and identify whether any long term trends have accelerated in the mid to recent time step, the present study used four map dates to produce three time steps: the earliest OS 1:10,250 county series from 1879 and 1907, the 1:10,000 map from 1971 (approximately 100 years after the early map series) and GNSS ground survey mapping using a Leica Smartnet RTK rover in August 2013. This was augmented by aerial photography flown on 19 February 2013 (i.e. after the 2012 wave event). Therefore the time steps used here are 1879-1907, 1907-1971 and 1971-2013. Although maps exist for intermediate years, the position of MHWS and MLWS had not been updated (such as the 1959 OS maps) and so were rejected for this analysis. The maps were downloaded from the EDINA Digimap and are digitally geo-corrected (thus avoiding many of the errors associated with distortion and other inaccuracies inherent in the use of historical maps (Burrough and McDonnell (1998)) and allowing direct import into a GIS package (ArcMap). The mapping errors quoted by Ordnance Survey amount to 5 m for the pre 1945 and 3.5 m for the post 1945 maps (Landmark Group, 2002), however a 1mm line at 1:10000 scale equates to 10m on the ground. Thus 10m may be the minimum detectable change on the ground using these sources. Accepting these caveats, the results compare the plotted positions of MHWS and MLWS from the time series maps and photography and establish the absolute movement of these relative to the OS National Grid.

3.2 Selection of Profile Steps

The rate and extent of past coastal change was established via 2D analysis of time-series historical OS maps. This was done by importing georectified Mean High Water Spring (MHWS) and Mean Low Water Spring (MLWS) positions from OS maps and surveys into a geographic information system (ArcMap). Numbered from the south, 205 beach locations spaced at 25 m intervals along the coastal frontage were used to calculate the change in distance between sequential positions of MHWS and MLWS using the Digital Shoreline Analysis System (DSAS) software (Figure 8). This programme computes rate-of-change statistics from multiple historic shoreline positions residing within a geographic information system. (http://csc.noaa.gov/digitalcoast/tools/dsas).

The rate of MHWS landward advance or retreat was established at each of the profile locations as was the rate and movement of MLWS and depicted on the plotted maps as colour coded lines relating to the date of the map. Mapping of the planimetric change in both MHWS and MLWS is depicted over the 2009 SNH/PGA aerial photography as the base. The rate of MHWS and MLWS migration was calculated as an average movement rate in metres per year, derived from the distance moved by the MHWS or MLWS position divided by the intervening time interval. The dataset created is thus both manageable and, when depicted as a line graph, clearly indicates the trend to show flattening or steepening profiles. In order to depict whether MHWS or MLWS had moved landward or seaward on the line graph, a negative number was used for landward movement (erosion) and a positive number for seaward movement (accretion), with a horizontal line along the central x-axis indicating no change in position. The movement of MHWS and MLWS also reflects the changes in beach width over the time steps.

3.3 Changes in the planimetric position of MHWS and MLWS

The changing positions of MHWS and MLWS are depicted on Figures 9a and 9b and the annual rate of movement of these lines over the same periods is reported below in sections 3.4 and 3.5. In the northern part of the Golspie beaches the overall movement of MHWS and MLWS (Figure 9a) has been landward movement from the1879 position, although a seaward movement of MLWS occurred between 1879 and 1907 with the 2013 position being close to the 1971 position. The 2013 MHWS showed a landward movement and attendant erosion up to the period 1971 to 2013 when the eroding coastal edge was protected and landward movement arrested.

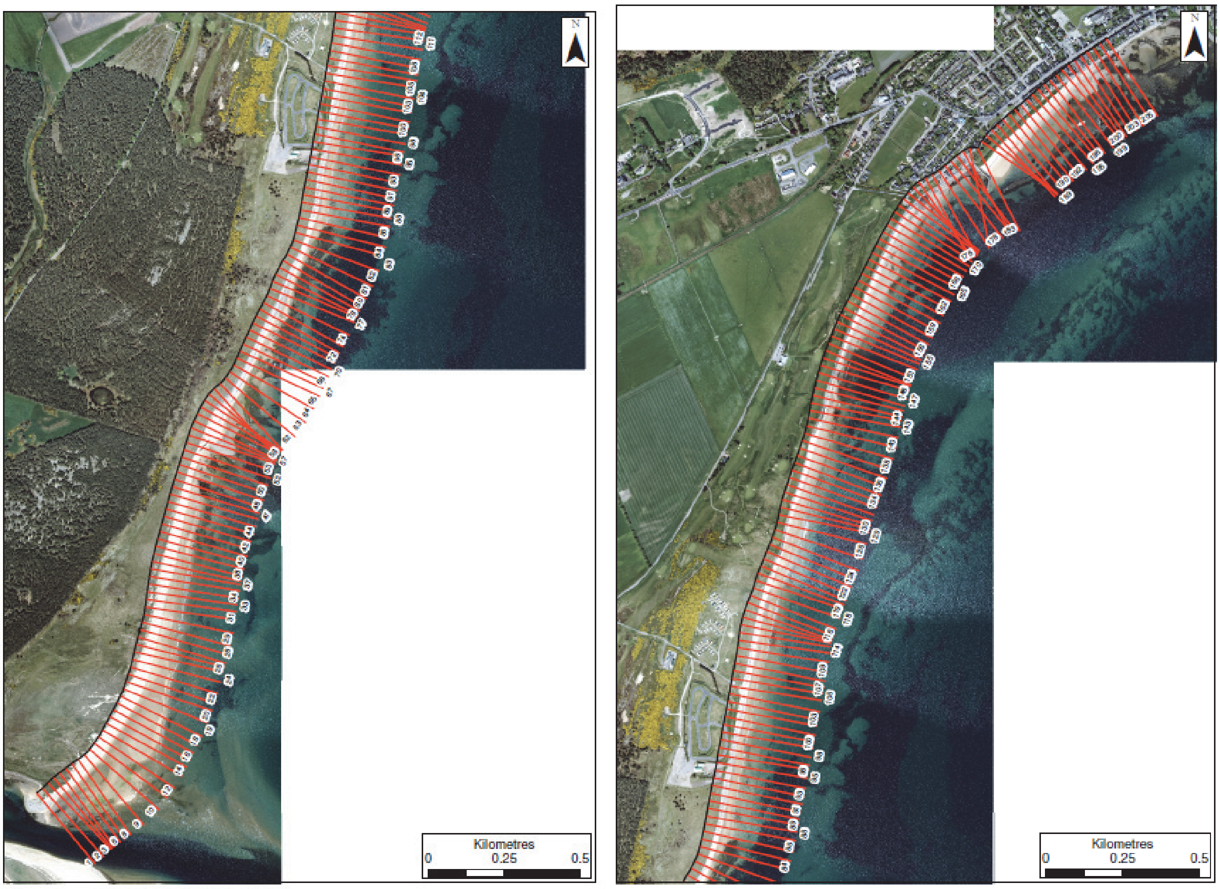

Figure 8: Location of the selected beach profiles using DSAS and 2009 aerial photography (Photography data licensed to SNH under the PGA, through Next Perspectives).

In the south (Figure 9b), the long term trend of MHWS migration landward continued, with substantial erosion and landward shifts to the south close to the Loch Fleet exit. In the north of this section both MHWS and MLWS are now at their furthest landward positions recorded and this trend extends to the south for MHWS with only minor areas of accretionary infill from the 1971 position. However, the movements of MLWS are more variable to the south of this point with a trend of accretion from 1879 to 1907 being continued until 1971 when MLWS reached its most seaward extent. By 2013, the position of MLWS shows a narrowing in extent particularly at the southern end to a position approximating the 1907 position. The plotted extent of MLWS toward the south is subject to due to variations in the extent of mobile sand banks related to the outflow of Loch Fleet. As a result the plotted position of MLWS in this area should be treated with caution.

The following maps are repeated with a different shading style in the Annex 1.

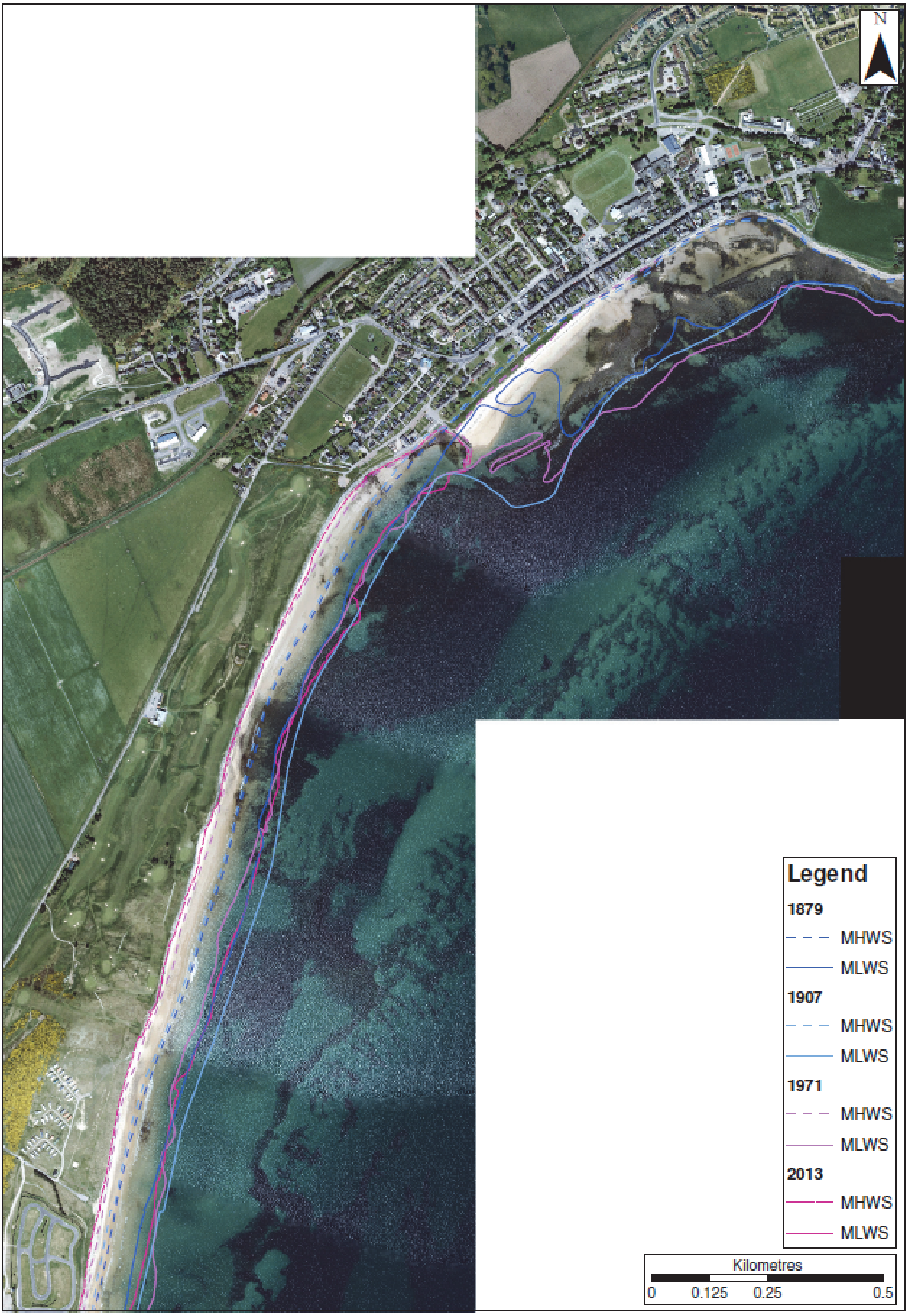

Figure 9a: Changes in the position of MHWS and MLWS in 1879, 1907, 1971 and 2013.

