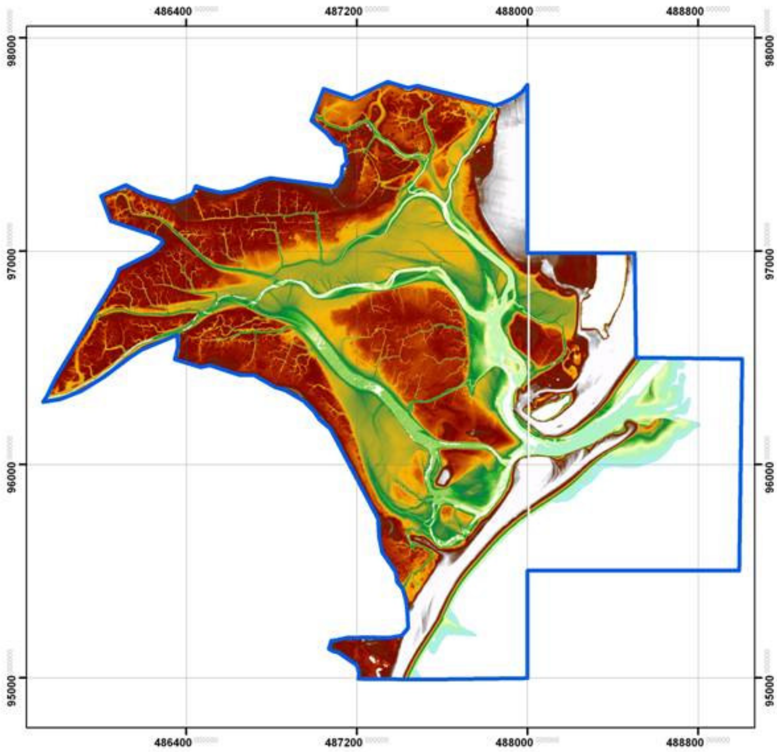

Pagham Coastal Defence Study

Geomorphological Assessment

Arun District Council

February 2009

Final Report

9T4740

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GLOSSARY

BP	Before Present – a means of dating before the present day.
c.	(circa) about.
CDS	Coast Defence Strategy – this sets out an approach to implementation of the SMP's strategic options and brings in more local detail of information.
DEFRA	Department for Environment, Food and Rural Affairs - the United Kingdom governmental department responsible for environmental protection, food production and standards, agriculture, fisheries and rural communities in England.
DTM	Digital Terrain Model - is a topographic model of the bare earth that can be manipulated by computer programs.
EA	Environment Agency - the principal environmental regulator in England and Wales.
EGA	Expert Geomorphological Assessment – the application of expertise to assess and understand the nature of past and potential future changes to landforms.
GIS	Geographic Information System - a computer system designed for storing, manipulating, analyzing, and displaying data in a spatial context.
Holocene	The Holocene is a geological epoch, which began approximately 10,000 years ago (about 8000 BC).
HTA	Historical Trend Analysis – a technique of using existing historic sources such as maps photographs and literature to identify change in landforms.
LiDAR	Laser Induced Direction and Range - a technique used to detect atmospheric constituents or related parameters such as atmospheric extinction coefficient.
LMU	Local Management Unit -
MHWN	Mean High Water Neap - the average of high water heights occurring at the time of neap tides.
MHWS	Mean High Water Spring - the average of high water heights occurring at the time of spring tides.
MLWN	Mean Low Water Neap - the average of the low water heights occurring at the time

	of neap tides.
MLWS	Mean Low Water Spring - the average of the low water heights occurring at the time of spring tides.
OD	Ordinance Datum - the standard sea-level of the Ordnance Survey, now taken as mean sea-level at Newlyn, Cornwall.
ODN	Ordnance Datum Newlyn - as above.
OMU	Operational Management Unit -
SCOPAC	Standing Conference on Problems Associated with the Coast – a group of operating authorities responsible for management of the coastline for coastal defence and flood protection.
SMP	Shoreline Management Plan – a plan setting out strategic options for management of the shoreline. A first generation SMP (SMP(1)) has been approved for this shoreline and a second generation SMP (SMP(2)) has been developed for it.
SSSI	Site of Special Scientific Interest – a national designation for features of nature conservation importance as a result of their biological, geological, or geomorphological interest.
U*	Shear velocity (ms^{-1}).
U* Threshold	Shear velocity at which particles become suspended (ms^{-1}).
V	Velocity (ms^{-1})
V mean	Velocity at mouth of river (ms^{-1}).

EXECUTIVE SUMMARY

This report forms an assessment of the morphological evolution of Pagham Harbour and its associated spits, beach and tidal inlet. The assessment comprises a Historical Trend Analysis (HTA), Expert Geomorphological Assessment (EGA), Tidal Prism Assessment (TPA) and Inlet Stability Analysis (ISA). The results and analysis presented herein shall feed into a wider assessment of other process based studies, including modelling of storm wave overtopping, flood routing and a barrier breach analysis.

The convergent gravel spits that define the Pagham Harbour entrance channel have behaved in a highly dynamic fashion over at least the past seven centuries. In the past, the harbour has operated as a natural system with the entrance shifting regularly, though to no discernable spatial and/or temporal pattern. After the closure of the harbour in 1877 the offshore delta deposits were reworked onshore leading to the build up of shingle and the creation of Pagham Beach. Since 1997 the tidal inlet channel has been increasingly deflected toward from its predominant west to east orientation to its current position. By 2005 the tidal inlet had adopted a new southwest to northeast orientation upon exiting the inner harbour, fed by littoral drift and the accretion and subsequent advancement of Church Norton spit.

Temporal and spatial patterns of erosion and accretion are strongly linked to the position of the tidal channel and the spit. The position of the inlet's ebb tidal delta also provides a considerable interruption to the north-easterly littoral drift, resulting in the net effect that the shoreline sediments arriving from the west, no longer naturally bypass the harbour inlet, but are stored within the former tidal delta where they have contributed to rapid spit accretion. Since 1997 there has been a marked change in the correlation between erosion and/or accretion, which may be taken as indicating a shift in the previous dominant coastal processes and/or development of a feedback mechanism in and between the external forcing parameters of hydrodynamic regime, sediment supply and geomorphological development during this period of time. Associated with this is a rapid increase in the accretion of Church Norton Spit since 2005 at a rate of approximately 106m per year over the period 2005-2008. This is a significant change over the prior periods analysed, during which time coastal accretion varied between 4 and 22m/year, illustrating that the rate has increased dramatically towards the present.

The Inlet Stability Analysis (ISA) has demonstrated that the harbour/tidal inlet is currently characterised as being of low stability as it does not have the required competence to transport littoral drifted materials towards the contemporary ebb delta. Material entering the tidal inlet will, therefore, have a choking effect, restricting flow through the channel. The effect of sea level rise on tidal prism alone results in an improvement in stability conditions up to 2080, but sea level rise could also result in increased longshore drift rates, meaning that the future system is likely, overall, to behave similarly to the present day in terms of conditions at the mouth. If there is no additional sediment then increased stability will result.
The current trend towards erosion at Pagham Beach cannot be assessed without consideration of the stability of the tidal inlet to Pagham Harbour and its associated effect on the stability, or otherwise, of the adjacent shoreline. The continued functioning of the harbour is intrinsically linked to the harbour entrance remaining open, which is linked to the migration of the spit to the northeast, which may result in the blocking of the harbour entrance should the current regime remain in place

The presented geomorphological assessment on the morphological evolution of Pagham Harbour and its associated spits justifies an interventionist approach to the morphological development of study site.

1 INTRODUCTION

This document presents a desk based assessment of issues related to the morphological evolution of the Pagham Harbour and its associated beach, spits and tidal inlet, and comments on the future morphological development of these features. It provides a summary of past morphological changes as part of a Historical Trend Analysis (HTA) of the study area, calculation of tidal prisms within Pagham Harbour, and how these relate to the regime of the tidal system and the inlet stability. The tidal prism describes the volume of water within the tidal system that drives processes of flow and sediment transport, the regime relates to an equilibrium form where the forces of erosion and deposition are balanced to produce a net morphology.

A historical perspective is essential for understanding the present coastline and particularly as a background to proposed developments. The coast is naturally dynamic and should not be assumed to be stable or have remained in its present form for many years. The findings of the Historical Trend Analysis (HTA) are utilised to inform an Expert Geomorphological Assessment (EGA) on the functioning of the study site. On the basis of this broad-based understanding, the report considers the relationship between Pagham Harbour and the surrounding coastline in the area and implications of potential changes in channel, beach and spit morphology for future management of the study site.

The report concludes with an Inlet Stability Analysis (ISA). In simple terms, this is an assessment of the relationship between the amount of sediment transported along the coast and the competence of the tidal inlet to move the sediment from its mouth as it arrives at/in it from the coast.

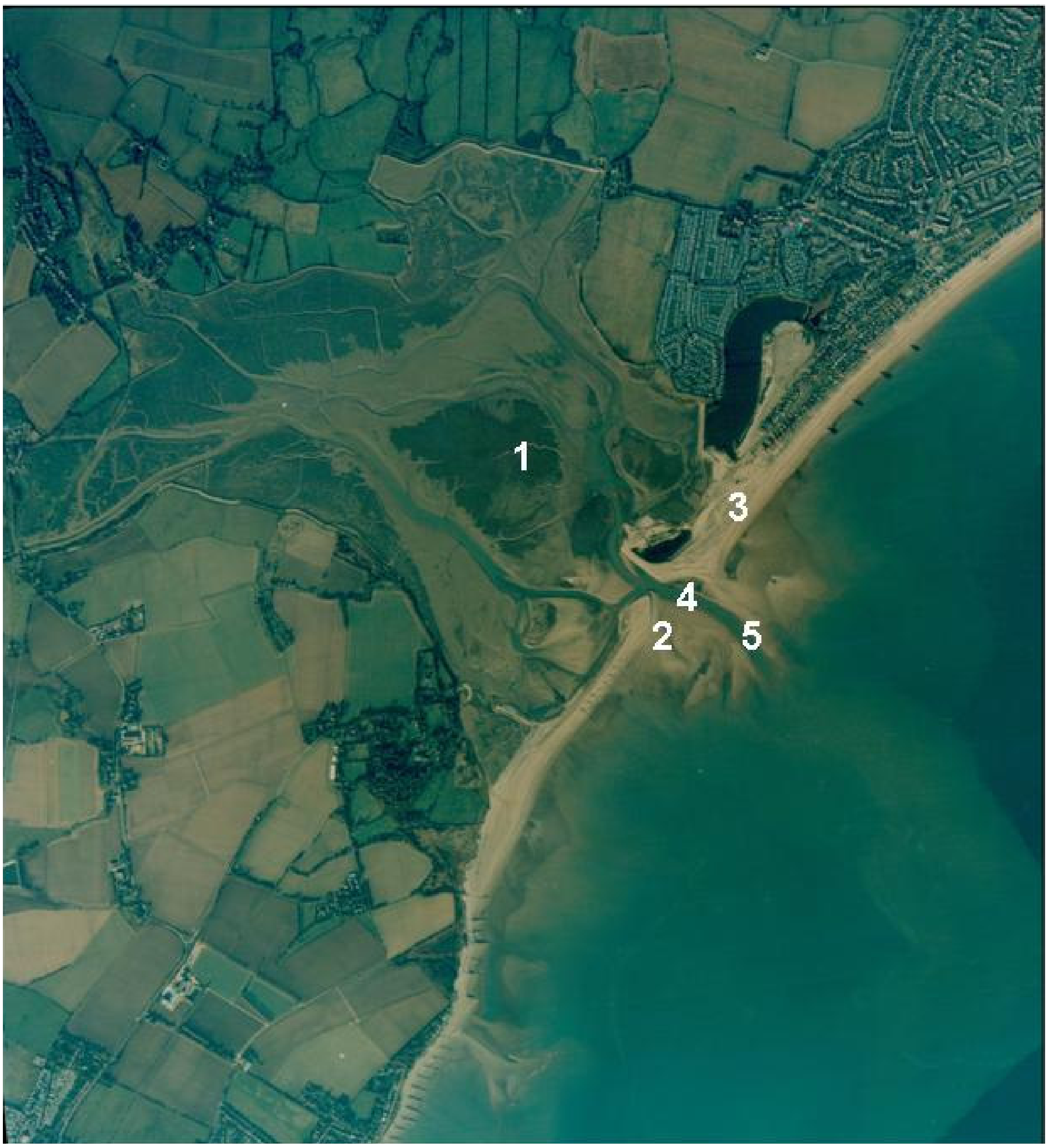
The report will feed into a wider assessment of other process based studies (including modelling of storm wave overtopping, flood routing and a barrier breach analysis). The assessment will support an options appraisal for the morphological evolution of Pagham Harbour and its associated spits and provide information required to inform whether an active intervention in the morphological development of study site is justified and sustainable.

1.1 Study site

Pagham Harbour is a small tidal inlet on the Sussex coast, characterised by no significant freshwater discharge into the harbour. The harbour has an area of some 2.83km^2, measured at high water level on spring tides (West Sussex County Council, 1994). The inner harbour is protected from marine inundation by the presence of a fronting, stabilised gravel barrier beach and spit, with the harbour itself being a product of Holocene sea-level submergence (see **Figure 1.1**). Key locations mentioned within the text are numbered for future reference.

The harbour is connected to the sea by a channel approximately 100m in width, which extends to circa -4m OD (Cundy et. al., 2002). The position of the channel and the size and elevation of its associated ebb tidal delta have been unstable since at least the 16th century (Steers, 1964). This is due to the flushing ability of the entrance channel (provided by the tidal prism) being much smaller than the magnitude of sediment supplied by longshore drift (Cundy et. al., 2002).

Figure 1.1 Aerial photograph (1997) of Pagham Harbour illustrating key locations (1. Pagham Harbour; 2. Church Norton spit; 3. Pagham Beach; 4. Tidal inlet channel, and; 5. Ebb tidal delta)



1.2 Previous and ongoing studies

Reconstructing historical changes can be challenging and time consuming because the relevant evidence is often disparate and has to be collated from a range of sources. However, this is a critical first step in the geomorphological assessment, as it is within a historical context that future evolutionary trends of both the coastal and intertidal systems shall be assessed. It is thus useful to first establish what main studies have already been undertaken or are ongoing in the study area to minimise any unwanted repetition of work previously completed or ongoing.

Work has been undertaken by the University of Sussex to assess morphological evolution of the Sussex coast. An output from this ongoing work is an educational pack designed to illustrate, using old and recent maps, some of the temporal changes to the morphology of the shoreline, estuaries and harbours including Pagham (available on line **www 1**). This provides a valuable resource and reference for key map-based and other literature.

The Standing Conference on Problems Associated with the Coast (SCOPAC) (**www 2**) Sediment Transport Study provides a comprehensive review of both historical and contemporary knowledge of sediment inputs, throughputs, stores and outputs along the coast which is extremely useful as a collation and integration of existing work.

Barcock & Collins were commissioned by Arun District Council to investigate beach erosion, thought to be linked to the presence of the tidal inlet channel to Pagham Harbour, along a 1km section of Pagham Beach. Barcock & Collins (1989) found that erosion rates were high, typically in the order of 3m/year, though decreasing from 1989 to 1995. Furthermore, the area of erosion was noted to migrate eastwards due to the migration of the ebb tidal delta, and was bounded on either side by areas of accretion. The area of erosion was attributable to localised wave refraction which caused a reversal of drift toward the inlet, resulting the observed erosion. Barcock & Collins (1989) concluded that a solution to the problem was not apparent and would require further investigation, though they did state that the beach would reach a state of dynamic equilibrium with the local wave climate and erosion would then reach a minimum, or cease. However, recently acquired data highlights that this indeed is not the case and in fact that erosion may be increasing.

Royal Haskoning, Land Drainage Study of the Manhood Peninsula (2005), presented findings of the study into the effects of siltation in and around Pagham Harbour. The report stated that 'Pagham Harbour has been getting drier and is generally understood to be gradually silting up'. Consequently there are concerns that Pagham Harbour may eventually be naturally reclaimed with associated closure of the Harbour mouth, impacts upon the drainage, environment and potential future flooding problems. The study considered: the actual rate of siltation; whether siltation would contribute to any possible storm induced closure of the entrance, and; the effects of future climate change, amongst others. The report noted that 'since 1963 the Harbour entrance has been fixed in its present position by a single northern training arm which was replaced during the 1980's', and that to the south there is a large mobile shingle spit which could block the mouth of the Harbour if it moves. If the training arm or the shingle spit were to breach then increased wave and tidal activity would result in the Harbour. This could aid drainage by reducing silt levels but increased overtopping is likely to more than counteract the effect of better drainage.

The accreting sediment within Pagham Harbour was deemed to be transported into the harbour from the sea, as opposed to being derived from the hinterland drainage system. Various research papers, available raw data and our observations were used to conclude the average long term rate is 3.8 - 8.3mm per year. The main impact that siltation will have on the existing drainage system is a restriction on discharge. As the bed of the Harbour is raised by siltation this will prevent the rifes/streams from draining down as low at low water. This will result in a reduction of available storage in the rifes/channels during times of rising tides/flooding tides and could result in flooding at certain locations.

Royal Haskoning further noted that storm induced closure of the entrance would be due to shingle being transported to block the entrance. This process is independent of siltation in the Harbour. The reduced tidal prism in the Harbour would reduce the potential for re-opening on an ebb tide.

The South Downs Coastal Group in their Beach Management Plan report (2007) provide a detailed overview of beach changes and wave and tidal measurements since the commencement of the Southeast Strategic Regional Coastal Monitoring Programme. Boundaries for the extent of the report are from Church Norton to Pagham comprising management units 2 and 2A, and include the Pagham Harbour frontage. As part of the Southeast Strategic Regional Coastal Monitoring Programme the beach has been surveyed three times a year since 2003. In addition to this bathymetric survey of the adjacent seabed was concluded in 2004 and 2006, and a network of tide and wave gauges were also established. The report presents changes during 2006-2007 as well as the period of the baseline from March 2003 to March 2007. A synthesis of the acquired data is presented in **Section 4**: Expert Geomorphological Assessment (EGA).

