NATURAL ENGLAND

Geomorphological Advice in respect of Pagham spit (West Sussex).

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Natural England Advice Request

1) Could the two recycling operations: i) 2010 and ii) 2012-13 have had a detrimental impact on the site's functioning and its geomorphological interest?
2) What are the best sources for the current sediment recycling proposals? Note two joint operations to be considered: i) HW erosion at western Pagham and ii) re-armouring of the exposed armoured groyne
3) Is the channel likely to close?
4) What are the possible ways in which the spit might develop, both in the short and longer term? Of these, which is the most likely?
5) Is the rock armour the most effective way to protect the properties?
6) Our current view is that the on-going evolution of the Church Norton spit is a key component in the conservation of the geomorphological interest of the SSSI. Are there other elements we should also be concerned about?

Glossary

Berm: A constructive wave-built beach face feature generally occurring at the swash reach associated with any particular high tide position. Cumulatively over the neap to spring tidal half-cycle, one berm is realized, associated with highest tidal position. On the falling spring-neap cycle, a series of berms may be realized at each successive lower position achieved by the swash-reach of each successive falling tidal level.

Cannibalisation: The tendency for a beach system where the longshore sediment supply has reduced or failed, to use the existing beach sediment as a further source for subsequent longshore sediment transport down-drift. Cannibalisation generally starts at an up-drift position and progressively works alongshore (down-drift) through the beach sequence. Cannibalisation is generally the cause for beach ridge swash-alignment to appear in the updrift area of a coastal cell

Coarse-clastic sediment: See **Grave**l.

Dissipative: One end of the beach morphodynamic continuum where the lowest beach slopes (generally with sand) are associated with a minimum of reflected wave energies.

Drift-alignment: Descriptive term indicative of a beach or beach-ridge system dominated by active longshore drift, and typical of prograded beach ridges. Drift-alignment is generally indicative of greater up-drift sediment input, than down-drift output. In plan-view, drift-alignment is associated with increasing beach width in a down-drift direction.

Facies: The observed characteristics of (generally) sediment size, morphology, or minerogenic composition, which show differentiation in time or space. Used as variable to describe the actual realized nature of sediment.

Gravel: An integrative term used to describe the texture of particles on the Wentworth Scale, which are between 4 and 256mm B-axis size (i.e., including pebbles and cobbles). In recent years, the use of 'gravel-dominated' in beach analysis tends to relate to sediment that is predominantly greater than sand (i.e. <2mm B-axis) and can be of a size from granules through to boulders. It is also sometimes referred to as **coarse-clastic sediment** when used in a coastal context.

Overtopping: Process in which a small percentage of swash flows reach the top of the beach (=crest). They have the potential to move particles to the ridge top and help to build up the crest. The crest is usually only included in such swash flows during storms.

Overwashing: Process in which swash flows reach the beach crest and pass over it to flow down the back of the sediment accumulation. Generally only observed when the beach is part of a freestanding barrier. Such flows have the potential to move sediment from the beach face, and beach crest, down the back barrier slope, and are central to the barrier rollover process.

Reflective: One end of the beach morphodynamic continuum where the steepest beach slopes (usually with gravel) are associated with a maximum of reflected wave energies.

Resilience: A variable time-based (diurnal tidal cycle to years) capacity by which gravel barriers may rebuild coherency and geomorphic function, despite experiencing extreme events that may have initially destabilized barrier form.

Rollover: A gravel beach which experiences overwash will in time transport beach face material to the back barrier. In so doing, this process exhumes old back-barrier deposition through the beach face as the beach crest and associated beach profile migrate landward. Over time, the whole beach ridge is rolled over itself.

Step: A mixed erosional and depositional ridge-like form usually located at the edge of gravel beaches at low tide and formed at the break point of LT incident waves. Traditionally seen as occupying the seaward edge of the swash zone. It may migrate onshore during the tidal cycle, but where a gravel beach is fringed by low-tide sand terrace, the step gets stranded at the break of slope between gravel and sand.

Swash alignment: Descriptive term for a beach or beach ridge system associated with weak longshore drift. The term applies to a sediment-starved single beach ridge, generally indicative of greater down-drift sediment output, than up-drift input. In plan-view, swash alignment is associated with diminishing beach width in a down-drift direction. Swash alignment is generally associated with cannibalization of up-drift beaches, and a subsequent breakdown of longshore barrier/beach continuity into segmented sections characterized by smaller scale up-drift beach bays leading into down-drift mini beach-accumulation headlands. Hence swash-alignment can be observed at different scales from coast cell (km) down to beach (m).

EXECUTIVE SUMMARY

i. It is essential to see the demands for longshore sediment reflected in Pagham spit's growth as being only the latest demand on longshore sediment supply and transport for the West Sussex coast between Selsey and Bognor. Pressure on coastline dwellings relative to diminishing buffering beach width is due to the century-scale changes imposed by the presence and absence of an ebb-delta and associated spit at the entrance to Pagham Harbour. The contemporary spit across the entrance to Pagham Harbour is only the latest in a sequence which has controlled downdrift sediment supply to Pagham frontage.

ii. Since the last Natural England geomorphological Advice statement for Pagham spit (2009), the spit's development strategy has changed. The spit's 2009-13 evolution has been dependent on both a declining sediment supply and a change in the subsurface bathymetry as the spit has tried to extend further eastwards. The rate of spit growth has been decreasing and the spit's morphology has been condensing into a narrow structure, which is more prone to onshore-directed rollover.