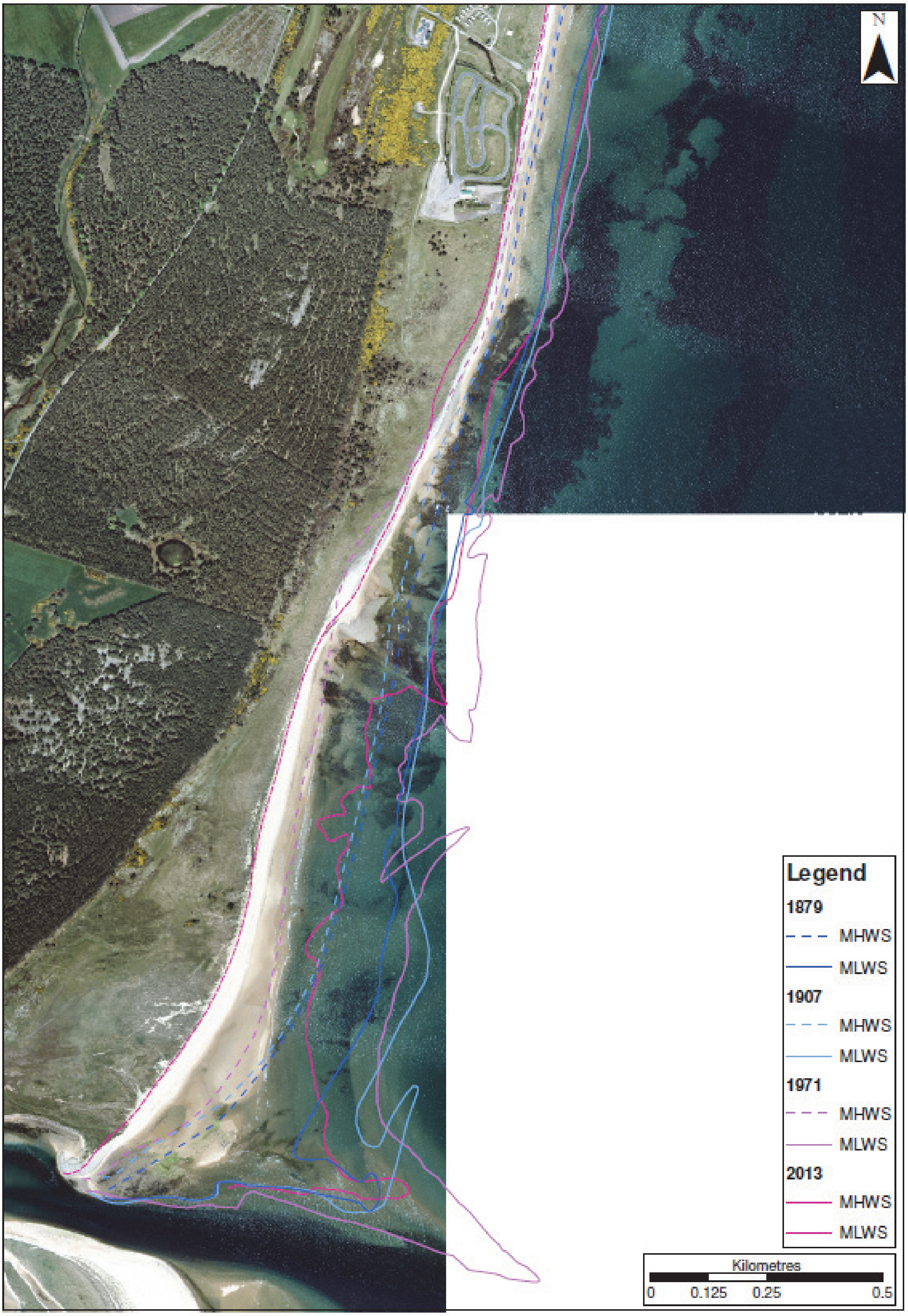

Figure 9b: Changes in the position of MHWS and MLWS in 1879, 1907, 1971 and 2013.

3.4 Rate of change in MHWS

Plotting the change in position of MHWS at each of the 205 cross-beach profiles allows rates of migration of the MHWS in each of the time steps to be graphed (Figure 10 & Annex). What this demonstrates is a long-lived landward movement in MHWS along much of the shoreface, an erosional trend that confirms the on-site observations reported over the years. The erosion between 1879 and 1907 was 0.5 m/yr in the north, rising to over 1m/yr in the south, including at the Loch Fleet exit, an erosional trend that accelerated between 1907 and 1971, particularly south from profile 80 where it reached 2 m/yr, an overall recession of 128 m. The inland trending suites of gravel ridges to the rear of the present beach profiles 64-52 are evidence of this erosion and mark the MHWS position at that time. North from profile 180 (the well end at Golspie town frontage) the construction of the cobble breakwater, made ground and early seawall construction can be seen with the MHWS either stabilised or accreted seaward by a small amount. Since the 1970s, much of the town and golf course frontage has been protected and this is shown in the stability of MHWS over the period 1971-2013. Between 1971 and 2013 profiles 71-51 accreted reversing the earlier erosion centred on profile 61. To the south of this point, erosion over the period 1971-2013 increased to 2.5 m/yr, albeit with slight decrease to 0.5 m/yr close to the Loch Fleet exit.

Taking the period 1879-2013 as a whole (dark blue dotted line) then the underlying trend is of a low coast that is susceptible to erosion of around 0.5 m/yr in the north increasing to 1.5m/yr in the south (Figure 10 & Annex). However, it should be noted that this overall trend masks a trend over the last 40 years of engineered stability in the north and natural erosion in the south with an area of accretion at the junction (profile 61) marked by the recent construction of a new gravel ridge (Figure 7). The rate of coastline erosion along the unprotected frontage of the Kart Track and caravan park (profiles102-120 on Figure 10) should be approximately the same as that along the protected rock armour revetment of the golf course north of profile 120 may be related to unofficial efforts of the managers of this stretch to replenish the eroding frontage with soft erodible sediments in order to slow erosion rates.

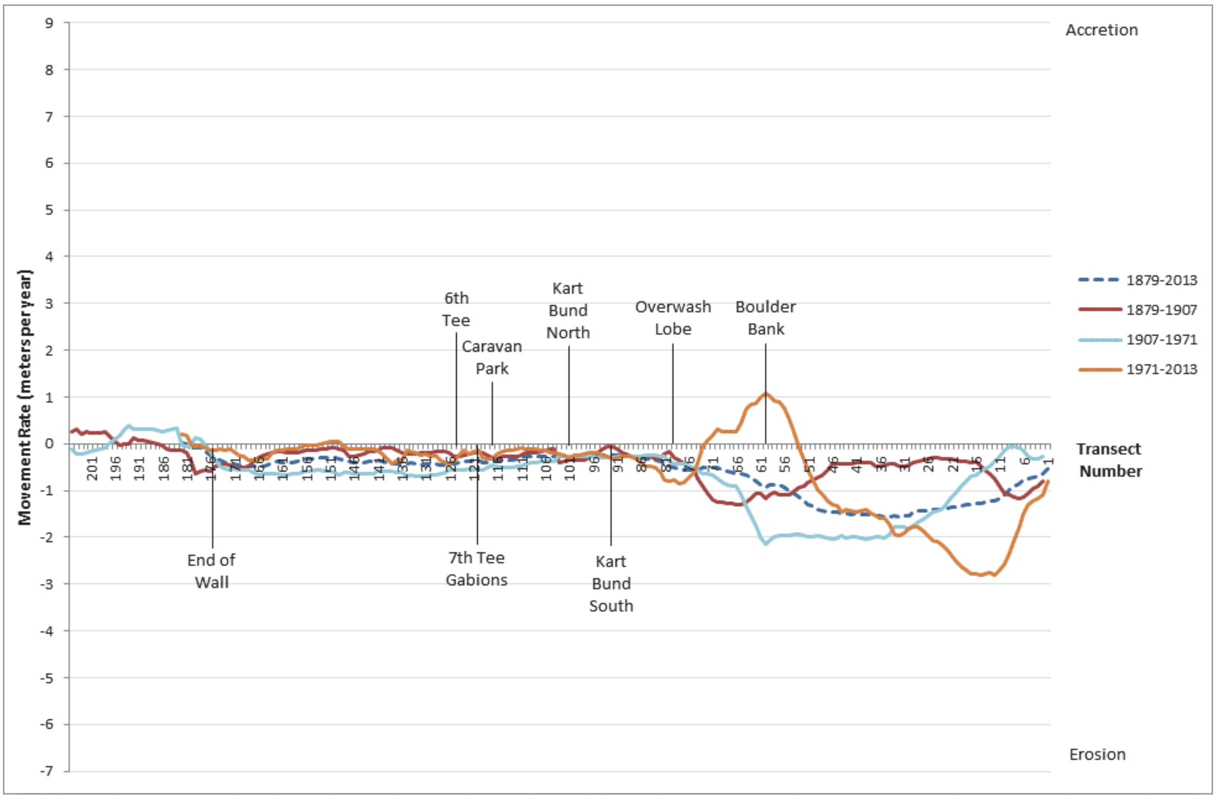

Figure 10: Mean High Water Spring Movement Rates (1879-2013).

3.5 Rates of change in MLWS

In comparison with the movement of MHWS, the rate of movement of MLWS is much more variable (Figure 11), which is often the case (Hansom, 2010). Over the period 1879-1907 (brown line), MLWS accreted seaward at Golspie by up to 8 m/yr on account of sediment moving south to be trapped updrift of the early timber pier at profile 180 (end of the Golspie sea wall). South of this the MLWS largely accretes seaward at an average rate of about 1 m/yr over this period, except close to the Loch Fleet exit where accretion occurs (Profile 16).

The period 1907-1971 (light blue line) shows a change in the balance toward an erosion rate of 0.5-1m/yr in the north and accretion in the south, largely in agreement with an expectation of sediment movement southward. 1971-2013 (orange line) reveals a low rate of MLWS accretion north of profile 120 and an accelerating but variable rate of erosion to the south of up to 7 m/yr. Overall the period 1879-2013 was characterised by MLWS movement seaward and landward and resolving into an approximately stable position in the north and a slight tendency toward erosion in the south with the exception of the Loch fleet exit where accretion dominates. However, it should be noted that this overall trend masks a trend over the last 40 years of erosion and landward movement of MLWS.

