Beachy Head to Selsey Bill Shoreline Management Plan

Appendix C (Additional): Recommendations for a No Active Intervention Policy at Braklesham Bay and Pagham Harbour

Contents

C.1 Introduction and Methodology

C.1.1 INTRODUCTION

Much work has been carried out previously on how both the frontage of Braklesham Bay and Pagham Harbour (Figure 1) may evolve in the future, with predictions covering periods from 30-100 years; for example **50 years** - Selsey Bill to Beachy Head Shoreline Management Plan (SMP) (HR Wallingford, 1997a, 1997b) and Pagham to East Head Strategy Study (Posford Duvivier, 1999); **30 to 100 years** – Solent CHaMP (Bray and Cottle, 2003a, 2003b); and **100 years** – Futurecoast (Halcrow, 2002). The conclusions drawn from these reports, suggest that a “No Active Intervention” policy would result in breaching of the existing frontage at Braklesham Bay and Pagham Harbour margins leading to flooding of the low lying land behind (the Manhood Peninsula).

This report forms a supporting study to the South Downs Shoreline Management Plan (SMP), which is the first review of the 1997 Selsey Bill to Beachy Head SMP. It aims to build upon the existing information, by developing scenarios for the potential evolution of Braklesham Bay and Pagham Harbour in more detail, focussing on the implementation of a “do-nothing” or a “No Active Intervention” (NAI) coastal defence policy in order to understand the potential impacts of policy decisions on each frontage including possible interactions between the two. The procedure involves geomorphological predictions of likely coastal evolutions over the next **100 years**, followed by assessments of some of the main consequences for the natural and human environments. The geomorphological appraisals have been informed by consideration of tidal prism and morphological changes over a 50 year period and under a scenario of 6mm/year of sea level rise, as per the latest Defra guidance (Defra, 2002). Taking this approach provides results consistent with the requirements of the second round SMPs.

The report firstly looks at the individual behaviour of the frontage along Braklesham Bay (Chapter 2), and secondly at the behaviour of Pagham Harbour (Chapter 3) under a “NAI” scenario. It then considers the potential evolution of both frontages jointly in the event of breaching of the highway and the formation of a tidal channel that would separate Selsey Bill from the mainland to form an island.

C.1.2 METHODOLOGY AND TECHNIQUES

This report has been produced in association with Dr Malcolm Bray of Portsmouth University, who acted as a technical advisor to Halcrow. The predictions were developed using the technical knowledge of the authors gained by carrying out previous studies on this coastline, in addition to the review of existing literature and new data developed specifically for this study using Geographical Information Systems (GIS). Some of the key results of a PhD thesis (Cope, 2004) that became available late during the course of the study have also been incorporated.

The study involved the following methodological steps:

1. Review of literature and existing knowledge;

2. Development of conceptual models of barrier breaching, tidal inlet evolution and hinterland flooding. These analyses were informed by selected quantitative data. For example, a GIS ground model was prepared of the entire study area using LIDAR data provided by the Environment Agency. The model was then was used to make assessments of the likely areas of land flooded and volumes of tidal exchange for different water levels. These values enabled further assessments of the likely behaviour of potential tidal inlets and evolving estuaries based on relationships developed by regime analysis, that were available within the Solent CHaMP (Bray and Cottle, 2003b).

3. Assessments of some of the main consequences of the scenarios developed above for the natural and human environments.

The "predictions" made within this report are approximate and relate to the specific scenarios constructed, therefore they should not be considered as being definitive. To perform the task a number of assumptions had to be made:

1. Selsey Bill remains defended by sea defences and will be protected in its present position, naturally, by the Mixon Reefs and other existing offshore banks.

2. For both Braklesham Bay and Pagham Harbour, the "NAI" scenario assumes that the embankment that supports the main highway (B2145) from Chichester to Selsey will remain and will continue to be maintained and upgraded preventing failure.

3. 6mm/year of sea level rise as recommended by Defra's PAG guidance and SCOPAC (Standing Conference on Problems Associated with the Coastline). Future climate changes occur broadly in accordance with assessments made by the SCOPAC Preparing for Climate Change Study (Hosking et. al, 2001).

4. Permanent breaches of shingle barriers on the open coastline are relatively rare so that the well documented examples of Pagham in 1910 (Cundy et. al, 2002) and Porlock in 1996 (Bray and Duane, 2001) are adopted as models and it is assumed that behaviour at Medmerry will follow similar general patterns.

5. Land uses and other human influences remain broadly as at present.

By making these assumptions, the predictions in this report are uncertain. To resolve this issue, each prediction (where necessary), has been assigned with a subjective value that represents the relative degree of uncertainty. Table 1.1 provides a list of these rankings for reference.

Table 1.1 Grading system of uncertainty

1	Low
2	Medium
3	High

The uncertainties relate to whether a particular action will occur, when it might occur, the speed, magnitude and duration of change and the extent to which change might stabilise due to restoration of a new equilibrium or steady state. The following elements can be distinguished and are referred to in the text where relevant to indicate the nature of the uncertainty involves:

- EVENT: whether a particular event is likely to occur;
- TIMING: when a particular event is likely to occur;
- DURATION: how long an event or process will last/operate;
- MAGNITUDE: the amount and/or intensity of change that is likely to occur;
- STABILITY: whether a new equilibrium or steady state is likely to become established that is likely to regulate or inhibit further change.

This report is designed to support strategic decision-making, it is recommended that further studies are taken to resolve uncertainties prior to any actual implementation of actions on the ground.

C.2 No Active Intervention Medmerry (Braklesham Bay)

C.2.1 INTRODUCTION AND HISTORICAL EVENTS

Bracklesham Bay has been protected by barrier type beaches for at least the past 2,000 to 3,000 years. The beaches are thought to have migrated several kilometres landward across a low-lying hinterland, suffering periodic breaches and resealing episodes. Documentary evidence suggests that the present barrier dates from at least the mid-16th Century (Carter and Bray, 2004). A persistent tidal channel formerly connected Pagham Harbour inlet with Bracklesham Bay so that Selsey existed as an island for many centuries. Some 400-500 years ago, the present Medmerry barrier beach grew to seal the inlet to Bracklesham Bay and successive reclamations and siltation reduced the channel area and its tidal prism leading eventually to complete reclamation of the ancient estuary by the late 19th Century (Wallace, 1996; Carter and Bray, 2004). The configuration of the ancient channel is indicated by the present day Broad Rife channel.