iii. In retrospect, the 2009-10 recycling of spit sediment for Arun Council's beach renourishment project has probably been detrimental to spit development. It is noticeable that since this extraction date, though possibly not causally linked to the extraction *per se*, the spit has shown a different vector of growth that has brought it closer to Pagham frontage. The landward movement of the spit has forced the Pagham outlet tidal channel to move onshore reducing beach buffer widths against some of the western houses of Pagham frontage. Furthermore the impact of the recycled sediment on the upper beach profile further to the east has already been nullified by recent wave reworking.

iv. The emergency renourishment of western Pagham beach frontage for properties showing flood-buffer ground loss during 2012-13 storms, using sediment from lateral sites protected by the spit, is probably the least-worse option in terms of benefit relative to impact. Renourishment sediment is nearly compatible in size to that eroded, and the source area changes are unlikely to impinge on long-term spit dynamics. However given the reduced size of the latest spit-extension and narrowness of the spit, this could be where future tidal channel by-passing through storm breaches may occur. In so doing it will expose the landward side of the tidal channel to the same potential forces that eroded the Pagham frontages in 2012-13. Again this will not impact on the spit's development cycle but will have impacts and risks for western Pagham frontages.

v. There is no purpose in Natural England opposing the proposed action by Arun Council to armour and replenish sediment volume at the root area of the first armoured groyne. The groyne is holding up the eastwards extension of the spit, but this intervention is unlikely to make any difference to the overall spit dynamics. The volume required for backfilling (c<100m^3) the new proposed defences should not be taken from the spit's delta basement (as proposd), which in the area of the current tidal channel exit is poorly supplied with spit delta sediment. Furthermore given the smaller sediment size available from this source, a source of sediment larger than currently on the upper beach needs to be found.

vi. From the perspective of its geomorphological interest, the continuing evolution of Pagham spit is proceeding at an exciting pace. These circumstances offer a high potential for monitoring to further the understanding of UK coastal spit dynamics. Some form of association with the Higher Education sector should be encouraged, as should the support of Arun Council and Environment Agency with respect to access to, and continuation of, remote sensing information for the overall Pagham shoreline. In particular, given the evident fluctuations in sediment supply rate now showing in the spit morphology, the offshore region at the root of the spit (Church Norton) needs immediate investigation via multibeam to establish likely sediment source regions and possible pathways for sediment supply to the spit.

Scientific assessment

vii. It is strategic to note that the West Sussex and East Hampshire coastline has a range of estuaries with flanking, flying and encroaching spits at their entrances. It has been 40-50 years since the initial work on the geomorphology of these spits was undertaken. The GCR has outlined some of this work, but it is more than time for an updating of these structures' geomorphology and sedimentology, especially at a time when coastal protection has been in place for many decades and forced multiple changes to these features. Recognition of the anthropogenic forcing and its impact on these features is in need of further analysis. Clearly the impacts of coastal squeeze along these coasts have been understood in terms of the major Medmerry re-alignment to maintain/replace habitats, yet nothing has been undertaken in terms of the classic geomorphology that has been damaged/lost by the demands of coastal protection. Shoreline Planning along this coast is based on 'hold-the-line' for the current epoch. There will undoubtedly be greater future demands on the coastal sediments that remain in these features. There is an on-going need to understand how these SSSI's are performing / going to perform under the changing forcing profiles of the next century, and the associated implications for their geomorphological designations.

Natural England Advice Responses

Some general coastal principles relative to understanding Pagham spit's behaviour

1. Pagham spit's developments are part of the process by which, in the context of the West Sussex coastal cell, sediment is transferred from the cell's western sediment source (around Selsey) and moved alongshore to an easterly sink, or cell's depositional area on the beach face towards Bognor. This transfer is undertaken in what is termed the transport corridor between source and sink, otherwise known as the beach. As the transport corridor's longshore energy potential diminishes relative to sediment load, then the complementary sink-status rises, i.e. deposited sediment remains. If however, longshore sediment availability diminishes, then reworking of existing sediment rises and the corridor-status likewise rises, relative to a falling sink-status.

2. Pagham spit should be viewed as part transport corridor and part sink, which in the past decade has been sink-dominated, hence longshore spit growth. As one moves progressively eastwards beyond Pagham spit, then the beach (Pagham frontage) is also part corridor and sink, the balance of which is dependent on the sediment volume that manages to bypass the tidal channel running in/out of Pagham harbour (defining the spit's terminus). A spit by definition is a form of sediment storage whose longshore transport has been checked by cross-beach channel flow, hence the spit's development. Spit presence will create a reduction in sediment supplies immediately down-drift from the spit, hence the likely recession of the beach face immediately down-drift of the spit terminus.

3. The structure of a spit is basically in two-parts. There is the visible spit above the mean low water line which is morphologically well defined and essentially wave-lain, and there is a depositional zone below the low water mark which tends to be less well defined, but is an necessary platform for the inter-tidal spit to be able to be built. Usually this platform is formed from both coarse and fine sediment assuming sediment size availability. The finer (sand and smaller sediment) in particular tends to be distributed seawards by the tidal inlet flows associated with the terminus of the spit. These flows carry the finer lower beach sediments seaward and build the wider sub-tidal platform, which bathymetrically then controls refracting wave attack that leads to the characteristic recurves of the main intertidal spit morphology. This sub-tide /low-tide platform is known as a spit-delta, or spit-basement. If the spit terminus is held up then the deltaic platform has time to build up and can push the low water platform out from the main spit's inter-tidal beach. The spit delta tends to be formed from finer sediments than that found on the spit and volumetrically may be greater than the sediment of the intertidal spit *per se*. If the spit is rapidly extending longshore, then there may not be the time for the deltaic platform to extend seaward. Likewise if the sediment load is dominated by gravel then there may not be the capacity for large deltaic deposition, as tidal current velocities reworking in the offshore direction do not exceed entrainment velocities required for gravel transport. This means that the spit will tend to a linear and spatially constrained feature. The greater the relative availability of sand compared to gravel in the supply, the more the spit will be broader with the possibility of eolian crestal deposition (e.g. Scolt Head).