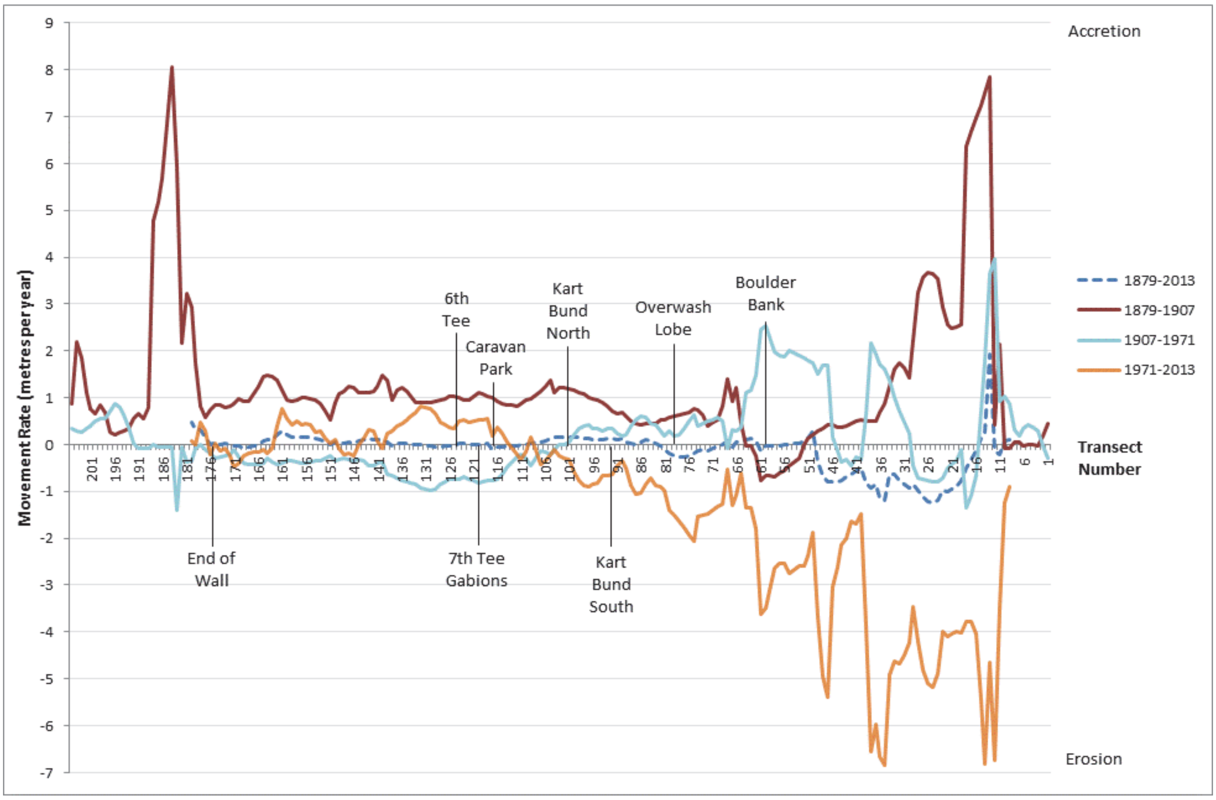

Figure 11: Mean Low Water Spring Movement Rates (1879-2013).

3.6 Changes in Beach Width

The changes in the planimetric position of MHWS and MLWS forces changes in intertidal beach width and gradient or height (Figure 12). Beach width north of the Golspie pier at profile 180 has remained relatively stable, showing a slight increase in width over its 1879 state (dark blue line). Everywhere to the south of this point, the beach in 1879 was narrower than at any time afterward, including in 2013. Between profiles 180 (end of the Golspie seawall) and 61 (the intertidal boulder bank), the beach width accreted up to 1971 (light blue line), but then began to reduce in width by 2013 (orange line).

This trend of a wide beach in 1971 continued to the south of profile 61 but became more variable due to the extent and orientation of sand bars at MLWS, a trend mirrored by the narrower 2013 widths at the south end of the beach. Beach widths are affected both by movement in MLWS as well by MHWS so that erosion of MHWS and a static MLWS leads to an increase in width. By the same token, seaward movement of MHWS either by accretion or by construction of defences seaward of their former position, together with a static MLWS leads to a reduction in beach width.

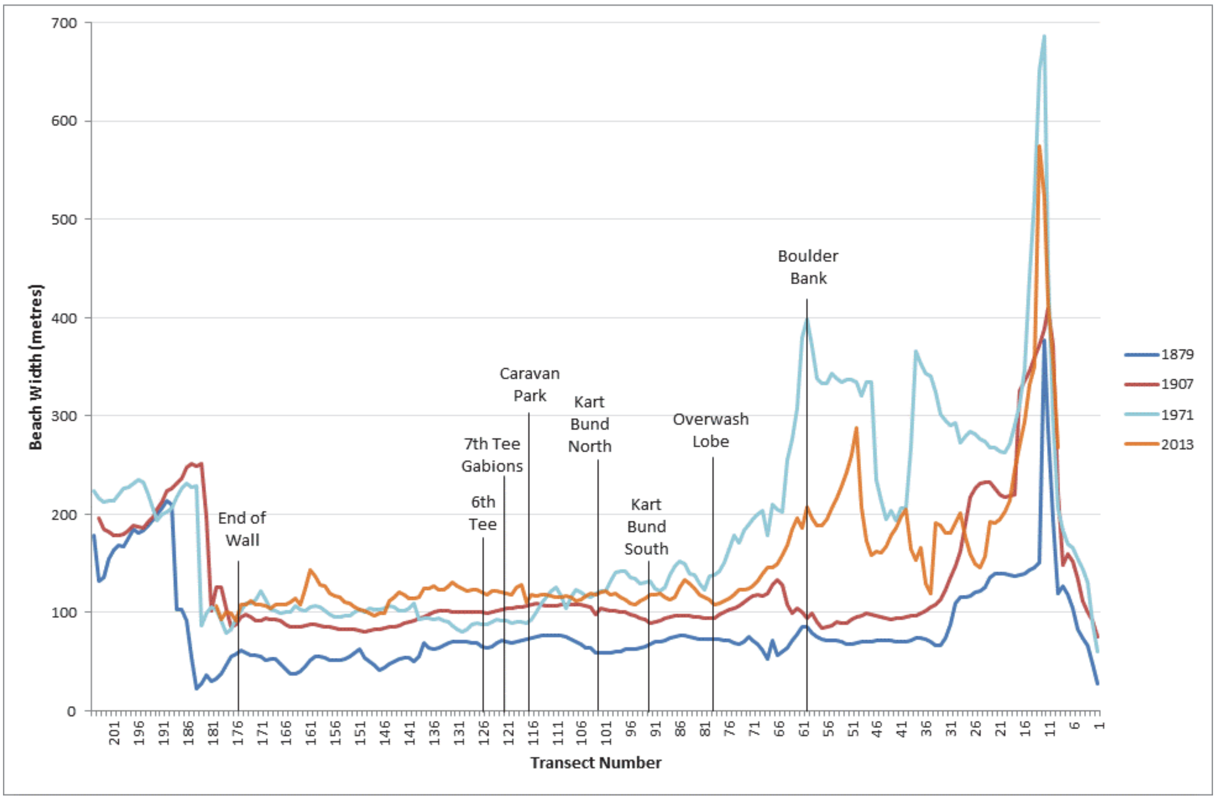

Figure 12: Changes in Beach Width (1879-2013).

4. LIKELY CAUSES OF COASTAL EROSION ALONG THE GOLSPIE DUNES

Coastal erosion at the Kart Track does not occur in isolation from the conditions that affect the rest of the Scottish coastline both over the short, medium and long term. The processes that cause erosion can be resolved into two broad categories: underlying causes and immediate causes.

4.1 Underlying Causes of Coastal Erosion

Modern coastal response to recent change is fundamentally affected by past history. Whilst it is widely accepted that a major driver of change at the coast is rising relative sea level (RSL), some have questioned its primacy preferring to cite enhanced storminess as the main driver. There is disagreement over whether the indices used to assess storminess convey reality and this has led to confusion about its impact on coasts. Other factors are also at work such as reductions in the availability of coastal sediment. The main concern for much of the sedimentary and developed coast is an underlying trend for erosion.

4.1.1 Relative Sea Level (RSL) Change

RSL is composed of a combination of two principal components: isostatic processes (changes in local vertical movements of the Earth's crust) and eustatic processes (changes in the global volume of the world's oceans and its elevational distribution due to gravitational changes). In Scotland, isostatic processes have mainly been driven by the effects of past glaciations and the weight of ice, with the last phase of deglaciation (Smith, 1997) allowing the crust to uplift rapidly in those places where depression had been greatest and subsiding where the ice sheet had been thinner or absent. The resulting Holocene isostatic adjustment has greatly influenced the geomorphology of Scotland's coastline (Smith, 1997). The second or eustatic effect relates to the increase in global sea level from about -120 m at the end of the last glaciation to its present level (Hansom, 1988). Both isostatic and eustatic processes have been subject to variation in the rate of change and this gives rise to local RSL rise and fall.

In the Golspie area before about 7000 years ago global sea level was rising faster than isostatic uplift and this led to the development of beaches inland of where they are now. However, this rapid rate of global sea level came to an abrupt halt about 6500 years ago allowing isostatic uplift to continue to elevate the newly formed coastlines to altitude. Thus the combined effect of eustatic and isostatic processes resulted in the creation of suites of emerged coastal landforms within the uplifting area (e.g. the emerged gravel ridges at Golspie).

Although it is known that isostatic uplift wanes over time, the rates are imprecise with Shennan and Horton (2002) placing rates in the Golspie area at about 0.7 mm/yr. Crucially, however the rate of global sea level has recently increased to exceed the uplift rate and tide gauges suggest that RSL may now be rising in the Golspie area by between 1 mm/yr and 4 mm/yr depending on the time period sampled (Rennie and Hansom, 2011) with the more recent time period agreeing with the global sea level rise figures of 3.4 mm/yr (Figure 13) (http://www.ngs.noaa.gov/GRD/GPS/Projects/CB/SEALEVEL/sealevel.html). It seems likely that if RSLR is increasing at a faster rate than previously then this will increase coastal erosion rates since waves access the coast at a higher level.

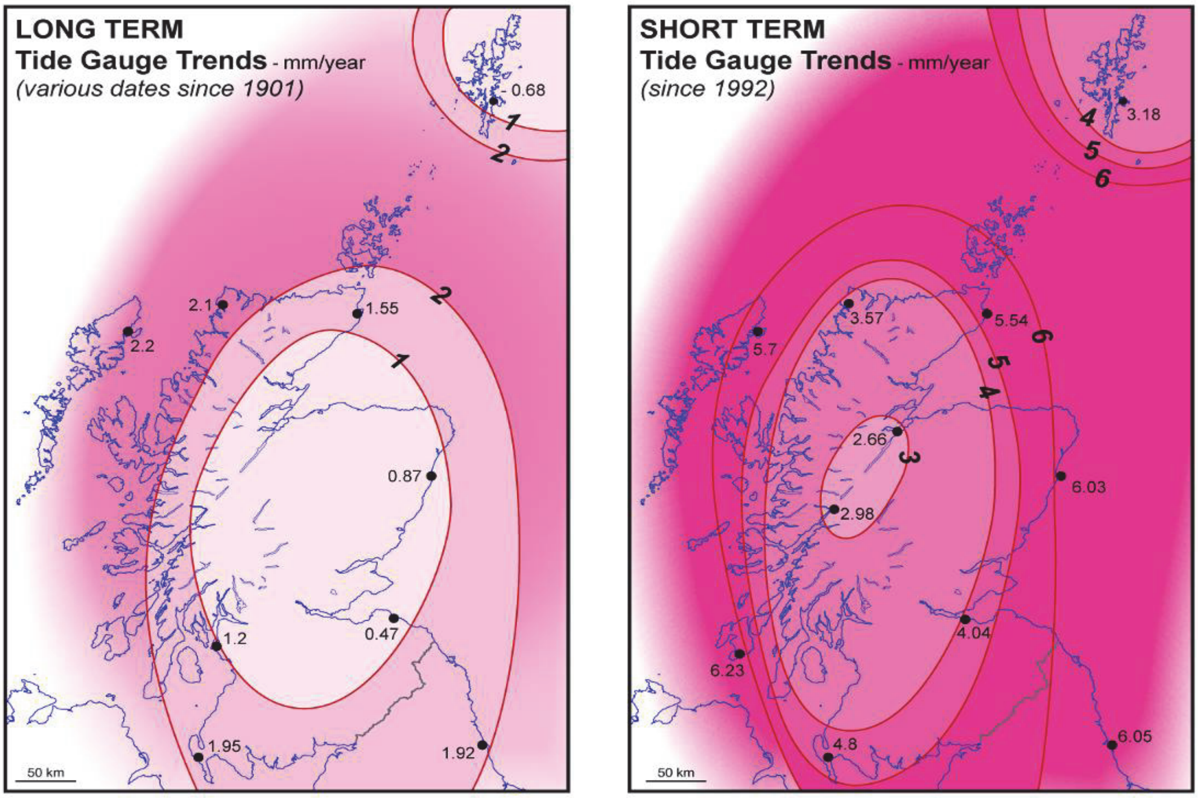

Figure 13: Short term tide gauge trends reflect an increase in relative sea level rise since 1992 over long term rates (from Rennie and Hansom, 2011).