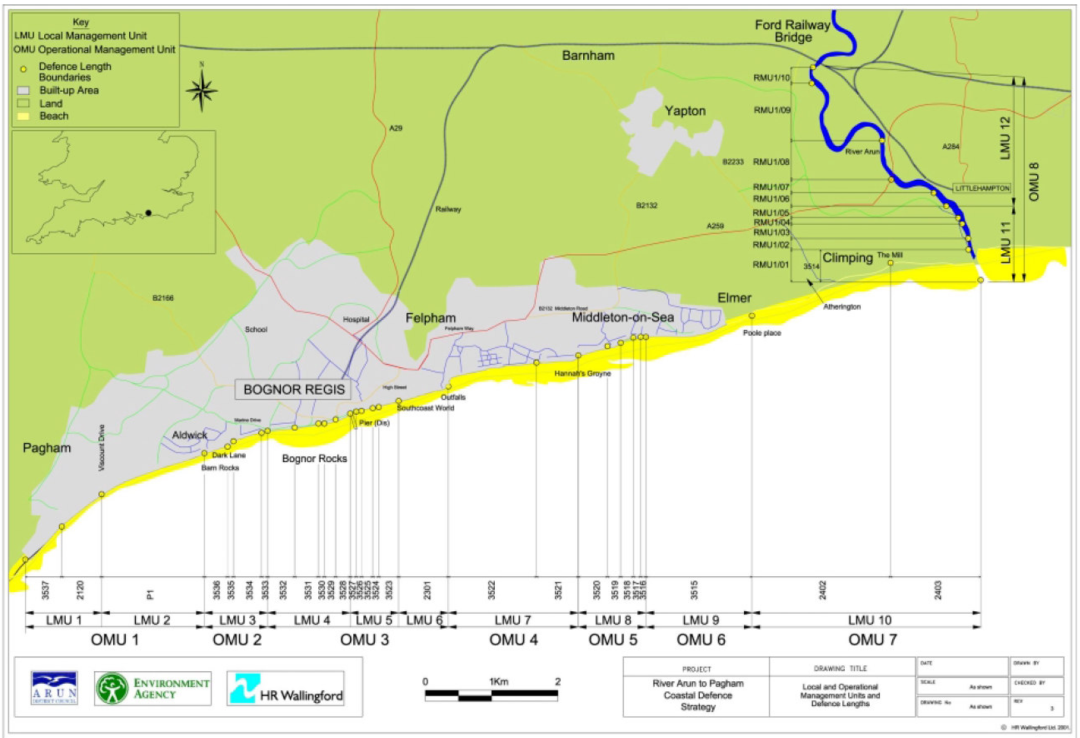
The present Coastal Defence Strategy (CDS) refines SMP management units to provide a management framework as: Defence lengths, Local Management Units (LMU) and Operational Management Units (OMU). The extent of the LMU and OMU are presented in **Figure 1.2**. The existing management policies for OMU, LMU and SMP MU are presented in **Table 1.1**.

Table 1.1 Existing management policies SMP (1997).

OMU	LMU	SMP MU	SMP Policy	Description of policy for each SMP management unit
1	1	2	Hold the line	Continue with the present arrangements of a shingle beach with widely spaced groynes over the western frontage and open beach over the eastern frontage
	2	3	Do nothing	The unit currently accretes and is mostly stable: it is not necessary to do anything at present except monitor beach levels.

Shoreline management units MU2 and MU2A, and include the Pagham Harbour frontage, are currently ‘hold the line’ to protect the wetland and mudflats in the hinterland that have been designated a Site of Special Scientific Interest (SSSI). The present Coastal Defence Strategy (CDS) contains no plans to replace the training arm, which currently fixes the tidal inlet location, once it is lost in several decades time.

Figure 2.1 Local and Operational management units and defence lengths (from HR Wallingford, 2004)



This report builds on these existing studies and other historical records and existing datasets to develop an understanding of the coastal and harbour systems and the interactions between them spatially and temporally.

1.3 Structure of this report

This report comprises 6 sections of which this introduction is **Section 1**. **Section 2** provides a brief method statement to the HTA and EGA while **Section 3** outlines data sources utilised and the results of the Historical Trend Analysis (HTA). The HTA provides an overview of the morphological development of Pagham since the Holocene (approximately 10,000 years B.P.), prior to focussing on recent historical trends (approximately the last 75 yeasr). Following this, **Section 4** presents the results from Expert Geomorphological Assessment (EGA). Both the HTA and EGA sections are concluded with a summary and discussion. **Section 5** presents the findings of the Tidal Prism Assessment, prior to concluding with an Inlet Stability Assessment (ISA) in **Section 6**.

2 METHOD STATEMENT

2.1 Historical Trend Analysis

The Historic Trend Analysis (HTA) involved a review of the past data and available records that relate to the Pagham coastline set within the broader context of the Selsey to Bognor coastline. This HTA covered the period between 1587 and 2008 and considered both natural and anthropogenic changes within the area, which is particularly relevant in the context of morphological evolution. The HTA provides an analysis of the historic behaviours of the system; from such an analysis assessment can be made of potential future change.

The analysis made use of the following primary data (see **Table 2.1**);

Table 2.1 Primary data utilised within the HTA

Historical Mapping	1587, 1932, 1938, 1969
Beach Profile Change Data	1995 – 2007 showing variations in beach morphology (Courtesy of the Southeast Strategic Regional Coastal Monitoring Programme).
Aerial photography	1947, 1950, 1955, 1972, 1986, 1997, 2001, 2005 and 2008.

Historical mapping aerial photography was compared to identify key changes in morphology through time. Desk based analysis and geomorphological interpretation were undertaken on the range of data available to understand the possible causes of change and determine future likely response on the basis of past behaviour.

2.1.1 Analysis of aerial photography and historical maps

Hard copy aerial photographs and historical maps were assessed visually in the first instance to identify the direction and degree of change. As a discrete exercise, this is an appropriate approach toward this data and has been applied on previous mapping of habitats, for example, by English Nature (e.g. Burd, 1989).

Rectified aerial photographs were also assessed visually and utilised to obtain quantitative data from via interpolation within the GIS. Rectified and geo-referenced photography have a number of distinct advantages over hard-copy originals as:

- Rectification means that the photographs have been warped to reflect actual distances on the ground, without this process it should be recognised that a non-linear distortion exits from the centre of the photograph and hence accurate quantification of distances (or levels) is not possible.
- Geo-referencing means the digital file is correctly adjusted to a known mapping co-ordinate system (OSGB).

Changes in coastal configuration can be detected by comparing sequential shoreline positions derived from aerial photography. This approach uses various analytical methods and equipment (GIS) to superimpose shorelines on a map and then to calculate rates of change both spatially and temporally. One way is to compare the earliest and most recent pairs of photos. This approach uses the longest span of years to determine an erosion or accretion rate. This 'end point' method can be a reliable proxy for predicting shoreline change in locations that have a steady erosion problem.

Another method, and the approach utilised herein, uses a time series of shoreline positions taken from a series of aerial photography (1938-2008). At any particular location, the horizontal position over time is used to calculate a linear regression or "best fit" to the data. This approach is favourable to reduce the influence of erosion and accretion cycles that may exist within a highly dynamic coastal environment.

2.2 Expert Geomorphological Assessment

Several techniques are available to investigate and predict the behaviour of coastal and harbour environments. Expert Geomorphological Assessment (EGA) is a technique which involves synthesising a range of data and integrating this with expert judgement to evaluate the current functional dynamics of a system and was applied to this study along with a HTA.

Data from a range of sources was compiled and analysed through both desk based review and Geographical Information System (GIS) interpolation. A combination of EGA and HTA allowed an evaluation of the geomorphological sensitivity of the coastal system at Pagham in the context of the wider Sussex coastline and the possible drivers of the evolution of the system to be identified. Following the EGA and HTA and taking account of local knowledge of site owners and other stakeholders, options to manage the morphological development of the coastal system were developed.

2.3 Inlet stability analysis

Three methods were applied to consider the potential stability of the tidal inlet to Pagham Harbour. The first two of these were effectively combined in the analysis stage for efficiency. The methods applied were:

1. Brown Method/Escoffier Curves – The development of Browns' 1928 method by Escoffier (1940) was to assess the degree to which velocity has potential to mobilise sediment. This uses the cross sectional area of the channel and mean velocity. As the cross sectional area increases so does velocity to a point where further cross sectional increases lead to velocity decreases. If the mean velocity exceeds the critical velocity for sediment motion then either an unstable or stable inlet may develop; the curves identify which this is.
2. Maximum Velocity Criteria – The peak velocity can be applied to the sediment mobilisation assessment using the relationship between the peak velocity and the critical velocity for sediment transport. Thus if the peak velocity exceed the critical threshold sediment will be swept from the estuary mouth and vice versa for sediment deposition.
3. K_c Criterion – Gao and Collins (1994) developed the Brunn and Gerritson 'r' Factor (a dimensionless parameter for sediment by-passing of inlets) to include the freshwater flows and tidal characteristics to produce a coefficient of inlet stability (K_c)

3 HISTORICAL TREND ANALYSIS

3.1 Introduction

The HTA has identified relevant studies that have previously been undertaken, or are ongoing, in the study area. This was to obtain the maximum possible benefit from previous work by reviewing their findings to provide an initial background context for the subsequent data analyses. It also considered the implications of such information in the context of the objectives that shaped the studies and subsequent reports. Importantly, the information was interpreted by applying EGA to help identify and focus further analytical work required to investigate and develop a fuller understanding of aspects on the coastal evolution.

Results from the HTA are presented in three discrete sections:

1. Holocene evolution (10,000 years B.P. onwards);
2. 1262 to present and,
3. 1932 -2008

For convenience, the presentation of results in three discrete sections may be considered as identifying change on a geological timescale (1); a century scale (2), and; a decadal scale (3).

3.2 Holocene evolution (10,000 years B.P. onwards)

During the last glacial cold stage (Devensian), sea level fell to at least -50 to -60m OD around the coast of Britain, with regional shorelines of southern England some 5-7km seawards of their present position. During this time the lower reaches of Sussex Rivers cut deep valleys far below the present day valley floors. Climatic amelioration in the Post-Glacial period resulted in the retreat of the ice sheets liberating large volumes of meltwater resulting in sea level rise, with the rapid recovery of sea level being recorded in complex minerogenic and organogenic sediments (SCOPAC, 2003). Evidence derived from these sediment sequences indicates that sea level stood at -27m at 9,000 B.P.; -15m at 7500 B.P. and -5m at 5500 B.P., at which time, as water levels continued to rise, low lying valleys were inundated by marine waters.

Holocene sea-level rise has therefore released a substantial quantity of sediment, including gravels derived from the ancestral Coastal Plain composed of Raised Beach, Coombe Rock (periglacial) and fluviatile (terrace) materials. Some of this continues to be available as scattered deposits on the seabed, but it is thought that much lies stranded offshore within submerged barrier beaches built during several stages of mid to late Holocene sea-level transgression. Wallace (1990 & 1996) has tentatively identified the foundations of several inundated barrier structures, some of which may have originally been independent barrier islands, separated by tidal passes (see **Figure 3.1**). Others may have become "anchored" to the predecessors of modern reefs, such as the Mixon, and once extended as far eastwards as Bognor prior to being submerged during one or more stages of rapid sea-level rise. Others continued to be driven landwards, probably by storms, to eventually produce the contemporary barrier form of Church Norton beach and spit. Part of the substantial sediment resource of earlier gravel barriers has been redistributed to modern stores such as the Kirk Arrow spit; the Inner Owers; and the Pagham Harbour spits and tidal delta.

The Holocene evolution of the study area can be conveniently divided into five stages as shown in **Table 3.1**, which can reasonably be applied to both the Pagham coastline and harbour (Jennings & Smyth, 2001).

Table 3.1 Stages of coastal evolution on the South Coast of England (Jennings and Smyth, 2001)

Stage	Date	Evolutionary processes
1	11,000 to 10,000 BP	Reworking of sediments with rising sea levels.
2	10,000 to 5,000 BP	Transport of sediment landward.
3	5,000 to 300 BP	Sediments transported onshore following the stabilisation of sea levels allowing development of accretionary landforms.
4	300 BP to present	Most available sediments transported onshore resulting in a switch from offshore/onshore sediment supply to longshore drift.
5	Present-future	Gravel is redistributed into sediment sources and sinks along the coast.

The reworking of fluvio/glacial sediments from stage 1 and landward transport of sediment during phases 2 and 3 will have created a shoreline much further seaward than the present shoreline, which has continued to transgress shoreward under a rising sea-level regime.

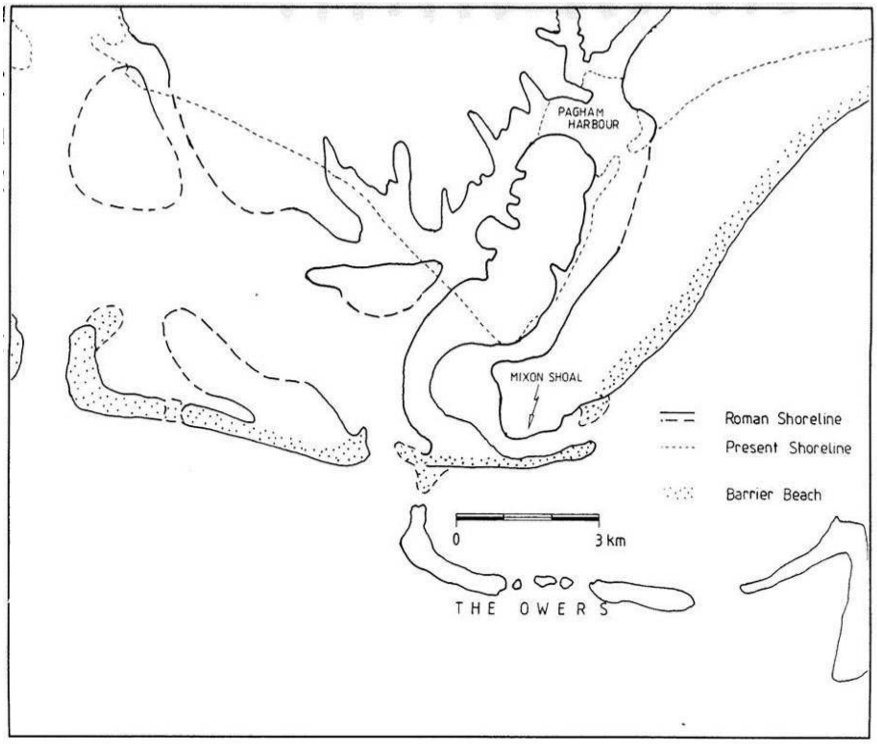
Figure 3.1 presents a probable configuration of the Selsey to Pagham coastline approximately 2000 years before present (B.P.) delineated using archaeological information and by tracing a submerged wave cut platform (Wallace, 1996). The platform is associated with a former period of static sea-level brought about as a result of sea-level falling at a similar rate to local land subsidence rates (Barcock, 1989). Archaeological and sedimentological evidence further supports the reconstruction of a continuous tidal creek linking Pagham Harbour with Bracklesham Bay (Thomas, 1998).

As sea-levels rose, quantities of sand and especially gravel were reworked and transported landwards as a series of ancestral shingle barrier-type beaches located seaward of the present shoreline (see The Owers; **Figure 3.1**). It is thought that the beaches were driven progressively landward by continuing sea-level rise and storm activity, and perhaps also by relative sediment shortages. The present beaches remain barrier-type features with a continuing tendency to migrate landwards (SCOPAC, 2003); this tendency however is prevented by the presence of numerous man-made defences within the larger study area.

The Medmerry barrier (west of The Owers) is believed to have reformed and breached several times since its formation (~2,000 yrs B.P.); at times isolating the Selsey peninsula as an island (see **Figure 3.1**). Archaeological evidence demonstrates that the coastline was some 2 to 3km seawards of where it is now at about 5,000 yrs B.P. (Thomas, 1998). According to May (1996) coastal erosion over this period must have occurred at a rate at least as fast as that recorded for the nineteenth and first half of the twentieth centuries. Other smaller bedrock and offshore banks within 3km of the modern coastline (e.g. Inner Owers, part of the Mixon Reef) appear to be sediment accumulations, possibly representing relict parts of a multistage barrier structure that was progressively segmented and submerged between 2,500 and 800 years before the present (Wallace, 1996).

Wallace (1996) has speculated that the Mixon reef formed a part of the coastline in early Romano-British times. It may have "anchored" the contemporary position of the barrier beach mentioned prior. Scopac (**www 2**) suggest that a 17m deep sediment-infilled v-shaped gap between the Mixon and Malt Owers mark the course of the ancestral River Lavant (see **Figure 3.1**). The latter is likely to have discharged via what is now Pagham Harbour prior to its diversion to Chichester and Fishbourne by Roman engineers in the second century A.D. Wallace (1990). Wallace (1990) suggests that barrier breaching and shoreline recession associated with rising sea-level and storm events caused The Mixon to become an offshore bank, or shoal, at approximately 950-1050 A.D..

Figure 3.1 Selsey and Pagham coastline 2000 years BP (after Wallace, 1998)



The recent historic development of the coastline at Pagham can be characterised by phases 4 and 5 in **Table 3.1**. During this phase artificial modifications have also have had a significant influence on the harbour morphology and adjacent coastline and are discussed in the following section.