Pagham Spit has a constrained deltaic platform that suggests a dominant gravel to subordinate sand supply.

4. Longshore sediment reworking has been the essential story of the Pagham frontage beach over the last century since the last major beach building phase (the consequence of late 19th century closure of Pagham Harbour outlet, and the subsequent longshore reworking of the then extant spit). By the late 20th century, this supply of longshore sediment had been reduced sufficiently for the start of reworking of Pagham frontage beach sediment through what is termed cannibalisation (see glossary). This multi-decadal loss of profile sediment from west Pagham through to east Pagham and beyond has been the baseline to activity along this frontage over the last century and is still ongoing. The beach profile retreats (moves onshore) as longshore sediment supply reduces. Such sediment losses at the high-tide position tend to be the most dramatic indicator of what is happening both across the whole inter-tidal profile and below the low-tide position. This on-going loss of beach volume from the Pagham frontage due to diminished longshore supply is the dominant driver of noticeable erosion along Pagham frontage. Any impact of the enlargement and longshore growth of Pagham spit is superimposed on this overall sediment deficit, down-drift of the spit terminus.

5. Any retreat of beach frontage can be also driven by a rise in relative sea level (RSL). During the 20th century such RSL rise rate was probably of the order of 1-2mm/year (mm a^{-1}) along the Wessex coast, with the equivalent annual retreat rate of any freestanding gravel barrier at about 1-2m a^{-1} in response to this rise in RSL. This suggests that the mean tide position would have retreated by c.200m over the 20th century. However given the substantial human intervention in the Wessex coastal system (directed as a 'hold-the-line' approach) any reaction of beach position to RSL change has been severely impeded, such that the actual retreat is far less than the prediction. However as another consequence of this high water 'holding-the-line' coastal protection, it is recognised that there has been rotational steepening of the overall beach profile throughout the west-Wessex shoreline, i.e. the low water position has moved further onshore than the high water position (Charleton and Orford, 2002). This 20th century rotation of beach profile has as a consequence, meant that waves now break closer to the beach face than previously (especially during storms) and hence effect changes at the high water position and above, in greater proportion than in previous centuries. The combination of both changing RSL and longshore sediment supply must form the background to any other analysis of recent coastal changes along the west Wessex coast.

6. Analysing contemporary coastal change with regard to their future stability is fraught with uncertainty especially given potential changes in future forcing conditions. Future increases in RSL are highly debatable, with DEFRA working to projected total RSL increase of c. 60cm by 2100AD (UKCIP09, 2009). UKCP09 also recognising the strength of scientific opinion that more severe RSL changes of >1m are possible (the H^{++} scenario). If the latter is achieved, then the Wessex coastline will experience substantial changes in shoreline configuration that will be likely to overwhelm the contemporary coastal defence strategies. Recycling sediment from existing beach stock is likely to be a very short-term solution to coastal protection under the >1m plus RSL rise scenario. The impact of any 'holding-the-line' policy, and its related consequent beach face

steepening, will only serve to reinforce the difficulty in maintaining adequate frontage beach width as a coastal defence for frontline properties over the coming decades.

7. The geomorphic issue in the last decade has been to what degree Pagham spit's recent growth spurt has also been responsible for down-drift losses along the rest of the eastern Pagham frontage. The history of human intervention in the Pagham system has been centred on trying to control down-spit erosion, principally by building groynes to reduce longshore transport, as well as create protective sediment compartments for the upper beach. The problem is that any temporary (or permanent) cessation of longshore transport will cause further down-drift erosion, hence any human intrusion in the beach transport corridor to hold up transport, will cause consequent down-drift erosion. In the long run (decades), it is likely that 'some" contemporary spit sediment will be transported beyond the spit's confines and added to the Pagham Frontage. The prediction of how much "some" is, and the time scale of "in the long run" are two items which can not be predicted with any certainty.

8. The important principle for understanding spit dynamics is that spits are highly dependent on longshore sediment supply variation. The spatial, morphological and sedimentological structure of any spit is related to the rate of sediment supply that:

   i) enters the system from the source area (= cliff and nearshore);
   ii) moves along the transport corridor (= beach face);
   iii) is deposited (= the spit and its associated delta platform) where longshore transport potential is physically checked; and
   iv) moves on from the spit terminus position, back into the general down-drift beach system.

9. A spit's terminal position is due to both:
   i) natural feedbacks by which the power of longshore transport (proportional to the angle of breaking wave thrust) is reduced to near-zero by wave refraction around a developing spit delta (the subtidal deposition essential for further spit longshore growth); and
   ii) the power of any cross-beach water forcing associated with the tidally driven Pagham Harbour inlet/outlet, which can both halt and redirect longshore sediment transport to assist in the sub-tide delta construction.

