NATURAL ENGLAND

Geomorphological Advice in respect of East Lane, (Suffolk) coastal changes and their impact on Shingle Street Barrier.

August 2017

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Glossary

Gravel: Originally in Wentworth's (1922) size classification of all natural sedimentary particles measured along the B-axis (intermediate axis of the three axes required to define a 3-dimensional particle). Gravel was an inclusive term for granules, pebbles, cobbles and boulders ranging from 2mm (-1p) to 4096mm (-12p). Later usage of the term gravel as a textural name for pebbles and cobbles (-3p to -7p) became common. The term "coarse clastic" is sometimes used for studies concentrating on particles other than sand and smaller (= fine-clastic sediments).

Realignment: A process when a segment of a barrier/ beach adjusts its overall longshore orientation through adjustment to both meso-scale (temporal) wave power and sediment supply reduction. Realignment is a process usually taking decades and differs from rotation (see below) in that sediment supply shifts are dominant in causing realignment, while rotation is usually dependent on shifting wave-approach vectors. When longshore sediment supply diminishes then subsequent barrier realignment adjustments are known as swash-aligned; if sediment supply is enhanced then drift-alignment changes take place down drift. Managed realignment is when the shoreline is spatially adjusted to some plan design by anthropogenic activities.

Roll-up: A descriptive term for macro-behaviour of a beach system, which shows progressive and systematic longshore loss of total beach area/volume in a down drift direction over time.

Rotation: The movement of a beach between two headlands (or blocks to longshore transport) as it adjusts in plan-view, to vector changes in wave forcing. Normally rotation is seen as a swinging of longshore beach orientation, pivoting on a quasi-central position, though asymmetric rotation can occur when the length of the two beach limbs are unequal. Such beach orientation shifts tend to be sub-decadal to multi-decade in duration. Rotation is accorded when such beach shifts show quasi-periodic reversals that may be associated with atmospheric-oceanic forcing changes. Rotation vector shifts are rarely more than 30^{o}, though again shift value is a function of local physical conditions and the strength and size of onshore wave directional vector differences.

Shingle: An old English term for the gravel associated with the dominant flint lithology found along many southern and eastern English beaches. Tradition has it that the term shingle was used as the packing of the flint gravels in upper beach sedimentation was similar to the overlapping of wooden shingle tiles on medieval houses. Given flint's anistrophy (lack of any preferred axis), shingle beaches rarely show a preferred dipping orientation, such that this terminological use is rarely justified by nature. Since Carter and Orford (1993) the term 'shingle' is giving way to that of 'gravel' in the textural sense, as it is lithologically neutral.

SSB: Shingle Street barrier is the gravel barrier/beach that connects East Lane to Shingle Street.

SSN: Shingle Street Ness is the accretional feature developing on Shingle Street barrier at its northern end (i.e. on the frontage to Shingle Street village).

Natural England Advice Request

i. The coastal defences at East Lane, Bawdsey (Suffolk) are becoming increasingly untenable as southerly storms result in damage to the old flood wall behind the beach, immediately north of the rock defences. Effectively this means the hard defence is creeping northward, into the SAC (SSSI, SPA & Ramsar) as cannibalisation of beach material progresses.

ii. The Crown Estate as well as the EA have reviewed coastal processes here and found recent net movement of material is north rather than south.

iii. This is contrary to the opinion and prediction set out at the time of the SMP, that material would move south from Shingle Street and protect the defences at East Lane.

iv. These issues and the new evidence have led the SMP group to commission a review of the SMP policy for the frontage (Currently Hold-The-Line (HTL) for 100 years '*subject to studies into sustainability*'.

v. How would the coast be likely to evolve under following future conditions?

   a. Hold the line (with likely intrusion into the SAC of hard defence as a continuation of the current line moving north from East Lane)

   b. Managed re-alignment (are there alternative options). Using East Lane and Shingle Street as Headlands of a sort of sub cell, or alternatively allowing possible inundation of the (Flood Risk 3) land in behind the beach and roll back of the barrier)

   c. No active intervention (how would the frontage react to a do-nothing approach, and what would be the effect of the Martello Towers along this frontage).

vi. What would the implications for shingle habitats be under these different options, in terms of future evolution, natural functioning, and natural processes?

vii. Site observational evidence use in this advice is based on site visit on 27th June 2017, with Nick Williams (NE), John Jackson (NE), Gary Watson (EA) and Mark Johnson (EA).

Executive Summary

1. Shingle Street barrier (SSB) on the Suffolk coast forms the southern limb of the SAC Orfordness-Shingle Street Priority Habitat of "Coastal Vegetated Shingle".

2. Incremental coastal protection (rock armouring) at East Lane (Suffolk) at the southern terminus of the SAC has been of concern to Natural England over the last decade. It is yet to be determined whether this protection is causing terminal scour (and hence retreat of SSB), or the retreat (roll-up) of SSB is due to other causes, thus leaving in its wake an exposed landward edge that needs to be protected in order to reduce the flood risk to agricultural reclamation lying landward of SSB.

3. The key to the barrier roll-up problem has recently been identified by HR Wallingford as due to an intensification of northerly directed longshore gravel transport in recent decades, which is contrary to the historical geomorphic perspective of long-term barrier development on the Suffolk coast as showing southwards transport domination.

4. This report presents an initial (and cursory) analysis of shoreline changes over the last 150 years to support a wave-sediment cell perspective that can help to explain SSB and its accretional ness (Shingle Street Ness: SSN) in terms of fluctuating long-term (multi-decade) southerly drift as against the more recent short term (sub-decade) northerly drift. The role of beach rotation as against beach realignment is also discussed in the context of the temporal changes in SSB's shoreline position.

5. On balance, SSB's sensitivity to these transport fluctuations supports a likely reduction in southern SSB volume, though the incremental growth at SSN appear to substantially offset the areal losses at southern SSB. On this budgetary basis, further sediment from either further north on SSB plus other sediment pulses in the lee of the Alde-Ore estuary mouth are required to support the development of a late 20th C. /early 21st C. accretions at Shingle Street ness, which exceed the annual SSB losses by c 2-3 times.

6. In summation, the Orfordness SAC is not being detrimentally affected by southern losses of SSB, given that new areas of shingle growth at SSN represent a natural dynamic changing environment which more than covers the losses elsewhere. The development of perennial vegetation at the ness does not appear to be keeping pace with the relatively rapid development of the gravel ridges, which may cause some concern that the new beach ridge accretions at the ness are yet to mature as appropriate venues for the required priority species.

7. A number of specific questions are answered over the likely optimal scenarios for the SAC's continuation which move the system from HTL to one of managed re-alignment: NE are recommended to support both cessation of further coastal armouring and the potential reinstatement of the reclaimed Alderton marshes, thereby reducing further pressure to maintain SSB as a Flood Defence Structure. This would reassert SSB's geomorphic potential as a retreating barrier under continuing relative sea-level rise.

Report

1. The use of the term ‘shingle’ in this report reflects a traditional recognition of a flint-based beach sediment that varies in size from granules(4mm) to very large pebbles (<64mm). In recent literature, the term ‘shingle’ has been displaced by either ‘gravel’ or ‘coarse-clastic’, neither of which reflect a specific sediment lithology.

2. In outline, the subject of this report is the changing conditions of the gravel beach/barrier system (in this report, termed the Shingle Street Barrier (SSB)) that currently commences at the East Lane (Bawdsey) coastal protection complex and ends at the down-drift southern edge of the Alde-Ore estuary (fig.1). The estuary in turn demarcates the southern end of the Orfordness gravel-dominated spit complex.

3. Natural England’s (NE) interest in the SSB is based on the SAC Orfordness-Shingle Street Priority Habitat of “Coastal Vegetated Shingle”, that includes perennial (including sea kale; yellow horn poppy; and pea) and fresh driftline vegetation. The SAC is essentially demarcated by the coastal gravels from the East Lane coastal defence battery point, through Shingle Street village (SSB) and across the Alde-Ore estuary (ebb-delta complex) and onto the main spit of Orfordness (Fig.2). The areal extent of the SSB gravel is a key concern, such that any changes in the gravel area due to human influences, may be influential in any ongoing conditional assessment of the site.