3.3 1262 to present

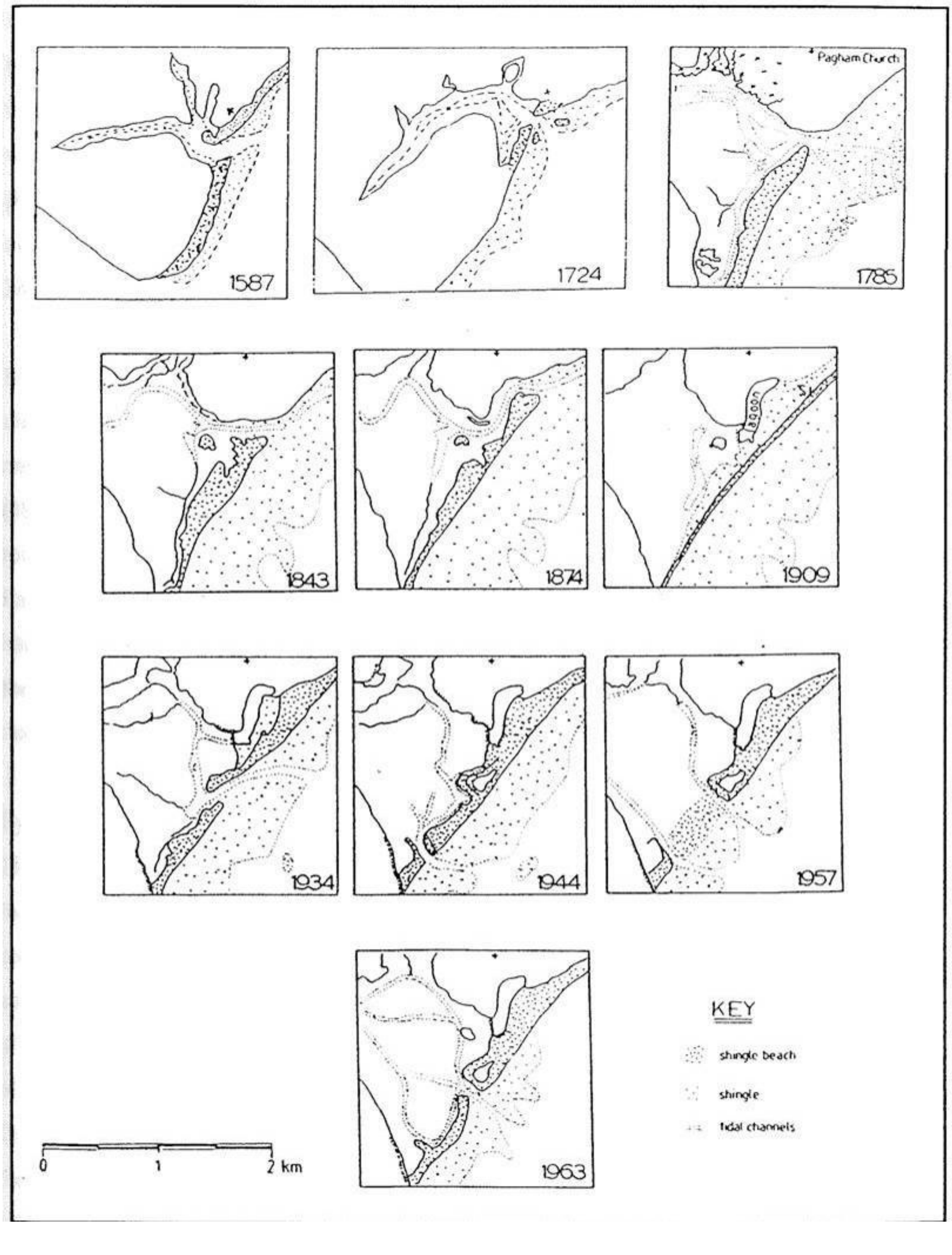
The following section presents natural and anthropogenic modification to Pagham Harbour and surrounding coastline. The Manhood Peninsula – Land Drainage Study provides evidence of modifications to the spit, harbour and surrounding coastline dating back to the 13th century (Royal Haskoning 2005). The summary of these changes are presented in **Table 3.2**.

Table 3.2 History of Pagham Harbour

Date	Description of change
1262 + 1267	New Town of Wardur, possibly sited on the eastern edge of Bremere Rife
1340	2700 acres lost to the sea, implying previous reclamation
1585	Land reclamation on eastern shoreline between Pagham and St. Andrews church, also indicating local inundation
1587	Earliest Map of Sussex Magistrates
1637	First evidence of Pagham Wall on map of this date
1774	Yeakell and Gardener plan reclamation by Mr Powell and Thomas Woods
1820	Breaching of the shingle spit
1800	Small scale reclamation
1809	Earth wall constructed at Sidlesham
1829	Breaching of the shingle spit
1840	Breaching of the shingle spit
1846	Reclamation beyond Pagham Wall
1854	Survey of the extent of Pagham Harbour parishes.
1843	Head of spit moved NE by 1800ft cutting low cliff through former mill site with a broadening of the shingle bank and deepening offshore with the 1 fathom line moving inshore by 100 ft.
1865	Reclamation below Mudland Road
1876-1910	Reclamation of the Harbour areas by blocking exit, and the maintenance of sluices of the Rifes outlet to sea at the Pagham Lagoon.
1910	Reopening of the Harbour mouth by storm surge
1911 - 1912	Secondary flooding of the Harbour and extended breaching of earlier reclamation walls.
1919	First survey of Spartina within the Harbour (Oliver 1920)
1937	New artificial opening at the approximate position of the 1910 breach, isolation of Pagham Lagoon and beach pushed inland.
1944	Concrete and steel retaining wall, (Church Norton) end of Harbour
1955	Secondary mouth opened to the north west isolating an island that was later pushed inland.
1950-1970	Smaller scale reclamations near Sidlesham.
1960-1961	Shingle accumulation extended from Church Norton blocking the 1937 opening to a point where the River Board erected defence work and groynes were established along the Church Norton Spit. Decline of Zostera within the Harbour
1961	Harbour entrance stabilisation location and subsequent maintenance and groyne protection of the Church Norton beach, and beach augmentation.
1991	Augmentation of Tern Island (Hawes 1991)
1991 - Present Day	Continuing maintenance of southern spit by recycling material from ebb delta to seaward face.

The development of Pagham Harbour has been complex, with many factors influencing its long history. Barcock & Collins (1991) in his study of coastal erosion associated with a tidal inlet: Pagham, West Sussex provides a synopsis of the evolution of the Selsey/Pagham coastline based on the earlier contribution of Robinson (1955), which is summarised and presented graphically in **Figure 3.2**.

Figure 3.2 **Changing morphology of Pagham Harbour from 1587 to 1963 (from Barcock, 1989)**



The Harbour extent and entrance have been changed numerous times by natural processes and human intervention. The current harbour is much smaller than that of the Roman period (ca. 2nd – 5th centuries AD) due to successive phases of land claim. The first map of the area was compiled in 1587 and shows three distinct tidal inlets linked to the sea by a narrow channel at the present location of Pagham Harbour. The map evidence suggests that the southern (Church Norton) spit had a configuration similar to the present, possibly in response to one or more breaches dating back to 1340-1410. A survey using 1724 shows that the shoreline had been altered considerably, with a long continuous spit almost enclosing the harbour entrance except for a 100m entrance at its northern end. According to SCOPAC (2007), between 1672 and 1724, the southern spit extended some 90 m north-eastwards. The survey of 1785 illustrates a similar morphology. Further surveys in both 1843 and 1876 show a marked change with rapid spit growth resulting in significant change in the position of the harbour entrance channel landward, which resulted in significant erosion of what is now Pagham Beach. Rates of spit advance during the period 1672-1875 average 5.5 m/yr to a maximum of 10m/yr between 1774 and 1875. Episodes of breaching interrupted the spit extension in 1820, 1829 and 1840. As the spit extended and thinned during this 100 year period, there may not have been a significant supplementary supply from inshore sources (i.e. migratory bars associated with the tidal delta).

According to Bracock (1989), assuming an average cross sectional area similar to today's (1989) this implies a supply of sediment in excess of 5,000m^3/yr between 1774 and 1875. Of further note is that during this period of rapid spit growth, Heron-Allen (1911) recorded increased erosion of the cliffs at Selsey (1-3 m/yr). The main source of sediment feed was therefore delivered by littoral drift along the shoreline from the south west. Rapid shore erosion occurring around the Selsey peninsula at this time would have provided a local source of sediment. Over this same period, the northern (Pagham) spit, the product of 'counter drift' determined by a transport divide north-east of the harbour entrance, experienced net erosion and recession. The entrance channel cut into the low clay cliff on the northern side, resulting in 170m of coastline retreat at this point between 1780 and 1840.

Natural change ceased in 1876, when both spits were partially stabilised and the inlet channel closed to effect the final land claim of Pagham Harbour in 1877. The northern part of the present harbour had been claimed in the mid 1880's AD by construction of an inner seawall. The whole Harbour was sealed and reclaimed in 1876 following an act of parliament and remained 'dry' for a period of some 34 years. Though this helped to create almost 120m of foreshore progradation until the defences were breached in December 1910. A large storm breached the spit at a point approximately halfway along its length, creating a 160m wide channel, allowing the harbour to become inundated by marine waters once again. The inner seawall, protecting the reclaimed north harbour, was also breached following this event. After the closure of the harbour the offshore delta deposits were reworked onshore leading to the build up of shingle and the creation of Pagham Beach. Part of the former tidal channel entrance remains within the harbour today as the Pagham Lagoon and first appears on maps dated 1909 (Barcock, 1989).

Subsequent events have been documented (SCOPAC, 2007), following the breaching in AD 1910. Pagham Harbour underwent colonisation by *Spartina sp*. This colonisation had been delayed by the isolation of the harbour between AD 1876 and AD 1910, as surrounding coastal inlets had already been colonised over the period from AD 1870 to AD 1910 (Cundy et. al., 2002). *Spartina sp*. swards were first observed in Pagham in

AD 1919, and by AD 1948, extensive saltmarsh had developed within the harbour, covering an area of 1.296 km^2. By AD 1986, the aerial coverage had decreased to 0.967 Km^2, giving a mean rate of saltmarsh loss of 0.0087 km^2/year. Though it should be noted, that marsh loss within the inner harbour is spatially variable. Of note is that the accuracy of the mapping exercise is not of such detail that these changes may be meaningfully interpreted to give an annual rate of change. Though they do provide of evidence of changing saltmarsh extent over the monitored period.

Between 1910 and 1934 the distal end of the spit progressed some 700-800m northeast towards Pagham Beach from the location of the 1910 breach location, and in the process deflected the tidal inlet towards Pagham Beach. According to Barcock & Collins (1991), such progradation would require in excess of 10,000m^3/year of sediment drifting along the coastal to accumulate within the spit. In order to prevent erosion at Pagham Beach, a new tidal entrance was cut in 1937 near the 1910 breach location, as shown in the maps dated 1944 (see **Photo plate 3.1**). The pre-1937 entrance gradually closed becoming marked by a low gravel berm. A further breach over a wide front between the 1937 and pre 1937 inlets occurred shortly after 1955 and by 1958 the entrance was some 700m wide. Rapid drift thereafter led to a further extension of the Church Norton spit across the inlet narrowing it to 250m by 1961. Since AD 1910, the entrance to the harbour has been artificially maintained, although its position has shifted periodically.

Photo plate 3.1 Pagham harbour and spit, 1950.

The training arms used to stabilise the channel are clearly visible seaward of the southern extent of the northern spit. By 1957 an extensive channel had opened to the inner harbour as a consequence of a second breach (to the northern spit). The island of shingle formed as a result of the second breach was then reworked into the inner harbour under wave and tidal processes. As sediment was supplied and reworked alongshore the spit accreted to the northeast and by 1960 the breach had been sealed. Following increasing urbanisation of this coastline from the 19th Century onward the beaches have become heavily managed. To maintain a fixed inlet the tidal inlet at

Pagham has been stabilised by training structures. These hard defence structures and interventions have had the effect of reducing major channel avulsion to the north. In 1963 the location of the tidal channel was stabilised into its present location.

3.4 1932-2008

This section presents both a qualitative overview of changes in coastal configuration and quantitative changes for the period 1938-2008. The analysis is based on an assessment of aerial photography amalgamated within a GIS as presented prior (see (**Section 2.1.1**). The qualitative assessment of changes in coastal configuration is based upon the creation of digital shoreline and tidal inlet positions derived from aerial photography.

Figure 3.3 presents changes in coastal configuration from 1932-2008. In 1938, the coastal configuration is largely similar to that of today, apart from the extent of the Church Norton Spit being volumetrically smaller, though similar in planform. The tidal inlet is orientated roughly southwest to northeast and the inner harbour intertidal channels displaying a broadly similar configuration to those of today. This is of particular importance and shall be discussed further in the summary and discussion section of the Expert Geomorphological Assessment (see **Section 4.11**). By 1947, the tidal inlet had been re-established and restrained by concrete and steel arms at Church Norton in the location of the 1910 breach. This resulted in development of a new tidal inlet and intertidal channel and creek system within the inner harbour. As with the intertidal channel and creek system at the 1932 location, this is discussed further in **Section 4.11**. Of importance with the 1947 configuration is the lack of any spit features to the south of the tidal inlet and a coastline that is characterised by an almost straight configuration devoid of any undulations that may be attributable to sediment accumulations. This may be taken as evidence of a period of coastal realignment to the new tidal inlet and the subsequent adjustment to changes in sediment transport processes during this time due to inability for littoral drift to bypass the newly established tidal inlet.

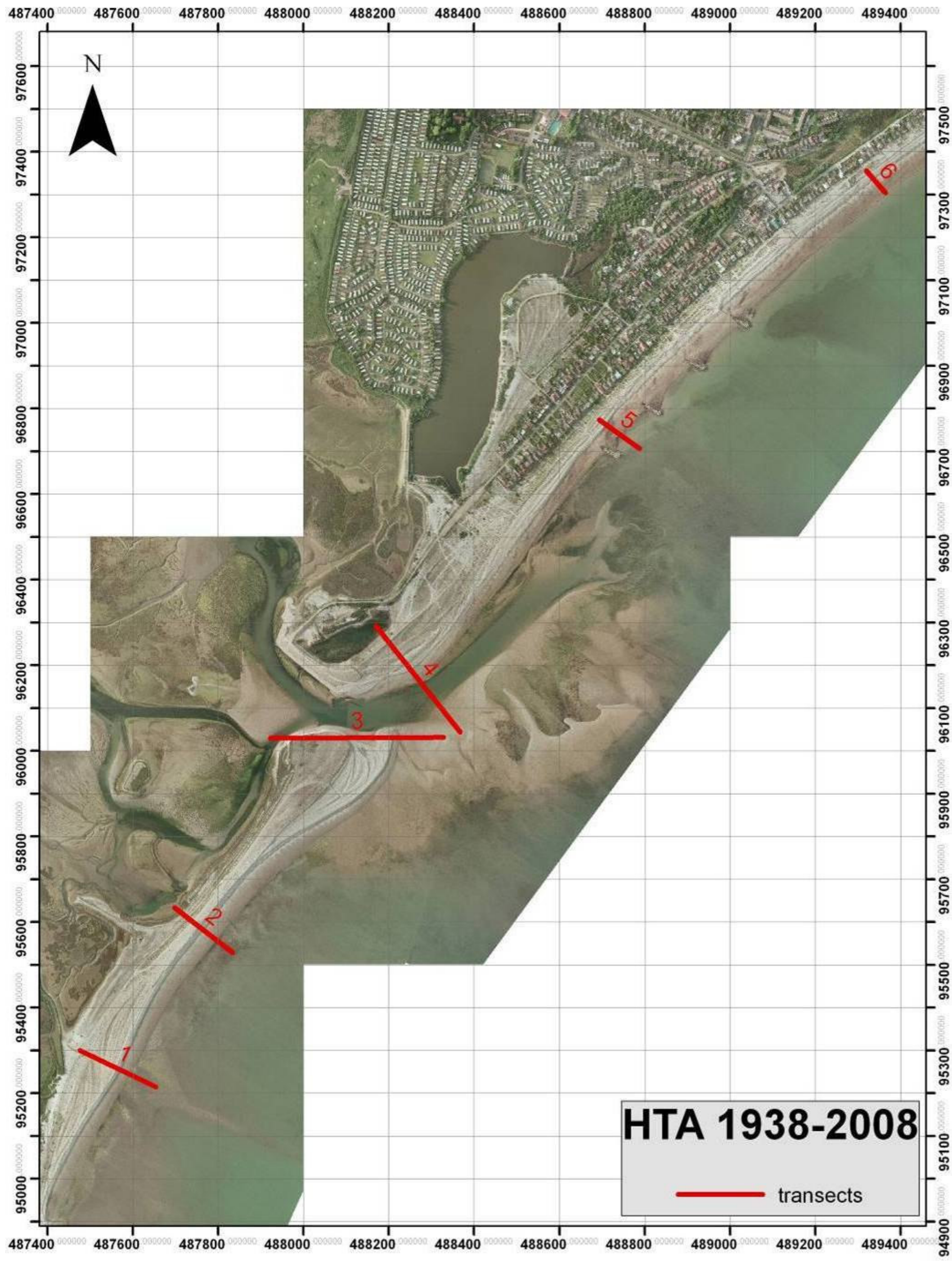
By 1969 the tidal inlet had migrated some 900m to the northeast, though albeit at a rate that was punctuated by various breaching and realignment events (see **Section 3.3**). By 1969 the tidal inlet, intertidal channels and creek systems had firmly established their location, which during the proceeding 28 years were to change relatively little, with the exception of minor bifurcation of the seaward extend of the tidal inlet, followed by short periods (2-3 years) of channel abandonment (Barcock & Collins, 1991). During the period 1969-1997 the general plan view of the coastline changed relatively little in comparison to the period prior (1938-1969) representing the establishment of a short- to medium-term period of coastal stability. The mapping of shoreline position in 1997 illustrates the first significant morphological change to the coastline. This is represented by the presence of a triangular (i.e. cupsate foreland) sediment body to the north of the tidal inlet. This accretionary form may be interpreted as representing the adjustment of the coastal system to the development of a more pronounced littoral drift divide to the north of the tidal inlet. The presence of the littoral drift divide is evident as the formation of the triangular sediment body being fed on its southern flank by the dominant longshore drift from the southwest to northeast, while the northern flank of the same body is being fed by sediment drifting from the northeast to southwest.

By 2001 the presence of the triangular sedimentary body has been partially realigned as a result of the northeast migration of the tidal inlet. This has served to erode and rework the sediment along the shore to such an extent that by 2005 all evidence of its previous existence has been removed.