10. The spit's terminal position identifies a major check to longshore sediment delivery, which is maximised in the inter-tidal zone. Sub-tidal transport by currents is still feasible alongshore, but usually with the finest sediment, which is unlikely to be deposited on the intertidal beach. This deposition in the near-shore is usually a sub-dominant component of beach face sediment supply. The cross-beach morphology associated with the tidal outlet is the dominant physical barrier, which has to be crossed by incremental growth of the spit (dependent on sediment supply) that forces the tidal channel alongshore. Under some specific conditions, if the tidal channel has been over-forced longshore, the channel may jump back alongshore. This is usually known as channel avulsion where under severe flow conditions an easier and shorter access route develops up-drift from the existing exit. This is only likely when the spit has been over extended and is relatively narrow and declining in its overall sediment volume. This avulsion process is likely with direct wave attack on the front of the spit

causing overwashing of the spit crest at high tide, in combination with storm-surge augmented tidal-flows attacking from the channel side. Once avulsion has occurred the down-drift extensions of the spit are now more easily reworked into new longshore sediment supply for down-drift beaches. There is evidence of recycling of sediment at a spit terminus positions by this avulsion process from other spits around UK coast (e.g. Orfordness and Shingle Street, and the Deben estuary). Longshore sediment by-passing of tidal channels/estuaries is a process that is not uncommon on mixed estuary/open coastlines, though in this regard, Pagham is unusual in the strength of contemporary spit control and the lack of sediment by-passing by channel avulsion in the last decade. In that respect, enhanced spit growth is generally regarded by Pagham householders, as the cause of down-drift sediment loss, which in turn is a factor in reducing beach frontage width. Therefore any accelerated assisted movement of Pagham spit sediment to down-drift positions is likely to be regarded as being a major element in any resolution of frontage erosion.

11. If, in the long term, it is likely that Pagham spit sediment will be delivered down-drift to the Pagham frontage, then it can be argued that there is nothing in principle wrong about taking sediment now from the spit and adding it to the frontage to resolve erosion problems, as that is where sediment will end up eventually. This is the general underlying justification for Pagham frontage requests for using spit sediment to alleviate beach erosion issues. Unfortunately, what looks in principle as being an obvious solution, has inherent difficulties. Sediment reworked around the spit terminus will be moved alongshore but predominantly along the lower beach, i.e. the area between mid-tide and sub-tide of the low tide position. The dominant sediment size of this zone is likely to be finer than that which resides at high water positions for sandy-gravel dominated coasts. This longshore sediment volume is then reworked across the beach profile with a further reduced sediment volume (coarser than average) selectively placed at the high water and storm reach positions on the profile. The overall value of this process is that the beach profile is slightly flattened by extending the beach face seawards. This ensures that waves break further offshore, hence reducing run-up and further dissipating swash flows affecting the upper beach.

12. The perceived source of the erosion problem along Pagham frontage is a reduction in the back-beach distance between storm beach and houses. This is mainly due to long-term erosion of the upper beach due to general sediment depletion over the whole beach profile, though residents' perception of an erosion problem is often caused by specific storm events, which can remove several meters from this apparent buffer zone in one high tide. Any one-off nourishment volume, drawn from the low tide area of the spit, and placed directly at the high water line in a remedial action to storm wave attack, is inevitably going to be wave-reworked with the finer sediment moving down-beach. The long-term retreat of the overall beach profile (mentioned above) is only going to be disrupted for a few years at best, by this type of one-off sediment nourishment exercise. Eventually the benefit of the nourished sediment is effectively winnowed away and the old erosion problem re-emerges at the beach crest and high tide area. Research elsewhere on a mixed sand and gravel spit (Bradbury and Orford, 2007) has identified the potential for accelerated loss of sediment offshore by the oversteepening of the upper beach via nourishment/re-profiling. Re-nourishment volumes should be placed on the lower beach and allowed to

rework naturally to lower the overall beach/near shore gradient to reduce wave attack. However, without an adequate coarse clastic component, as coarse, if not coarser than what was initially eroded, the problem of upper beach erosion is unlikely to be alleviated to a level of resident satisfaction, without continual phases of renourishment being used. This means that one-off nourishment exercises tend to be ineffectual, and initial demands for limited sediment can become a continual demand that can't be met by available coastal supply.

Site Review

13. Since 2009 (the previous Advice related field visit), the Pagham Spit has increased eastwards dominantly in the inter-tidal zone of the spit, and by limited extension of the low tide and subtidal deltaic platform upon which the spit develops. The basic analyses of this site's structural elements and associated dynamics have been identified in the previous Advice report to Natural England (Orford, 2009).

14. The following analyses of spit behaviour and associated sediment supply are based on limited data post-2009. Any results have to be set in a context that the scales of results still need to be calibrated against general conditions of spit dynamics over the last decade.

15. Two air photographs identify the nature of a change in overall spit dynamics since 2009. Fig1 shows the spit extent in 2010 after the first major recycling scheme (late 2009) where the sediment was used to bolster up frontage width east of the four armoured groynes. Prior to this extraction, Natural England Advice expressed the view that any extraction could be detrimental to the spit's development, though the level of such detriment depended on the scale of sediment extraction. Comparison of Fig1 and Fig2 shows the extent of spit development in 2010-12, as well as identifying the changing trajectory of spit evolution. The solid green line on Fig2 shows the extraction edge and a distinctive low tide/sub-tidal morphology (hook feature) that had been left as the seaward edge of extraction (see Fig1) and thereby formed the base time line for changes during the next two years.

16. The time comparisons of spit growth and delta extent are seen superimposed on Fig2. Two subsequent forms of spit change are evident between 2011 and 2012: i) the limited development of the subtidal delta; and ii) the extension of the spit both alongshore and onshore. The extraction feature (para 14) seems to have persisted and become a focus of possible infilling deposition. Its form is clearly identified from 2010 to 2012. However its longshore shift (indicative of the delta generally) has been retarded relative to the spit's development, such that by late 2012 it had lagged behind the spit's terminus by nearly 200m. The lack of a substantial delta platform may then account for the next obvious stage of spit development *per se*. The spit during 2010-2012 moved closer shorewards, over-riding recent recurves (2011 terminus positions), as well as thinning down in width by c 40%.