4. NE’s principle concern at this site has been the apparent northwards shift of the southern terminus of the SSB (roll-up) that might be detrimental to the area of the SAC. The reason for this shift is a point of discussion between NE and the Environment Agency (EA). As the gravel SSB terminus has appeared to shift northwards, it left in its wake, potential breaching sites for flood waters (under coastal surge) to impinge on the reclaimed marshes (Steers, 1948) to the north east of Bawdsey, east of Alderton and southwest of Shingle Street (i.e. landward of SSB). EA’s policy since 2000 has been to place protection rock armour along the growing exposed area, in the wake of the retreating (rolling-up) gravel barrier. NE has been concerned that the extension of the armouring simply displaces a terminal scour point at the armouring terminus, which in turn only serves to roll-up the gravel beach further northwards.

5. East Lane marks an approximate zone whereby the Bawdsey cliffs (London Clay and Red Crag) fall away in elevation to underlie the reclaimed marshes north east of Bawdsey village (termed in this report Alderton marshes). Reclamation of these marshes for agriculture, is related to a series of flood banks, one of which runs north-west from East Lane and marks the approximate back stop to the contemporary gravel beach as it shifts northwards. Coastal protection of the East Lane site has been ongoing since an initial private-funded late-Victorian coastal wall and bulkheads were emplaced. These defences have now been over-printed by rock armouring which now uses the old flood wall as its backstop. This action has been condoned by the local SMP recommendation for Hold-the-Line at this point till 2050.

6. Recent and continuing projection of gravel beach roll-up identifies a number of related issues:

   i) Has there been significant loss of the SAC's shingle area in the roll-up process?

   ii) The EA's consideration of further continuation of coastal armouring as untenable (on a cost/benefit basis) in the light of any further barrier longshore failure.

   iii) The divergence of the current barrier alignment and the old flood bank, such that any future breach will be without benefit of the flood bank to act as a backstop to armouring and hence the need for some new impermeable defence to act as the backstop (unsustainable cost).

   iv) Is the beach system entering a new phase of instability which requires a radical rethink of the coastal management options for the Alderton marshes?

7. This report is essentially driven by consideration of item i, but some consideration of items ii-iv will also be necessary in the specific advice questions asked.

8. To understand the contemporary gravel behaviour, one needs to understand the general beach sediment movement spatially and temporally between Bawdsey cliffs and the distal end of Orford Ness, and the possible variations in terms of available wave direction and power that have been the forcing controls on the SSB gravel system during the last century.

9. The pre-20thC. historical geomorphological perspective for sediment behaviour in Orfordness, and by inference to SSB, is provided by Steers (1948: p385-389). A long-term (centennial scale) southerly directed net sediment drift is invoked for the major extension of Orfordness between the 17th and 20th centuries. Implicit in this explanation of Orfordness's evolution is that Shingle Street and its southern marshes had some form of fringing beach (gravel?) system that was sourced from a mixture of pre-Orfordness southward directed coastal supply (overtaken by Orfordness's southern expansion) as well as elements of sediment from Bawdsey cliffs moved by a northerly directed wave power. Some of this residual sediment could now be in the contemporary western shoreline of the modern Alde-Ore, immediately north of Shingle Street village. More pertinently, more of this sediment may well be in the remnant sections of a likely swash-aligned proto-SSB lying landward of the contemporary SSB (Fig.3).

10. Steers (1948) mentions a severe storm in 1897 that beheaded the last mile of the then Orford spit (by a likely repositioned Alde-Ore exit breach). The sediment from this beheaded distal section, moved onshore at Shingle Street "in considerable quantities" (Steers: p.389) to prograde a new seaward beach ridge that also "formed a lagoon between old and new ridges" (Steers: p.389). The sediment volume was also sufficient to add to the pre-existing beach that fronted Alderton Marshes and probably represents the last major resupply of the SSB from the north. Figure 4 shows the 1919 Ordnance Survey map, which shows likely post-1897 storm reworking of this Shingle Street storm sediment oversupply, as well as the

re-establishment of a southerly directed flying spit to mark the southern edge of the Alde-Ore estuary mouth. Figure 5 is an enlargement of Fig.4 which shows by 1919 how this reworking (southerly directed?) has narrowed the beach front at Shingle Street. It's not clear from Steers (1948) whether his perspective of a new lagoon was based on the remnant one south-east of Shingle Street, or one held in the lee of the flying spit shown in Fig.5.

11. Figure 6 from the OS (1937-61) shows, in comparison with Fig.5, that Shingle Street gravels have changed in the first half of the 20th C, given that the ebb-directed flying spit at the Alde-Ore entrance has been pushed onshore and reworked by northerly drift into a new multi-recurved flanking spit, north of the original flying spit. This is directed to the northwest and acts as the southern boundary to the Alde-Ore exit. The reworking is substantial with the dominant (net) sediment drift direction shifting from southwards to northwards by mid-20thC.

12. The extent of change of the Shingle Street ness (SSN) is outlined by comparison of air-photos/satellite imagery obtained via Google Earth@. Figure 7A-D identifies a switch towards net deposition at the frontage of Shingle Street in the late 20thC. The 1945 absence of any ness feature at Shingle Street (Fig.7A) is maintained in the OS map of the 1950s (Fig.6). However by 2000 (Fig.7B), there has been a radical shift with the development of an asymmetrical ness at Shingle Street. This asymmetry reflected a dominant northerly drift along the SSB, which had realigned the near-straight shoreline of 1945 into a cuspate form. This form has been forced in the energy lee provided by a new flanking spit as the southern boundary to the Alde-Ore exit. There is clearly a longshore wave cell boundary formed at Shingle Street at this stage. By 2011 the extent of the flanking spit has diminished while the ness remained. By the latest imagery (c. 2017: Fig.7D) the sub-littoral platform of the flanking spit remains evident (even if the intertidal area has diminished compared to Fig7B and 7C). Figure 7D compares the 1945 shoreline with that of 2013 to show how the ness has become constructed as a depositional feature during recent decades. The detail of the ness's beach ridge orientation in Fig 7E showing drift-alignment, identifies a dominance of northerly drift in recent decades, while the bifurcation of ridges and overlapping of seaward ridges by new single ridges (spit-like) is a reflection of the temporal variability in this northerly directed sediment supply.

13. The late 20thC to early 21stC growth in the SSN is a strong indicator of a dominant northerly-directed longshore sediment transport of gravels. This is seemingly at odds with the dominance of southerly drift identified in the centennial persistence of Orfordness spit growth to the south. This net sediment drift issue has been further examined by HR Wallingford working for the Crown Estate (2016). This study has been exhaustive in considering shoreline change from Bawdsey to North Weir Point (mouth of the Alde-Ore estuary), while also modelling longshore wave power variability over 1981-2015 for which meteorological forcing data has been available. Figure 8 shows the relative wave height and gross breaker direction as either northwards (RHS) or southwards (LHS) directed. The percentage sum shows that northwards-directed wave power generally has a higher percentage occurrence over southwards-directed wave power. There is a suggestion that the general northwards-directed power has been growing annually, relative to the southerly sediment drift since 1980. However, note

that there is considerable north/south longshore power variation on an annual basis. The potential longshore drift can be modelled from this wave power statement and Fig.9 shows the annual drift rates, both northwards (blue bars) and southwards (red bars) and their budgetary outcome (black line = blue minus red). Net longshore drift rate shows a virtually consistent northwards potential, but it is not considered as a major force given that the peak is usually less than 5k/m^3/yr, a relatively slow coastal conveyor volume. Note that during the 2013-14 winter-spring storm events, the northerly directed drift rate peaked at nearly twice this long-term trend. The annual fluctuations in these low longshore northerly transport rates can be considered as probably forcing the 21stC. variation in beach ridge development at the SSN (paragraph 10).