Barrier breaches and tidal inundations have been recorded since the 8th century presenting a hazard to the use and occupation of the hinterland. The Medmerry barrier has been artificially maintained/managed to various extents since the construction of the first Broad Rife sluice in 1884, to provide flood protection to the backing low-lying land. Management has largely involved the construction of groynes (1930s) with beach replenishment (1976-80), re-profiling and/recycling from the 1970s, such that today, the barrier is almost entirely artificially maintained. During storms in December 1989, the shingle barrier beach was breached in three places, and 70% of the recharge material (placed over the period 1976-1980) was lost from the frontage, hence the scheme only lasted nine years (EA Internal Document, 2003). Several major storm surges during the winters of 1998-9, 2000-1, 2001-2 caused overwashing, crest lowering and beach drawdown, with a 300m breach in 1999. This has necessitated emergency replenishment totalling over 500,000m^3 of gravel (taken from inland sources), together with continued beach face scraping and profile reconstruction (Carter and Bray 2004).

The groynes at Braklesham Bay today are of poor standard and are no longer of sufficient capacity to retain the existing beach material (Figure 2.1). The beaches are now only sustainable through ongoing management practices, such as beach recharge, recycling and re-profiling, all of which are currently carried out by the Environment Agency. Despite beach recharge from 1989 to 2002 (no recharge took place from March 1994 to December 1998, only recycling), the bank has only been maintained at a width of between 7 and 10m at its narrowest point and 25m at its widest. As seen in the past, the shingle barrier can be dramatically reduced after just one storm. In 1994, the barrier width reduced from 20m to 3m at Broad Rife over a length of 500m. The shingle bank has subsequently been breached at least 10 times since 1994 and the natural drift from Selsey has slowed down over the years (EA Internal Document, 2003), hence the Braklesham Bay shingle barrier is especially sensitive to breaching at Medmerry (Figure 2.2).

Figure 2.1 Groynes at Braklesham Bay (source: Malcolm Bray, Portsmouth University)

Figure 2.2 Storm Event at Braklesham Bay (source: Malcolm Bray, Portsmouth University)

In summary, a low-lying frontage of some 4km is protected by the Medmerry barrier which has historically migrated landward and has suffered numerous episodes of overwashing, breaching and resealing. Latterly, it has been maintained in its present position by groynes and intensive beach management. The conversion to a static managed condition has resulted in depletion of beach sediments and lowering of the foreshore in front of the barrier. To maintain its function as a coastal defence, the barrier has been oversteepened through continuous bulldozing of the seaward face (beach re-profiling) to maintain a crest of some 5m to 5.5m OD and a width of 7m to 25m. The natural barrier form would normally be expected to be considerably lower, flatter and wider.

C.2.2 CONDITION OF DEFENCES

Using existing data and information for "NAI" scenarios and the analogy of barrier failure at Porlock, Somerset, UK (Bray and Duane, 2001), it was possible to make an assessment of how the Medmerry shingle barrier-beach could behave under a "NAI" policy. Posford Duvivier (1999) predicted how the defences would respond to implementation of "do-nothing" (NAI) policy from Selsey West Beach to Medmerry (summarised in Table 2.1) – note a length of sheet piling sea wall extends along part of the West Sands caravan park frontage.

Table 2.1 Development of defences with time under a "do-nothing" (NAI) scenario

Selsey West Beach		
TIMESCALE	**IMPACT ON DEFENCES**	**IMPACT ON COASTLINE**
0 years	Gradual deterioration of groynes	Reduction in upper beach levels Sediment supply to the west (East Head)
	Gradual loss of beach	
	Increased overtopping of seawall	
	Increase in exposure of the seawall and substratum to wave attack	
5 years	Breaches in the seawall	
	Progressive collapse of the seawall	
	Progressive erosion of the exposed shoreline	
10 years	Total loss of defences	
	Ongoing erosion and flooding	
Medmerry		

TIMESCALE	**IMPACT ON DEFENCES**	**IMPACT ON COASTLINE**
0 years	Breaches in shingle bank	Flooding of low-lying agricultural land and loss of grazing marsh habitat forming Braklesham SSSI. Long-term creation of coastal lagoons, saltmarsh, mudflats and brackish grasslands Breach resulting in cessation of direct coastal access between Selsey and East Wittering.
	Progressive lowering and widening of breaches	
	Regular flooding in 1:1 year area	
	Increase in overtopping of sheet piled wall	
	Increased exposure of sheet piled wall to wave attack	
	Gradual deterioration of groynes	
5 years	Shingle bank generally ineffective as coastal defence	
	Collapse of sheet piled wall	
	Accelerated deterioration of groynes	
	Intermittent flooding in 1:50 year and 1:200 year area	
	Ongoing erosion of cliffs	
10 years	Total loss of effective defences	
	Saltmarsh established in 1:1 year flood area	
	Ongoing erosion and flooding	

C.2.3 COASTLINE EVOLUTION

C.2.3.1 The Barrier Beach

It is anticipated that under a policy of NAI, the beach would become further depleted of sediment, exposing the groynes beneath, which would be likely to fail, or be ineffective due to their dilapidated condition. The soft lower foreshore in front of the beach would continue to be lowered, allowing larger waves to strike the barrier at high tide (waves are less depth limited). With cessation of artificial beach re-profiling the oversteepened berm would be reworked by regular storms resulting in excavation of material from the crest and deposition further down the beach face to flatten the profile. Where the crest is narrow, this “cut-back” process would break through the crest and considerably lower it. As the crest is lowered the frequency of overwashing during storm wave action is likely to increase resulting in the landward pushing back of beach material to form wide washover fans and resulting in a landward migration of the barrier. This process would be especially severe on those parts of the barrier with limited material volume. The possibility of a storm breach during this period is high and could occur at any time, for example, the first winter of implementing a NAI policy. Two types of breach scenario can be conceived:

1) Breaching due to a high storm surge coincident with strong wave action. Cope (2004) tested barrier sensitivity to a range of water level and wave conditions using Bradbury’s (1998) parametric overwashing model and concluded that the present summer barrier profiles were susceptible to breaching during a 1 in 50 year storm wave event, or a 1 in 1 year swell wave event. Sensitivity would be even greater for winter profiles subject to crest cut-back. In this case breaching would follow from the severe flattening by the overwashing alone. Cope (2004) identified that the barrier between Environment Agency profiles SUSXA 55 to 57 was most sensitive.

2) Overwashing and landward migration of the barrier such that the beach sediment is pushed into back-barrier ditches, or areas of low topography. This immediately reduces the crest height and considerably increases the likelihood of severe overwashing. Such conditions exist where (i) Broad Rife backs the barrier immediately west of the West Sands caravan park; and (ii) 1200m to further to the east where Broad Rife once again backs the barrier (Figure 2.3). The former site coincides also with the sensitive segment identified by Cope (2004). It should be noted that the permanent 1996 breach at Porlock occurred when the barrier retreated back into an existing drainage ditch (Bray and Duane 2001).