17. While it is uncertain as to what has caused the reduction in delta growth, it is likely that the lack of sub-tidal delta meant that the locus of further spit extension had been pushed onshore by c 140m, thereby squeezing the Pagham outlet channel against the first armoured groyne (see below), as well as driving tidal channel incision into the landward bank of the outlet

channel in the proximity of the first Pagham houses (cause for the 2013 renourishment request). The sediment recycling operation of 2010, is probably not the cause of this reduction in delta development *per se*, but would have not assisted the spit's capacity to maintain the existing line of the spit in post-2010 extensions. From paragraph 3, it could be argued that this loss of delta is a reflection of a major shift in sediment supply (especially of finer sizes). Therefore in retrospect, the 2010 extraction of delta sediment has exerted an influence on the on-going spit development that was unforeseen in 2010.

18. The reducing sediment supply may well be reflected in the inter-tidal dynamic changes exhibited by the spit during 2010-2012. Again referring to Fig2, the rate of spit growth can be assessed for both 0m and 3m elevation changes. The former is indicative of the general spit platform, while the latter relates to mid-beach elevation changes. Fig2 data refers to March and October surveys during 2011 and 2012 and offers a measurement of changing spit extension rate on a rolling six-monthly and annual basis.

19. The 0m-datum changes indicate a reducing rate of spit terminus extension at near the low water position. Over the two years the extension rate has reduced from over 100m a^{-1} (early 2011) to half that by the closing period of 2012. On the open flank of the spit the 0-contour remains virtually in the same place over the two years. As mentioned in para16 the delta platform shows small changes in longshore growth, at c 50% of the spit terminus growth rate. This lack of longshore growth is also reflected in the reduction of the spit extension width, which from 2010 appears to be reduced down by c 40% compared to the width of pre-2010 growth. This change may relate to the old late-20th century delta platform, whose presence allowed the spit the foundation for prograding (i.e. width increasing). Without that spit-delta platform, further spit progradation is less likely, as is the case now. A new element in the late 2012 is the further retreat of the terminus onshore, which caused the associated incision of the inner protected beach frontage on the landward side of the tidal channel. This sympathetic movement is related to the hydraulic efficiency of the channel, if the one side of the channel is forced landwards by wave action, then the other side of the channel is eroded in compensation to maintain tidal flow.

20. On Fig2 the 3m-contour identifies a different response of the upper beach. The longshore extension of this zone by recurves is dominated by wave refraction into the tidal channel exit. The longshore growth over the various rolling time periods in 2010-12 identifies an accelerating extension rate from negative (erosion) in early 2010 up to c130m a^{-1} in late 2012 as the effective bathymetry for refraction is missing. This means that sediment lost into recurves (pre 2010) remains as available in the spit terminus extension, hence the increase in extension rate of the upper beach This accelerated growth is also likely to be associated with a loss of overall beach width on the up-drift spit flank with a persistent retreat rate of c 13m a^{-1} during 2010-12. It is likely that this is part of a new sediment source area required for the accelerating upper beach spit extension. Both this evidence of cannibalisation of existing spit, and the thinning of the newer spit extension, supports the general contention that the spit is experiencing overall a falling longshore sediment supply.

21. There are further indications of a fluctuation in sediment supply observed from the morphological changes on the spit, e.g. swash and drift alignment

of upper beach berms, spit recurves and truncation of recurves by the rolling onshore of the contemporary active beach ridge. Whereas in the 2009 report these were interpreted as fluctuations (possibly episodic supply issues), the 2010-12 spit structural changes are probably indicative of more deep-seated supply changes rather than just weather-related episodes of transport variation. That stated is well to remember that in 2010-2013 winters there have been major periods of easterly and south-easterly wave generation (against the overall spit growth trend) and recent differences in spit behaviour may relate to these changes.

22. A spit can be relatively short-lived as a depositional feature, with a life span of years to centuries. The life of a spit is a function of sediment volume supplied and longshore transport potential redistributing the volume. The current Pagham spit is not unusual in this regard, as map evidence shows it is but the latest in a series of historically recorded spits since the 16th century (Barcock and Collins, 1991) which have developed as a consequence of sediment recycling of the feature through both erosion and rebuilding. The importance for Natural England in the current spit cycle at Pagham, are the speed and extent of the latest spit's constructional phases, and their relationship to broader sediment supply changes. This makes the consideration of recycling requests somewhat more difficult to answer, especially if the spit switches into a more dominant cannibalisation-phase.

23. The latest position of the outlet's seaward extension from Pagham Harbour (tidally dominated) is causing some local concern due to associated loss of upper beach face sediment landward of the contemporary outlet (2012-13). The overall outlet channel has been pushed eastwards by the latest spit growth and is now fixed longshore by the position of the western armoured stone groyne (Fig3). The groyne has caused a 90 degree turn on the extension of the outlet channel onto the deltaic platform and as a consequence may be currently holding up further spit extension by the force of the outlet channel across the delta that is moving any spit's extensional sediment seaward rather than allowing longshore transport to continue. Analysis of recent air-photographs showa some limited growth in the deltaic basement around this exit position. However the contemporary stagnation in extension of the spit terminus in the lee of the groyne may lead further development of a spit platform at this position, which would be supportive of any later eastward movement of the spit terminus (sediment permitting).