4.1.2 Storminess and Waves

The capacity of sea level to effect erosion rather than inundating the land, *per se*, is largely a function of the wave energy that now impacts the shore at an elevated level. In other words, waves are the driver of erosional events. Unfortunately, the availability of wave data is spatially patchy and does not extend far into the past. However, wind speeds and wave heights are closely related and, as a result, there has been much interest in examining the storm or gale record as a proxy for the trend in high energy wave events. For example a close relationship between wind speed and wave height was seen between the simultaneous record of wind at Leuchars and wave heights at the North Carr Light vessel off Fife Ness (Green, 1974).

One of the longest records of gale days available for Scotland relates to Edinburgh (Dawson *et al*., 1997). Spanning 1767-1990, it shows three peaks of storminess, each with over 50 gale days annually. The first and greatest was between 1810 and 1820, the second from 1880 to 1890, and the third and weakest from 1975 to 1990. However the number of gale-days may be a poor predictor of the severity of the gale and the waves generated. It is well known that the impact of storms on the coast is highly sensitive to the storm-track and its landfall so that substantial modification can occur as a result of a very few high magnitude events that may not produce the same impact at adjacent coasts (c.f. the 2005 storm impact on the Western Isles was related to the timing and coincidence of tide, surge and wave conditions and demonstrated in the marked difference in damage sustained by the Western Isles compared to the Orkney Isles). The greatest storm impact on shores is less likely to be the number of gale-days and more likely to be as a result of a few extreme events weakening the fabric of the coastal structure so that any secondary events may have a more damaging effect (Chadwick *et al*, 2005).

In spite of the absence of evidence of an increase in the frequency of storms, there is evidence of an increase in the severity of storms as represented by increases in storm wave height over recent decades. For example, Gunther *et al*., (1998) detected an increase in significant wave heights in the West Atlantic of 2.5-7 mm/yr over the period 1955-94. This is supported by observational data indicating a 1-3 mm/yr increase in North Atlantic wave height over the last 30 years (Gulev & Hasse, 1999). If this is the case then it is likely that the maximum height of extreme waves in the Atlantic has been subject to increase over the last 30 years. Similarly, Bacon and Carter (1989; 1991) demonstrated that North Sea wave heights have increased from 1960 to peak values in 1980 and continued to increase in height through the 1980s, to reach the greatest values of the late 20th century. Although imprecise, there is emerging evidence of increases in the severity of waves during major storms in both the North Sea and Atlantic that will enhance coastal erosion in the future as predicted by DEFRA (http://ukclimateprojections.defra.gov.uk).

4.1.3 Changes in Coastal Sediment Supply

One of the indirect effects of sea level change driven by glacial cycles is on the delivery and availability of coastal sediment. When sea levels are rapidly changing there is always new sediment on the sea floor being accessed by waves. However, an important implication of the reduction in the rate of sea level rise from about 7,000 years ago was that the total volume of sediment lying within the offshore ‘bank’ and within effective wave-base (and therefore available) was finite. Early in this process substantial amounts of sediment accumulated on beaches and was then blown into sand dunes, however progressively the sediment ‘bank’ has become depleted and many of the accreting beach systems that were formerly fed by these sources are now erosional (Hansom, 1988; 2001; Hansom and Angus, 2001). In addition, many beaches that were formerly fed by fluvial reworking of glacigenic deposits now experience a much reduced sediment supply from such sources and very few rivers still deliver significant amounts of sand and gravel to the coast (May and Hansom, 2003). Although some areas of the Scottish coast may still be supplied by sediments from the nearshore zone, downdrift of longshore drift systems and at the exits of a few rivers, the bulk of Scottish beaches are subject to sediment supply deficits and no longer receive the volume of sediment required to sustain them in their present position and condition.

One of the indicators of a reduction in sediment supply is where the Mean High Water Mark (MHWS or historically MHWOST) has migrated shoreward at a different rate from that of Mean Low Water Mark (MLWS or historically MLWOST) so that the intertidal cross-profile does not retreat or progress as an equilibrium profile, but develops towards a steeper profile to produce coastal steepening (Soulsby et al. 1999). This is of importance since as the gradient of the intertidal increases and beach width narrows so too does the wave energy accessing the upper beach, resulting in increased exposure, coastal erosion and risk of inundation. The phenomenon has been recognised for some time, having first been reported as a general problem in the United Kingdom by the Royal Commission on Coastal Erosion and Afforestation in the early 20th century (Bird & May, 1976) and recently Taylor *et al*. (2004) identified that 61% of the coastlines studied in England and Wales had become steeper over the last 113 years. Hansom (2009) also identified similar steepening to be occurring on many open coast beaches in Scotland as a result of the position of MLWS moving landward at a much faster rate than MHWS. This may be on account of waves operating for less time at MHWS than at MLWS, greater resistance presented by resilient but erodible materials to the rear of the beach at MHWS than at MLWS and the fixing of MHWS by artificial shore defences to prevent its migration. On all of these counts, MLWS is not so constrained in its migration and as such its more rapid landward retreat relative to the MHWS is of concern.

4.2 Immediate Causes of Coastal Erosion

The immediate causes of coastal erosion in the Golspie area are firstly the coincidence of storm wave activity and high tidal conditions and secondly the impact of artificial modification of the shoreline both at the site and on the adjacent coast.

4.2.1 Storm Wave Activity

Much of the east coast of Scotland is affected by storm wave activity from the north and east and the coast at Golspie is no exception. Indeed Smith and Mather (1973) recognised that this area of the coast is affected by strong easterly winds during the spring and autumn, particularly if the landfall of the storm is coincident with high tide. The orientation of the coastline between Golspie and Embo is more or less north-south and, for 29% of the time, waves approach from between northeast and southeast, this also coinciding with the direction of approach of the most severe storms (Hansom and Black, 1996). With net southward tidal and wave-induced currents, the net long term sediment transport direction is to the south with a moderately high rate being likely (Ramsay and Brampton, 2000). On the 14th and 15th December 2012 a low pressure system in the North Sea produced south easterly gales that generated a predicted 0.5m storm surge and observed inshore waves of up to 6m high (http://www.bbc.co.uk/news/uk-scotland-north-east-orkney-shetland-20746956). The storm landfall coincided with a predicted high spring tide overnight on the 14th at Helmsdale and which produced widespread damage, erosion and flooding along the east coast. This was followed by a second period of erosion and flooding on the next high tide on the 15th before the wind began to abate. It is clear that at Golspie this event impacted on a shore that had been armoured at its north end and had undergone decades of lowering in front of the defences.

4.2.2 Human Modification of the Shoreline

Human attempts at remedial work to prevent or slow erosion in the Golspie area have been relatively successful in fixing the position of MHWS at the immediate protection site but at the expense of long-term sustainability. This is because the eroded sediments are prevented from entering the system to feed the fronting beach immediately seaward of the protected stretch as well as having an impact of the beaches and dunes downdrift. The construction of seawalls or rock armour, such as those at Golspie, represent direct intervention aimed at slowing or halting erosion of MHWS at specific locations and whilst many are successful in this aim, they are also responsible for two major effects.

Firstly, 'beach draw-down' is a process whereby the beach lowers and erodes, commonly in response to an increase in wave reflectance associated with hard, steep impermeable coastal defences leading to basal scour at the toe of the structure. Such structures also contribute to beach steepening and the reduction of sediment supply previously contributed from erosion of the backshore (Hansom, 1988). The effect is most severe where vertical or stepped concrete seawalls are used, since these are efficient wave-reflectors that also enhance scour at their toe. However, reflection and toe-scour is also a characteristic of rock armour defences particularly where these are seated directly on top of erodible beach materials and raked at angles that are in excess of a natural beach ridge. At Golspie, earlier concerns were raised about beach lowering in front of the sea wall town frontage (HR Wallingford, 1996) and Ramsay and Brampton (2000) report low beach levels in front of the vertical sea wall and highlight concerns that the rock revetment along the Golspie Golf Club frontage would effectively cut off any fresh supply of beach material along a frontage already badly depleted of beach material due to net loss to the south.

Secondly, since the protective structure serves to reduce or halt the delivery of material formerly eroded from the coastal edge, this results in a reduction in the rate and amount of beach sediment exported downdrift. An erosional bight at the downdrift end of the protected shore usually develops and progressively extends to affect downdrift sections of the coast. This 'text-book' response is exactly what has occurred at Golspie with the background erosion that has affected the golf course frontage for years beginning to accelerate following the construction of the sea wall and pier at Golspie town. The planning authority's response was to construct a rock armour revetment that arrested the erosion but also reduced the supply of beach material downdrift to the caravan park and Kart Track frontage and produced another erosional bight at the 7th tee where the rock armour ends. If this is set against a longer term reduction in beach sediment supply and a rising sea level then the underlying causes of erosion can be seen to compound the effect of the immediate causes. It is no exaggeration to state that armouring of the coastline on the northern frontages using a combination of sea wall and boulder revetment exacerbated the erosional situation on the frontages immediately to the south. This has resulted in a pre-existing narrowing of the coastal dune and edge over time to the extent that it did not have the volume or height to prevent overtopping and overwash during the flooding event of December 2013. The underlying vulnerability of low lying land compounded the situation further.

Figure 14 is based on SNH's PGA photography flown pre-2012 storm in May 2009 and shows the southern end of the rock armour at the 6th and 7th tees where landward movement of the coastal edge and an erosional bight at the 7th has been subsequently protected by a short extension of boulder revetment, which itself has created an erosional bight at its southern end. The storm of 2012 exacerbated the erosion at, and just south of, the 7th tee rock revetment leading to excavation of the 7th tee surface and landward movement of the already thin and low coastal edge immediately to the south.