Breaching occurs when the crest is cut back and lowered sufficiently by overwashing such that tidal exchange occurs between Bracklesham Bay and the low-lying hinterland. Concentration of tidal flow across the barrier acts to excavate a channel, although drift along the barrier can act to infill the channel and seal the breach naturally. Whether the breach becomes a permanent tidal inlet, or whether it reseals will depend upon the relative magnitudes of the tidal exchange and sediment drift. Areas of the barrier unaffected by breaching are likely to suffer overwashing leading to landward retreat by the generic “rollover” process described by Carter (1988), with associated lowering, flattening and widening of the barrier and formation of washover fans. Winnowing out of fines from the shingle barrier during the “rollover” process would make the barrier more permeable, aiding stability by increasing the infiltration of swash. Furthermore, the landward migration would expose a greater width of foreshore in front of the beach enabling enhanced wave dissipation and compensating for historical foreshore losses. So long as landward migration remained possible, this new lower and wider beach profile would be expected to effectively dissipate wave energy, although some residual overtopping and overwashing would be expected in the future with climate change and sea-level rise. Thus, in a similar manner to the beach barrier at Porlock Bay (Bray and Duane, 2001), it is anticipated that the static stability of the existing managed barrier would be exchanged for the dynamic stability of the new natural form.

C.2.3.2 Evolution Inlet Channels, Lagoon/Estuary and Associated Features

Initial breaching of the barrier is likely to take place immediately to the west of Selsey at West Sands due to existing sensitivity of the barrier profile and the potential for its transgression landwards, into the channel of Broad Rife (OS Ref. 835942). A more natural, lower and wider dissipative beach could result, whilst large areas of hinterland would be inundated during major overwashing events (Posford Duvivier, 1999). As seen at Porlock (Bray and Duane, 2001), there could be as much as 30m retreat of the landward edge of the barrier beach and up to 2m of crest lowering. The timing of the breach is uncertain, although it is anticipated that it could take place following the first major storm surge, especially if accompanied by swell wave activity or even possibly within 1st year of policy implementation (Uncertainty Rating: EVENT 1, TIMING 1 or 2).

Once a significant breach occurs, the new opening is likely to be inundated on normal tides, resulting in flooding of a large low-lying hinterland. As the tide ebbs the lowering water level in Bracklesham Bay would result in strong outflow of the floodwaters through the initial breach which could result in rapid cutting of a channel into the sand/clay substrate below. This would further concentrate tidal flow and form a deepened channel encouraging more efficient exchange of tidal waters and increased potential for flooding of the hinterland. A new tidal inlet is therefore likely to become established by this positive feedback mechanism. Cope (2004) undertook an analysis of the relative magnitudes of the likely tidal exchange and drift along the beach in order to determine whether the inlet would remain open or naturally reseal. Results indicated clearly that the inlet once formed would be very stable because of strong tidal exchange and insufficient sediment transport for closure of the breach (Uncertainty Rating: 1). It was estimated that for closure to occur would require either transport to increase to 180,000m^3/yr (presently 3,000 to 7,000m^3/yr) or for the tidal prism of the new estuary/lagoon to reduce from 3.6 million m^3 to 0.13 million m^3.

Large-scale flooding and permanent inundation of the reclaimed harbour margins and low-lying land between Braklesham and Sidlesham is expected to occur, with floodwaters being retained by the raised embankment of the B2145 (Figure 2.3). It is likely that the present channels and tributaries of Broad Rife would become adopted as the main tidal channels within the new estuary. A summary of the results calculated for a series of present and likely future water levels using GIS techniques are shown in Table 2.2. The estimated tidal prism for the new inlet at Medmerry under current tidal levels (Mean High Water Spring, 2.4m) would be in the region of 3.6million m^3, with a mouth that is anticipated to be shallow and wide with an area of around 300m^2 (based on regime analysis, Section 2.4) or 246m^2 based on alternative analyses by Cope (2004). The GIS analysis also indicated that significant increases in the areas inundated and the tidal prism would be likely in the future due to the effects of sea-level rise and storm surges.

Table 2.2 Calculations for Braklesham Bay inlet Tidal Prism

Water Level (mODN)	Area Flooded (m^2)	Volume (m^3) (Tidal Prism)
Current MHWS (2.4m)	4,653,084	3,609,943
MHWS + 50 years SLR (3m)	6,410,989	6,973,512
Current 1:200 years water level (4m)	10,665,471	15,453,220
1:200 years + 50 years SLR (4.6m)	13,243,017	22,707,123

An ebb-tidal delta would form at the mouth of the new inlet, possibly containing as much as 500,000m^3 sands and gravels (50-100 years). As the ebb tidal delta grows it may tend to intercept and store much of the loose sediment along Braklesham Bay, until it reaches an equilibrium volume determined by the tidal prism of the inlet (Bray and Cottle, 2003a; 2003b). During this period, the extension of the ebb tidal delta into the zone of littoral transport would result in the formation of drift reversals. Areas downdrift, such as East Head, would be liable to sediment starvation (Bray and Cottle, 2003a; 2003b). Conversely, areas closer to the tidal delta would become increasingly stable, as wave energy is dissipated over the growing delta (Bray and Cottle, 2003a; 2003b) (Uncertainty Rating: 2). Recurved spits would also form flanking the inlet. These would serve to reduce wave penetration from Bracklesham Bay into the new lagoon/estuary.

At the western end of the bay, the shingle beach-barrier would continue to roll back, until eventually it encroached into a second section of Broad Rife (OS822925), where a second breach could form. The initial tidal channel could focus the majority of the tidal flows in and out of the newly formed inlet, whilst the secondary breach may be subject to cyclical closure and breach. This behaviour would be determined by the availability of sediment for longshore transport to the west, which in turn would be determined by the potential impacts that the initial enlarged ebb tidal delta would have on local drift reversals (Uncertainty Rating: 3). Thus it is uncertain whether a second breach could remain open and form a permanent second tidal inlet.