24. The structural control wielded by the first armoured groyne on the direction of the tidal outlet has served to create the latest problem for Pagham frontage. The tidal channel is directed at a right angle across the spit and aligns with storm waves moving directly onshore in from a south-easterly direction, with wave energy maximised at high tides. Over the winter of 2012-13, the tidal channel has been in receipt of storm waves over several storm episodes. In conjunction with high water, these waves have been directed directly on the landward shore of the tidal channel and specifically caused highly localised retreat of the upper beach adjacent to the up-drift (south-western) side of the armoured groyne (with c. 6m recession of upper beach in one storm event). Fig4 indicates the nature of this erosion, which has now exposed the original wooden groyne that formed the landward base line to the armoured groyne (Fig3).

25. The present spit terminus is not necessarily the final position of the outlet, or that of the spit *per se*. If there is further eastward growth of the spit

through continuing longshore sediment transport, then there is the possibility of the outlet being deflected round the end of the armoured groyne and moving longshore into the next armoured-groyne defended sediment-cell. The hydraulic power of the current tidal outlet is such, that it is unlikely that the spit will be able to seal off the outlet completely, hence the likelihood of further down-drift deflection of the outlet position.

26. Any further extension of the spit, however, will depend on the rate of longshore sediment supply. If it is maintained at its present value, then the spit is probably going to extend eastwards, but at a reducing rate given the diminishing longshore sediment supply rate being delivered per unit length of the increasing spit length. If this reducing supply position is the case, one would expect to see associated increased erosion along the length of the spit through a new phase of spit cannibalisation to support further spit extension.

27. However, maintained-supply is unlikely to be the contemporary supply status, given that the spit extension over the last two years has produced a single beach ridge morphology on the latest spit extension. This feature is rolling onshore (shown by the overtopping and truncation of underlying old spit terminal recurves: Fig2 and Fig5). This structural change relates to the move from prograding drift units laterally extending the spit on a broad-front zone (i.e. the spit was increasing in width as it increased in length), to a single beach ridge-foreshore system that is now extending longshore (i.e. the width is not increasing as the length increases). This is a change in spit depositional behaviour that could be identified as an indication of a reduction in the effective longshore sediment load, per unit beach-length of new spit extension.

28. The beach-face structuring of gravel facies can also be indicative of supply state. Fig6 identifies some of the classic structures of gravel facies first proposed by Bluck (1969) whereby relative zonation (sorting) of particle size and shape due to dominant cross-beach transport can be seen. This domination arises when longshore transport is subsiding, allowing the cross-beach particle zonation by swash action to dominate. The observed sequence of cross-beach particle sorting zones reflects the current sediment status of the beach. It would need persistence of these sequences over time and space, to identify a substantial reduction in longshore sediment supply. However taken with the rolling onshore of the beach ridge, there is indication of a current reduction in sediment supply. If this persists, then it’s further indication of a cannibalisation phase occurring on the main Pagham spit (Church Norton section), supporting probable pulsed longshore sediment-supply for any future limited spit extension.

29. If a cannibalisation phase becomes dominant, then in the longer term any spit extension will be at the expense of spit width. This over-elongation phase of spit length extension opens the reducing spit width to possible opportunistic ridge breaches during storms when storm surge can overwash the ridge crest. The probability of shifting the tidal outlet channel back to the west, by up-spit breaching, has to be regarded as increasing the longer the cannibalisation phase persists. The narrowing of the post-2010 spit extension would also aid any possible channel bypassing. Spit breaching will require storm-surge conditions in combination with high tide to force excess tidal prism water into Pagham Harbour. Then on the ebb, the excess water volume may try to engage with any overwash breach (that is

low enough) to force a new seaward-directed outlet position. This may take several storm events before any such proto-breach becomes sufficiently dominant to abstract the full tidal prism evacuation of Pagham Harbour, and allow a tidal channel switch to occur. The occurrence of such a breach is going to be associated with declining beach face longshore sediment supply situations.

30. The current development of dominant cross-beach transport, the rollover of a single beach ridge and the evidence of upper beach washover during winter 2012-13 are probably indicative of a change in contemporary sediment-supply regime. This may be a temporary phase only, due to more dominant easterly to south-easterly wave conditions during recent winters holding up easterly-directed longshore supply, and forcing an apparent sediment scarcity position. The contemporary spit behaviour does underline the dynamic nature of Pagham spit, which also underlines its scientific importance. Likewise the need for more direct observation and analysis of phases of spit behaviour with local tidal and wave climate conditions is required. Without some sense of these seasonal-annual relationships, the ability to fully interpret overall spit behaviour will always be uncertain. It is unfortunate that no on-going monitoring of the spit's morphological changes has been undertaken, as these are the short-term changes (<1 year) that are poorly understood in terms of their contribution to overall spit dynamics. They are the result of formative processes that need further elaboration in conjunction with tidal state and wave climate data.

31. Further analysis of the detailed air-photo sequence that is now available for the site is urgently required in order to support both on-site investigations and the above type of sediment supply analysis.

Response to specific Pagham Advice Questions

32. Q: *Could the two recycling operations: i) 2010 and ii) 2012-13 have had a detrimental impact on the site's functioning and its geomorphological interest?*

33. A: The 2009-10 recycling of sediment drawn from the deltaic platform may seems in retrospect to have had some effect on the subsequent slower development of the platform in a down-drift direction. The fact that the excavation form still has an imprint in the contemporary spit platform indicates that sediment replenishment has not reoccurred through out this zone as was anticipated. The reduction in longshore sediment supply since 2010 was also not fully anticipated. Whatever the control on subsequent deposition this low-tide material is inappropriate as renourishment sediment for upper beach profile accretion. There is a substantial volume reduction due to the disequilibrium of sediment size between the required profile position and the renourishment source area, such that the result of this 2010 recycling process is already nullified after three years.