INSERT FIGURE FOR COASTAL CHANGE

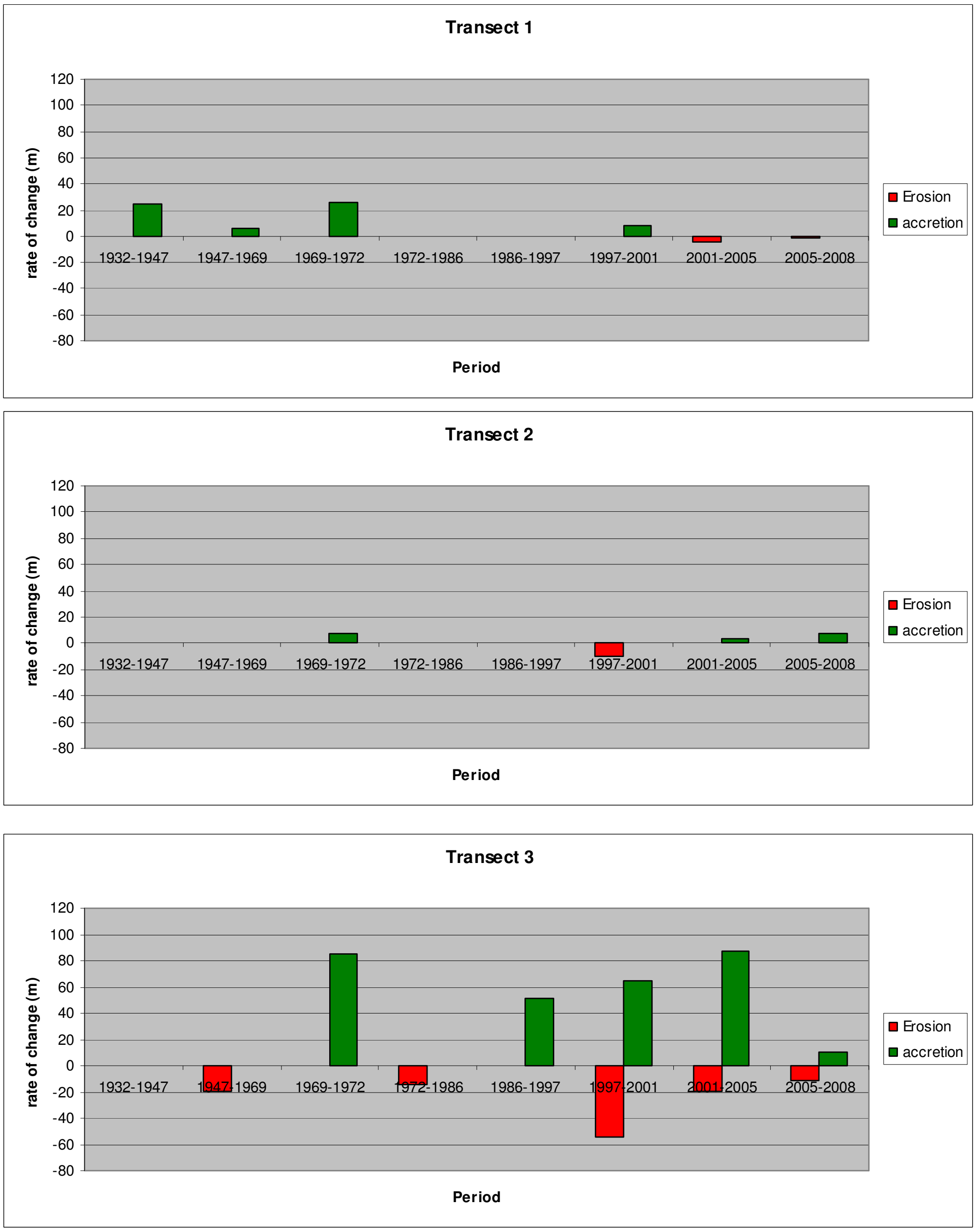
The following short section present quantitative changes in coastal configuration along six fixed point, shore normal transects (see **Figure 3.4**) noting the position of the berm crest, with changes associated with either erosion or accretion measured relative to successive berm crest locations over the assessment period.

Figure 3.4 Beach change (1938-2008) monitoring transects.



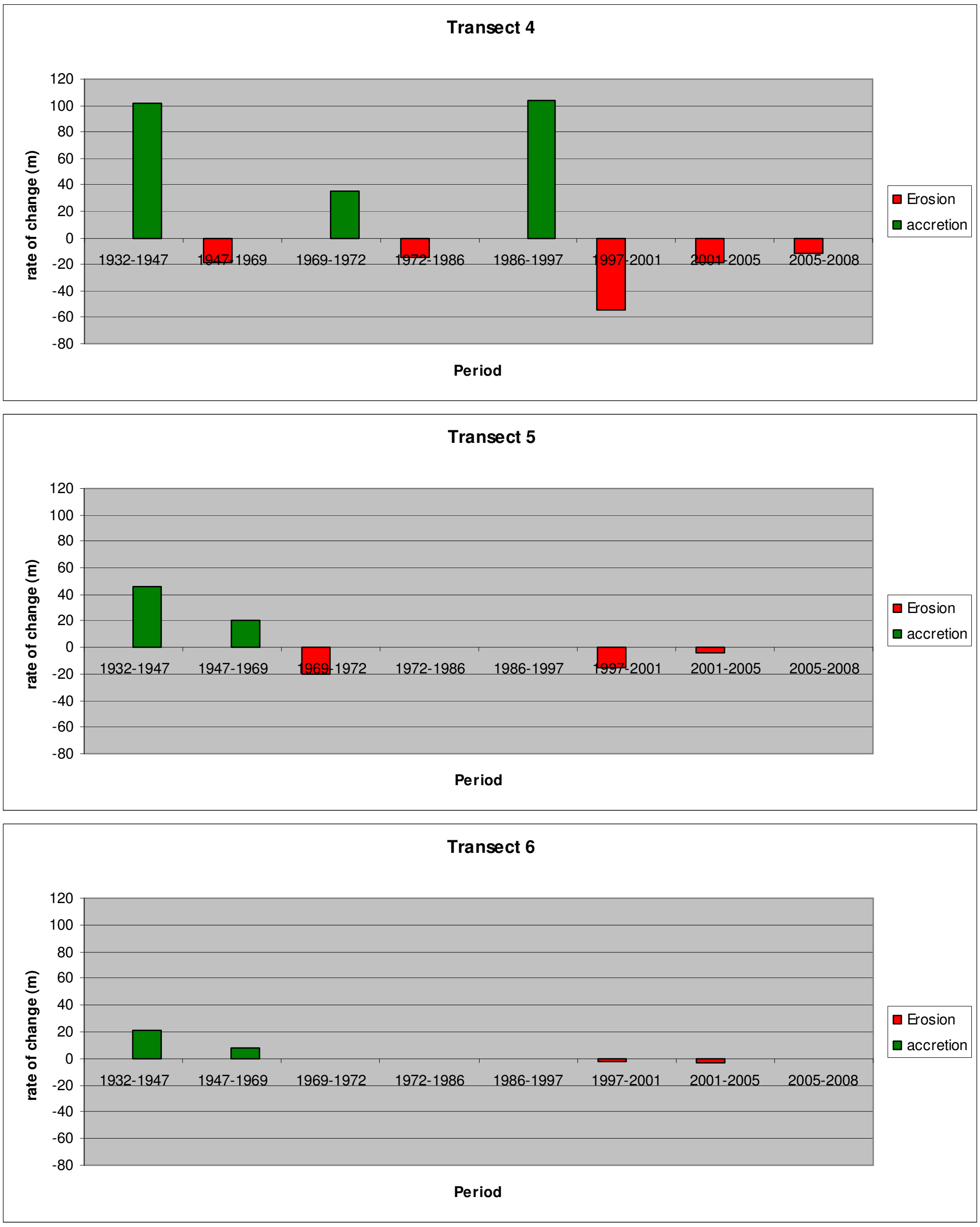
As presented in **Figure 3.4**, two transects are located along both Church Norton and Pagham frontages, with two further transect locations to the north and south of the contemporary tidal inlet, respectively. **Figures 3.5 & 3.6** present graphically the results from this analysis of coastal change during the monitored stages, whether the trend is towards erosion (red) or accretion (green) and the distance of observed change over the period. Analysis of graphs presented in both **Figures 3.5** and **3.6** highlight that changes in coastal configuration are much more pronounced to both the north and south of the tidal inlet in comparison to other locations along the study frontage.

Figure 3.5 Changes in coastal configuration 1938-2008, Transect 1-3.



Transect 1 displays a trend of decreasing changes in coastal configuration moving towards the present. Indicating that the coast at this location is relatively stable, experiencing only minor phases of erosion and/or accretion. This section of the frontage is characterised by a long-term trend towards accretion from 1932-2001, though this pattern has recently changed to one of minor erosion since 2001. Transect 2 displays a similar trend of small scale changes over the monitoring period with no discernible pattern to the temporal phases of accretion and erosion. Transect 3 displays more pronounced changes in coastal configuration than other locations to the south (Transects 1 & 2), with accretionary periods being more substantial than erosion phases.

Figure 3.6 Changes in coastal configuration 1938-2008, Transect 4-6.



As with Transect 3, Transect 4 displays more pronounced changes in coastal configuration than other locations to the north (Transects 5 & 6), with accretionary periods being more substantial than erosion phases. However, the section of the frontage for which Transect 4 provides information on changes in coastal configuration is characterised by a dominant trend towards erosion. Both Transects 4 and 5 both display a similar temporal pattern in that during the period 1932-1969 these sections of the frontage were characterised by periods of accretion, since which time there has been a phase shift from one of accretion to erosion.

Analysis of changes in coastal configuration associated with accretion and erosion trends along Transects 3 and 4, south and north of the tidal inlet display a similar trend temporally in terms of erosion and accretion from 1932-1997. However, since 1997 transects display a marked change in the correlation between erosion and/or accretion, which may be taken as indicating a shift in the previous dominant coastal processes and/or development of a feedback mechanism in and between geomorphological units during this period of time. This is discussed further in **Section 4.11** (Summmary and Discussion of EGA).

Figure 3.7 presents mean annual rate of erosion derived from historic shoreline positions. Data are calculated based on the average erosion and/or accretion rate for all periods. This average is then divided by the number of years in each period to derive an average annual rate of change. **Table 3.3** presents data on the analysed period, number of years within each period and the average annual rate of change per year.

Table 3.3 **Mapped period, number of years within each period, average rate of change for all periods and average annual rate of change per year.**

Average of ALL periods for ALL transects		Erosion (m)	Accretion (m)
		-23.3	37.7
period	**years**	**mean rate/yr**	**mean rate/yr**
1932-1947	9	-2.6	4.2
1947-1969	22	-1.1	1.7
1969-1972	3	-7.8	12.6
1972-1986	14	-1.7	2.7
1986-1997	11	-2.1	3.4
1997-2001	4	-5.8	9.4
2001-2005	4	-5.8	9.4
2005-2008	3	-7.8	12.6

Figure 3.7 and 3.8 present graphically mean annual rates of erosion and accretion derived from historic shoreline positions presented in **Table 3.3**. Both **Figures 3.7** and **3.8** clearly present that changes in coastal configuration, whether erosion or accretion, have increased linearly over the analysed period.

Figure 3.7 **Mean annual rate of erosion derived from historic shoreline position 1932-2008.**

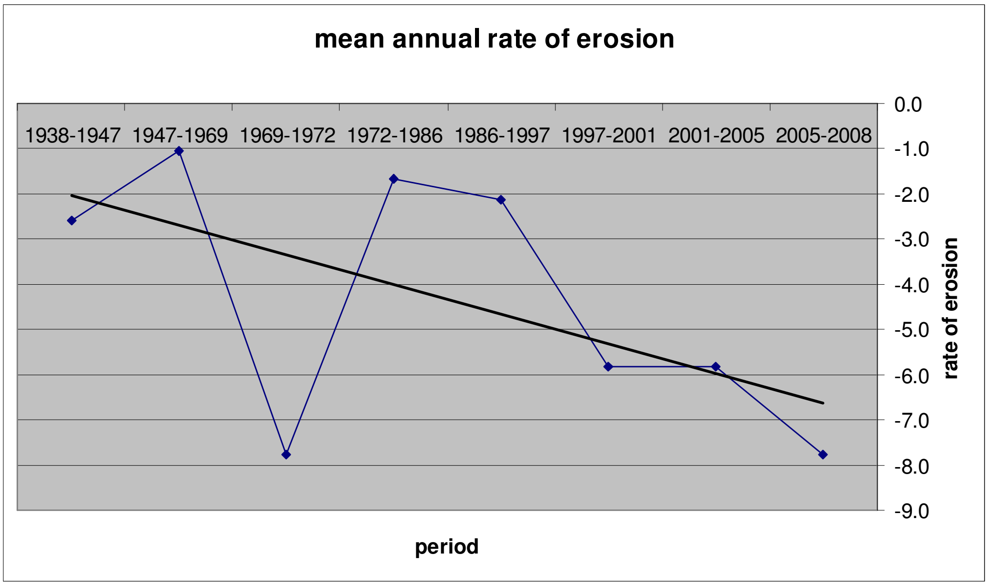
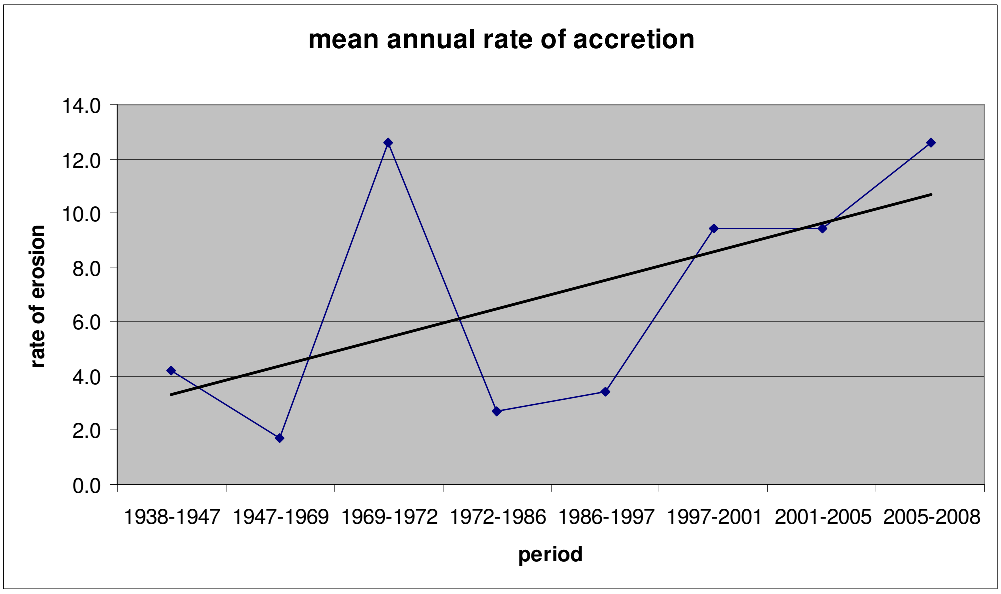


Figure 3.8 **Mean annual rate of accretion derived from historic shoreline position 1932-2008.**



3.4.1 Changes in tidal inlet position 1932-2008

The following section presents quantitative results for the changing position of the tidal inlet relative to the fixed position of Pagham Lagoon (see Figure 3.9). The results are discussed in terms of the morphological evolution of the study site in **Section 3.5** (Summary and Discussion of HTA). **Figure 3.9** presents the results of changes in channel position and configuration for the period 1932 to 2008. The analysis is based on an assessment of aerial photography amalgamated within a GIS as presented prior (**Section 2.1.1**). The assessment of changes in tidal inlet position and configuration is based upon the creation of digital tidal inlet positions derived from aerial photography.

FIGURE 3.9 CHANGING CHANNEL POSITION

As mapped in 1932 the tidal inlet displays a ‘classic’ trumpet shaped morphology with a discrete flared seaward distal end, with the channel orientated east to west. The northern channel bank is located some 250m south of Pagham Lagoon. The intertidal channel/creek system of the inner harbour is dominated by a single large sinuous channel with a smaller creek running of the southwest at its southern most extent. By 1947 the tidal inlet has shifted dramatically in position being located close to Church Norton, the most southerly position occupied over the analysed period. The intertidal channel system is dominated by discrete channels running northeast and northwest respectively. The seaward extent of the tidal inlet is not visible from the aerial photography and is therefore not mapped (see **Figure 3.16**).

By 1969 the tidal inlet is located some 660 m south of Pagham Lagoon, indicating a significant shift both to the north and seawards from the 1947 position. The intertidal channel system is dominated by a main channel orientated east southeast to west northwest with smaller creeks feeding of to the north and south respectively (see **Figure 3.9**). This orientation of the intertidal channel and creek systems within the inner harbour is maintained through to 2001 when changes in the inner harbour configuration become apparent. In 1972 the seaward extent of the tidal inlet is orientated west to east and displays bifurcation of its distal end (see **Figure 3.9**). By 1986 the bifurcation of the distal end of the tidal inlet channel is absent though the channel displays a distinct curvature towards the southeast, which is maintained in the 1997 location, when the northern bank of the tidal inlet is some 590m south of the lagoon.

By 2001 the seaward extent of the tidal inlet channel displays pronounced curvature, initially exiting the harbour in a west to east orientation before turning abruptly to the south then returning to its previous west to east orientation. In 2001 the northern channel bank of the tidal inlet is located some 430m south of Pagham Lagoon. By 2005 the tidal inlet channel has adopted a new southwest to northeast orientation upon exiting the inner harbour, being located some 355m south of Pagham Lagoon. The channel also displays bifurcation of its distal seaward end. By 2008 the 2008 the tidal inlet has maintained its location relative to Pagham Lagoon, most likely as a result of the constraint applied to the system by the presence of the retaining wall. However, the seaward end of the tidal inlet channel displays a marked increase in length and is increasingly deflected toward the north.

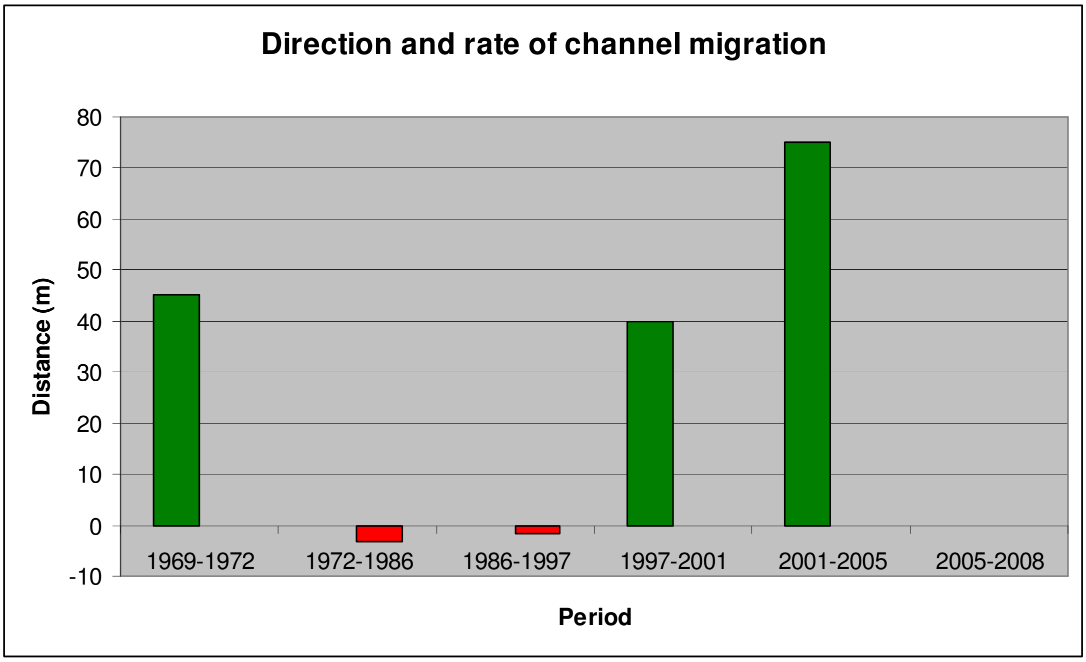
Table 3.4 presents changes in channel position as measured from the southern most point of Pagham Lagoon, mean rate of channel migration per year and the direction of migration. The results are also presented graphically in **Figure 3.10** as direction and rate of change over the analysed period. As presented in both **Table 3.4** and **Figure 3.10** changes in the rate of channel migration were in excess of 45m per year during the period 1969-1972 after which time the rate of change was of a magnitude smaller. During the period 1969-1972 the direction of channel migration was to the north (green in **Figure 3.10**) after which time the channel migrated to the south, albeit at a much slower rate between the period 1972-1997.