14. HR Wallingford considered the growing intensity in +NAO conditions as a possible driver for the increase in net northerly beach sediment transport in the last few decades. The NAO is an index of general north Atlantic atmospheric conditions whereby + conditions indicate that the southern British Isles are dominated by easterly-moving low-pressure depressions that bring SW storms into the lower North Sea and hence drive northerly directed transport along the Suffolk coast. This is in comparison to –NAO conditions whereby blocking anti-cyclonic high pressure exists over Scandinavia and northern Europe driving easterly and north-easterly directed winds against the Suffolk coast that lead to southerly beach drift.

15. Consideration of the Shingle Street ness is only part of the changes in the SSB. Over the last few decades, the ness's growth needs to be related to a source-sink sediment cell that is related to the dominant northerly drift of beach sediment. If the ness is a sediment sink to a wave-driven cell, the cell source must be based somewhere between Bawdsey cliffs and the ness that has become operational over the last few decades.

16. Given the continuing development of coastal protection around East Lane, any recent cell development on SSB would be hinging on this position as the updrift cell boundary. There seems to be very little possibility of beach gravel transport around this protection on a scale sufficient to maintain the contemporary position of the southern end of the SSB. Assuming this is the cell starting position then the source area for sediment lies in the existing beach gravels of the SSB. The probability of cannibalisation of this sediment volume given the net northerly drift is high. To see if this is in operation, then a comparison of SSB shorelines over the last century is needed.

17. Figure 10 derived from Burningham's work (cited by HR Walingford, 2016), shows the nature of "shoreline" change for the SSB between the 1881-1919 OS map (Fig.4) and a ground survey in 2012, using map and aerial photography for intervening years. The definition of shoreline is normally related to mean tide or mean spring high tide, but given the variety of map and photo sources, there will be some uncertainty about any line used as a comparison in century ranging material. However, given that caveat, Fig 10 is the most usable statement concerning the changes in the SSB beach face position since the late 19thC.

18. Figure 10 identifies four spatially adjacent zones of differing shoreline behaviour along SSB: South (sediment source); Central hinge point (transport corridor); North (temporary sediment sink) and SSN (sediment

sink). These four zones reflect generalised beach behavioural zones. Their longshore boundaries appear persistent over the 20thC. and are likely linked to dynamic variation of longshore wave power direction and sediment supply. Although it is likely given the coastal configuration of SSB and SSN that they are part of a consistent coastal wave-sediment cell, over a century, there are likely to be variation in wave power and available sediment volumes that will drive smaller (spatial) sub cells that are responding to local sediment surpluses and deficits. The position of SSN and its offshore linkages with the southern boundary of the Alde-Ore and sub littoral platform of the ebb delta is likely to be influential in SSN development and its immediate connection with SSB to the south.

a. South: This sector shows a net retreat of the SSB shoreline through the 20thC. The various shorelines (Fig.10) show a consistent landward retreat, pivoting on the Central hinge point at the northern end of this section. The maximum beach retreat (135m) is recorded at the frontage of the East Lane armouring. The emergence of the East Lane as a protected hardened drift divide appears to have been associated with an accelerating realignment trend since 1999. The realignment is possibly due to either the loss of beach gravel due to northerly net beach drifting as a function of the SSB beach re-alignment, or it may be that as the coastal armouring has been extended piecemeal northwards, its role as a terminal scour generator moving longshore has become more pronounced.

b. Central hinge point: This has the smallest net change in the overall shoreline position (25m). There is both landward and seaward movement of the shoreline post 1881: with the early 20th C. shorelines prograding, while the late 20th C / early 21st C have retreated back to the 1881 position.

c. North: There is no clear counter rotation of shorelines in this zone matching those observed in the South, as the presence of a fluctuating SSN acts as a secondary hinge point and sediment sink which may influence the development and alignment of any counter seaward rotation. There is progradation in the early 20thC. (before 1957), that could be matched to the South's shoreline retreat. The North shoreline then retreats rapidly till 1999 (90m net), after which. it remains without major change through the early 21stC., albeit these shorelines are connected to a further rapid phase in SSN progradation (170m) suggesting the North shorelines are now dynamically acting as transport corridors for the aggradation on SSN under northwards wave directed transport

d. SSN: Refer to paragraph 11 for the behaviour of this sector.

19. It is important that the changes observed in these 4 zones are treated as interdependent. The SSB should be considered as a coherent entity. The 1881-1919 OS map shoreline shows SSB with its foremost seaward beach location at East Lane (in the available record), with a skewed swash alignment of SSB running into the Shingle Street progradation. There is no way of testing whether this progradation is a result of the 1898 storm and associated sediment redistribution that Steers comments upon (para.9). SSB's form is more commensurate with a dominant southerly drift that is scouring downdrift of SSN (North sector) and maximising deposition in the

South sector, given the offshore protection to the SSN provided by the Alde-Ore offshore delta.

20. The dominant change over the first half of the 20thC. along the SSB is a retreat of the shoreline at East Lane and a counter seaward progradation immediately south of SSN in the same period. It is probable that this is driven by a dominant northwards-directed longshore wave power. Sediment volume from the South section is likely deposited in the North section (temporary spatial sink), but effective northern-directed wave power is still available to cause the retreat of SSN overall. This SSN retreat shows continuing sediment loss through to 1973. SSN then shows rapid growth by 1999 which appears to be fuelled by new erosion south of SSN and northern drift building along SSN. This 1999 shoreline and later 21stC. shorelines are interpreted as providing the key sediment source area for SSN from the South sector (sediment provided as the SSB rolls-up).

21. The consistency of SSB's southern retreat could identify realignment that may be a regime driven by beach rotation. Rotation has been defined where two controlling headlands act as boundaries to an oscillating beach alignment which rotates on a central pivot between the headlands. Underlying the concept of beach rotation is the sense of spatial/temporal oscillation (Klein et al.,2002; Short & Trembanis, 2004; Phillips et al., 2010), of the beach identified with variation in ocean/atmospheric forcing (such as the NAO). Such beach rotation is usually on a quasi-decadal basis. On this definitional basis, it is hard to call SSB's single directed beach re-alignment, persistent over multi-decades, as 'rotation' per se. Potentially if the suggested +NAO is causing a shifting balance in net longshore transport such that northwards net drifting can account for the northwards beach roll-up and associated retreating alignment, then there may be a case for something termed 'asymmetric rotation', especially where –NAO (generation of southward drift) is insufficient to balance out the northerly directed transport. Alternatively, one needs to find a forcing variation that may account for temporal oscillation on a multi-decade to centennial basis, to possibly match the macro decadal-plus observed changes in SSB (and SSN) over the 20th C.

22. The human response to the SSB historical changes is identified principally in the coastal protection starting in the late-19thC.(?) and continuing to the present day. The contemporary coastal armouring at East Lane has been extended northwards, on a serial basis over last 20 years (Fig.11), as the SSB appears to be rolling-up in its realignment process (Fig.11). This leaves a moot question as to whether coastal protection follows beach loss, or vice versa in that longshore coastal protection causes rollup through terminal scour.

23. Are these changes in the southern SSB affecting the SAC gravel area? There has been area changes relative to the initial boundaries. Based on a generalised analysis of Fig.10, since 2000 (approximate start of the SAC) the system has lost c.13,500m^2 (mean annual loss of 840m^2) of its areal extent at East Lane. This should be compared to the 1919-2000 loss of c.37,700k m^2 on the frontage (mean annual loss of 388m^2 y^{-1}). These figures are only 1st order approximations and should not be taken as definitive. However there does appear to be an acceleration of change since 2000 in areal loss: but this is not volume per se. Any loss needs to be assessed in terms of areal gains elsewhere along the SSB and SSN. Given

the radical shifts in ness shoreline with both major loss and progradation in the 20th C, it is best to deal with post-2000 changes in SSB only, when approximately 25,000 m^2 prograded at North and SSN (up to the apex of SSN). This works out at an annual net gain of c. 1,500 $m^2\ y^{-1}$. This indicates that since 2000, there has been something approaching 3-4 times the areal accretion on the ness relative to the loss at East Lane These figures are only first order of magnitude and should not be used as a definitive indication of change, requiring more constrained areal analysis. However, given the relative areal loss/gain it's certain that the SAC has gained in gravel area at SSN, easily outweighing its losses at East Lane. The nature of the rapid deposition on SSN can be gauged from the vegetation density difference between the older beach ridges prior to 2000 (Fig.12A) and the modern beach ridge at SSN (Fig12b), the latter photo identifies the broad post-2000 beach ridge development and the inevitable lag in vegetation encroachment. SSB's areal imbalance of loss and gain does beg the question as to where the source for the extra sediment at the ness is located?