Sediments eroded at the evolving inlet and along the retreating barrier would tend to be sucked into the new estuary to feed strong sedimentation at the headwaters of the tidal channels and rapid formation of intertidal flats (by rapid initial sedimentation) and saltmarsh vegetation would be expected. Analyses by Cope (2004) indicate that the range of elevations with respect to tidal levels would be suitable for development of a full vegetation succession from algae (*Enteromorpha* and *Ulva*) and Zostera around the channels and creeks up to Spartina saltmarsh and Halimione dominated upper saltmarsh. The time frame over which this takes place would be dependent on when the breach occurs, which if based on breaching taking place within the initial winter months to 2 years of policy implementation, this could involve sizeable pioneer communities developing within 5 years. Upper Saltmarsh growth is likely to occur between MHWS and extreme water levels (i.e. 2.4m and 1:200 -

4m ODN). The land flooded (currently grazing marsh) could be between 1 and 3m, as shown by Figure 2.3, hence there is significant potential for intertidal habitat creation. Large areas of land are available for inundation at elevations between 2.4m (present MHWS) and 4.0mOD giving ample space for landward migration of habitats as sea-level rises in the future. It means that the habitats of the new estuary should be resilient to future changes and would be unlikely to be affected by coastal squeeze in the foreseeable future.

C.2.4 REGIME ANALYSIS AND THE TIDAL PRISM

The long term equilibrium of the new estuary will be determined by its tidal prism, and is likely to follow a pattern defined by the behaviour of other relevant UK estuaries. Understanding the regime of an estuary provides insights into its stability and its potential sensitivity to natural change and major modifications, such as land reclamation. Regime theory suggests that the optimum inlet cross-section area should develop for a given tidal prism, thus optimising dissipation of wave and tide energy. An estuary with a meandering shallow channel and extensive intertidal flats will best provide frictional resistance to wave and tidal energy, therefore reach a state of equilibrium most efficiently.

This relationship was first expressed in an empirical relationship proposed by O’Brien (1931), where the spring tidal prism and the cross-sectional area of the entrance at mean tide level has the general form:

$$A = C.P^n$$

Equation 2.1

where A is the cross-sectional area (m^2) and P is the tidal prism (amount of water entering and leaving the system on a tide) and C and n are empirical coefficients. The University of Newcastle (2000) later developed this relationship by applying it to the estuaries of the UK, observing that some of the Solent Estuaries did not conform to the general UK relationship. Bray and Cottle (2003a and 2003b) further analysed this data, plotting measured tidal prisms and inlet cross section areas for (i) UK estuaries and (ii) Solent estuaries. Coverting this data to log (x) values facilitates plotting and statistical analysis (as presented in Figure 2.4) enabling predictive relationships to be established for each data set so that the likely equilibrium inlet area can be established for a new estuary if its tidal prism is known.

Using the likely tidal prisms of the new estuary determined by GIS analysis, as discussed in Section 2.3.2, it was possible to determine the likely inlet mouth cross section area that would be generated by the calculated tidal prisms using the relationships determined by the Regime Analysis carried out for the Solent CHaMP by Bray and Cottle (2003b) (refer to Table 2.3 below).

Table 2.3 Estuary regime relationships for Braklesham Bay

Water Level (mODN)	**Tidal Prism m^3**	**Mouth Area m^2**	**Log Tidal Prism**	**Log Mouth Area**
Current MHWS (2.4m)	3,609,943	294	6.56	2.47
MHWS + 50 years SLR (3m)	6,973,512	535	6.84	2.73
Current 1:200 years water level (4m)	15,453,220	1102	7.19	3.04
1:200 years + 50 years SLR (4.6m)	22,707,123	1564	7.36	3.19

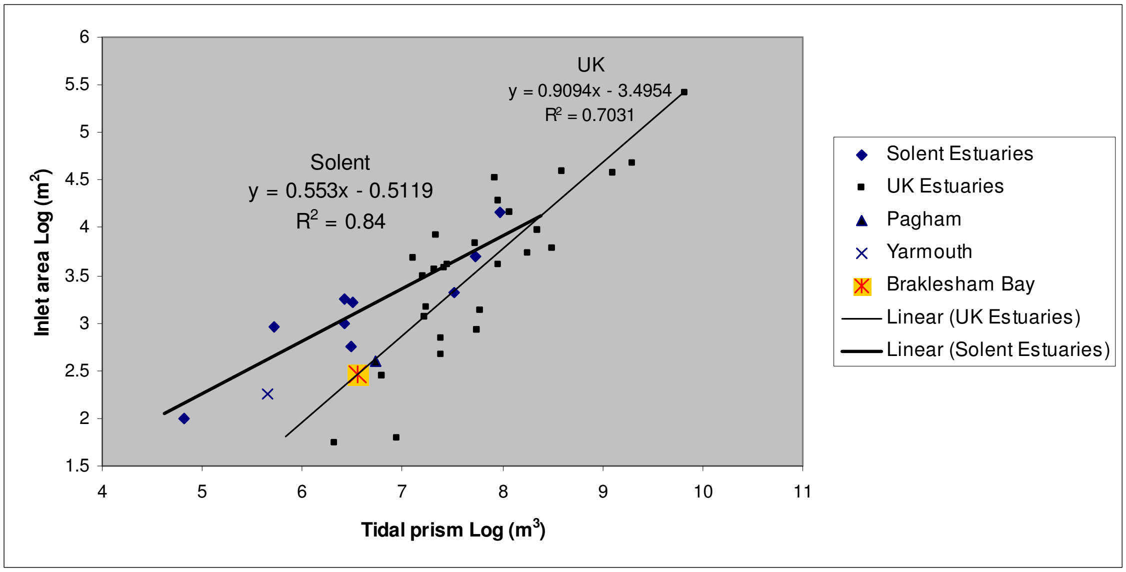

Figure 2.4 Regime Relationships for Solent, UK estuaries and Braklesham Bay (Source: Posford Haskoning, 2003a; 2003b (adapted for this report).

In this case it was felt that the new inlet and estuary that would form at Medmerry would be likely to be most similar in character to neighbouring inlets such as Pagham, Chichester and Langstone Harbours (coastal plain estuaries with moderate wave exposure at the mouth) rather than the typical Solent estuaries (drowned river valleys with low wave exposure). Thus, the relationship for the UK rather than the Solent estuaries was applied to predict the inlet cross section area of the new Medmerry inlet. The inlet mouth areas predicted represent equilibrium values towards which processes of change would work and several decades of readjustment may be required before the equilibrium is established.

Results suggest that a modest inlet (smaller than the present Pagham inlet) would become established initially, although it would be likely to enlarge considerably in the future potentially reaching a size of up to 50-75% of the present Langstone inlet.