34. A: The 2012-13 recycling has been drawn from a high tide position to renourish losses of high tide beach width to the west of the first armoured groyne. There is value in using this material as it has closer affinity in size to that which has been eroded. The selection site from the landward bank of the tidal channel (Fig7) is for the moment unlikely to cause difficulty, as long as the spit offers protection to wave attack. However the exposure of beach

frontage sites where the tidal channel is situated identifies the type of risk to the whole frontage if the spit protection is lost through by-pass process.

35. Q: *What are the best sources for the current sediment recycling proposals? Note two joint operations to be considered: i) HW erosion at western Pagham and ii) re-armouring of the exposed armoured groyne?*

36. A: It would seem from experience that any further use of the spit platform sediment in renourishment of upper beach profiles will be both short term, and detrimental to the sediment volume and morphology of the spit platform. It is unclear to me the extent to which Arun intend to use the current high-tide source for further renourishment sediment. It has the virtue of being similar in sediment size distribution of that sediment lost, but increasingly as the frontage recedes by any erosion, it is working its way into coarser storm beach sediment, which even high-tide sediment may be under-sized to match. There is an associated further problem in that use of high tide sediment may be disrupting possible evolution of any coastal vegetated shingle or bird habitats designated for this site.

37. A: While in the field Arun's Technical Director outlined a proposal to landward armouring and sediment backfill to the 1st armoured groyne that has been laterally exposed by the associated frontage retreat. This is a pragmatic response to the contemporary erosion of the foundational root of this feature. This armouring and replenishment of the eroded beach profile across the upper beach face will not affect the spit directly and has no substantial impact on the spit dynamics *per se*. The presence of the groyne has already impacted on the spit dynamics in terms of providing a structural control on the outlet position, so the armouring of this feature is viewed as a required defensive action for frontage householder need, but is unlikely to make any difference to the overall spit dynamics, which are core to the SSSI designation statement. The beach volume required for backfilling the groyne's new armouring (<$100m^3$) is proposed to be taken from the spit's immediate deltaic platform around the tidal channel exit line. Though this volume could be considered marginal to the general sediment volume available in the spit complex, I do not now think this sediment should be drawn from the spit platform. For future site stability this sediment should be of a mean size that is greater than the current high tide sediments being used in current recycling operations. Arun Council should be asked about any material size difference, and if they regard it as having any bearing on anticipated plan-outcome success.

38. Q: *Is the channel likely to close?*

39. A: In the short term, no channel closure should be expected. Any further spit extension is unlikely to force closure of the tidal channel. As the spit extends, I would expect the tidal channel to be forced around the groyne tip and retain a coherent channel. However given the reduction in spit extension rate in late 2012, it is possible that the reducing sediment supply for further spit extension and the lack of effective delta platform will not see any major closing of the channel in the immediate future.

40. Q: *What are the possible ways in which the spit might develop?*

41. A: i) The spit can extend given any continuing longshore sediment supply; or ii) the spit could holds its current position as the contemporary sediment

supply reduces; or iii) the spit may thin in width and extend under any reduce-supply induced cannibalisation phase.

42. Q: *Of these, which is the most likely?*

43. A: I regard iii) and as a variant of it, ii) above, as the most likely responses, though any spit extension will take some time and be prone to possible by-passing breaching. The latter is more likely along the post-2011 narrowed width spit zone, which unfortunately mirrors the houses to the west of the 1st armoured groyne where the latest renourishment operation has been carried out.

44. Q: *Is the rock armour the most effective way to protect the properties?*

45. A: I assume this request refers only to the 5-6 frontage properties affected by the 2012-13 erosion. My judgement on 'most effective way' depends on the anticipated planned standard of protection associated with the design and the depth to which rock armouring is to be inserted. These points need to be taken up with Arun Council. Armouring of sand/gravel does not work in the long-term, i.e. it will not protect beaches from sand loss in the long-term, if wave activity is still able to reach the site. In this specific situation, it will need movement of the outer channel outlet, or spit extension, to induce a reduction in wave attack and lessen the erosion potential. Armouring is not to be undertaken lightly as it is rarely if ever removed, even if proven to be ineffectual.

46. Q: *Our (Natural England) current view is that the on-going evolution of the Church Norton spit is a key component in the conservation of the geomorphological interest of the SSSI. Are there other elements we should also be concerned about?*

47. A: The Church Norton spit changes are central to the geomorphological SSSI status and should be the centre of any potential scientific study. Attention should be focused on the full range of spit alterations with sediment supply variation, tidal state, and wave climate (as discussed) above. Likewise the volumetric changes of the tidal channel need to be understood in terms of tidal prism timing variation. The local wave climate of the English Channel has been exposed to considerable change over the last three autumn-winter seasons due to the southern-positioning of the jet stream, which as a consequence has produced both an unusual run of westerly depression along the channel, as well as strong anti-cyclonic easterly winds due to dominant high pressure over the UK. These events will have had major effects on Pagham spit dynamics and are in need of analysis.