24. Without detailed assessment of longshore coastal changes to determine sediment drift patterns, the type of above analysis (para 22) is cursory and generalised to accommodate meso-scale changes. A major conditioning effect is related to wave-shadowing from protruding coastal features. The protection of SSN by the ebb delta and estuary mouth flanks of the Alde-Ore tidal outlet, as well as the growing hardpoint of East Lane, to both southwards and northwards-directed wave drift has been pronounced especially during the latter half of the 20th C. Such wave shadows can drive emergent cuspate and alignment features that in turn effect localised coastal changes (Ashton et al., 2001; Ashton and Murray, 2006). In particular, the northwards drift dominance of the last few decades would have driven initial beach changes along the southern end of SSB, but would be difficult to explain the initial retreat of SSN (1950-70), though could help to explain the last pulse of beach ridge accretion on SSN commensurate with the loss of sediment immediately south of SSN. Some of the shoreline changes can viewed through the lenses of swash and drift alignment, but it's not a simple cell perspective as the marginal pulsing of northward /southwards drifting has added an extra layer on the spatial simplicity of cell adjustment. During the early to mid-20thC. the SSB shoreline north of the Central zone shows a southwards drift domination that reduced the presence of SSN, with associated sediment prograding the northern end of SSN. This was reversed during the post-1970s by a northwards drift domination that eroded the southern SSB (tending to swash alignment), eroded the northern SSB (excess of northwards longshore power) and commenced drift-alignment at SSN (reduction of northerly power as shoreline alignment moved from SSW-NNE to SW-NE) which is associated with the marked development of SSN post-1973. The influence of the ness on SSB in the 21stC. under a favoured northern-directed sediment drift is reflected in the 'retreating' re-alignment of south SSB; onshore movement of the central zone; slight retreat of northern SSB; progradation and subsequent maintenance of SSN.

25. At this abstracted level of analysis, the capacity for change will depend on the continuing close balance between south and north directed longshore sediment volumes; and the degree to which the Alde-Ore estuary mouth deposition system will act as wave protection (on SSN). The degree of

uncertainty as to the future development of the system is high given these controls.

26. The evidence for overall (temporal generalisation) SSB rotation is identified. The cause can be logically correlated to a shifting northwards sediment regime, but the cause of this in terms of changing intensity of +NAO in the last 30 years is plausible, but unlikely to be the overall cause for the bulk of 20th C. changes. There is a probable need to consider local effects from a site context which includes the emergence and continuation of a fixed (hardened) East Lane coastal headland, as well as the development of a wave energy lee (attracting ness deposition) south-west of the Alde-Ore outlet.

27. NE's immediate concern over the loss of southern SSB gravel from the SAC should be lessened in the context of increasing ness accretion as a counter balance. Although the issue of whether such change is due to natural barrier changes or due to human intervention (coastal protection) is still open, the scale of overall SSB changes suggests natural forcing, though the subsequent intervention around East lane is likely to have some terminal scouring effects, but they are likely to be marginal to natural changes. However, of more immediate concern is how East Lane site conditions are changing as SSB's southern shore-alignment is trending away from that of the old flood bank used as the back stop to armouring. The redefining alignment of beach away from that of the floodbank is increasing the width of the back-barrier zone between gravel barrier and flood bank. This may well allow a more geomorphologically functioning barrier under storms and surge conditions (regardless of direction) to develop by allowing free barrier migration, which has not been seen in last 100 yrs due to the close spatial attachment of armouring to old flood wall. This non-managed barrier form change in turn may reduce longshore losses (Bradbury and Orford 2007), but such changes under the existing sedimentary budget balance, are unlikely to radically effect longshore SSB balance given the SSN surplus.

28. The requirement for continuing coastal armouring has been based around the risk to the reclaimed marshes given the possibility of an overwash-induced breach in the wake of the rolling-up barrier. Without a detailed analysis of relative reclamation elevation in the context of scenarios of a developing breach (ranging from episodic to semi-diurnal water exchanges), the incursion of salt water into protected grasslands is problematic and sits outside of the remit of this advice. As the alignment of SSB and the old Flood wall diverge in future years, the development of a breach and effective channel for overwash water volumes to move onto the reclaimed land, will reduce in the short term (Epoch 1), until such time that overwash+tidal volumes are able to form a channel behind SSB, down to the main reclamation drainage slough in the Centre zone. The salinity of contemporary back-barrier lagoon may therefore increase over time, but not to the detriment of the SAC qualification. The long-term protection (Epoch3) status of HTL for this reclaimed area has to be reconsidered (via the ongoing review of the SMP). The current management approach can't be maintained by integrating any future coastal defence with the SSB in any sustainable way (cost effective) as to maintain reclamation integrity. The probability of retaining reclamation integrity will reduce over time, a process likely to accelerate with increasing future relative sea-level rise rate.

29. Consideration of three final questions:

    a. What process change accounts for the dominance of northwards drift observed over the last two decades, and inferred to have been in operation for much of the last century and more? This northwards dominance is of a low magnitude and very unsteady in terms of annual changes such that years of net southern dominance do occur. The sensitivity of SSB to such changes is perhaps diminished with the small annual beach drift changes as found in this analysis. The association of directional trend with NAO variability is intriguing and has been found elsewhere (Thomas et al., 2010) in the UK, albeit on a more exposed coast where western depression variation can account for beach rotation under such conditions. Use of + or – NAO has been used for longer periods of beach/dune structure hiatus on east coasts (Orford et al., 2000), but this finer temporal resolution (sub-decade) on the east coast is new and worth wider exploration.

    b. Are the changes of SSB at East Lane related to beach rotation or beach realignment? Valid rotation should see sediment movement from one end, matched to the other end of the beach system. In the case of SSB, losses from the south have been relatively consistent at a centennial scale, yet any associated growth at the SSB northern end has not been matched in time or in space to say that beach rotation has been occurring. Likewise, the shift between north/south transport dominance might be used as a process basis for rotation, but the temporal scale of such wave changes are not replicated in the behaviour of SSB which shows multi-decade to centennial timing of macro morphology changes. On balance the scale of SSB changes is more sediment supply related, such that realignment of the southern SSB is taking place as a result of a dominance of northwards directed sediment transport. It is also being supported by the emergence of a drift divide at East Lane that has become more accentuated in the late 20thC.The clarity of any simple realignment (developing swash-alignment in the south and drift-alignment at SSN) has been somewhat confused by the likely interactions between northern wave transport, blocking SSN and potential wave dampening around the Alde-Ore estuary mouth.

    c. What is the nature of the linkage between coastal protection and SSB roll-up: association or cause and effect? It is unlikely that there can be an unequivocal answer to this. From the above advice, I can only suggest that there has been a centennial northwards domination of the SSB and that the coastal protection issue has enhanced this process, but one that is unlikely to be the definitive cause of the barrier change. The coincidence of protection and the old flood bank has held the two elements in quasi juxtaposition. This may well alter given the likely spatial divergence of the two elements in the future.