Since 1997 the channel has returned to the trend of northerly migration increasing from the period 1997-2001 to 2001-2005 until during the period 2005-2008 migration north ceased as a consequence of the retaining wall on the northern bank of the contemporary tidal inlet.

Table 3.4 **Mapped period, number of years within each period and average annual rate of change per year.**

Year	Distance from Pagham Lagoon	Intervening period	Years	Mean rate/yr	Direction of change
1932	250	NA	NA	NA	NA
1947	NA	1932-1947	9	NA	NA
1969	660	1947-1969	22	NA	NA
1972	524	1969-1972	3	45.3	North
1986	570	1972-1986	14	3.2	South
1997	590	1986-1997	11	1.8	South
2001	430	1997-2001	4	40	North
2005	355	2001-2005	4	75	North
2008	355	2005-2008	3	0	NA

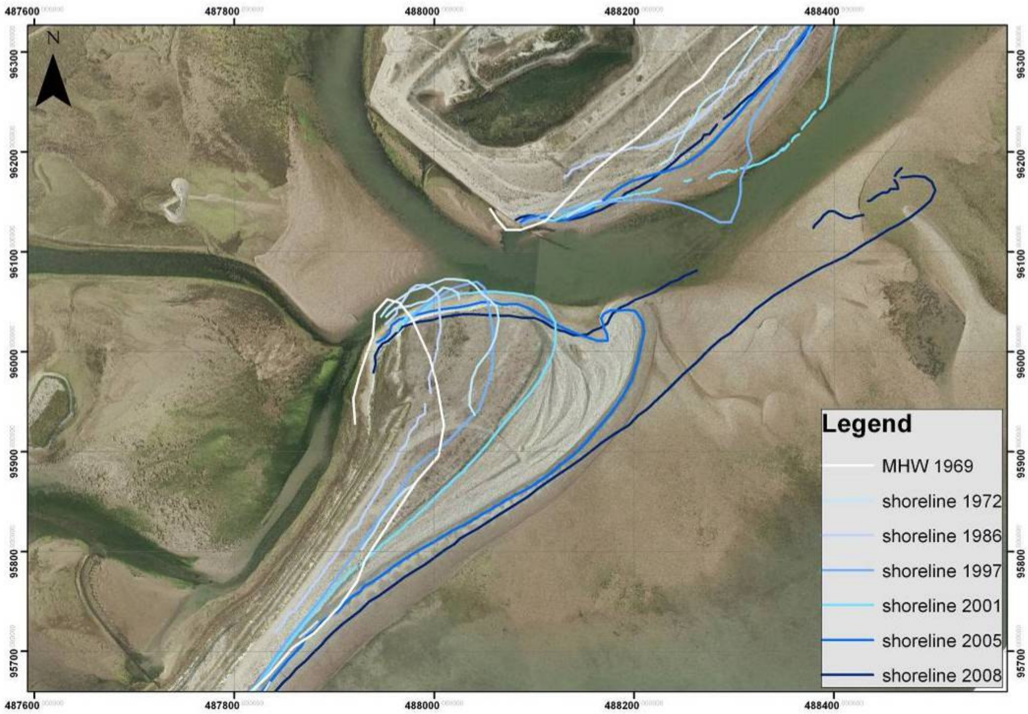
Figure 3.10 **Direction and rate of channel migration.**



3.4.2 Changes in coastal configuration 1972-2008

The following section presents changes in coastal configuration associated with Church Norton Spit from 1972 to 2008 based on analysis of aerial photography supplied by Arun District Council and the digitisation of historic shoreline position derived from berm crest locations. Historic shoreline positions are presented in **Figure 3.11**. **Table 3.5** presents the period analysed, inclusive number of years, the distance of change in coastal configuration, whether the change is associated with periods of erosion or accretion, the direction of change and the annual rate of change.

Figure 3.11 **Historical shoreline positions 1969-2008**



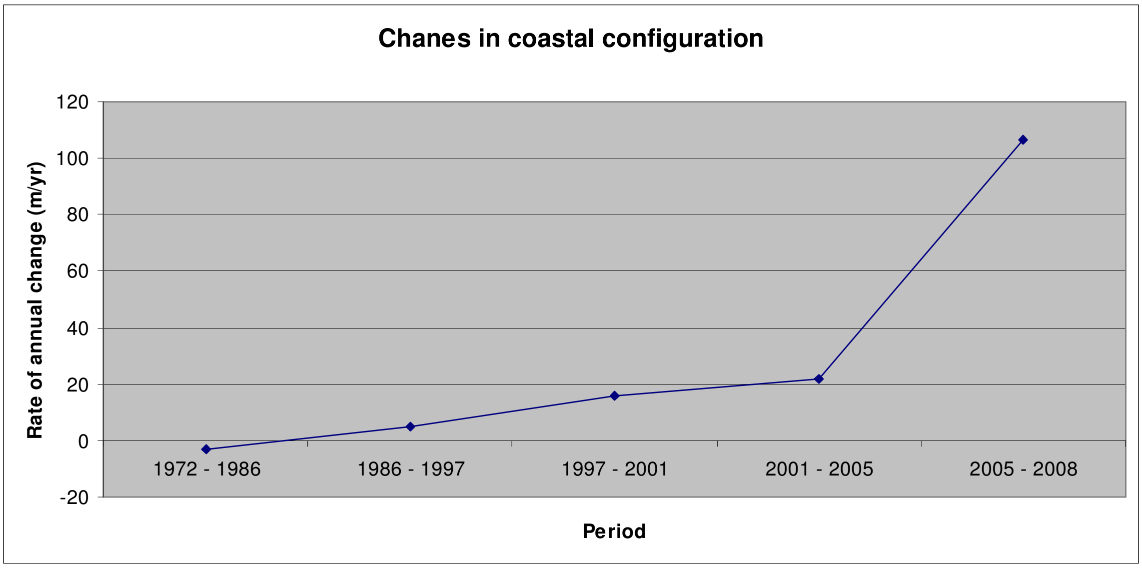
This section is differentiated from the analysis of changes in coastal configuration along fixed point transects (**Section 3.4**) in that the approach utilised herein analysed the rate of change along the maximum direction of change. The direction of change was typically west to east for periods of erosion and the opposite direction (east to west) during periods of accretion. However, this trend is not consistent during the analysed period, since 2005 the direction of change has been predominantly to the northeast (see **Figure 3.11**).

Table 3.5 **Changes in coastal configuration (1972-2008).**

Period	Years (inclusive)	Distance (m)	Trend	Direction	Annual rate of change (m/yr)
1972 - 1986	18	58	Erosion	West to East	3.2
1986 - 1997	11	53	Accretion	East to West	4.818
1997 - 2001	4	64	Accretion	East to West	16
2001 - 2005	4	88	Accretion	East to West	22
2005 - 2008	3	320	Accretion	Northeast	106.66

As presented in **Table 3.5** and graphically in **Figure 3.12**, the rate of change in coastal configuration has increased rapidly since 2005. Associated with this phase of rapid accretion is the advancement of Church Norton spit towards the northeast. This change has been at a rate of approximately 106m per year over the 3 year period analysed and is a significant change over the prior periods analysed, during which time coastal accretion varied between 4 and 22m per year. The results presented in Table 3.4 strongly support those presented in **Section 3.4** and **Figures 3.7** & **3.8** for an increase in the rate of coastal change towards the present.

Figure 3.12 Graphical representation of changes in coastal configuration (1972-2008).

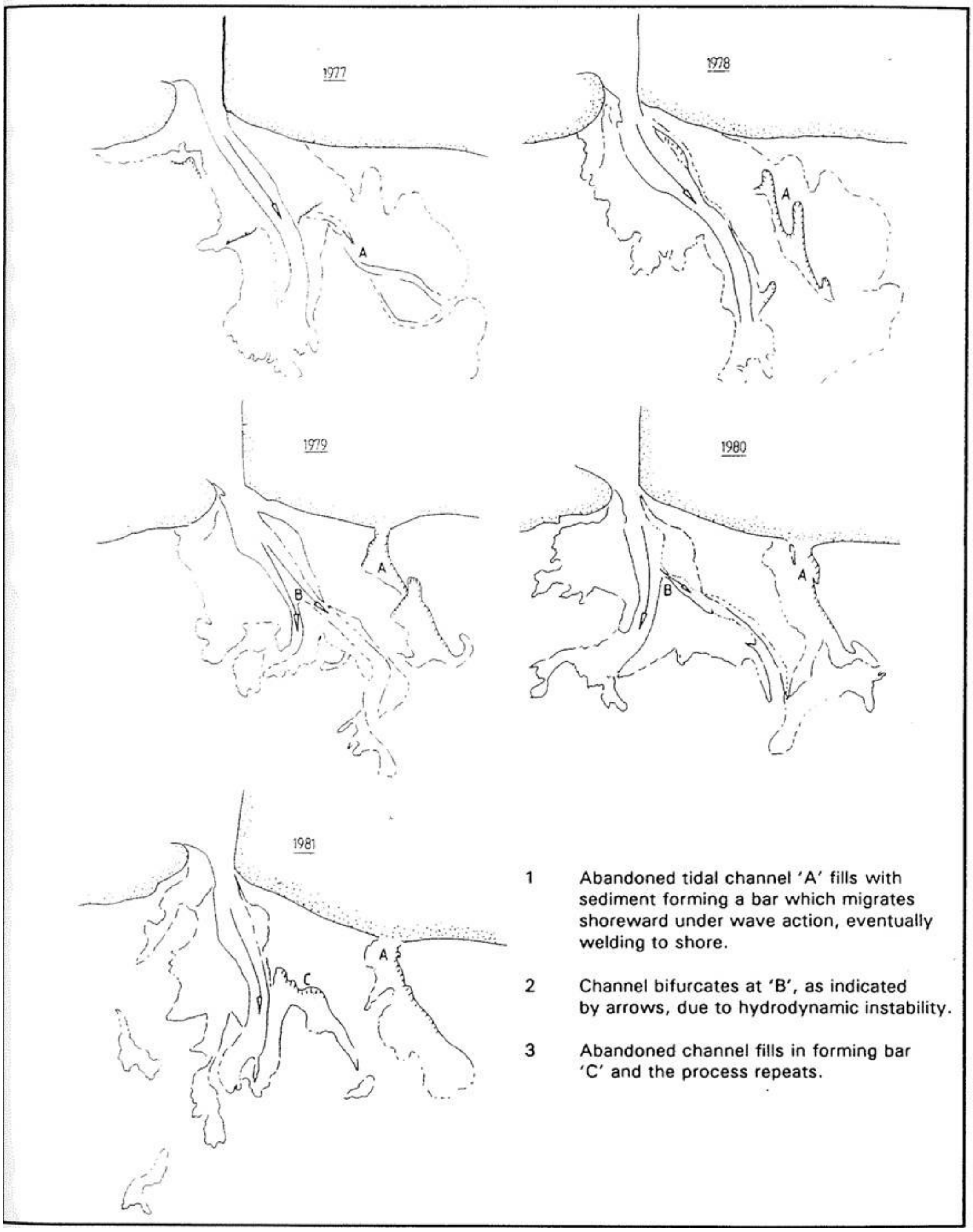


3.4.3 Migration of inlet channel and bars 1977-1981

According to Barcock & Collins (1991), over long periods of time the tidal inlet migrates to the northeast, although they noted that in 1989 that this process had halted due to the stabilisation of the channel. **Figure 3.13** presents an example of migration of the inlet channel and bars over the period 1977 – 1981. The development of the tidal channel and bars is characterised by the initial development of a fairly long, straight channel bordered by levee type bars (see **Figure 3.13** 1977). Under wave action the outer channel migrates towards Pagham Beach (see **Figure 3.13** 1978) until a position of instability is reached when a new channel breaches the old causing bifurcation (see **Figure 3.13** 1979). The new straighter channel is rapidly established and the old channel filled with sediment under wave action (see **Figure 3.13** 1980) and the process repeats.

Barcock's 5 year cyclic model (1989) illustrates a short period during which the channel was characterised by periods of channel avulsion and bifurcation. Associated with these changes, Barcock & Collins (1991) model illustrates relatively small changes in coastal configuration (see **Figure 3.13**). This is supported by results presented herein (see **Sections 3.4** & **3.5**).

Figure 3.13 Migration of inlet channel and bars during the period 1977-1981 (from Barcock 1989)



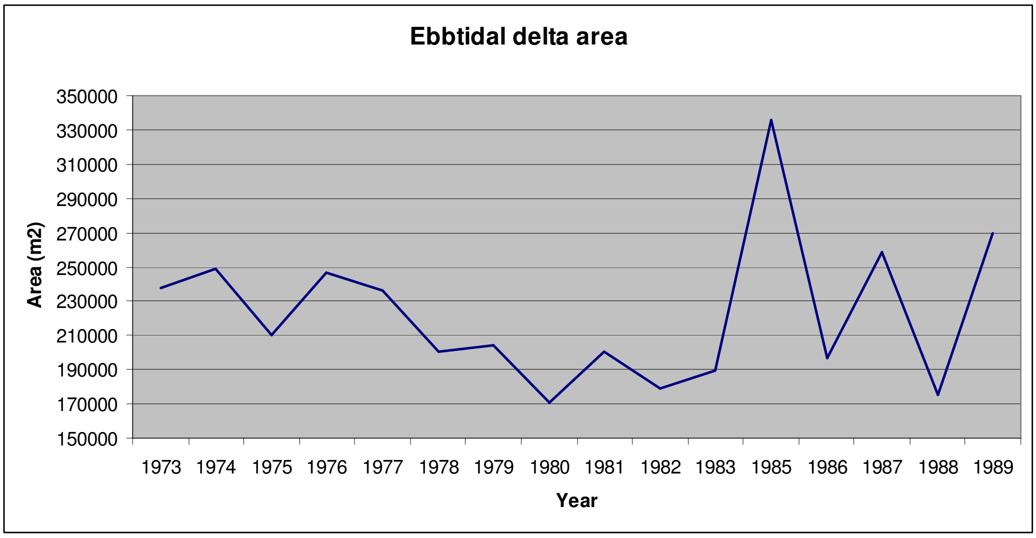
3.4.4 Ebb tidal delta

The evolution of Pagham and its associated estuary and shoreline morphology may be related in part to the position and stability of the tidal inlet and ebb tidal delta, with the delta providing a considerable interruption to the north easterly littoral drift with the bars acting as a large sink for littoral materials. Barcock & Collins (1991) briefly considered the effects of materials entering the ebb tidal delta, which are summarised herein.

Material entering the tidal inlet will have a choking effect, restricting flow through the channel. To regain stability, the channel must move this material via tidal currents towards the ebb tidal delta. The ebb tidal delta size will therefore be dependant upon the ability of the system to move this sediment seaward and the rate of littoral drift. As historically the main source of material has been from littoral drift, the channel has migrated in the direction of this predominant drift system. In their analysis of aerial photography they noted that the evolution of the ebb tidal delta was characterised by periods of inlet migration and breaching, stable inlet processes and ebb tidal delta breaching (Barcock & Collins, 1991).

Calculations of the delta area derived from aerial photography suggest prior to 1982 that the bar area was decreasing, after which time the area increased, though at a spatially and temporally variable rate. Barcock & Collins (1991) suggest that this may have been linked to an increase in littoral drift during this period (post 1982), though they could not substantiate this at the time. **Figure 3.14** presents changes in the ebb tidal delta area between 1983 and 1989; after Barcock & Collins (1991).

Figure 3.14 Changes in ebb tidal delta area 1973-1989 (after Barcock & Collins 1991).



Prior to 1973, historic maps and aerial photography illustrate that both the position and size of the ebb tidal delta varied considerably. **Figure 3.15** presents an OS map of Pagham Harbour and its associated tidal inlet and ebb tidal delta as mapped in 1938. The tidal inlet shows a broadly similar orientation to that of present day, though its location is roughly midway along the contemporary barrier/spit. By 1947 (see **Figure 3.16**) the presence of any ebb tidal delta deposits are not readily visible in the acquired aerial photography. This may be subject to their total submergence under tidal waters. Of note is that fact that the tidal inlet is located to the south of the barrier/spit in the vicinity of Church Norton, and area that is currently not bathymetrically elevated in comparison to the immediate offshore at Pagham Beach.

Figure 3.15 1938 OS map of Pagham Harbour.