As active management is ceased under a “NAI” scenario, and breaching of Medmerry Barrier at Braklesham Bay takes place, new coastal landforms (mobile barrier and spits, inlet and estuary, mudflats and tidal channels) would be generated that could adjust to the new conditions. Bray and Duane (2001) report on a breach at Porlock, where changes in landform are comparable to a potential breach at Braklesham Bay. In their report, Bray and Duane (2001) found that the initial rapid and abrupt changes had taken place within approximately 3 years of breaching, following which there would be ongoing change at a gradually diminishing rate. They also suggest that the new inlet is unlikely to achieve full adjustment or static stability, due to the dynamic nature of the landforms involved. Instead, variations in environmental forcing brought about by future climate change are likely to induce continued responses and readjustments from the new landforms in the form of barrier migration, spit extension, inlet enlargement and sedimentation and saltmarsh development within the estuary. If the findings of Bray and Dune are applied to the Braklesham Bay, then it can be concluded that following a number of initial adjustments (as described in Section 2.3), the inlet could take a more natural form becoming more dynamically stable (as opposed to statically stable), with a relatively well-adjusted regime, although this would be subject to change due to continuous change in forcing factors, such as sea level rise and wave climate. It would appear that these changes would be extremely favourable for creation of new habitats including tidal mudflats, saltmarsh and vegetated shingle. Potential adverse impacts could relate to the effect of the new inlet and its tidal delta upon the open coast transport system and the possibility that neighbouring frontages could temporarily become starved of sediment.

C.3 No Active Intervention Pagham Harbour

C.3.1 INTRODUCTION AND OVERVIEW

Assuming a policy of "NAI" for Pagham Harbour means that the groynes that presently help to retain and stabilise the spits at Pagham would no longer be maintained and eventually fail. Recycling and renourishment practices carried out along the spits would also stop. The training wall that currently helps to stabilise the northern spit and fix the harbour mouth in its present position would also be allowed to fail, allowing the spits and harbour entrance to move freely and naturally. Under this scenario, the mouth is unlikely to remain in a fixed position (unless the tidal energy passing through the harbour entrance is sufficient for it to remain open), but instead be subject to a series of cyclical changes as was the case prior to artificial stabilisation (Robinson, 1955). The present inlet is highly unstable because historical reclamation of the harbour has reduced the tidal prism such that tidal currents can barely maintain the inlet against constant infilling by rapid SW to NE drift (Geodata Institute 1994; Cundy et. al, 2002). Following relaxation of management, this instability will once again govern the coastal behaviour. For example, as the training wall fails the northern spit could erode and the southern spit could elongate northwards. Consequently, the existing harbour mouth would move north with the southern spit. Following or during this event, the southern spit could breach potentially forming a second opening to the harbour. This breach could stay open, whilst the existing northern one closed, since it is unlikely that two entrances could exist simultaneously for any significant period. A further key factor is the likely enlargement of the harbour and its tidal prism as harbour embankments fail or are overtopped in the future. Again there is uncertainty as to the timing of events and the implications of these events, hence the predictions made in Section 3.3 give only a best estimate of potential future evolution.

C.3.2 CONDITION OF DEFENCES

In the Strategy Study for Pagham to East Head (Appendix G-Economic Appraisal), Posford Duvivier (1999) estimated the deterioration of the defences at Pagham under a "NAI" policy. These are summarised in Table 3.1.

Table 3.1 Development of defences with time under a "do-nothing" (NAI) scenario

Pagham Beach/Harbour		
TIMESCALE	**IMPACT ON DEFENCES**	**IMPACT ON COASTLINE**
0 years (beach)	Deterioration of groynes and harbour arm	Overtopping of the lagoon and coastal grassland
	Gradual loss of beach	

	Breaches in shingle banks/spits	Inundation and loss of footpath Erosion of mudflats and saltmarsh
	Progressive lowering and widening of breaches	
	Regular flooding within 1:1 year areas	
	Intermittent flooding within 1:50 and 1:200 years	
	Deterioration of Pagham wall	
5 years (beach)	Increased wave attack on the harbour shoreline	
	Reduction in effectiveness of the harbour to drain the surrounding area	
15 years (harbour)	Breach in Pagham Wall	
	Regular flooding in 1:1 year area	
	Intermittent flooding in 1:50 year and 1:200 year area	
20 years (beach)	Failure of harbour arm	
	Further increase in wave attack to the shoreline of harbour	
	Further reduction in effectiveness of harbour to drain surrounding area	

C.3.3 COASTLINE EVOLUTION

C.3.3.1 Pagham Harbour Entrance

The beaches and shingle barrier at Church Norton are very sensitive to sediment drift from the south-west, hence any change to the headland at Selsey Bill would significantly impact on the future evolution of the coastline at Church Norton and the spits at Pagham Harbour. Saltmarshes are confined at their margins by defences and are consequently sensitive to coastal squeeze under accelerated sea level rise (Bray and Cottle, 2003a; 2003b). The embankments themselves would suffer erosion as sea levels rise and they become more exposed to wave attack as the fronting saltmarsh recedes landward. In turn, water depths seaward of the defences would become less depth limited (i.e. increased water depths, less attenuation of wave energy), increasing the capacity of waves to erode, run-up and overtop the embankments. It is estimated that within the first 20 years of policy implementation, the embankments would fail.

If sediment supply from the south-west reduces, the southern spit could become sensitive to overwashing (Bray and Cottle, 2003a; 2003b) and beach crest lowering. As the southern spit would no longer be managed, it could become sensitive to overtopping and permanent breaching, to form a lower and wider barrier beach. A new mouth could form to the south. There is potential for two mouths to exist at this point, one to the north and the other to the south, although it is expected that the northern mouth would soon close, whilst the southern mouth would remain open. This behaviour is dependent on the change in configuration of the harbour itself, since the timing of the opening and closure of the inlet mouths is not solely dependent on sediment supply, but also the strength of the tidal inflows and outflows through the mouth (tidal prism) to keep it open. As the southern spit regrows, it could force the new mouth to move north. Again, the cycle could repeat itself as the southern spit weakens, due to any shortfall in material being supplied from the south west, and breaches; and the process described begins again. The sustainability of this process is, however, dependent on the harbour tidal prism; and the sustainability of the present management practices at Selsey and Church Norton. If the tidal prism were to increase, the inlet would become more stable and its migration would be reduced. If the present management practices were to continue, there would be a depletion of the sediment from the source to East Beach/Church Norton. More short-term and localised variations are expected to occur around the mouth.

The position of the ebb delta is determined by the position of the harbour mouth, hence any movement of the entrance to the north or south would result in movement of the ebb tidal delta in that direction. If a new inlet became established within the southern spit, the existing inlet and its delta would cease to be maintained and much of the material contained within the existing delta could migrate back onshore and move to the north, towards Aldwick and Bognor. As the ebb tidal delta moves, an existing drift reversal zone located immediately to its east would also shift by several hundred meters to the north-east, moving the zone of erosion along with it. This could result in some erosion of the coastline to the west of Aldwick. After several decades the old tidal delta would become depleted of sediment and reduce in its influence.