Specific responses to Advice requirements

30. *Q: How would the coast be likely to evolve under Hold the line (with likely intrusion into the SAC of hard defence as a continuation of the current line moving north from East Lane)?*

31. A: If HTL dominates management approach, then presumably there would be a planned continuation with armouring as a response to any further loss of SSB i.e. the current status quo. The issue of potential further roll-up of SSB is not addressed and will start to worsen as the current SSB alignment diverges from the old Flood bank which acts as the backstop to current armouring. This would require new intervention to deal with the increasing gap between flood bank and back-barrier. Ironically as the SSB terminus detatches and progressively loses sediment volume under the northern drift, then southern SSB will evolve into a functioning overwashing barrier and start to move into a more defined swash aligned orientation (given it would now have access to the back-barrier accommodation space that the current terminus does not have). That development might be constrained by adhering to HTL, given that any detachment of the barrier terminus from the armoured flood bank would not be allowed to occur, as this would be the vulnerable position whereby storm-surge access to the agricultural reclamation area was most likely. SSB would be modified into a flood-defence structure (FDS) and held in place by probable armouring. The SAC would continue to lose area of exposed shingle and any creation of the SSB into a FDS would reduce or prohibit SAC vegetation from expanding. An FDS structure would attempt to deny gravel moving northwards, such that focus of barrier sediment losses would also move northwards to a position beyond the protection. This might engender fresh deposition at SSN and add area to the SAC, but one could not identify a positive conditionality for the SAC given so much human intervention. The tempo of such changes would accelerate under relative sea-level rise. This overall scenario would be extremely costly to support.

32. *Q: How would the coast be likely to evolve under Managed re-alignment (are there alternative options). Using East Lane and Shingle Street as Headlands of a sort of sub cell, or alternatively allowing possible inundation of the (Flood Risk 3) land in behind the beach and roll back of the barrier)?*

33. A: Any answer to this question must be taken as a conceptual development only at this stage. This question in turn begs further questions as to what form of managed realignment could be undertaken on this shoreline and to what end (natural or economic) any such management would be employed to achieve. In the present political and financial climate, reduction of future capital investment is a priority such that I assume that stopping the current incremental creep of coastal armouring has the highest priority. To achieve that action means the storm flood hazard and hence risk currently attached to Alderton reclaimed marshes has to be radically changed by switching from the current agricultural output (behind the protection) to a nature-based output that allows for restoration of a wetlands and coastal marsh ecosystems (abandonment of armoured protection and breaching of current flood banks) across the reclaimed area. That could be facilitated by planning for future incursions of surge storm water around the southern terminus of SSB, which would reactivate the back-barrier area (currently

seaward of the old Flood bank) as an intermittently brackish/saline lagoon. The evolution of any such change would not affect the nature of the SAC, but may alter the geomorphological activity (and status) of SSB in future decades, when the barrier would be free to evolve naturally with rising sea level. The current lack of beach sediment supply around East Lane protection works and the dominance of northwards-directed sediment means the likelihood of any future SSB managing to re-attach itself to this hard point is very limited. This reduces the likelihood of SSB achieving overall swash alignment.

34. *Q: How would the coast be likely to evolve under No active intervention (how would the frontage react to a do-nothing approach, and what would be the effect of the Martello Towers along this frontage)?*

35. A: There is likely to be a similarity between a future SSB under the managed realignment option (para. 32), and the do-nothing option, as both options assume that current coastal armouring would cease and therefore attempts to anchor southern SSB would stop.

36. A: What would be the influence of the Martello towers? There were 4 Martello towers along SSB (early 19thC.), one of which has now disappeared presumably with SSB changes (not mapped). The remaining three are privately owned. One is currently behind the East Lane defences and is unlikely to be effected by any future change in SAC management options unless with a do-nothing option, maintenance of existing armouring would also cease. The next Martello north lies behind the SSB (Centre) and will become an issue if the centre zone of SSB retreats. The final Martello is at the south end of Shingle Street and sits in the lee of the gravel accumulation (SSN). Only the centre Martello is likely to be at risk with future coastal flooding, which is likely to worsen if SSB is allowed to migrate under managed realignment. The issue of central Martello protection, given its Heritage listing status, lies outside NE remit, but would become an area of discussion with any future onshore movement of SSB.

37. *Q: What would the implications for shingle habitats be under these different options, in terms of future evolution, natural functioning, and natural processes?*

38. A: The key process for shingle vegetation is ground stability, and as such none of the management options are going to enhance this aspect, when the dominant drift of beach sediment is northwards which is leading to net erosion along south and central SSB with retreating shorelines. As the southern barrier erodes, its sediment is likely to end up at SSN, and even here in the existing progradational beach ridge regime, it is taking many years to see natural vegetation developing (Fig.12A&B).

Fig.1: Position of SSB and SSN from Bawdsey to Shingle Street and the Alde-Ore estuary outlet.

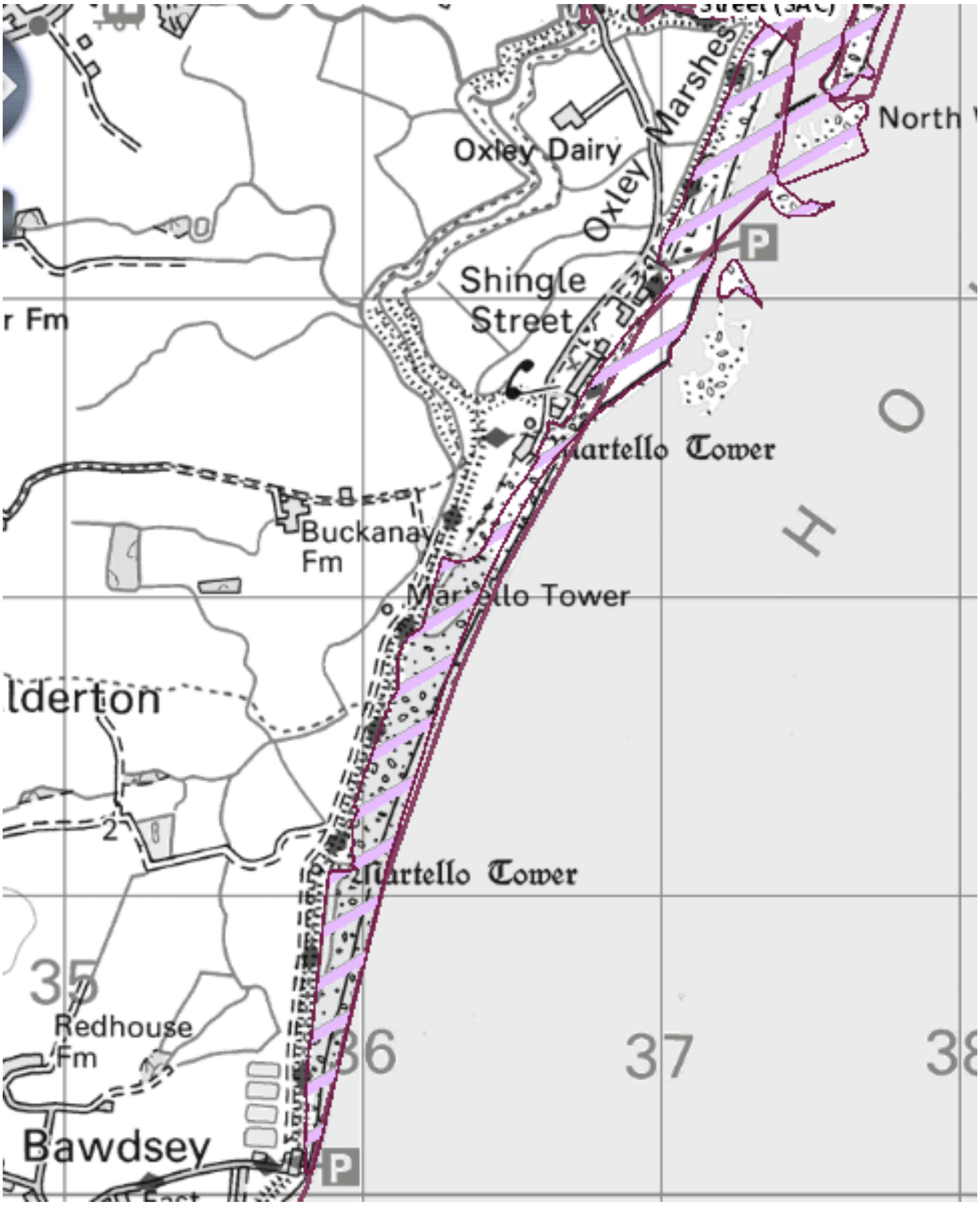

Fig.2: Orfordness-Shingle Street Priority Habitat Area of SAC (purple shading)

Fig.3: Google Image of SSB and SSN (2008) Note the swash-aligned barrier remnant behind the centre of SSB and the sub tidal shoal flanking SSN that is related to the flood orientated structures at the mouth of the Alde-Ore immediately to the RHS of the image.