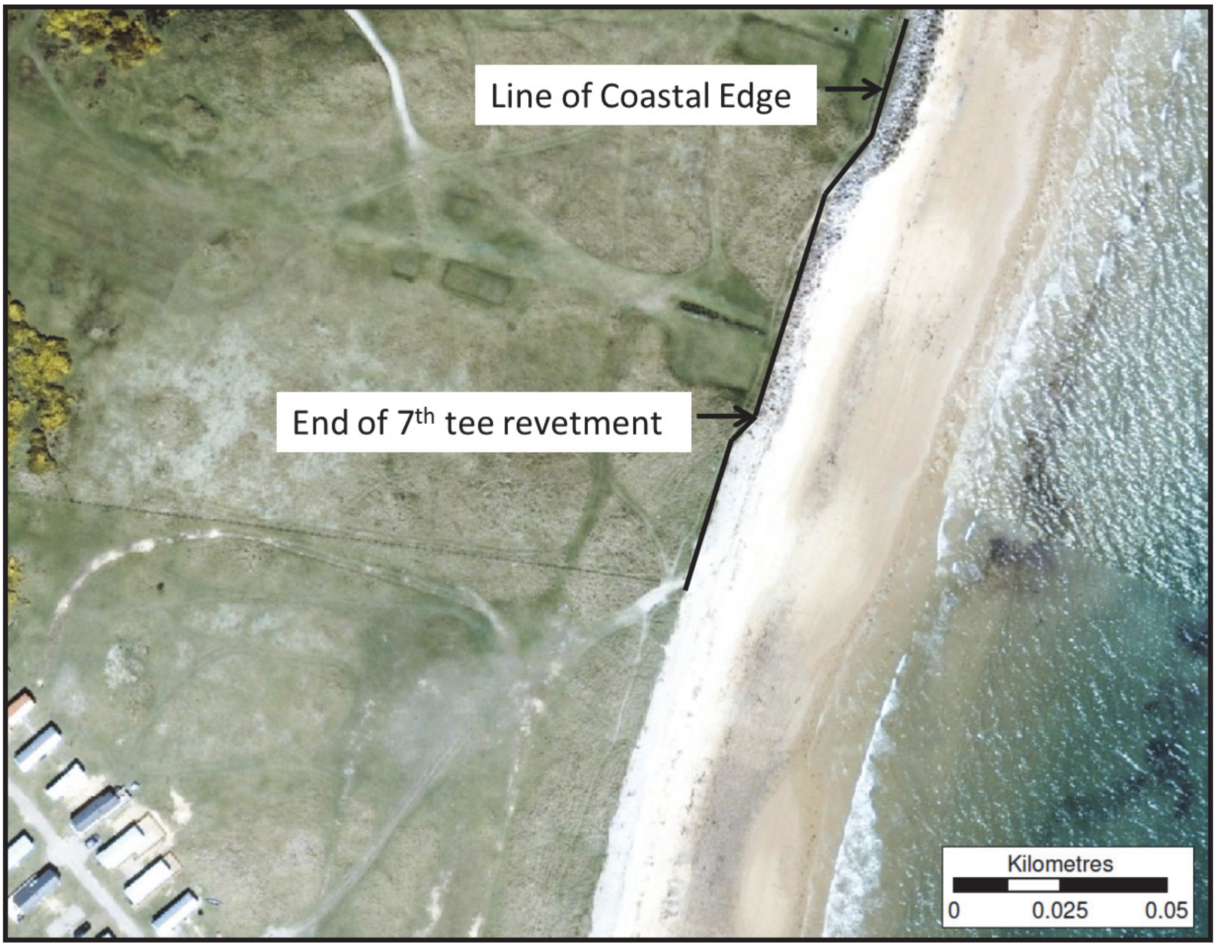

Figure 14: 2009 PGA photography showing the presence of a pre-2012 erosional bight at, and south, of the 7th tee.

The coastal edge was lowered and overtopped at this point. Ground photography taken at this position during the storm on 15th Dec 2012 clearly shows the boundary fence of the caravan park (at profile 120) and two areas of overwash, one at the boundary fence and one at the 7th tee, both of which led to flooding of the low lying area behind (Figure 15).

The centre distance of the photograph clearly shows an unusual triangular apex which is an exceptionally large partially broken wave. Such peaked waves are common where a reflected wave generates positive interference on interaction with an incoming wave, resulting in a higher wave than would otherwise be expected at this point. At this site, and under the conditions experienced in December 2012, it is very likely that waves at this location were reflected southward from the end of the rock armour at the 7th tee (possibly augmented by reflection at the 6th tee) and then positively interacted with incident waves to the south to produce higher waves than otherwise would have been the case at this point. Higher waves produce higher wave run-up than on adjacent stretches and the local conditions for enhanced erosion and overwash are enhanced.

Figure 15: Large peaked wave at the 7th tee, 15 December 2012 (Photo: Neil Morrison).

5. ALTERNATIVE MANAGEMENT OPTIONS

The fourth part of the Climate Change (Scotland) Act 2009, places a duty on public bodies relating to climate change. The Act (section 44) requires that a public body must, in exercising its functions, act:

- in a way best calculated to deliver any statutory adaptation programme; and
- in a way that it considers most sustainable.

Bearing in mind the overarching requirements of the Act it is possible to summarise the beach management options for the Golspie coast into four categories, each of which carries varying levels of consonance with the requirements of the Act.

5.1 Do nothing

Since much of the 2012 damage and undermining done to the rock armour revetment at the Golf Course frontage has been reinstated to a design standard in excess of the previous revetment, it could be argued that no more should be done along this frontage. This approach ignores the long term trend of lowering beach levels along this frontage as well as the lowering beach level in front of Golspie town itself, set against the long term increase in sea level and severity of storms. A key point is that the reinstated rock armour revetment along the golf course frontage is seated onto mobile beach sediments that are likely to lower and be transported south over time. If these sediments are scoured by wave activity, as they were in 2012, then it follows that the new rock armour revetment will be undermined again during a future event. This also ignores the inexorable rise in sea level which drastically reduces the return periods of large storms, and will increase the impact that future storms will have.

Doing nothing also ignores the thin and fragile coastal edge at the caravan park to the south and the rubble bund at the Kart Track. Both of these sections are vulnerable to erosion and overwash and flooding at low points in the coastal edge (ie. at the northern end of the caravan park and at the southern end of the Kart Track bund). Both of these sections suffer from a cessation in the sediment supply previously delivered from the formerly eroding and now protected areas updrift, to the extent that they are now largely fed by beach lowering of these northern sections. It is also clear that an erosional bight had formed immediately at the south end of the golf course at the 6th and 7th tees before the 2012 event and that this had directly contributed to the narrowing of the coastal edge to the extent that it was highly vulnerable to even a minor amount of erosion and overwashing (Figure 14).

The management response to the erosion and overwash at, and just south of, the 7th tee has been to insert over 100 gabion baskets on the east (fronted by boulder armour along the toe) and south of the tee (fronted by boulders harvested from the immediate beach) as shown in Figure 16. This has likely been constructed in the hope that beach accretion would infill the beach between the ends of the gabion wall. This section of the fronting beach is currently of lower elevation due to harvesting of gravel and boulders to replenish the reinstatement works.

However, there remains a risk that it may never be fully filled due to sediment deficits updrift. When storm activity recurs then it is highly likely that the presence of the gabion wall, reinstated rock armour and extended gabion wall around and south of the 7th tee, will serve to increase the potential for erosion at this point. Storm wave activity is very likely to be reflected to the south by the northern wall to meet with waves reflected to the north from the southern curved wall and positively interact to produce higher waves than would otherwise be the case (see Figure 15). The ground level photograph of the tee (Figure 3) shows the post-reinstatement geometry and the embayment produced. It follows that the potential for further erosion, overtopping and flooding along these frontages is likely to increase in the future. The use of gabions is normally restricted to the upper part of sandy beaches or within estuaries, since they are not sufficiently durable to withstand regular direct wave action. Generally the use of gabions on open coasts characterised by small calibre sediments is unlikely to provide a medium term solution, without considerable ongoing maintenance efforts. In addition, gabion baskets are unsuitable on gravel beaches due to abrasional impact and basket damage. Indeed the baskets at the 7th tee are already deteriorating with smaller gravels escaping through the mesh sides.

At the Kart Track frontage, the 4-5 mOD band or embankment is composed of sand and gravel and faced and toed with a mix of coarse rubble and rock armour. It is likely that this material will continue to be progressively undermined (along the front) and flanked (at the southern and northern ends) and this is already under way. This means that flooding and erosion is likely both at the northern and southern end of the Kart Track. Doing nothing is not an option in the present circumstances.

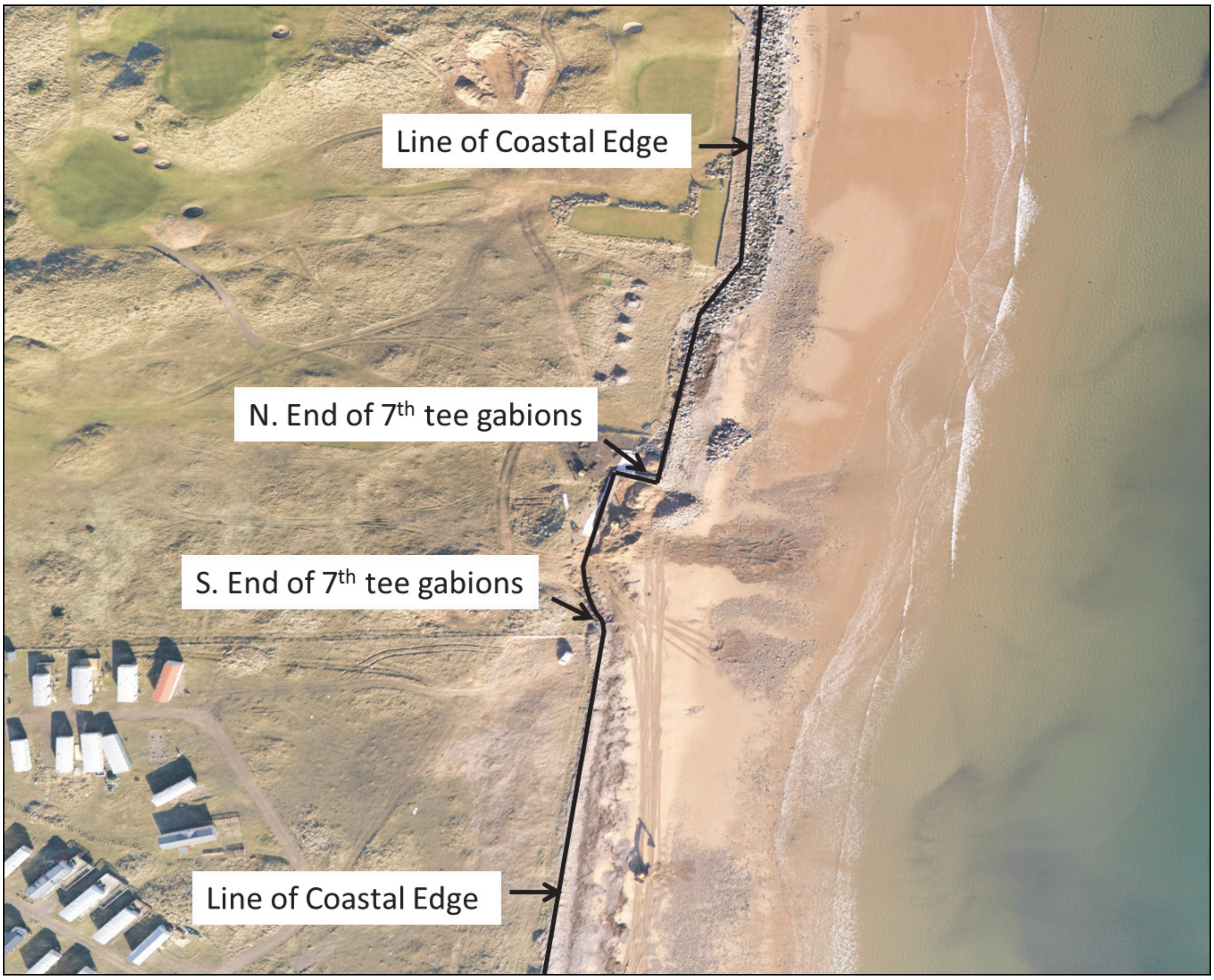

Figure 16: The line of the coastal edge post-2012 storm showing the erosional bights at the southern end of each protection and the rectilinear bay created by the gabion walls.