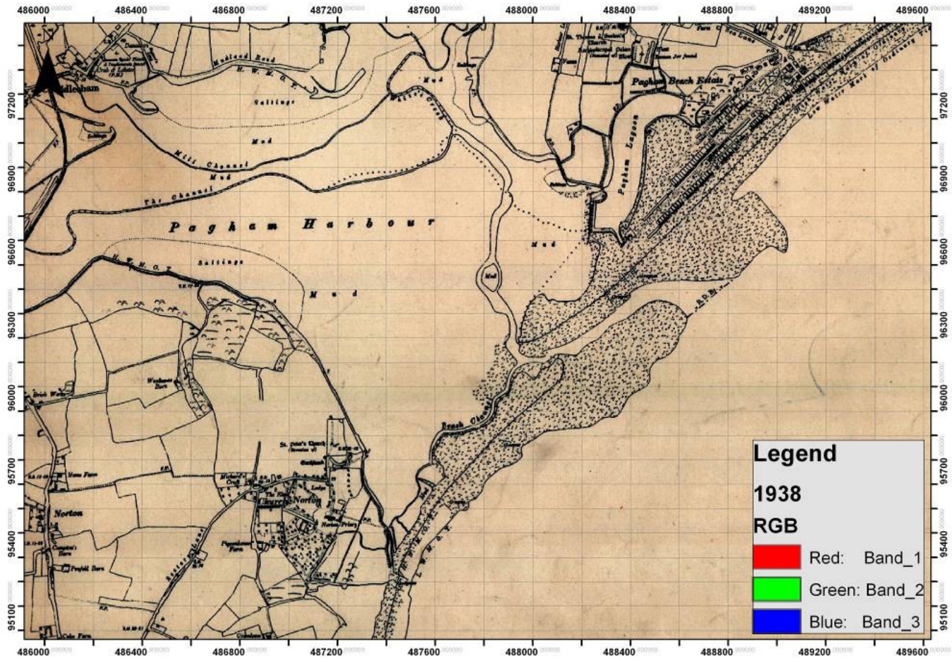
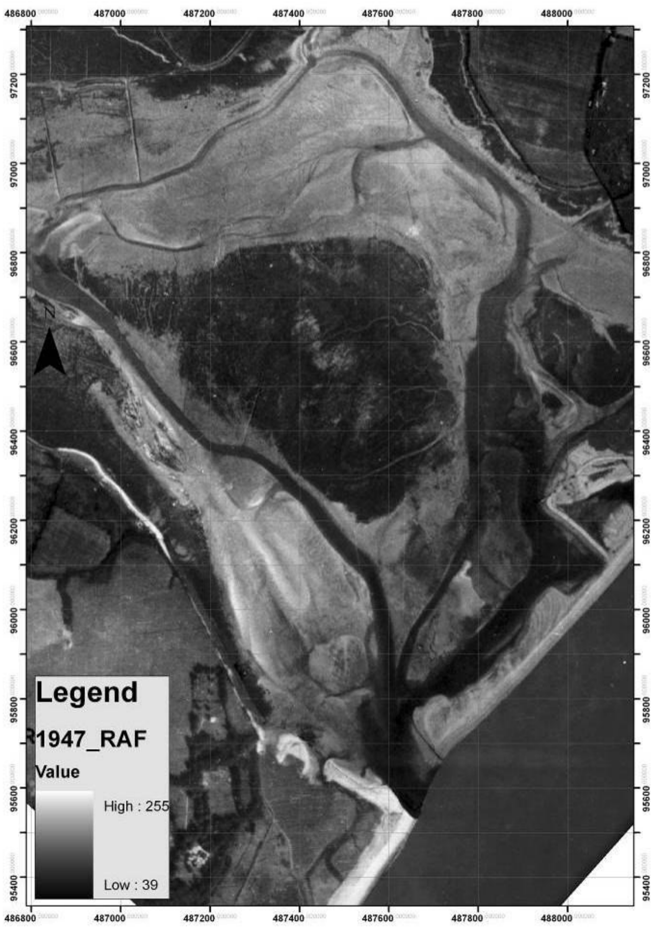
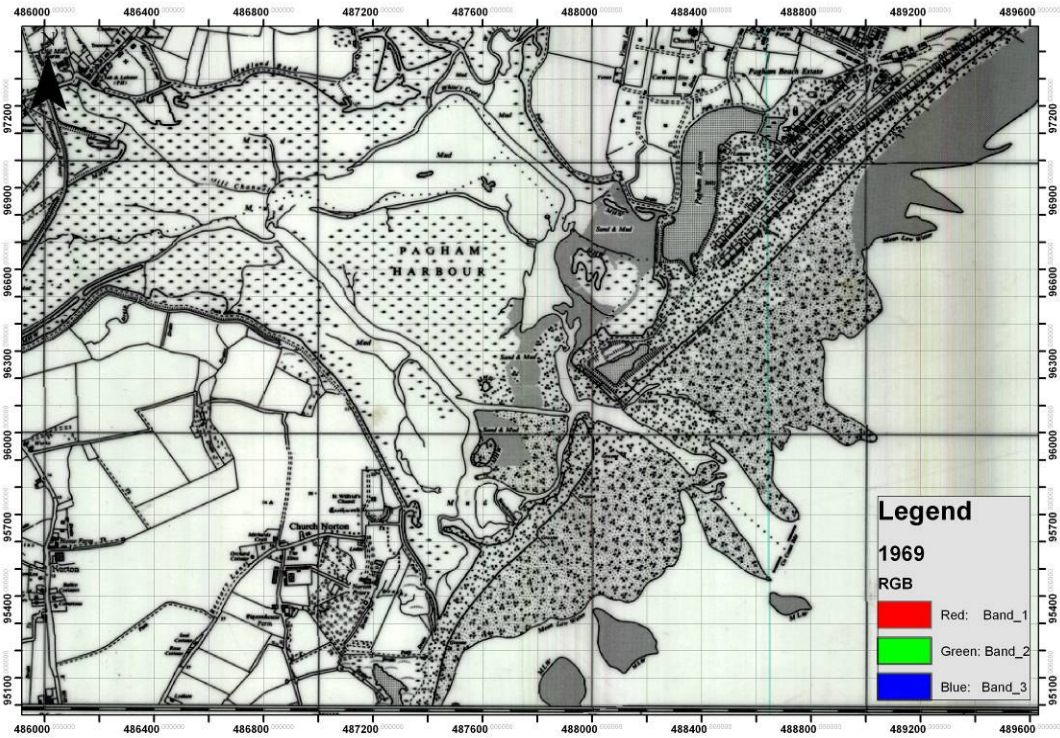


Figure 3.16 1947 RAF aerial photograph of Pagham Harbour.



By 1969, four years to prior to the analysis of data by Barcock & Collins (1991), the 1969 OS map of Pagham (**Figure 3.17**) illustrates a laterally extensive ebb tidal deposit, substantially larger than what has been noted subsequently. However, these maps should be treated with a degree of caution as the purpose of them was not merely document offshore/subtidal deposits and may therefore be somewhat over represented.

Figure 3.17 1969 OS map of Pagham Harbour.



3.4.5 Inner harbour

The earliest record of land reclamation within the harbour is in 1580, with the first major flood embankment constructed in 1637 (SCOPAC, 2004). Approximately 1.26 km^2 were reclaimed between 1672 and 1809 and the remainder was reclaimed in 1877.

Breaching in 1910 led to rapid inundation of the present harbour area of 2.83 km^2. It can be postulated that the ebb tidal would have reduced in size and area as the tidal prism was reduced and it is likely that much sediment was driven ashore from 1876 to 1910 when there was no active inlet. Furthermore, the absence of any significant river entering the inner harbour has facilitated reclamation in the past.

Cundy et. el., (2002) identified a reclamation surface associated the inner harbour reclamation aged between AD 1846 and AD 1910. Cundy commented that the absence of similar stratigraphic horizons in the deeper sediments may be taken as indicating that this type of reclamation event had been rare during the mid- to late Holocene, or alternatively that erosion and reworking of harbour sediments has destroyed earlier records of such events.

3.5 Summary and discussion of Historical Trend Analysis

Based on the presented Historical Trend Analysis **Table 3.6** presents key stages in the morphological development of the study site.

Table 3.6 Key dates and description of changes in the evolution of Pagham Harbour

Date	Description of change
1587	Earliest Map of Sussex Magistrates
1820	Breaching of the shingle spit
1829	Breaching of the shingle spit
1840	Breaching of the shingle spit
1877	Reclamation of Pagham Harbour
1910	Reopening of the Harbour mouth by storm surge
1937	New artificial opening at the approximate position of the 1910 breach, isolation of Pagham Lagoon and beach pushed inland.
1944	Concrete and steel retaining wall, (Church Norton) end of Harbour
1955	Secondary mouth opened to the north west isolating an island that was later pushed inland.
1957	700-800m wide tidal inlet established
1960-1961	Shingle accumulation extended from Church Norton blocking the 1937 opening to a point where the River Board erected defence work and groynes were established along the Church Norton Spit. Decline of Zostera within the Harbour
1961	Harbour entrance stabilisation location and subsequent maintenance and groyne protection of the Church Norton beach, and beach augmentation.
1991-2004	Continuing maintenance of southern spit by recycling material from ebb delta to seaward face.
2001-2005	Rapid accretion of Church Norton Spit
2005-2008	Realignment of tidal inlet to the northeast

The key natural and artificial modifications described in **Table 3.6** that have affected the historic development within the study site are:

- Tendency for shingle barrier/spit breaching episodes.
- Reclamation of land within the harbour.
- Constraint of the tidal channel due to training structures.
- Rapid spit accretion and migration of the tidal inlet channel.

The above phases in the historic development of the study site are now summarized in the following short sections, drawing upon information presented prior.

The first map of the area was compiled in 1587 and shows three distinct tidal inlets linked to the sea by a narrow channel at the present location of Pagham Harbour. The map evidence suggests that the southern (Church Norton) spit had a configuration similar to the present, possibly in response to one or more breaches dating back to as early as the period 1340-1410. The survey of 1724 shows that the shoreline had been altered considerably with a long continuous spit almost enclosing the harbour entrance, except for a 100m entrance at its northern end, in the location of the present tidal inlet.

As highlighted in **Figure 3.2**, the tidal inlet occupied a similar position to that of today, in that it was orientated southwest to northeast. During this period extensive erosion of Pagham Beach occurred as the tidal inlet was deflected to this orientation. The advancement of Church Norton spit was fed by littoral drift from the erosion of cliffs at Selsey Peninsula. This contributed to the deflection of the tidal inlet, during which time the further accretion of the spit lead to the sealing of the harbour prior to the reclamation of the harbour in 1877. However, episodes of breaching interrupted the spit extension in 1820, 1829 and 1840. As the spit extended and thinned during this 100 year period, there may not have been a significant supplementary supply from inshore sources (i.e. migratory bars associated with the tidal delta). Rates of spit advance during the period 1672-1875 are quoted as averaging 5.5 m/yr to a maximum of 10m/yr between 1774 and 1875 (Barcock & Collins 1991).

The natural evolution of Pagham changed considerably in 1876, when both spits were partially stabilised and the inlet channel closed to effect the final land claim of Pagham Harbour in 1877. Subsequent to the reclamation of the harbour in 1877, the inner harbour remained 'dry' for a period of some 34 years. After the closure of the harbour the offshore delta deposits were reworked onshore leading to the build up of shingle and the creation of Pagham Beach. This resulted in almost 120m of foreshore progradation until the gravel barrier/spit was breached, approximately halfway along the barrier, by a large storm in December 1910. The resultant tidal inlet and its associated intertidal channel and creek system being clearly visible today as a remnant of this former stage of evolution.

In the past, the harbour has operated as a natural system with the entrance shifting regularly, though to no discernable spatial and/or temporal pattern. Since 1937 there have been several attempts to control the harbour entrance with training arms, firstly north of Church Norton at the 1910 breach location, and more recently at its current location in the 1960's. However, the entrance has remained dynamic and several breaches of the southern spit have occurred from the 1820's up until 1910. Sediment has accreted relatively rapidly in the north-eastern part of the harbour, depositional energy has decreased and extensive marshes have developed around the margins of the entire harbour and in its central area. The fine sediment required to build these marshes is likely to have come from the erosion of existing deposits within the harbour, and assisted by colonization of intertidal areas by *Spartina sp*.

The presented findings illustrate that the convergent gravel spits that define the Pagham Harbour entrance channel have behaved in a highly dynamic fashion over at least the past seven centuries. Between 1910 and 1934 the distal end of the spit progressed some 700-800m northeast towards Pagham Beach from the location of the 1910 breach location, and in the process deflected the tidal inlet towards Pagham Beach. In order to prevent erosion at Pagham Beach, a new tidal entrance was cut in 1937 near the 1910 breach location. In 1938, the coastal configuration is largely similar to that of today, apart from the extent of the Church Norton Spit being volumetrically smaller, though similar in planform. The tidal inlet is orientated roughly southwest to northeast and the inner harbour intertidal channels displaying a broadly similar configuration to those of today. The pre-1937 entrance gradually closed becoming marked by a low gravel berm. A further breach over a wide front between the 1937 and pre 1937 inlets occurred shortly after 1955 and by 1958 the entrance was some 700m wide. Rapid drift thereafter led to a further extension of the Church Norton spit across the inlet narrowing it to 250m by 1961. Since AD 1910, the entrance to the harbour has been artificially maintained in this location, although its position has shifted periodically.

As presented in **Figure 3.2**, in 1874 the tidal inlet displays a broadly similar southwest-northeast orientation to that of present day, which provides an important analogue to the morphological development of the contemporary tidal inlet/spit/harbour system functionality. This orientation has resulted in significant erosion of the Pagham frontage in the past and since the onset of this orientation near present continues to contribute significantly to the continued erosion to the south of the Pagham frontage. Previous periods of erosion on Pagham Beach however have been noted. Over the period 1780-1840, the northern (Pagham) spit, the product of 'counter drift' determined by a transport divide north-east of the harbour entrance, experienced net erosion and recession. The entrance channel cut into the low clay cliff on the northern side, resulting in 170m of coastline retreat at this point between 1780 and 1840.

Since 1932 changes in coastal configuration are much more pronounced to both the immediate north and south of the tidal inlet in comparison to other locations along the study frontage, such as the Pagham to Aldwick frontage to the north or the Church Norton frontage to the south.

Presented data for changes in coastal configuration display a marked trend of decreasing changes in coastal configuration moving towards the present for all transect locations with the exception of transects 3 and 4. This may be taken as Indicating that the coast at this location is relatively stable, experiencing only minor phases of erosion and/or accretion. Transect 4. to the north of the tidal inlet, provides information on changes in coastal configuration and is characterised by a dominant trend towards erosion. Both Transects 4 and 5 both display a similar temporal pattern in that during the period 1932-1969 these sections of the frontage were characterised by periods of accretion, since which time there has been a phase shift from one of accretion to erosion.

During the period 1969-1997 the general plan view of the coastline changed relatively little in comparison to the period prior (1938-1969) representing the establishment of a short- to medium-term period of coastal stability. According to Barcock & Collins (1991), over long periods of time the tidal inlet migrates to the northeast, although he noted in 1989 that this process has now halted due to the stabilisation of the channel. Though its location and orientation have varied considerably over time, the system has tended to develop towards an east to west orientation. However, since 1997 the tidal inlet channel has been increasingly deflected toward the north-northeast to its current position, orientated north-south, from the harbour entrance along the Pagham Beach frontage.

The mapping of shoreline position in 1997 illustrates the first significant morphological change to the coastline. This is represented by the presence of a triangular (i.e. cupsate foreland) sediment body to the north of the tidal inlet. This accretionary form may be interpreted as representing the adjustment of the coastal system to the development of a more pronounced littoral drift divide to the north of the tidal inlet. The presence of the littoral drift divide is evident as the formation of the triangular sediment body being fed on its southern flank by the dominant longshore drift from the southwest to northeast, while the northern flank of the same body is being fed by sediment drifting from the northeast to southwest. By 2001 the presence of the triangular sedimentary body has been partially realigned as a result of the northeast migration of the tidal inlet. This has served to erode and rework the sediment along the shore to such an extent that by 2005 all evidence of its previous existence has been removed, indicating a change in the dominant external forcing parameters of hydrodynamic regime and sediment supply.

Presented mean annual rates of erosion and accretion derived from historic shoreline positions clearly illustrate that changes in coastal configuration, whether erosion or accretion, have increased linearly over the analysed period. Prior to 2005, the direction of change was typically west to east for periods of erosion and the opposite direction (east to west) during periods of accretion. However, this trend has not consistent since 2005, with the direction of change being predominantly to the northeast over the former ebb tidal delta.

Calculations of the delta area suggest prior to 1982 that the area was decreasing, after which time the area increased, though at a spatially and temporally variable rate. This was suggest as being linked to an increase in littoral drift during this period (post 1982), though it could not substantiate at the time (Barcock & Collins 1991). Of importance in terms of the evolution of the tidal inlet/ebb delta system and resultant changes to coastal configuration is the former position of the ebb tidal delta. While the ebb tidal delta was orientated predominantly east to west, bar and delta deposits built up to both the north and south of the system within the offshore. As the tidal inlet began to migrate to the northeast under the influence of the predominant longshore drift system, the ebb tidal delta and submerged bar deposits provided an elevated surface over which Church Norton spit could prograde rapidly.

In 1947 the tidal inlet had shifted dramatically in position being located close to Church Norton, the most southerly position occupied over the analysed period. The position was only to be maintained temporarily and by 1969 the tidal inlet had migrated some 660 m south of Pagham Lagoon, indicating a significant shift both to the north and seawards from the 1947 position. The intertidal channel system at 1969 was dominated by a main channel orientated east southeast to west northwest with smaller creeks feeding of to the north and south respectively. This orientation of the intertidal channel and creek systems within the inner harbour was to be maintained through to 2001 when modifications to the inner harbour channel/creek system configuration were to become apparent.

By 2001 the seaward extent of the tidal inlet channel displayed a pronounced curvature, initially exiting the harbour in a west to east orientation before turning abruptly to the south then returning to its previous west to east orientation. By 2005 the tidal inlet channel had adopted a new southwest to northeast orientation upon exiting the inner harbour, being located some 355m south of Pagham Lagoon. By 2008, the 2008 the tidal inlet had maintained its location relative to Pagham Lagoon, most likely as a result of the constraint applied to the system by the presence of the retaining wall.

During the period 1969-1972, changes in the rate of channel migration were in excess of 45m per year after which time the rate of change was of a magnitude smaller. During the period 1969-1972 the direction of channel migration was typically to the north after which time the channel migrated to the south, albeit at a much slower rate between the period 1972-1997. Since 1997 the channel has returned to the trend of northerly migration increasing from the period 1997-2001 to 2001-2005 until during the period 2005-2008 migration north ceased as a consequence of the retaining wall on the northern bank of the contemporary tidal inlet.

The presented HTA indicates that the continued functioning of the harbour is intrinsically linked to the harbour entrance remaining open, which is linked to the migration of the spit to the northeast, which may possibly result in the blocking of the harbour entrance. The possibility of the system closing as a consequence to its future morphological development is addressed in **Section 6** (Inlet Stability Analysis).