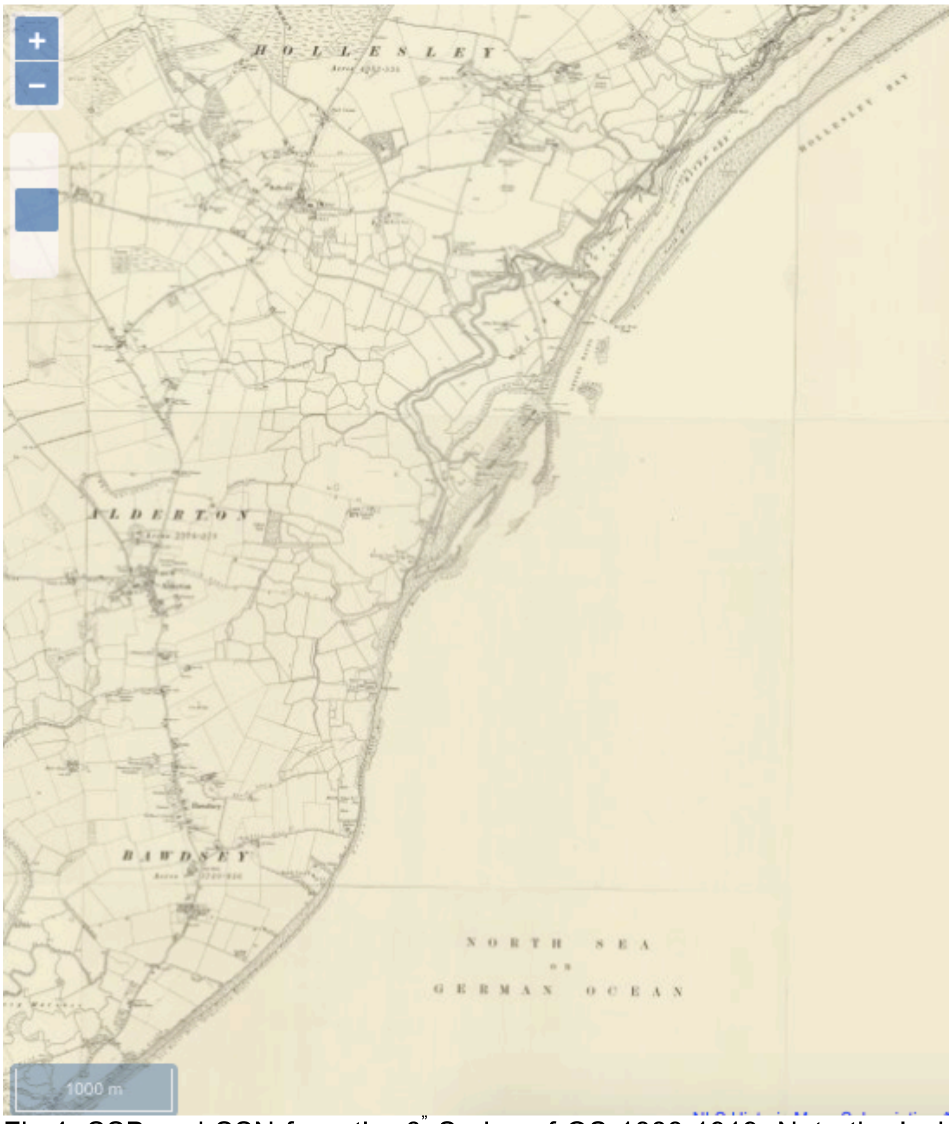

Fig.4: SSB and SSN from the 6" Series of OS 1888-1919. Note the lack of a ness feature and the strong southerly orientation of estuary mouth side bars of the Alde-Ore.

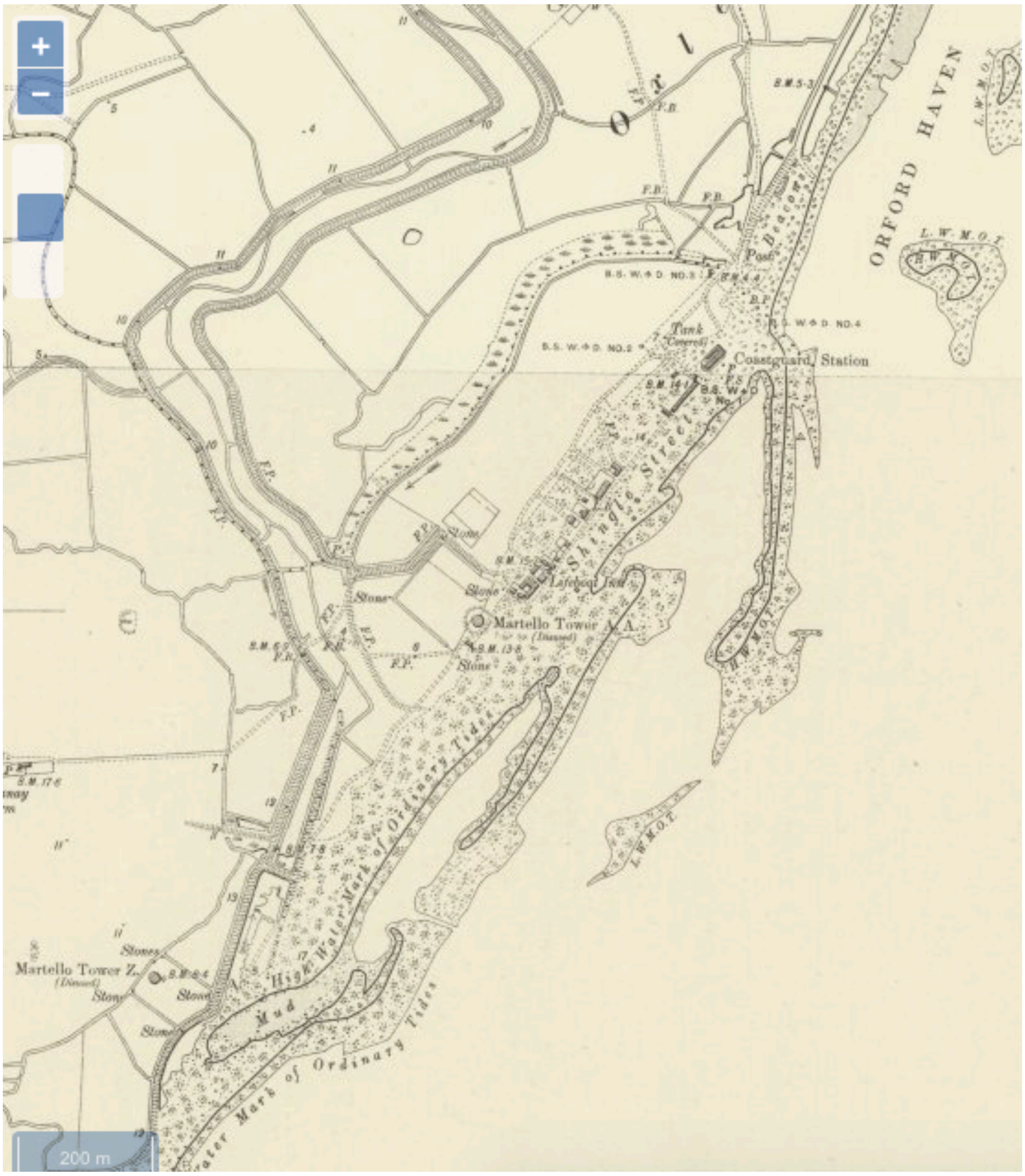

Fig.5: Enlargement of Fig.4 to show detail of lagoon at Shingle Street that might be that referred to by Steers (1946).