5.2 Extend or elevate the existing rock armour revetment

Since much of the coast in the northern part of Golspie Bay has been protected there is an argument that the rock armour protection should be extended to include both the 430 m caravan park and 320 m Kart Track frontages. Since the golf course frontage has been reinstated to a higher elevation than before, it would seem sensible to design any extension of rock armour defences along the caravan and

Table 1: Costs of rock armour protection (from Hansom et al., 2013).

Appropriate Locations	Sites suffering severe and ongoing erosion where important and extensive backshore assets are at risk.
Costs	High using rock armour (£150,000 - £300,000/100m length) but with low maintenance. Moderate using gabions (£5000-£50,000/100m length) but with maintenance costs.
Effectiveness	Rock armour revetment has good long-term protection. Can be extended or modified to allow for future shoreline change. Unlimited structure life. Gabions have a limited life depending on basket deterioration.
Benefits	Low risk option for important backshore assets. Gabions are a good alternative where rock armour revetment is deemed too costly and where wave energies are lower. Both have permeable faces to absorb wave energy and encourage upper beach stability.
Problems	Strong landscape impact. Can alter dune systems permanently as sand tends not to build up over the rocks if beach erosion continues. Deterioration of baskets is unsightly and ineffective.
Based on the above costings…	
S. Golf course	The installation of rock armour along the 100m at 7th tee would cost £150,000 +
Caravan Park	The installation of rock armour along the 340m length at the caravan park would cost £510,000 +
Kart Track	The installation of rock armour along the 350m length at the Kart Track would cost £525,000 +.

Kart track frontages to the same specification as those to the north, a total of 750 m. The line of extension of any new rock revetment would be a coast parallel extension along the line of the front of the 7th tee to infill the embayment created by the gabion wall, which would then be redundant. This would have the effect of reducing both the erosion of the coastal edge and the risk of wave-focused overtopping at the 7th tee but would not remove the risk of flooding of the Kart Track land via low parts of the NNR. Indeed flood risk is likely to increase on account of more rapid erosion at the downdrift end of the Kart Track bund. Thus a flood bund may need to be inserted perpendicular to the coast along the southern perimeter of the kart track land to connect the end of the coastal embankment with inland higher ground to the west.

The negative effect of extending the rock armour south is that erosion will accelerate down drift to the south and the area of beach lowering will also be extended into the NNR. In time this is likely to lead to undermining of the rock armour as has occurred in the 2012 event and the need for costly reinstatement works in the future (Table 1).

5.3 Beach nourishment, reprofiling and recycling

Beach nourishment is also known as beach feeding or recharging and involves importing sand or gravel to make good erosional losses. If the source of material is local and has been transported from the eroding area by coastal processes then this approach is known as recycling. Nourishment schemes can vary from a few lorry loads to repair a small eroded area up to multi-million pound schemes. The key to beach nourishment is that the most flexible and energy absorbing coastal defence structure is a natural beach and as a result beach nourishment can be used to great effect with appropriate calibres of feed material. Considerable scientific literature exists on the primacy of sediment supply as the key control on beach stability (Bird, 1985; French 1997). The coastline of Golspie Bay is a good example of a sediment depleted shoreline that would benefit from a beach nourishment scheme, either along the entire northern protected section or targeted at those areas where the coastal edge remains unprotected or is narrow and low. These targeted sections would be the 430 m frontage of the caravan park and to a lesser extent the 320 m frontage of the Kart Track. Either way, the aim here would be to recreate a full and healthy beach profile in front of the existing coastal edge be it protected with sea wall, rock armour or not. The reinstatement of a beach allows wave energy to be dissipated by interaction with the beach material and its rearrangement into a new energy-absorbent profile.

The source material is important since if it contains sediments that are very dissimilar to the natural beach then the beach geomorphology may be adversely affected with finer calibres winnowed out of the nourished beach by wave activity and volume lost. The success of any recharge programme would also be enhanced by choosing a feed calibre with a size distribution slightly larger than the resident sediment. This results in the feed material having a longer residence time before being mobilised / carried down coast. The ideal beach feed for Golspie would be the coarse gravels and boulders found along the existing upper and lower intertidal. If a local solution were to be adopted then this would involve recycling sand, gravel and boulders from an area of accretion. Potential borrow areas may include:

1. The substantial amounts of coarse gravels that comprise the emerged gravel ridges forming the spine (interior) of the Golspie spit (Figure 1). These gravels reach 10 mOD along much of their length and are thus likely to be at least 10 m in thickness. They are not part of the active beach system and so their use as feed materials would not impact negatively on beach processes. The area is understood to be part of the Sutherland Estate and thus their use could be justified as helping protect land leased from that landowner. It also lies partially within the NNR, so liaison with SNH is encouraged.

2. There are several commercial sand and gravel quarries in the immediate area that would provide suitable recharge material. Much of the sediment on the beach at Golspie is glacigenic in origin and, since the same sediment occurs in local sand and gravel quarries, it would be a good choice of recharge sediment.

3. Substantial gravel ridges occur within the NNR in the area of profile 61 at MHWS, along the upper beach, and along the lower beach. Such material could be used as recycling material to replenish sediment deficient areas to the north. The advantage of using such sediment is that it is the same material as updrift and that it is simply being returned to the sections of beach that it came from under storm conditions. The disadvantage of using such sediment is that it is part of the modern beach dynamic and so its removal might result in acceleration of the erosion that already occurs within the NNR. Care would have to be taken in selecting the borrow areas if this route was favoured.

With any of these options, the delivery of such recharge material to the receptor area would involve a degree of beach reprofiling so that the finished profile presents a gradient and volume in excess of the existing profiles. The impact of beach recharge schemes is generally benign both for the recharged beach and for any beach systems downdrift, with the technique being adopted worldwide. For example, the entire low-lying south coast of the Netherlands is recharged on a 5-year cycle. A key advantage lies in its sacrificial nature with the recharge sediment providing a naturally changing buffer to absorb wave energy (reducing the size and cost of any engineered structure to the rear) and allowing longshore sediment transport to adjacent coastal stretches (no end-of-defence terminal scour issues that plague the conventional hard defences e.g. at Golspie golf course).

The renourished beach will also readjust to a high energy erosional or flood event and so the overtopping risk is less than that which would be expected with a rigid structure. The drawback of beach recharge schemes is that they require ongoing maintenance and recharge at periodic intervals and thus tend to be resourced from maintenance budgets rather than one-off capital budgets (Table 2).

Given the relatively short length of unprotected frontage along the caravan park section, it seems that a cost-effective solution to reducing both the erosion and overtopping risk to this section and so reducing the flood risk to the Kart Track land behind would be to selectively recharge this frontage. If the recharge programme extended north of this point to commence at, and to infill, the gabion embayment at the 7th tee, then it would also negate the now enhanced risk of wave-focused overtopping on account of the gabions at the 7th tee.

It would also be beneficial to recharge the southern end of the Kart Track bund to prevent overtopping and the penetration of flood water onto the low lying land behind. This would leave the Kart Track embankment intact and undergoing slower erosion than at present since it would be fed by sediment moving south from the caravan park section as would the NNR beyond to the south.

An added safeguard could be to insert a limited number of short rock groynes within the upper beach to increase the residence time of the fed material.

Table 2: Costs of beach nourishment, reprofiling and recycling (from Hansom et al., 2013).

Appropriate Locations	High value amenity beaches. Shorelines suffering erosion due to updrift construction works. Mixed sand/gravel beaches with moderate to high value backshore assets.
Costs	Moderate to high, and depends on availability of source materials, requires ongoing maintenance (£5,000-£200,000/100m frontage). Recycling is low to moderate cost but requires ongoing maintenance (£1000 - £20,000 /100m length). Control structures (groynes) may be needed at extra cost.
Effectiveness	Short to medium term defence against wave erosion, and enhancement of natural recovery since gravel beaches provide good resistance to storms. 1 to 10 year life before first major recharge.
Benefits	Erosion protection without hard structures. Accelerates natural recovery of gravel beaches, ridges and fore dunes and provides short to medium term defence against storms. Longshore transport of sediment continues. Natural beach processes retained. Recreational value of beach enhanced.

Problems	Erosion protection without hard structures. Accelerates natural recovery of gravel beaches, ridges and fore dunes and provides short to medium term defence against storms. Longshore transport of sediment continues. Natural beach processes retained. Recreational value of beach enhanced.
Based on the above costings…	
S. Golf course	Beach recharge and reprofiling along the 100m at 7th hole would cost £5,000 - £200,000 depending on source material: using recycled gravels £1,000-£20,000
Caravan Park	Beach recharge and reprofiling along the 340m length at the caravan park would cost £17,000+ depending on source material: using recycled gravels £3,400 +.
Kart Track	Beach recharge and reprofiling along the 350m length at the Kart Track would cost £17,500 + and using recycled gravels £3,500 +, with both depending on source material.

5.4 Re-evaluation of land-use priorities

An often overlooked option where land is at risk from erosion and flooding centres on the sustainable land-use in low-lying coastal areas. Does the existing or planned land–use require a vulnerable coastal location? Clearly the town of Golspie itself has existed in a coastal location for many years and contains properties and livelihoods that necessitate continued protection effort, and may also deliver positive cost benefits. However, the land to the south does not fall into this category since it comprises land uses that do not, *a priori*, require an exact location at the coastal edge. Golf course fairways, greens and tees can be remodelled/redesigned with minimum impact on fixed infrastructure away from eroding areas yet preserve the ocean views and links course openness that is challenging and popular with golfers. A case in point relates to the protection of the 6th and 7th tees of the golf course. Erosion at the 7th is a direct function of wave reflection from the change in armour orientation at the 6th and the gabion wall inserted at the 7th represents a costly response that may exacerbate the situation in the future. Why the 7th was not simply moved 10 or 20m inland is unclear since a minor reduction in length would likely have minimal impact on the playability of the hole. A similar argument can be put forward for the land-uses to the south, although access to the coast represents an attractive asset for the caravan park users rather than the actual location of the facilities at or close to the coastal edge. Exactly the same point could be levelled at the Kart Track's construction of a coastal embankment that is both higher and slightly seaward of the line of the adjacent coast in order to combat erosion and flooding. Certainly the threat of imminent erosion of the race track could be reduced by remodelling/redesigning the eastern loop of the Kart Track away from the adjacent coastal edge, although this may incur significant costs to the Kart Track. Similarly this investment could be compared with the cost of defences.

In more general terms the adoption of alternative approaches to future coastal erosion and flooding will involve adaptation of our existing coastal land use to make it more sustainable in the medium and long term, since this will lessen the risk in the future. This will involve moving coastal facilities to higher positions inland in order to remove them from harm's way and release low-lying and vulnerable coastal land to adjust to both reduced sediment supply and rising sea level and also release coastal managers and landowners from unsustainable defence costs. A point particularly pertinent where these defences are being funded by those renting the land, rather than the owner.

5.5 Recommendations

A lack of meaningful evaluation of the various options facing land that is at risk from flooding and erosion is widespread on inhabited coasts worldwide and a failing of sustainable coastal management planning that is not unique to the Golspie shoreline. However, the reality is that substantial investment has already been made in land-uses within vulnerable areas and in protecting sections of the coast and any recommendations for remedial action need to be cost-effective, sustainable and achievable.

Given that the key areas that have not yet undergone rock armour reinstatement are the caravan park, and to a lesser extent the Kart Track, it is clear that ‘Option 5.3 Beach Nourishment’ above represents a low-cost and sustainable route to lessen the risk of future erosion and flooding related to wave overtopping of the coastal edge. It will also serve to sustain the alongshore feed of sediment to the beaches to the south. Whilst option 5.3 may be an appropriate route to sustain the coastal edge in approximately its present position for the owner-occupied caravan park land, the Kart Track land is not owner-occupied land and is leased from Sutherland Estates. As a result there remains an unresolved issue related to the position of Sutherland Estates in the protection of land that they own and is subject to erosion and to the length of time the Kart Track wishes to continue investing in the defence of land that they do not own.