As the Church Norton spit migrates to the northeast via the accumulation of littoral drift materials, the tidal inlet is forced towards the northeast with the harbour entrance becoming increasingly constrained. The narrowing of the entrance may result in increasing the speed of flow of currents into and out of the harbour, assuming that the tidal prism remains available to maintain flows. This may lead to increased erosion along the Pagham Beach frontage, and is discussed further in **Section 4.11** (Summary and Discussion of EGA).

3.6 Key points

- The convergent gravel spits that define the Pagham Harbour entrance channel have behaved in a highly dynamic fashion over at least the past seven centuries.
- In the past, the harbour has operated as a natural system with the entrance shifting regularly, though to no discernable spatial and/or temporal pattern.
- After the closure of the harbour in 1877 the offshore delta deposits were reworked onshore leading to the build up of shingle and the creation of Pagham Beach. This resulted in almost 120m of foreshore progradation
- Historically there has been a tendency for shingle barrier/spit breaching episodes.
- In order to prevent erosion at Pagham Beach, a new tidal entrance was cut in 1937 near the 1910 breach location which has constrained the tidal channel due to the presence of training structures.
- Presented data for changes in coastal configuration display a marked trend of decreasing changes in coastal configuration moving towards the present for presented transect locations to the north and south of the tidal inlet.
- Since 1932 changes in coastal configuration are much more pronounced to both the immediate north and south of the tidal inlet in comparison to other locations along the study frontage
- During the period 1932-1969 the majority of the frontage was characterised by periods of accretion, since which time there has been a phase shift to one of erosion.
- Since 1997 the tidal inlet channel has been increasingly deflected toward the north-northeast to its current position,
- By 2001 the seaward extent of the tidal inlet channel displayed a pronounced curvature,

- By 2005 the tidal inlet channel had adopted a new southwest to northeast orientation upon exiting the inner harbour, being located some 355m south of Pagham Lagoon.
- By 2008, the tidal inlet had maintained its location relative to Pagham Lagoon, most likely as a result of the constraint applied to the system by the presence of the retaining wall and build up of sedimentary materials within Church Norton spit.
- Past periods of extensive erosion of Pagham Beach occurred as the tidal inlet was deflected to this orientation.
- The advancement of Church Norton spit has been fed by littoral drift
- The continued functioning of the harbour is intrinsically linked to the harbour entrance remaining open, which is linked to the migration of the spit to the northeast, which may possibly result in the blocking of the harbour entrance should the current regime remain in place

4 EXPERT GEOMORPHOLOGICAL ASSESSMENT

4.1 Geology

Most of the surficial geology within the study area is of Pleistocene or recent origin with only a few occurrences of older Eocene strata. At the base of the geological sequence lies the London Clay above which lie the Bracklesham Beds, a dark green medium to fine glauconite sand, which dip gently to the south and are up to 100m in thickness. These Eocene formations are in turn unconformably overlain by Pleistocene deposits.

Many of the surface features observed at present within the study area are remnant of the last period of glacial activity. A band of 'erratics' marks the earliest Pleistocene deposits in the area (Reid, 1892). Above the erratics lie a series of marine and estuarine mud indicative of a regressive phase of sea-level change (Palmer & Cooke, 1923). A series of littoral sands and gravels overlie these regressive deposits, indicating a change to a transgressive sea-level regime, which are in turn overlain by raised beach deposits. The deposit is composed predominantly of compact coarse flint and gravel (≤125mm in diameter) with a matrix of finer material of sand. The raised beach deposits and the underlying marine deposits form the source of much of the local beach material in the area. The recent geological evolution of Pagham Harbour and beach are the result of rising sea-level the reworking of the Pleistocene deposits under spatial and temporally variable hydrodynamic conditions.

4.2 Sea-level rise

4.2.1 Historical Recorded Changes

Relative Sea-Level (RSL) is widely accepted to have risen 4.5m since ~3.6 k yrs B.P., with the rate of sea level rise fluctuating, though the rate of RSL rise has oscillated between 1 and 5-6mm/year. These figures, however, should be treated with caution as they are mean values which may otherwise simplify the complex behaviour of local and regional Holocene sea level change; it is most likely that this change was not progressive, but rather represents a slower long-term transgression punctuated by a series of minor rapid transgressions (SCOPAC, 2006). Such variations in the rate of RSL rise exercised dramatic control upon coastal evolution on the South coast of England, in terms of sediment supply, accommodation space and the external forcing parameters of wave and tidal energy gradients. The generally accepted stages of which are highlighted in **Table 3.1** (Jennings and Smyth 2001).

According to Barcock & Collins (1991) sea level rise estimates vary, between 0.75 and 7.8mm/year within the study area (Cundy and Croudace, 1996; Geodata Institute, 1994). However, over the past hundred years, there is a general consensus that mean eustatic sea-level has risen about 1–2mm/year globally (Gornitz, 1995). The GeoData Institute suggests that local investigations between Selsey and Portsmouth have assessed that mean sea level rise is approximately 4.5mm/year. Other local assessments are between 3-4.5mm/year.

4.2.2 Predicted Future Changes

The UK Climate Impacts Programme (UKCIP 2005) has presented future changes in regional net sea-level. Calculations are underpinned by estimates of present rates of relative land/sea-level changes from the work of Shennan (1989). UKCIP present a regional isostatic subsidence rate of 0.5mmyr for the southeast England region coupled with a low and high emissions scenario of sea-level rise in the range of 14 and 74cm by 2080. For sensitivity studies, UKCIP (2005) advise to consider changes in sea-level for each scenario that are approximately ±50% of those presented. Therefore, in terms of potential rates of sea-level rise at the site, the following rates of sea-level rise should be considered in any design context up to the year 2080. The range of predicted sea-level rise and subsidence rates are illustrated in **Table 4.1**

Table 4.1 UKCIP Low and High Emissions sea-level rise scenarios and subsidence rates for London.

	2080	Subsidence (cm)	Sea-level + Subsidence (cm)	±50% sea-level rise rate (cm)	Range of predicted sea-level rise 2080 (cm)
Low Emissions Scenario	14	3.6	17.6	7	10.6-24.6
High Emissions Scenario	74	3.6	77.6	37	40.6-114.6

The best estimates from the Intergovernmental Panel on Climate Change that the combined effect of sea level rise and crustal subsidence will result in a net relative sea level rise of 6mm/year across the South East region. Defra recommends that an allowance of this amount is given when designing coastal defences for the South East. Considering this rate of sea-level rise (6mm/yr) the resultant rise in sea-level would total some 43.2cm by 2080. Of importance is that this figure excludes any land subsidence.

4.3 Future storminess

Significant debate has been conducted over recent years with regards to the influence of increased storminess on coastal defence structures, amongst other studies. The UK Climate Impacts Programme states that there is a low probability of winter depressions (storms) becoming more frequent in the foreseeable future. To investigate the importance of the issue of storminess for the study area, HR Wallingford (1997) analysed wave data over the past few decades and concluded that the data did not display any discernable change that could be attributed to increased storminess.

4.4 Hydrodynamics

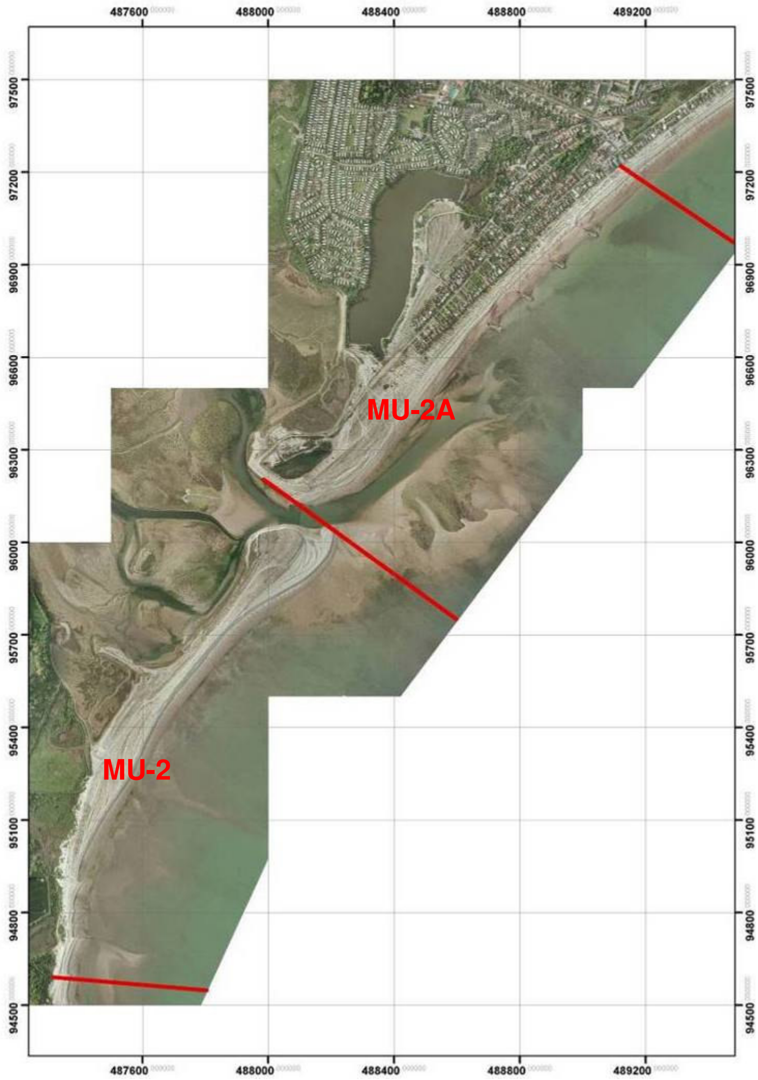
4.4.1 Tides and tidal currents

Tides at Pagham are semi-diurnal, with a mean spring range of 4.9m and mean neap range of 2.7m (SCOPAC www2). However, the Mean High Water Spring (MHWS) and Mean High Water Neap (MHWN) levels as identified in the Beach Management Plan Report, Pagham Harbour (2007) are presented below in **Table 4.2**. For locations of the Management Units (MU) see **Figure 4.1**. Table 4.1 highlights some discrepancies in and between the various quoted sources I terms of tidal range and elevation within the study site. For the purposes of this study Royal Haskoning shall utilise the tidal levels and ranges reproduced from Beach Management Plan (2007).

Table 4.2 Tidal levels along the Pagham frontage

Tide height metres OD		
Tide level	MU2	MU2A
MHWS	2.4	2.55
MHW	1.95	1.9
MHWN	1.5	1.25
MSL	0	-0.5
MLWN	-1	-1.25
MLW	-1.55	-1.9
MLWS	-2.1	-2.55
Spring range	4.5	5.1
Neap range	2.5	2.5

Figure 4.1. Locations of the Management Units (MU)



The tidal pattern is typically asymmetrical, with the ebb phase shorter than the flood. This causes stronger ebb current, leading to an ebb dominated tidal regime. Currents generated by tidal exchange at the Pagham Harbour entrance are effective in interrupting littoral drift. As at Chichester Harbour entrance, the ebb current (1.0 – 1.5 m s^{-1}) is more powerful than the flood (0.4 m s^{-1}) so sediment movement into the entrance channel by littoral drift is mostly flushed seaward to form a significant ebb tidal delta.

According to the East Solent Shoreline Management Plan (1997), the study frontage is characterised by shore parallel currents, except in the vicinity of the harbour entrance. Maximum nearshore current speeds are typically in the range of 0.5-0.75m/s^{-1}, with a maximum tidal inlet current of 1.0-1.5m/s^{-1}. Extreme water levels are presented in **Table 4.3**., with water levels being similar throughout the harbour (East Solent Shoreline Management Plan, 1997).

Table 4.3 Extreme water levels.

Probability	1:1 year	1:10 years	1:50 years	1:100 years
Maximum water level (m OD)	2.99	3.38	3.53	3.69

4.4.2 Waves

The coastline is open to a moderate to high-energy wave climate comprising English Channel wind generated waves from the south-east, south and south-west as well as swell waves propagating up the Channel from the west that become diffracted around the Isle of Wight (SCOPAC, 2003). Wave shoaling and refraction is complicated by the presence of the submerged offshore reefs, shoals, banks, scarps and troughs. Wave climate for any one location on this coastline is a result of complex relationships between offshore to inshore transformation as a function of shoreface width and water depth; seabed relief; approach angles and interaction between wave and tidally induced currents in the breaker zone. Generally, waves steepen where tidal currents flow in opposition to dominant wind wave direction of approach.

Given this complexity, it has been difficult to develop a quantitative wave climate. HR Wallingford (1995), using the TELURAY model, calculated a maximum annual wave height of 2.85m for the shoreline west of Selsey Bill. For mean inshore wave heights, Posford Duvivier (2001) re-ran HR Wallingford's (1995) data, using additional values derived from field measurements in 1998 and further refinements based on ENDEC model results (HR Wallingford, 1998). For annual recurrence, the maximum wave heights obtained south-west of Selsey Bill was 2.17m.

Maximum significant wave heights are substantially greater than this, in the order of 15-20m for offshore waves off Selsey Bill (Hydraulics Research, 1974; HR Wallingford, 1992, 1993); HR Wallingford (1995) report maximum significant wave height (Hs) to be 3.94m at the Pagham Harbour entrance. Inshore breaking wave heights, and incident angle of approach, directly control potential rates of longshore sediment transport, and are one basic explanation for the spatial variations observed. The shoreline orientation and dominant wave climates have resulted in a classic drift aligned shoreline from Selsey Bill to Pagham Harbour.

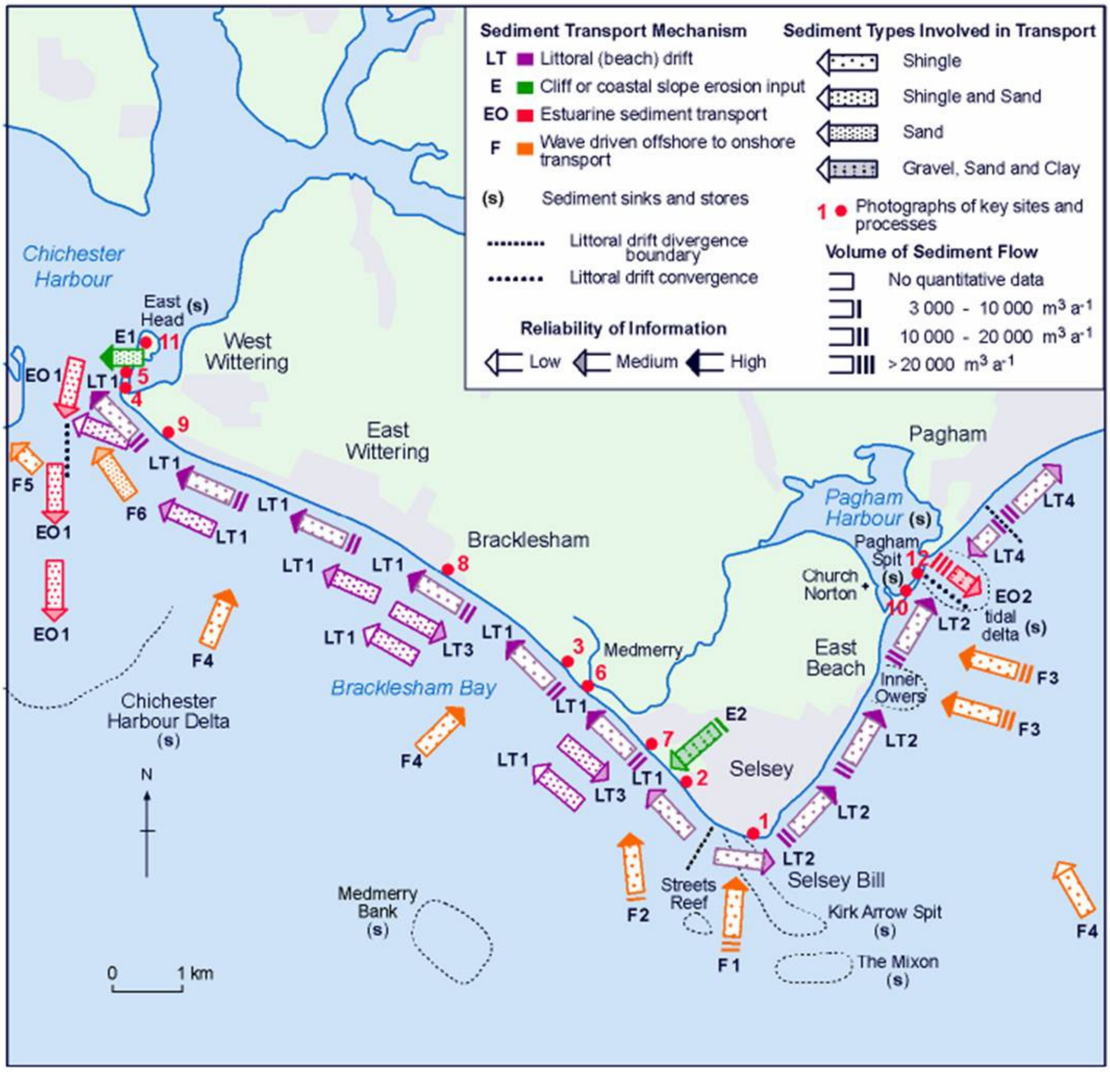
The shallow nature of the inlet bars and surrounding bathymetry causes strong localised wave refraction. Wave action is modified by local refraction induced by complex bathymetry, but HR Wallingford (1993) calculated a mean significant wave height of 1m, and a maximum of 4.5m, at Pagham Harbour Entrance.

Analysis of aerial photography and refraction modelling demonstrates that a local reversal of the north easterly drift direction occurs to the east of the inlet. The point at which the drift divides is likely to be located is the area where medium term beach changes trend from erosion to accretion and *vice versa*. This point is not discrete, but moves depending on wave conditions and tidal elevation. The reversal is likely to be less exaggerated at low tidal elevations.

4.5 Sediment transport

Figure 4.2 presents East Head to Pagham sediment transport pathways (SCOPAC www2). The study site is characterised by a littoral drift system from the southwest to the northeast and wave driven offshore to onshore transport in the vicinity to the south of the harbour entrance. Sediment types involved within each source are principally shingle materials in the region of 10,000-20,000m^3/year from each respective source. The reliability of data pertaining to these sources and quantities is deemed to be high. As highlighted in **Figure 4.2** there are two discrete sediment drift divides, one to the east southeast of the harbour entrance, the other to the northeast of the harbour. The divide immediately offshore of the harbour inlet is dominated by the transport of shingle materials to the offshore ebb tidal delta and totals 20,000 m^3/year. The drift divide to the northeast is inferred to transport between 3,000-10,000 m^3/year of shingle materials back toward the harbour inlet.