C.3.3.2 Inner Pagham Harbour and the Tidal Prism

Within the harbour, the flood embankments could be exposed to overtopping. Eventually they could fail, breach and thus enable flooding of the low-lying hinterland behind. The extent of flooding could largely be determined by the height of the land and the long-term equilibrium of the estuary, and with time, could be determined by the extent to which this process increases the tidal prism.

Assuming a breach of the flood embankments, the potential floodplain for Pagham Harbour was calculated using GIS techniques. This process was calculated for a number of water levels, including present Mean High Water Springs (MHWS), MHWS + sea level rise (SLR); 1:200 year and 1:200 year plus SLR. The results of the calculations are shown in Table 3.2 and Figure 3.1 shows an estimate of potential flooding for Pagham Harbour under a “NAI”. The analysis indicates that major enlargement of the harbour and its tidal prism is likely in the future due to sea-level rise and storm surges.

Table 3.2 Calculations for Pagham Harbour Tidal Prism (based on calculations in GIS)

Water Level	Area Flooded (m^2)	Volume (m^3) (Tidal Prism)
2.4m (MHWS)	6,575,030	8,568,270
3m (MHWS + 6mm/year SLR)	7,786,106	13,063,546
4m (Extreme)	10,631,624	22,412,316
4.6m (Extreme + 6mm/year SLR)	13,349,276	30,346,777

C.3.3.3 Habitat Change

Major inundation of the reclaimed areas (grazing marsh) around the harbour margins would occur, extending up the relict Lavant Valley and its tributaries. Strong sedimentation would occur at the headwaters of the tidal channels, and following that, the rapid formation of intertidal flats and saltmarshes. Saltmarsh growth is likely to occur between MHWS and extreme water levels (i.e. 2.4m and 1:200 - 4m ODN). This change could be of similar extent to that which took place following the storm (December 16th, 1910), when a portion of the harbour that was initially reclaimed in 1876 and was subsequently inundated, with rapid development of mudflats and approximately 1.3km^2 of saltmarsh over a period of 38 years.

The Solent CHaMP (Bray and Cottle, 2003a; 2003b) estimated the potential saltmarsh change, based on extrapolation of historical trends. The CHaMP estimated an increase in saltmarsh area from 107.5ha in 2004 to over 126ha in 2101 assuming that defences were maintained and recent saltmarsh expansion continued. This would imply that there is sufficient sediment for accretion to keep pace with recent sea level rise. Studies suggest that between 4 and 8mm of accretion per year has taken place since the 1910 breach, hence the occurrence of breaching on this scale again could result in rapid salt marsh regeneration around the newly inundated areas that could generate an additional 500-700ha of saltmarsh and 600-800ha of mudflat (Bray and Cottle, 2003a; 2003b). The change to the tidal prism resulting from sea level rise should also be factored in, and with that the continued availability of sediment to sustain saltmarsh growth or stability. Predictions of future salt marsh change would also be dependent on whether the process of *Spartina* die back would quickly affect the newly established areas, or whether they would be resilient, therefore marsh areas should be monitored and, as suggested by the Solent CHaMP (Bray and Cottle, 2003a; 2003b), predictions should be continually updated with the new findings.

The Geodata Institute (1994) recorded that land reclamation in 1676, reduced the flood plain of the estuary from 4.5km^2 to 2.83km^2, resulting in reduced stability of the tidal inlet, which could have in turn reduced the volume of the ebb tidal delta. It can therefore be assumed that failure of the flood embankments would result in the opposite, with the increased tidal prism causing increased stability of the inlet, which would in turn increase the volume of the ebb tidal delta. The timing of this harbour enlargement is expected to be within the next 20 years with the associated readjustments occurring over several following decades (Uncertainty Rating: 2).

C.3.4 REGIME ANALYSIS

The long-term equilibrium of the estuary will be determined by its tidal prism and is likely to follow a pattern as defined by the behaviour of other UK estuaries. Regime theory, suggests that the optimum inlet cross-section area should develop for a given tidal prism. University of Newcastle (2000) observed that some of the Solent Estuaries did not conform to the general UK relationship. Section 2.4 discusses this relationship in more detail. Geodata Institute (1994) estimated a tidal prism of 5.3million m^3 and a mouth area of 400m^2 for Pagham Harbour. This compares to a tidal prism of just less than 8.6 million m^3 and a mouth area of around 650m^2 as calculated using GIS techniques and the UK estuaries regime relationship for this study (and a water level of 2.4m), which assumes the boundaries of the present harbour. The analysis suggests that the inlet mouth area is likely to enlarge considerably in the future, potentially reaching a size comparable to the present Langstone inlet.

Table 3.3 Estuary regime relationships for Pagham Harbour

Water Level (mODN)	Tidal Prism m^3	Mouth Area m^2	Log Tidal Prism	Log Mouth Area
Current MHWS (2.4m)	8,568,270	645	6.93	2.81
MHWS + 50 years SLR (3m)	13,063,546	946	7.12	2.98
Current 1:200 years water level (4m)	22,412,316	1546	7.35	3.19
1:200 years + 50 years SLR (4.6m)	30,346,777	2036	7.48	3.31

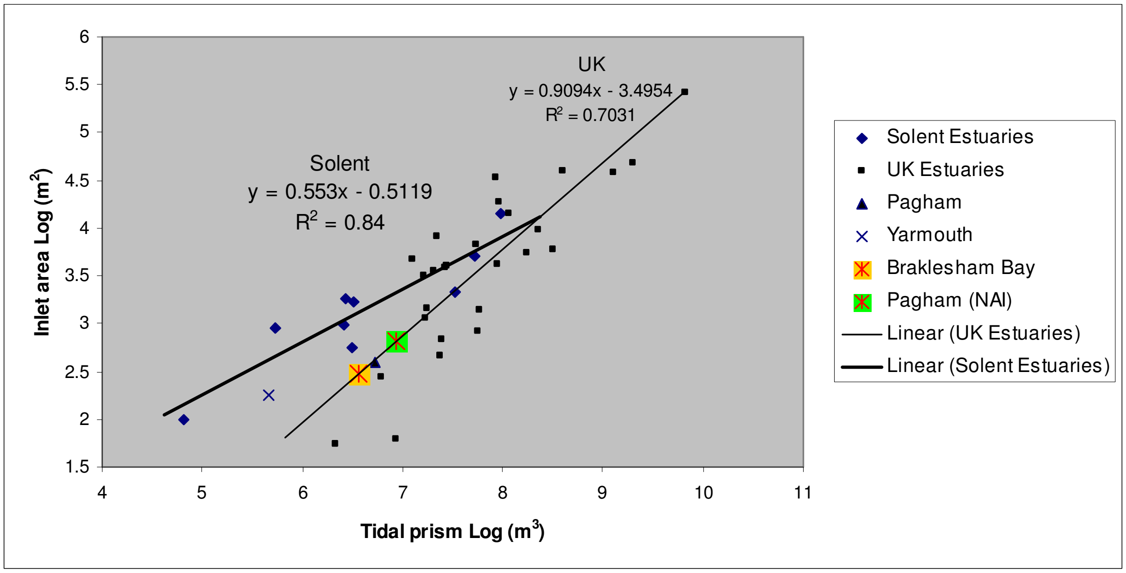

Figure 3.2 Regime Relationships for Solent, UK estuaries and Pagham Harbour (Source: Posford Haskoning, 2003a; 2003b (adapted for this report).