The key elements of option 5.3 are as follows:

- Nourishment of the beach is recommended along with reprofiling to reinstate a natural beach profile composed of one substantial beach ridge;
- The recharge material used should be mainly coarse gravels and boulders sourced either from the emerged gravel ridges of the mainly wooded Golspie spit, or won from nearby commercial quarries, or recycled from the beaches to the south, or a combination of these. Early liaison with Sutherland Estates and SNH is encouraged;
- The crest of the gravel ridge should be approximately orientated along the line of the existing coastal edge and it follows that the slope will extend well onto the upper intertidal;
- The recharge area should commence along the frontage between the 6th tee and 7th tee and extend to join the embankment at the northern end of the Kart Track. A further area of recharge should start at the southern end of the Kart Track embankment and extend south for approximately 100 m.
- A flood bund composed of sand and gravel could be constructed normal to the coast along the southern limit of the Kart Track to connect the coastal embankment with higher ground inland.

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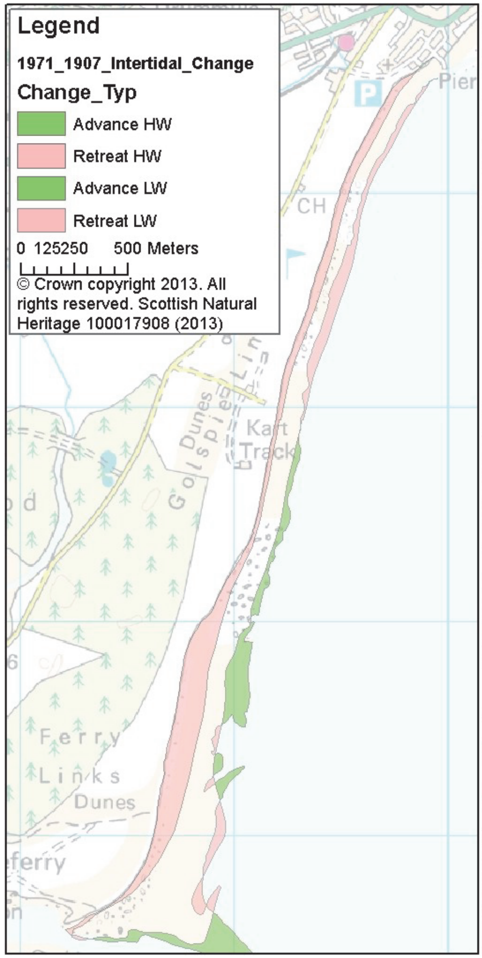
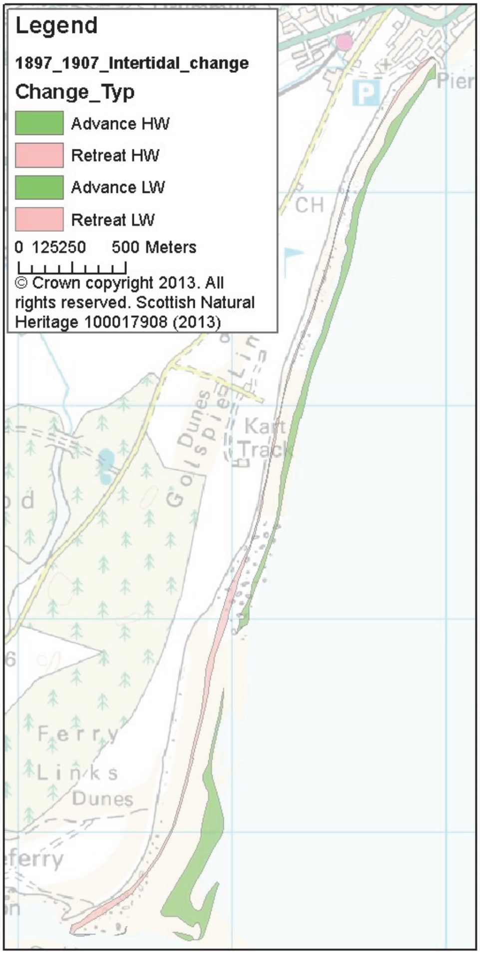
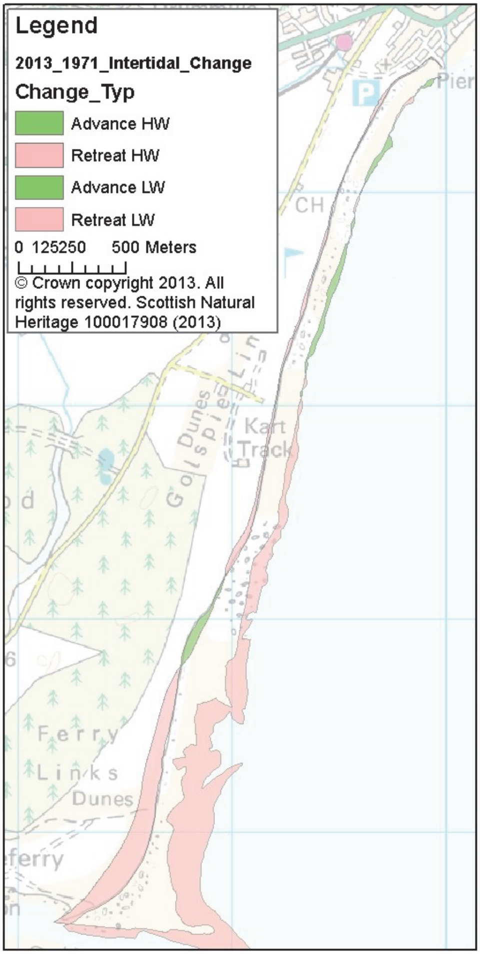
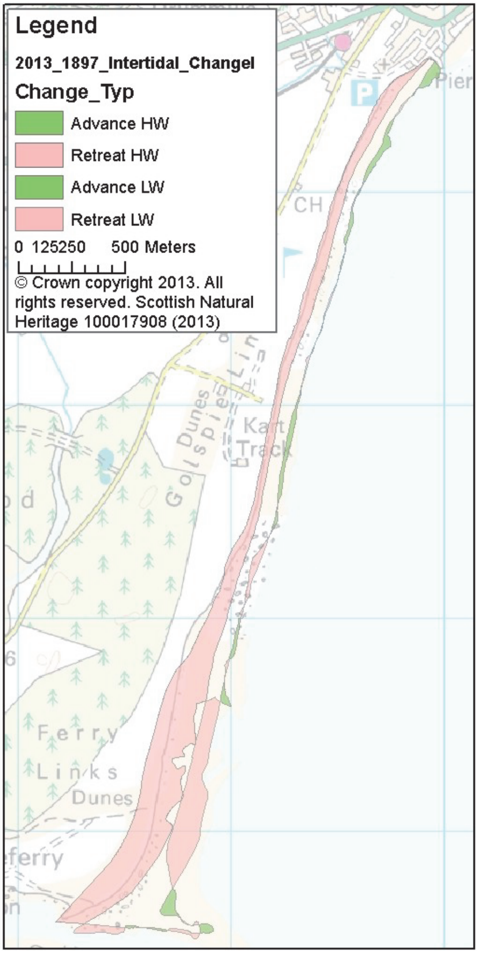
ANNEX 1: MAPS