Fig.6: Section from OS 1:25000 available 1961. Note the lack of a ness at Shingle Street and the accompanying northerly directed spit at the Alde-Ore entrance as a reversal of structures at the mouth of the Alde-Ore exit (North Weir Point) compared to the early 20thC. (cf. Fig.5).

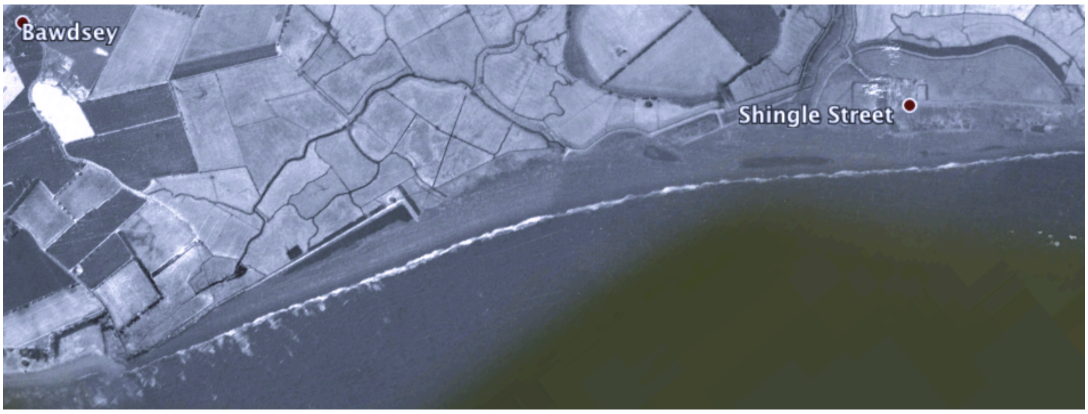

Fig.7A: SSB in 1945 (Google earth image).

Fig.7B: SSB in 2000 (Google earth image).

Fig.7C: SSN in 2011 (Google earth image).

Fig.7D: SSB and SSN shoreline changes between 1945 (yellow) and 2013. Note the salient change in estuary mouth side bars plus growth of SSN.

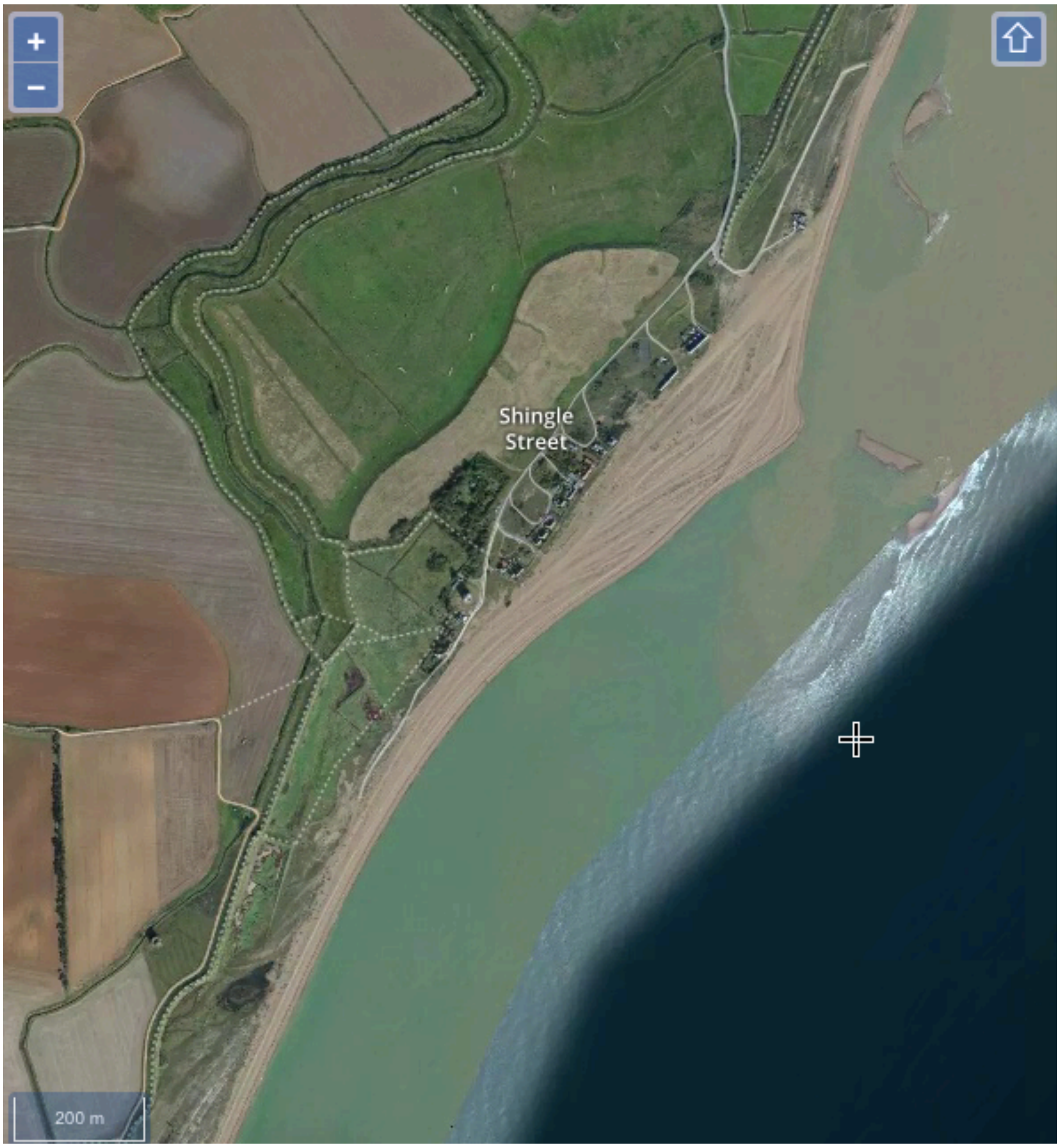

Fig.7E: SSN morphological structure as of 2017 (Google Earth) Note the early 21st C. accretion to the northeast of the Ness that could be related to the increased dominance of northwards-directed transport identified by HR Wallingford (2016).