As part of the CHaMP, Bray and Cottle (2003a; 2003b) carried out a detailed study on the regime analysis of the Solent Estuaries. The main findings of this work are:

- Pagham Harbour is a coastal plain type estuary, with a relatively well-adjusted regime. The fact that it plots along the UK trend line, indicates that the inlet is presently maintained by its training structure and is in reasonable equilibrium with its tidal prism, although the inlet itself is naturally unstable due rapid drift that tends to infill it.
- As Pagham Harbour is close to its equilibrium it has a higher potential for adjustment in response to any imposed changes away from that equilibrium between the inlet area (mouth) and tidal prism. For example, an increased tidal prism due to inundation of the harbour margins is likely to trigger rapid enlargement of the inlet. Incidentally, as the tidal prism enlarges the inlet will improve in its ability to flush out drifting sediments so that it should become more stable and less likely to migrate in response to drift along the spits.

C.4 No Active Intervention Braklesham Bay (Medmerry) and No Active Intervention Pagham Harbour

C.4.1 INTRODUCTION

This scenario follows similar procedures devised for the "NAI" polices at both Braklesham Bay and Pagham Harbour, but allows for overtopping and/or breaching of the B2145 highway that currently separates the two areas of low-lying land. As part of the Strategy Study, Posford Duvivier (1999) performed an assessment of the vulnerability of the B2145. The assessment found that if the flood defences at Braklesham Bay and Pagham Harbour were allowed to fail, the section of the B2145 that passes through low lying land would breach in a 1:1 year event. This assessment is also supported by the findings the existing data/information, identified in the main introduction.

C.4.2 BRAKLESHAM BAY (MEDMERRY) AND PAGHAM HARBOUR

Initially the coastline at Braklesham Bay and Pagham Harbour will behave as has been described in Chapters 3 and 4. The Medmerry shingle barrier could breach and a new tidal embayment/inlet could form. One main tidal channel along approximately the orientation of the present Broad Rife and extending east towards Siddlesham Ferry is likely to focus the majority of tidal flow into and out of the new Medmerry inlet. At Pagham Harbour the mouth could initially experience a series of renewed cyclical changes, but would be likely to enlarge and become more stable with time as the tidal prism increases. However, in the absence of maintenance, the raised highway (B2145) that currently connects Selsey Bill to the mainland would be overtopped and eventually fail.

As shown on Figure 2.3, the raised highway stands at its lowest to the immediate west of Pagham Harbour, close to the visitor centre, at a height of around 2.6mOD. With a MHWS level of 2.4mOD, the highway embankment would initially protect the low-lying area behind from flooding. As sea levels rise and water levels reach 3m (MHWS +SLR), there would be tidal exchange between Pagham Harbour and the low-lying hinterland behind as water overflows the embankment. The potential failure of the culvert/sluice near Ferry House would result in additional exchange of water between these locations.

As sea levels continue to rise and the likelihood of an extreme event is increased (4mOD), the raised highway would be at greater risk of failure. Initially, the raised highway would be subject to continued overflow, before the crest of the embankment lowers and eventually breaches. Breaching of the embankment could take place across its lowest elevations, which is largely an area that extends from Sidlesham, southwards to Norton. With time, the two inlets could connect, via one main tidal channel, such that Selsey Bill forms an island (Uncertainty Rating: EVENT 1, TIMING 3). It is assumed that "Selsey Island", as it would become, would be fixed in its present position firstly by the Mixon Reefs, and secondly by continued coastal defence and management methods (Uncertainty Rating: 3). This prediction of potential future evolution is also supported in the Strategy Study for Pagham to East

Head (Posford Duvivier, 1999); Futurecoast (2002); and the Solent CHaMP (Bray and Cottle, 2003a; 2003b); the timing of which is predicted to take place within 50-100 years.

Reclaimed areas would flood and become inundated, significantly increasing the tidal prism (discussed in Section 4.3 of this report). There would be a significant change to the existing flood plain, as drainage of the relict Lavant Valley and the low-lying flood plain, grazing marsh, and intertidal habitats that presently surround Pagham Harbour takes place. The full extent of the potential new tidal inlet is shown in Figure 4.1.

C.4.3 CHANGES TO THE TIDAL PRISM

Using GIS techniques as part of this study, the total tidal prism for the unified Medmerry estuary and Pagham Harbour has been estimated. The results are shown in Table 4.1, indicating that the overall tidal prism would increase as the two inlets became connected. There are two major uncertainties involving: (i) the distribution of the estuary tidal prism between the Medmerry and Pagham inlets, and (ii) the magnitudes, timings and directions of the tidal currents that would be likely to flow across the old road embankment between the Medmerry and Pagham estuaries. It is recommended that numerical tidal simulation model be set up if reliable answers are required to these questions. For example, it is possible that one of the inlets could “capture” some of the tidal prism resulting in potential enlargement of that inlet with corresponding reduction, instability and possible closure of the other inlet (Uncertainty Rating: 3 all elements). If a significant tidal exchange becomes established between the eastern and western portions of the unified estuary, then it is likely that new channels could also be eroded within the underlying geology (alluvial substratum that forms that Manhood Peninsula), not currently exposed.