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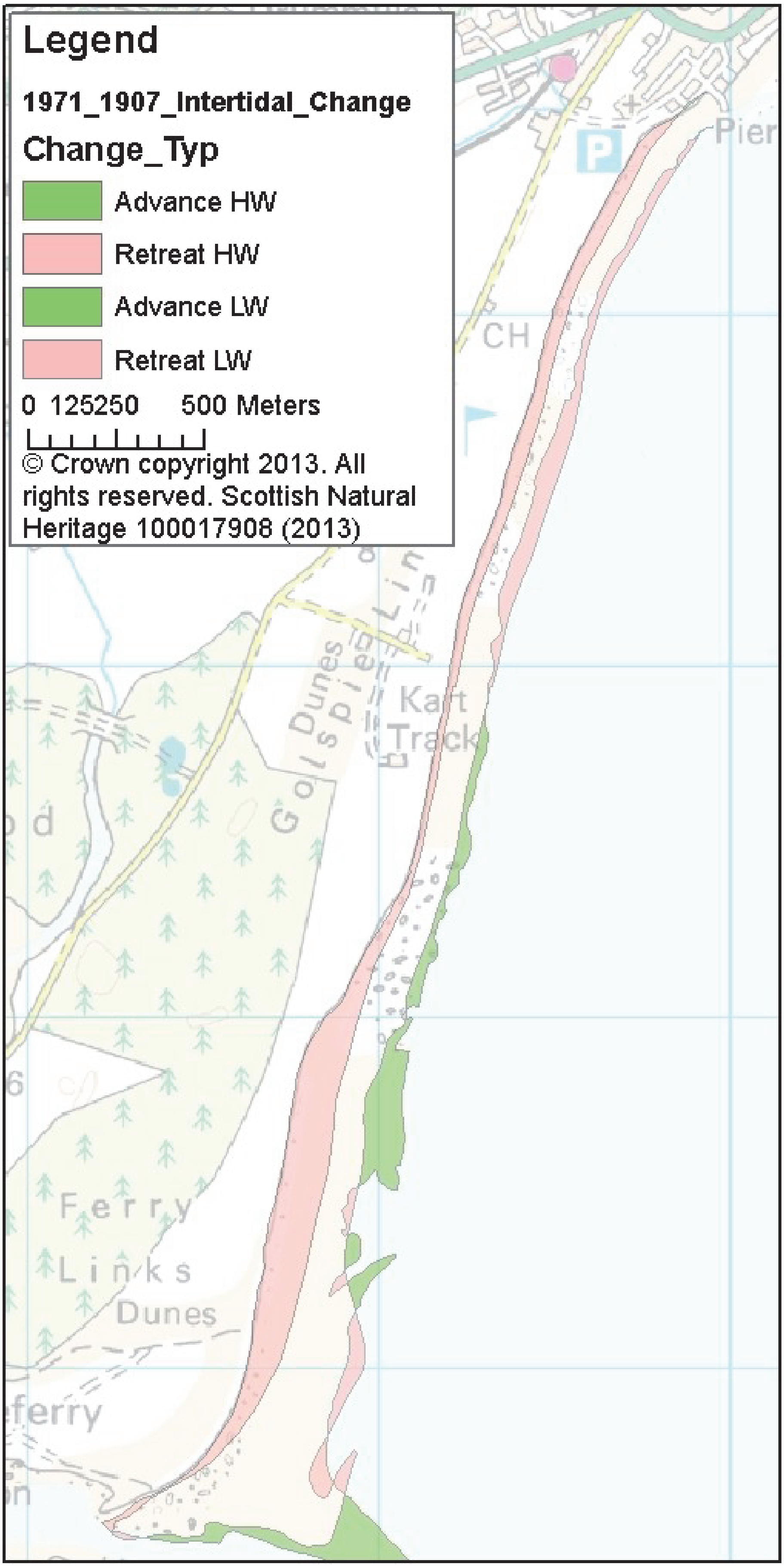
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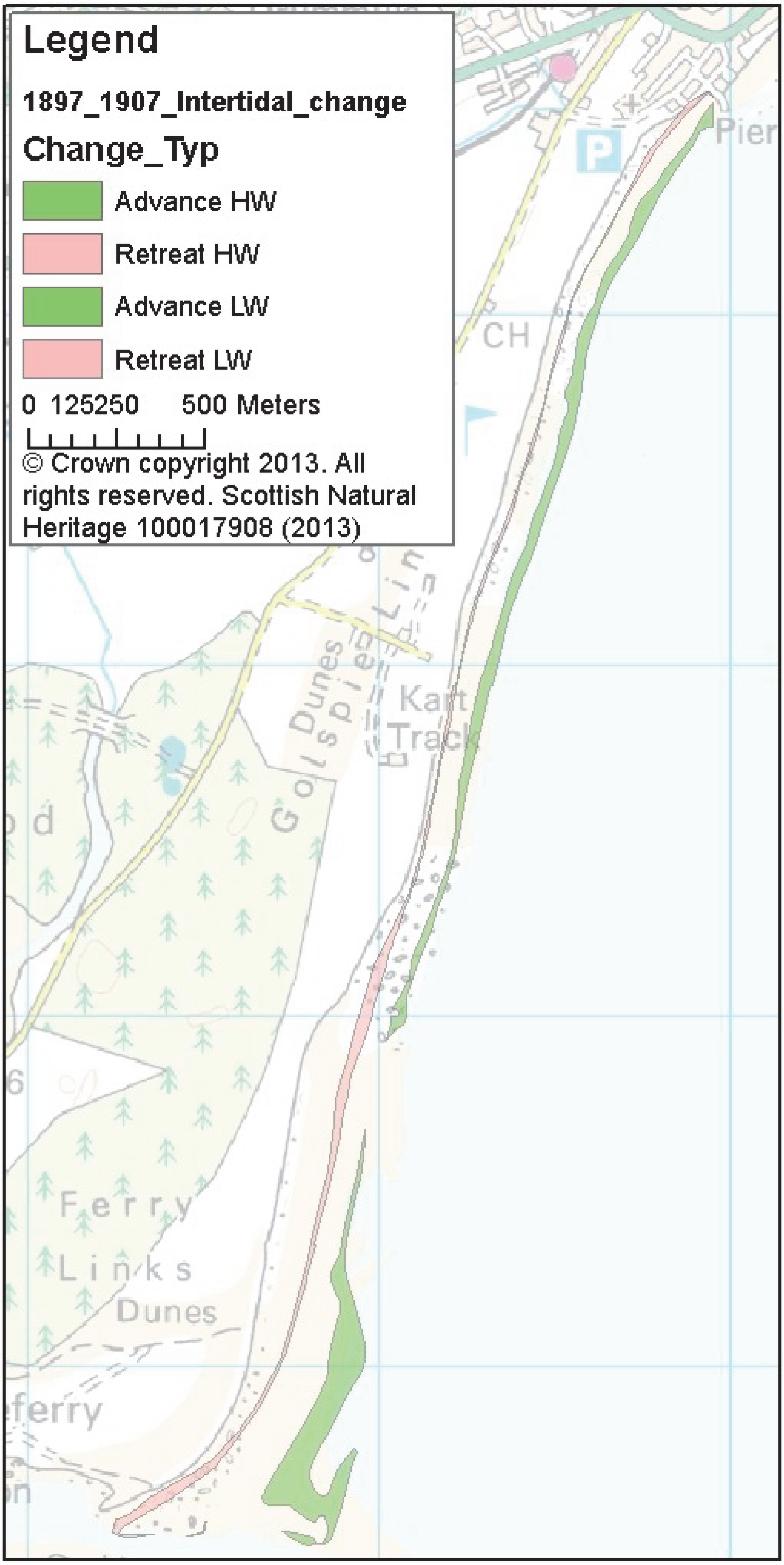
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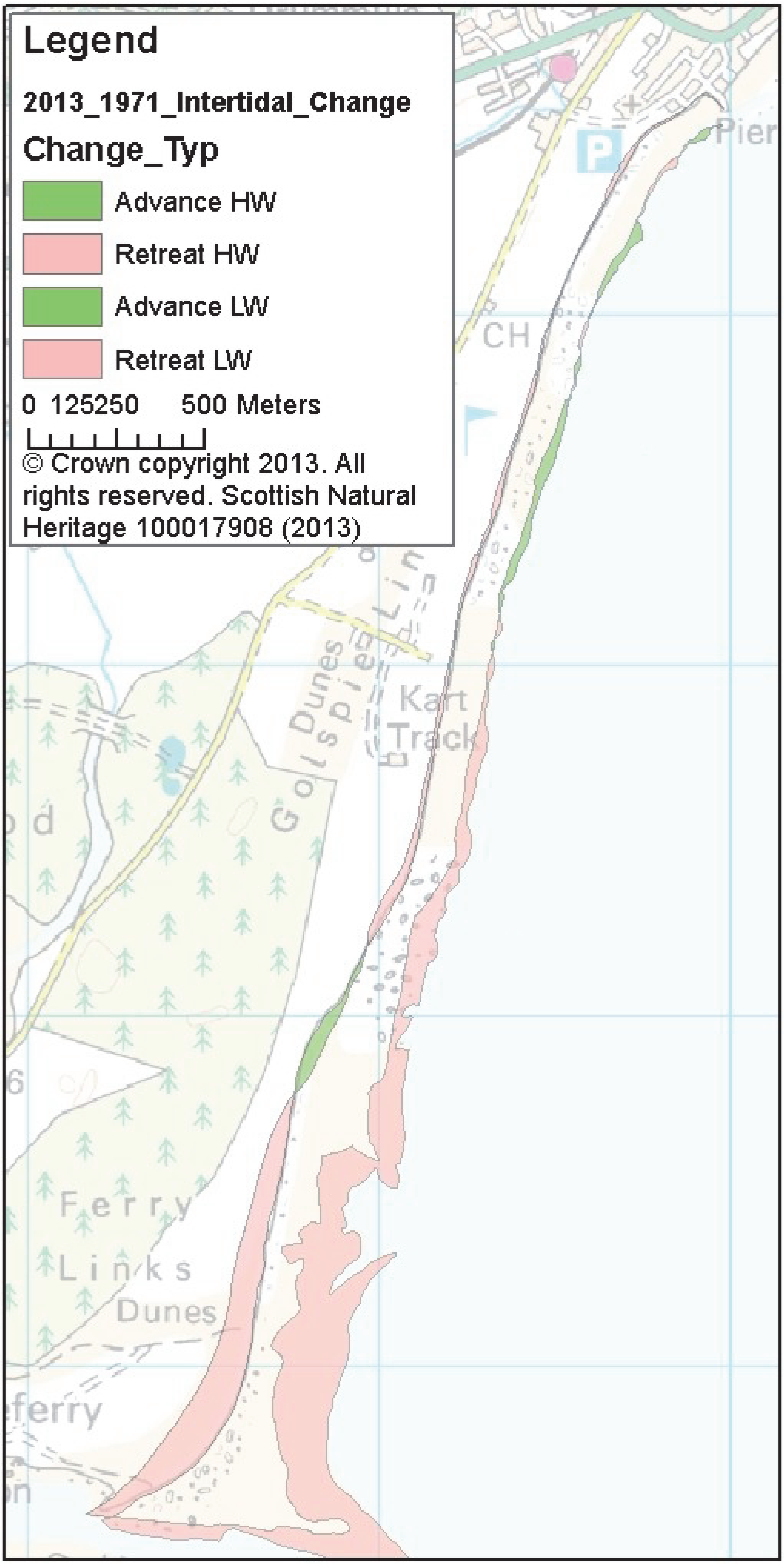
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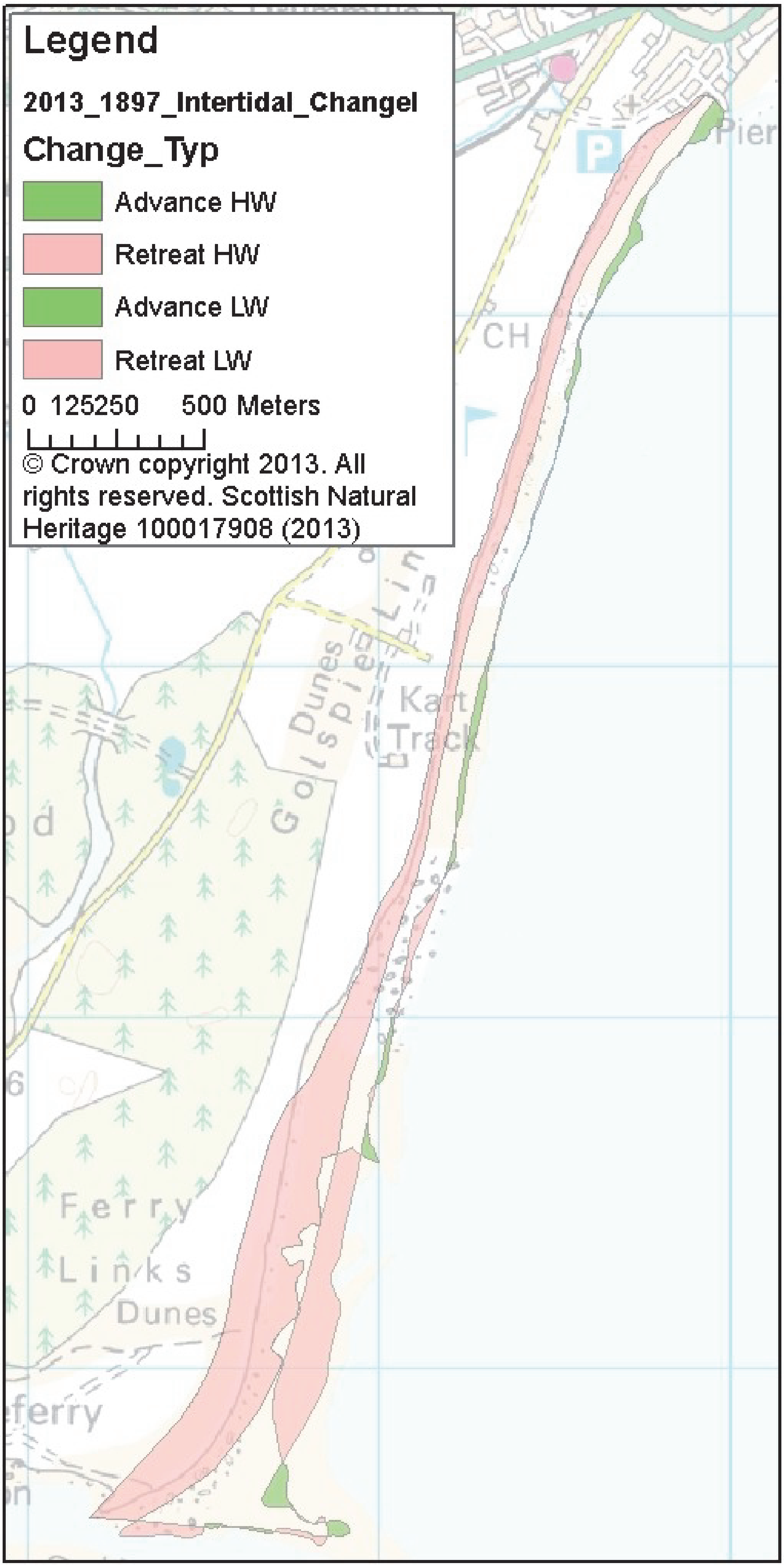
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Policy and Advice Directorate, Great Glen House,
Leachkin Road, Inverness IV3 8NW
T: 01463 725000

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