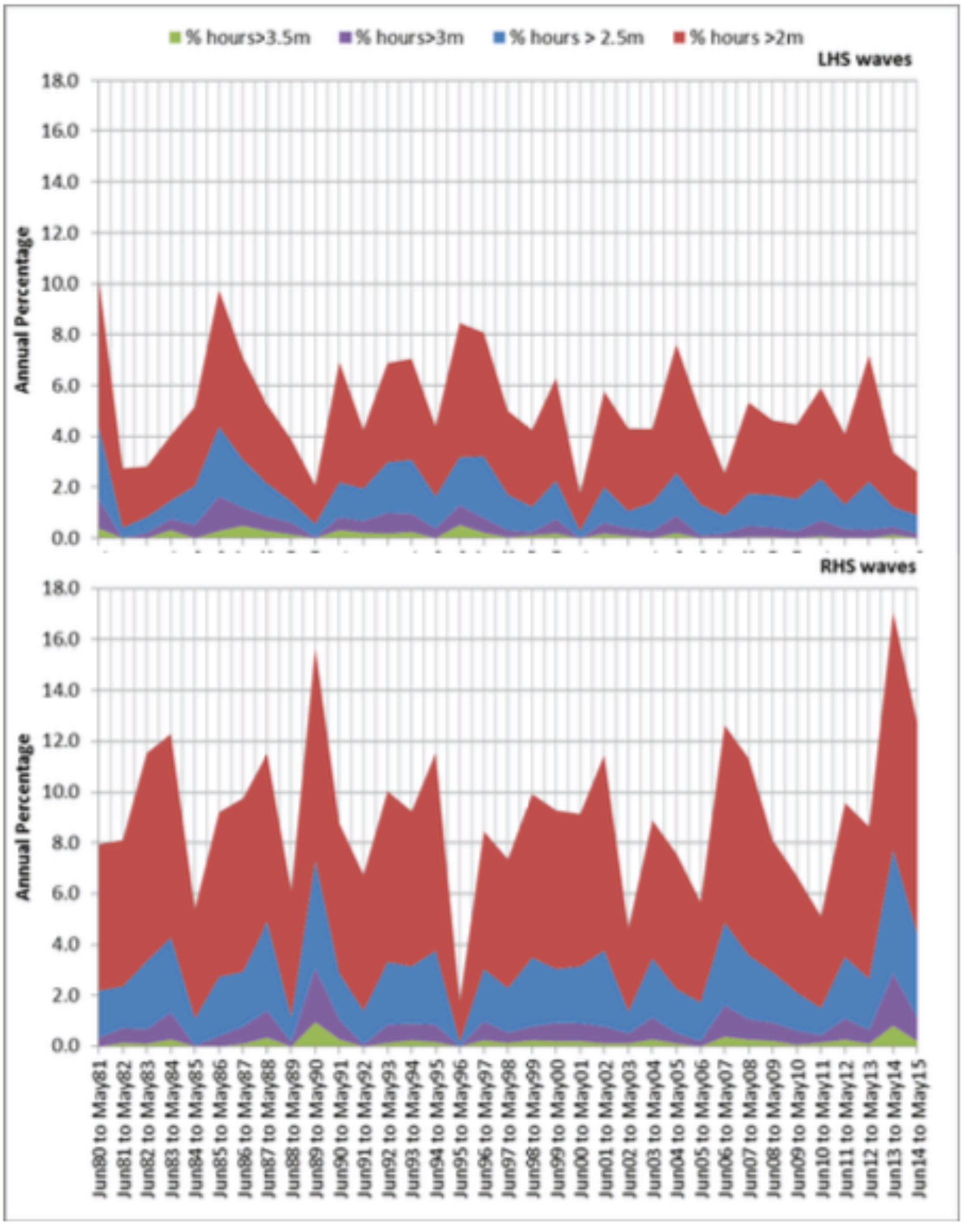

Fig.8: Hindecast occurrence of inshore wave height and direction between 1981-2015. LHS waves refer to southerly-directed waves and RHS waves refer to northerly-directed waves along SSB. Note the temporal variance and the excess of northerly wave power compared to southerly-directed wave power. (After HR Wallingford, 2016)

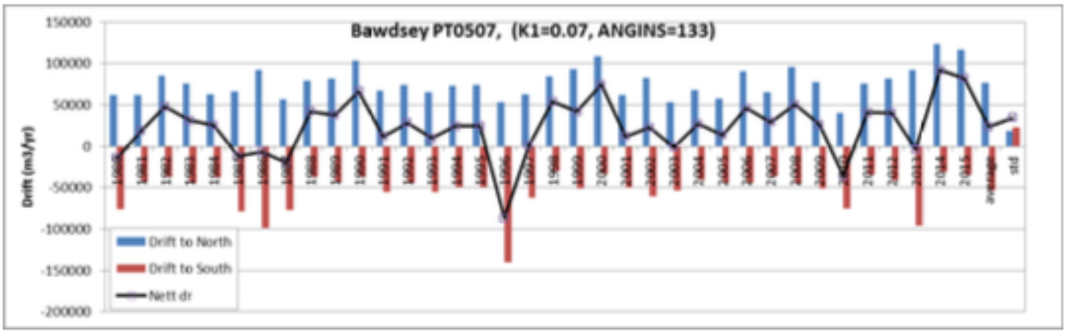

Fig.9: The annual relative balance between north- (blue) and south-directed (red) sediment transport for south SSB. The black line is the net transport rate and direction. Note the relatively small transport loads, and the multi-annual (sub-decade) values of quasi-periodic variation. Such variation show that net northwards roll-up of the southern SSB will be slow but persistent. (After HR Wallingford, 2016)

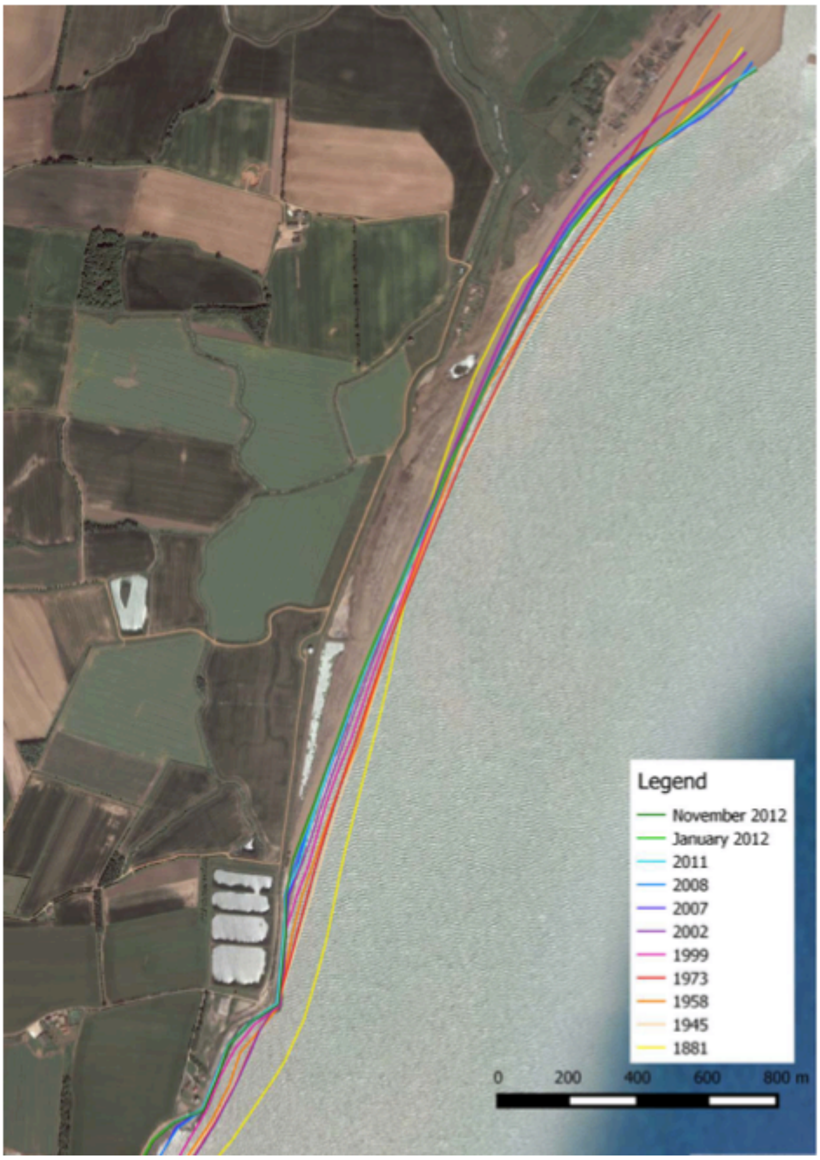

Fig.10: Shoreline positions identified by Burningham (2016) supplied via HR Wallingford (2016).

Fig.11A: Looking northwards towards SSB. Serial coastal protection (rock armouring) along the old Flood Bank.

Fig.11B: Looking southwards at the current engineered terminus to the SSB and the encroaching armouring.

Fig.12A: Vegetation (Sea Kale) density variation over SSN ridges getting younger to the LHS of the image.

Fig.12B: Lack of vegetation on recent beach ridge sediment influx (post 2010) at SSN. Note the northern-most Martello Tower at Shingle Street.

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c. EA Bawdsey Report: http://www.channelcoast.org

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