Table 4.1 Calculations for Braklesham Bay and Pagham Harbour Tidal Prism (based on calculations in GIS)

Water Level	Area (m^2)	Volume (m^3) (Tidal Prism)
2.4m (MHWS)	11,228,114	12,178,214
3m (MHWS + 6mm/year SLR)	14,197,095	20,037,057
4m (Extreme)	21,297,095	37,865,536
4.6m (Extreme + 6mm/year SLR)	26,592,293	53,053,900

The new inlet at Bracklesham would be of sufficient size and orientation for the fetch across the new inlet to generate waves that could erode the embankment along the B2145 and this could hasten failure and breaching of this feature. Differences in existing tidal levels at Braklesham Bay and Pagham could also mean that the water levels to the eastern and western ends of the new estuary could differ throughout the tidal cycle generating powerful currents within the estuary (tidal model recommended in order to define the nature of any such currents). Based on knowledge of the currents that operate on the open coast off the Selsey peninsular, west to east flow might be expected on the flood tide with a corresponding east to west flow during the ebb (Uncertainty Rating: 3). It should be noted that regime analysis cannot be applied to the unified estuary because we cannot yet determine the likely distribution of tidal prisms between the two inlets.

C.5 Conclusion

This study presents estimations for the potential evolution of Pagham Harbour and the Medmerry frontage at Braklesham Bay, assuming a policy of “NAI” at these locations and along the B2145 embankment, and a policy of “hold the line” at Selsey Bill. It was found that a new inlet could potentially form at Braklesham Bay, whilst Pagham Harbour inlet would increase in size with a corresponding increase in tidal prism. It is expected that without maintenance, the embankment that currently supports the B2145 would breach (no timescale has been defined for this occurrence), resulting in a new, connected estuary or channel that is open to the sea both to the west (Bracklesham Bay) and to the east. It is uncertain how much interaction there could be between the inlets and whether both inlets would co-exist, or whether one or other would assume dominance.

It is likely that the channel and its intertidal margins would develop in a similar way to a coastal plain type estuary, thus having a higher potential for adjustment and enabling equilibrium to develop between the inlet(s) areas (mouths) and tidal prism. The likely behaviour and inlet dimensions have been estimated within Sections 3 and 4 assuming that there is negligible interaction between the east and west portions of the combined estuary, but further work would be required in order to estimate the likely behaviour if the interaction were strong. In that case, a numerical tidal model would be required to analyse the tidal flows and currents generated by a two inlet system.

The analyses undertaken indicate that the changes predicted would be extremely favourable for creation of new habitats including tidal mudflats, saltmarsh and vegetated shingle. Potential adverse impacts could relate to the effect of the new Medmerry inlet and an enlarged Pagham inlet in promoting growth of tidal deltas on the open coast. These features would dissipate wave action and contribute towards coastal stability locally, but the sediments that they accumulate raises possibility that neighbouring frontages could temporarily become starved of sediment.

The findings of this report present a broad review of the potential linkages between the frontages of Braklesham Bay and Pagham Harbour that can be used to support the appraisal and development of shoreline management policy for each frontage. It provides commentary identifying the scope and potential magnitudes of the likely future changes, but considerable uncertainties remain relating to understanding of the likely timings of events and with respect to the behaviour of the connected two inlet scenario.

C.6 References

Bradbury, A. 1998. Response of shingle Barrier Beaches to Extreme Hydrodynamic Conditions. PhD Thesis, School of Ocean and Earth Sciences, University of Southampton.

Bray, M.J. and Cottle, 2003a. Solent Coastal Habitat Management Plan. Volume 1. Summary of Habitat Change. Final Report.

Bray, M.J. and Cottle, 2003b. Solent Coastal Habitat Management Plan. Volume 2. Technical Report.

Bray, M.J. and Duane, W.J., 2001. *Porlock Bay: Geomorphological Investigation and Monitoring*. Gravel Barrier Breaching and Tidal Lagoon Development. RACER, Department of Geography, University of Portsmouth. Report to the Environment Agency. Report Reference: STCG024.

Carter, D.J. and Bray, M.J. 2004. Pagham Harbour to East Head. Sediment Transport Study. Report to SCOPAC by University of Portsmouth.

Carter, R.W.G. 1988. *Coastal Environments.- An introduction to the physical, ecological and cultural systems of coastlines.* Academic Press, London.

Cope, S. 2004. Breaching of UK coarse-clastic barrier beach systems: methods developed for predicting breach occurrence, stability and flooded hinterland development. PhD Thesis Department of Geography, University of Portsmouth, 281p.

Cundy, A. Long, A. Hill, C. Spencer, C. and Croudace, I. (2002) Sedimentary response of Pagham Harbour, southern England to barrier breaching in AD 1910. *Geomorphology*, 46, 163-176.

Defra, 2002. UK Climate Impacts Programme 2002. Climate Change Scenarios: Implications for Flood and Coastal Defence: Guidance for Users. R & D Technical Report W5B-029/TR.

EA Internal Document, 2003. *Summary of Shingle Recharge to the Medmerry Frontage Selsey*. Ed. J.P.Pett, 26th February 2003.

Geodata Institute, 1994. Pagham Harbour: Review of Physical and Biological Processes. Geodata Institute, University of Southampton.

Halcrow, 2002. Futurecoast. Report to Defra.

Hosking, A.; Bray, M.J.; Moore, R. and Lee, E.M. 2001 *Preparing for the Impacts of Climate Change.* Report to SCOPAC. 100p. plus 5 appendices (Hard Copy and CD-ROM formats).

HR Wallingford, 1997a. East Solent Shoreline Management Plan, Stage 1. Volume 1: The Open Coast. Report EX3441. Report to Local Authority Consortium (Chichester DC, Havant BC, Portsmouth CC, Fareham BC, Gosport BC); English Nature and Environment Agency, 65 pp and Appendices.

HR Wallingford, 1997b. East Solent Shoreline Management Plan, (Stage 2). Volume 2: The Open Coast. Report EX3441. Report to East Solent Shoreline Management Plan (SMP) Consortium, 28 pp plus Tables, Figures and Appendices.

O'Brien, M.P., 1931. Estuary Tidal Prisms related to Entrance Areas. Civil Engineering 738-739.

Posford Duvivier, 1999. Pagham to East Head. Coastal Defence Strategy. Draft Final Report.

Posford Haskoning, 2003a. Solent Coastal Habitat Management Plan. Volume 1. Summary of Habitat Change. Final Report.

Posford Haskoning, 2003b. Solent Coastal Habitat Management Plan. Volume 2. Technical Report.

Robinson, A. H. W., 1955. The Harbour Entrances of Poole, Christchurch and Pagham, Geographical Journal, 121(1), 33-50.

University of Newcastle, 2000. Potential Effects of Dredging Activities in the Solent. Coastal Geomorphology Partnership, University of Newcastle report to English Nature. Taken from Posford Haskoning, 2003b.

Wallace, H., 1996. Sea Level and Shoreline between Portsmouth and Pagham for the past 2,500 Years. Part 2 Chapters 1 to 4. Published privately by author: Major H. Wallace and MY Curlew. Chichester yacht Basin, Birdham, Chichester, West Sussex P20 7EJ.