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Figures

Fig1: Spit terminus position in 2010 after the major recycling operation in which 10,000m^3 was extracted from the top of the sub-tidal deltaic platform. The sharp edge reflects the extraction limit and is noticeable as a marker line in later images (Fig2). Notice the hook of sediment left in the sub-tidal position seaward of the extraction zone. This becomes a focus of subsequent subtidal deposition. (@Arun Council)

Fig2: Spit terminus and delta changes 2011-2012. The solid green line (2011) relates approximately to position of spit terminus shown in Fig1. Note the change of spit axis post 2010 with a major landward shift in spit deposition and the sympathetic shift onshore of the tidal channel as the spit moved landward. Also note the absence of major deltaic platform with this new spit deposition. (@EA)

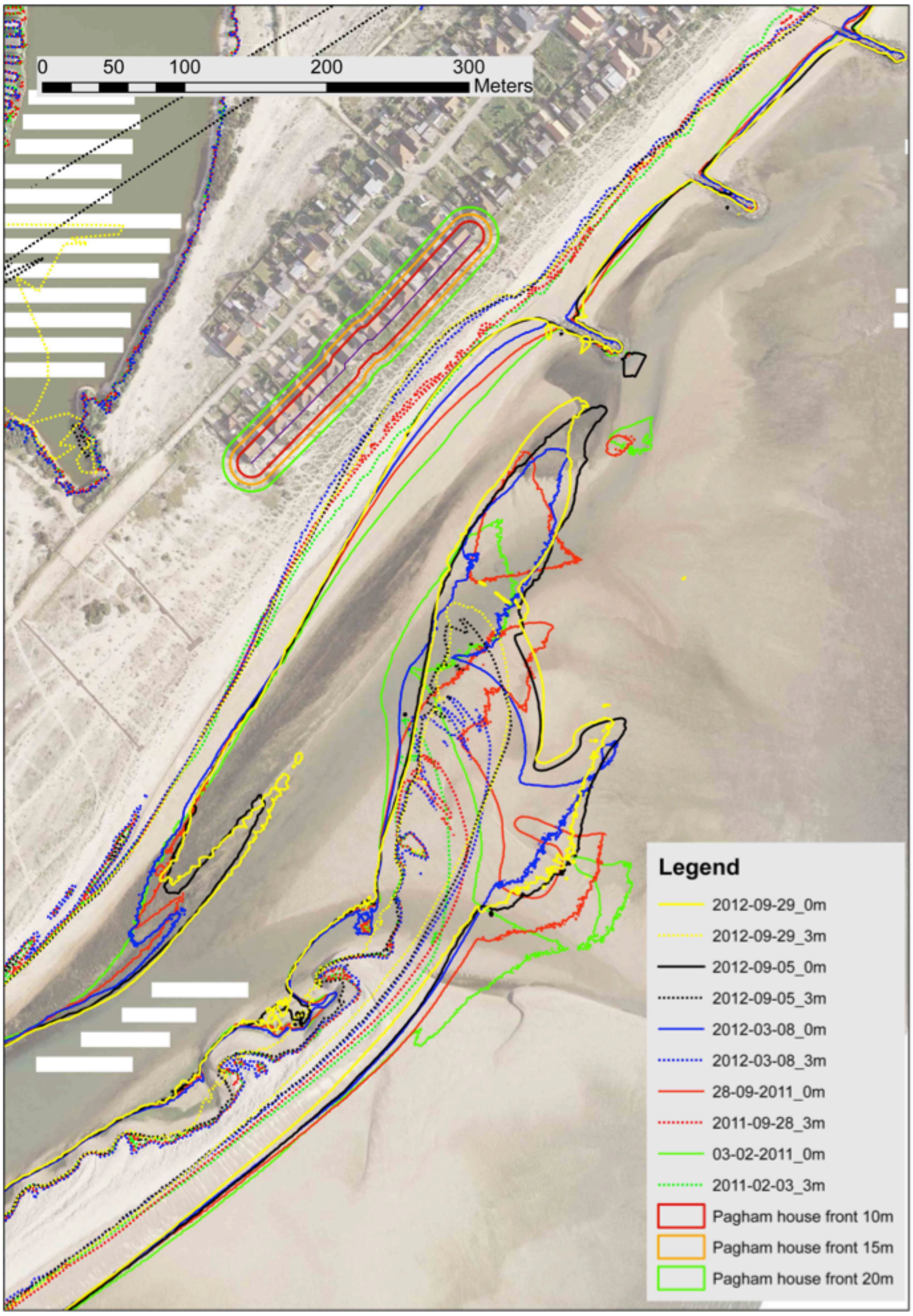

Fig3: Upper beach erosion (winter 2012) at western end of Pagham frontage. Recycling sediment shown is being drawn from further westward at the edge of the tidal channel in the old upper beach sediment. (@Arun Council)

Fig4: Pagham Frontage - upper beach erosion exposing the older wooden groyne root of the 1st armoured groyne. Rock armouring is proposed to protect upper and mid-beach sections at landward end of the current armoured groyne. Placement of renourished sediment on the upper beach in front of the houses has already been undertaken. Sediment for back filling the rock armour is planned to be taken from the deltaic platform on far right hand side of image (see text). (@JDO)

Fig5: Cross section of 2011-13 spit extension showing the single coherent beach ridge rolling over the spit recurves of the 2009-10 period. Part of the 2010 extraction zone can be seen on the RHS of the image. (@JDO)

Fig6: Pagham Spit - the contemporary beach face of pre-2009 section of the spit. The upper beach (LHS) is the seaward face of where rolling over of the beach ridge has occurred; the mid beach shows a ‘sand-run’ with cross-beach linear gravel accumulations forming proto cusps; they merge into an incipient ‘gravity collection zone’ at the beach step (RHS), where the largest particles come to rest at the foot of the beach slope. The development of these cross-beach zones reflects a lack of longshore transport and an emphasis on cross-beach movement and associate sediment sorting. These gravel zones are derived from Bluck (1967). (@JDO)

Fig7: High tide sourcing of beach sediment for the renourishment of eroded beach frontages west of the 1st armoured groyne. (@Arun Council)