Figure 4.2 **East Head to Pagham sediment transport pathways.**



According to SCOPAC (www2) the seabed is covered with shingle in a sand and silt matrix. The shingle is generally angular to sub-angular, and as such is distinct from the more rounded beach material. The shallow bathymetry of the area subjects deposits to intense wave action and may provide a path by which shingle can be transported onshore. Jolliffe & Wallace (1973) stated that active sorting processes selectively transport smaller shingle onshore via wave action with the larger particles remaining offshore and consolidating. At several points between Selsey and Pagham Barcock & Collins (1991) states that large spit structures can be seen trending seaward, perpendicular to the shore, with the exception of the Pagham Harbour delta. Most shingle is transported ashore via shallow spits/bars which trend seaward, perpendicular to the shore, at an estimated rate of 42,000m^3/year.

The dominant south westerly winds lead to the easterly drift of beach material from Selsey Bill towards Pagham. Estimated rates of drift vary between 24,000m^3a^{-1} (Lewis and Duvivier, 1976) and 42,000m^3/year (Wallace, 1988). According to Barcock & Collins (1991), both sources agree that the majority of this material is likely to be derived from offshore, since the stabilisation of Selesy Bill in 1960 reduced beach feed from cliff erosion to an insignificant level. Prior to 1960 Barcock & Collins (1991) states “beach feed from cliff erosion was probably only between 4-8,000m^3/year”.

Net beach and (nearshore) longshore transport is from southwest to northeast along the coast. The northeastward deflection of the contemporary tidal channel together with the pattern of sediment retention in the southern spit provides evidence of this drift direction (see **Figure 4.3**). Locally strong ebb and flood tidal currents are generated by the exchange of tidal waters at the tidal inlet thus, helping to maintain a mouth in its location.

4.5.1 Shoreline Management Units MU2 and MU2A

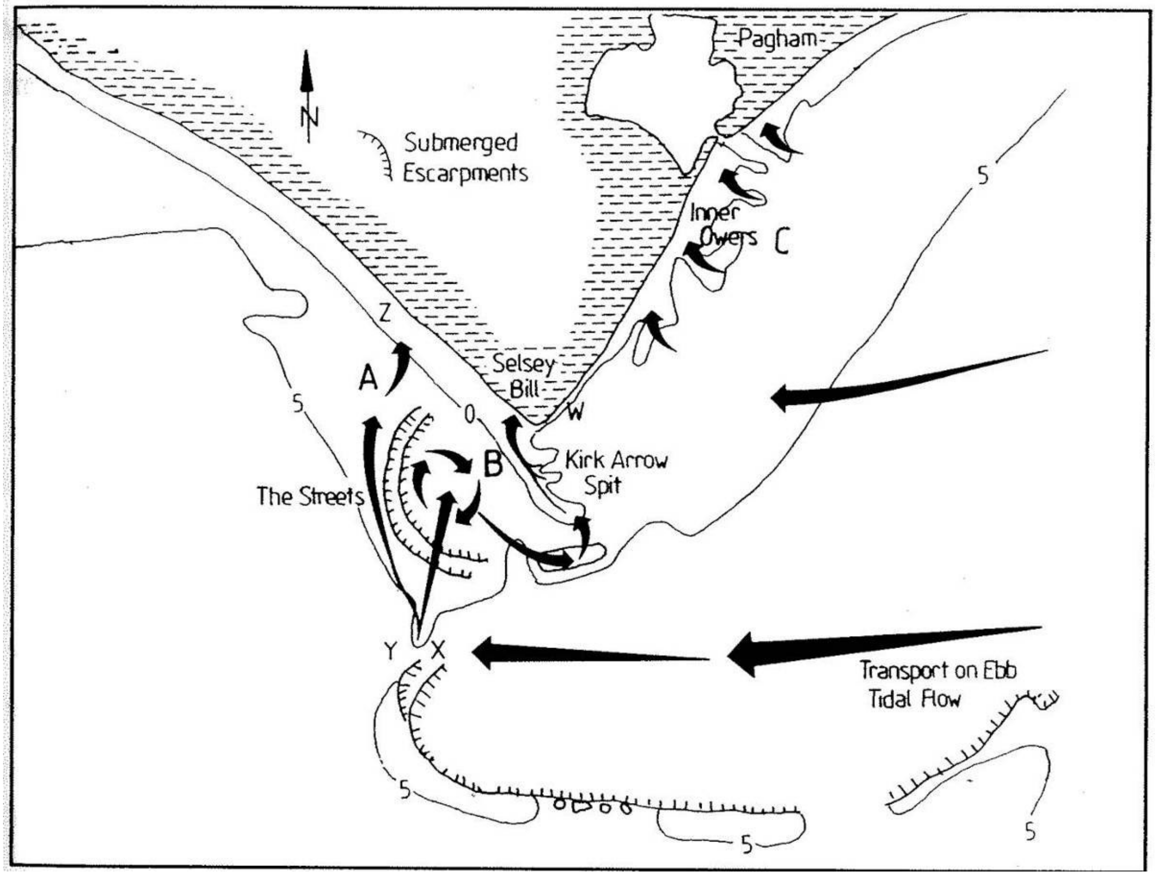
Along the MU2 frontage the sediment generally drifts in a southwest to Northeast direction from Selsey Bill (South Downs Coastal Group, 2007). Along the MU2A frontage sediment generally drifts in a Northeast to Southwest direction from approximately 500-600m east of the harbour entrance, where a drift divide (dotted line) and hence erosion occurs. Locations of sediment transport pathways, the location of the inferred drift divide and Management Units (MU) are presented in **Figure 4.3**, over.

Figure 4.3 **Location of Management Units (MU) along the Pagham frontage.**

4.6 Sediments inputs

Wave-transported sediment supply to the beaches of this coastline derives from several discrete sources, such as the Owers, the Mixon Shoal and the Kirk Arrow Spit, as detailed below (see **Figure 4.4**). Tidal currents are not considered to be an independent mechanism of sustained onshore transport, but wave and tidal stream interaction creates complex patterns of turbulence that can entrain sediment. Of importance in terms of interpreting **Figure 4.4**, is that it does not present dominant longshore drift directions, only offshore to onshore directed sediment sources.

Figure 4.4 **Inferred sediment transport around Selsey and Pagham.**



Taken from Barcock & Collins (1991)

The Kirk Arrow Spit is a mobile gravel bank with a mean volume of 20-40,000m^3 exposed at low water some 300-500 m offshore from Selsey Bill. The bank comprises mostly weed- rafted flint clasts deposited as a result of turbulence generated by interaction of waves and tidal currents off the apex of Selsey Bill (Jolliffe and Wallace 1973). It is believed that shingle is periodically transported onshore from the spit to feed adjacent beaches when waves approach from the south or south-west. Evidence for this is mainly circumstantial and comprises reported observations and air photos. These sources suggest that beach levels opposite the spit are maintained by sudden onshore-directed influxes of shingle induced by high energy (storm) waves. However, an "outer circulation" of weed-dragged shingle may occupy an anticlockwise pathway that links several offshore banks and reefs with northern East Beach and Church Norton beach (Joliffe, 1978; Wallace, 1990). The circulation may be vital in replenishing the Kirk Arrow spit during intervals between onshore influxes.

According to SCOPAC (2007) air photos indicate gravel influxes from the bank to the shore during the periods 1959-60, 1971-72, 1986-92 and 1997-99 and corresponding extensions of the bank shoreward such that they temporarily attach to the shore. This suggests that gravel is transported onshore from the inshore end of the bank by shoaling waves approaching from the south.

Wallace (1990) also calculated that 5 million cubic metres of shingle have accumulated south of the entrance to Pagham Harbour since 1866, giving a mean rate of 41,677

m^3/year, a value that corresponds well with the four month estimate from 1989. The major sources are regarded as net onshore supply from both the Kirk Arrow Spit and from the nearshore Inner Owers bank (see below), and his figures would appear to include both. It can be concluded that strong circumstantial evidence exists indicating significant but intermittent onshore transport of gravel from the Kirk Arrow Spit. The quantitative estimates of this feed are of medium reliability because it apparently occurs as high magnitude, low frequency pulses that are not easily measured. Additional information is required on the frequency, volume and duration of typical pulses, as well as on the pattern of changes in the shape and volume of the spit itself. Better knowledge is required of how it came to expand rapidly in the late 1980s to become habitually exposed during low water spring tides, thus creating a wide inter-tidal foreshore. However, during the previous three decades, it was detached and only rarely emergent. Ultimately, over a long timescale that cannot be determined at present, the Kirk Arrow Spit represents a finite source of supply, as there is a probability that its sources of replenishment will decline over time and eventually become exhausted.

The Inner Owers are a series of mobile nearshore gravel banks (see **Figure 4.4**), situated between East Beach, Selsey and Pagham Harbour inlet, which periodically migrate onshore. They are built onto the western margins the Pagham tidal delta and are characterised by a gentle offshore slope and a steeper inshore slope (Lewis and Duvivier, 1977). Their shape and form is determined by wave diffraction and refraction. Gravel is supplied to the local beaches in wave-driven pulses in a very similar way to Kirk Arrow Spit. The behaviour of these bars is analogous to that of swash bars that are widely associated with sand dominated estuaries in North America (Fitzgerald, 1996). The gravel supply process has been investigated by means of air photos and site observations (Lewis and Duvivier, 1977; Wallace, 1990). Based on estimations of the reasonably constant shape and volume of these gravel banks, observed during their migration phases, a total input of 10,000 m^3 was calculated for the period 1970-75; a longer term average input of 3,000-5,000 m^3/year is quoted by Lewis and Duvivier (1977). This process has been observed directly via diver surveys, and as its contribution to beach levels is evident, this information is regarded as of medium to high reliability. Further quantitative information is currently not available, so that research and monitoring over an appropriate timescale (at least 10 years) is necessary to determine long-term supply pathways and rates.

Littoral drift of gravel is from Selsey Bill north-eastwards to the entrance to Pagham Harbour. The main evidence for this comprises inter-tidal beach level observations and analysis of volume changes (Lewis and Duvivier, 1955; Duvivier, 1960; Wallace, 1990; HR Wallingford, 1995; Gifford Associated Consultants, 1997; Posford Duvivier, 2001). Littoral drift pathways therefore diverge in the vicinity of Selsey Bill (see **Figure 4.2**). Detailed analysis of maps, air photos and beach level measurements and observations in groyne compartments enabled Lewis and Duvivier (1976), Harlow (1980), HR Wallingford (1995, 1997) and Posford Duvivier (2001) to locate this regionally significant drift divide between Warner Road (net westward drift) and Hillfield Road (net eastward drift). At this point, groynes and a seawall have been constructed, either side of which erosion has occurred, thus forming an artificial headland. Immediately north-east of Selsey Bill the potential for drift is much greater due to the sudden change in shoreline orientation to face south-east. However, the precise position of the drift divide fluctuates up to 300-400m, depending on prevailing wave conditions. Estimations of rates of drift have involved both assessments of changes in beach volumes and transport modelling approaches based on hindcast wave climates. The most effective studies have sought to compare the results of the two techniques. According to SCOPAC (www2) studies have either focussed upon accretion of the Church Norton Spit, or upon beach volume changes throughout the pathway as follows:

Church Norton Spit Growth

The approach to quantifying sediment accumulation involved measurement of accretion immediately south of Pagham Harbour entrance and attribution of all material accumulating to littoral drift from Selsey and East Beach. Wallace (1990) determined a mean drift rate of 41,500m^3/year over the period 1866- 1989, with a maximum of 76,000m^3/year in 1962. Lewis and Duvivier (1977) calculated the marginally higher potential rate of 50,000m^3/year for the period 1875-1909. Modelling using the LITPACK numerical model (Gifford Associated Consultants, 1997) suggests drift of 71,000m^3/year for all sediment grades. Both studies neglect possible direct inputs to beaches flanking Pagham Harbour inlet from sources such as offshore gravel banks, and so probably overestimate actual drift rates. Their approaches also fail to allow for variations in supply resulting from both periodic upgrading of groynes and recharge operations.

In more recent studies, HR Wallingford (1995) calculated a drift rate of 33,000m^3/year for East Beach, reducing to 8,000m^3/year when adjusted for assumed groyne efficiency in their model studies. For Selsey Bill, their equivalent figures are 13,700 and 5,500m^3/year. Barcock and Collins (1991) have re-calculated the prevailing drift rate between East Beach and Pagham Harbour entrance to be between 24,000 and 42,000m^3/year. This is based data on the frequency distribution of wave heights and approach directions and considers sediment exchanges with Pagham tidal delta. Using HR Wallingford's (1995) DRCALC model, updated by later wave climate information, Posford Duvivier (2001) propose a potential drift rate of 32,000m^3/year. Actual rates are considered to be 25-30% of the above volumes due to the role of groynes.

Various estimates have been made of sediment movement along the Selsey to Pagham coastline (**Table 4.4**).

Table 4.4 Estimated values of sediment movement (cited in SCOPAC, 2003).

Parameter	Estimated value	Sources cited
Net northeast ward drift of shingle to the southern side of harbour mouth.	10, 000 – 20, 000 m^3/year	SCOPAC (www2)
Wave driven offshore to onshore transport.	10, 000 – 20, 000 m^3/year	SCOPAC (www2)
Net southwest ward drift of shingle to the northern side of harbour mouth.	3, 000 – 10, 000 m^3/year	SCOPAC (www2)
Potential rate of sediment transport 1875-1909	50,000r m^3/year	Lewis Duvivier 1977
LITPACK numerical model for all sediment grades	71,000 m^3/year	Gifford Associate Consultants 1997
Littoral drift rate at Pagham	33,000 m^3/year Reducing for groyne efficiency to 8,000	HR Wallingford 1995

Parameter	Estimated value	Sources cited
	m^3/year	
Littoral drift rate between East Beach and Pagham	24,000-42,000 m^3/year	Barcock & Collins 1991
Annual rate of shingle accumulation at the entrance to Pagham Harbour	41,677 m^3/year	Wallace 1990
Maximum annual rate of shingle accumulation at the entrance to Pagham Harbour	76,000 m^3/year	Wallace 1990
Material incorporated within the Church Norton spit, 2005-2008.	25,644 m^3/year	Calculated herein
Migration of the Inner Owers towards Pagham	10,000 m^3/year	Lewis Duvivier 1977

4.7 Sediments outputs

One potential source of sediment is identified for the study site comprising onshore to offshore transport and potential shore erosion (see **Figure 4.2**). This location is associated with the tidal inlet and sediment feed to the ebb tidal delta, fed by longshore sediment drift from the southwest via Church Norton. The possible release of sediments from Church Norton spit to feed the ebb tidal delta has been supplemented in recent decades by beach replenishment at several sites, though no recycling of shingle has occurred along the Pagham frontage within the last 3 years (Beach Management Plan 2007).

Currents generated by tidal exchange at the Pagham Harbour entrance are effective in interrupting littoral drift At the harbour entrance, the ebb current (1.0- 1.5ms-1) is more powerful than the flood (0.4ms-1) so sediment movement into the entrance channel by littoral drift is mostly flushed seaward to a significant ebb tidal delta (Barcock and Collins, 1991). Between 30-75,000 m^3/year is potentially available at the entrance to the harbour comprising convergent longshore transport from the south-west and north-east. A proportion of this becomes stored in the beaches that make up the twin spits, potentially leaving around 24-40,000m^3/year to enter the entrance channel (Gifford Associated Consultants, 1997). Based on an assumption of bedload transport rate at the harbour entrance and calculation of the tidal prism, output to the delta by ebb current flushing is likely to be between 16-40,000 m^3/year (Gifford Associated Consultants, 1997). However, a significant proportion of this quantity represents material introduced into the entrance channel by wave transport of gravel and coarse sand from landward migrating offshore banks that are already components of the tidal delta (Geodata Institute, 1994; Barcock and Collins, 1991).

4.8 Sedimentation rates within the inner harbour

According to the Manhood Peninsula Land Drainage Study (Royal Haskoning, 2005), Pagham Harbour has been getting drier and is generally understood to be gradually silting up. Consequently there are concerns that Pagham Harbour may eventually be naturally reclaimed with associated closure of the Harbour mouth, impacts upon the drainage, environment and potential future flooding problems.

Stratigraphic investigations of intertidal sediments have demonstrated that sediment has accumulated relatively rapidly, at a rate of between 4 and 8mm/year (Royal Haskoning, 2005), though rates vary between studies. However, these averaged rates have exceeded the relative rate of sea level rise, during which time wave and tidal energy have decreased, and extensive marshes have developed within the inner harbour. A reduction in sediment accretion rate through time, as predicted in various theoretical models of salt marsh accretion, has not yet been observed in Pagham Harbour.

According to Royal Haskoning (2005), very little silt comes from the existing drainage system compared to the silt that is transported into the Harbour from the sea. Various research, available data and Royal Haskoning's observations (2005) were used to conclude the average long term rate is 3.8 - 8.3mm/year. It is clear that the rate of siltation will vary across the Harbour and be influenced by depth of water, amount of vegetation and exposure.

Research conducted by Brighton University suggests that fresh sediment is imported into the Harbour from offshore during stormy conditions (HMLF events), with the landward flux of sediment being observed at the beginning of the flood tide. The research concluded that less sediment appears to be deposited at the sites closer to the entrance, suggesting that fine sediment is recycled at the landward edge of the harbour, particularly within sheltered environments. Of importance in terms of the spatial pattern of siltation within the inner harbour is the fact that the results showed a tendency for increased siltation on the western side of the Harbour.

Earlier work by Cundy et. el., (2002), identified the AD 1846 to AD 1910 reclamation surface within the inner harbour. Based on its depth range, a sediment accumulation rate of 3.9 - 6.1mm/year had been inferred, derived from a (Cs^{137}) activity versus depth profile. They also inferred an accretion rate of 7mm/year tentatively derived from the first appearance of Cs^{137} within the sediment sequence in the inner harbour. An alternative lead (pb^{210}) model indicated an average vertical accretion rate of ~5mm/year, with no prolonged large scale variations in accretion rates since the breaching of the barrier in 1910 (Cundy et. el., 2002). However, when the model was run according to the CRS methodology of Goldberg (1963), average post breaching accumulation rates varied from 4.3 – 8.3mm/year.

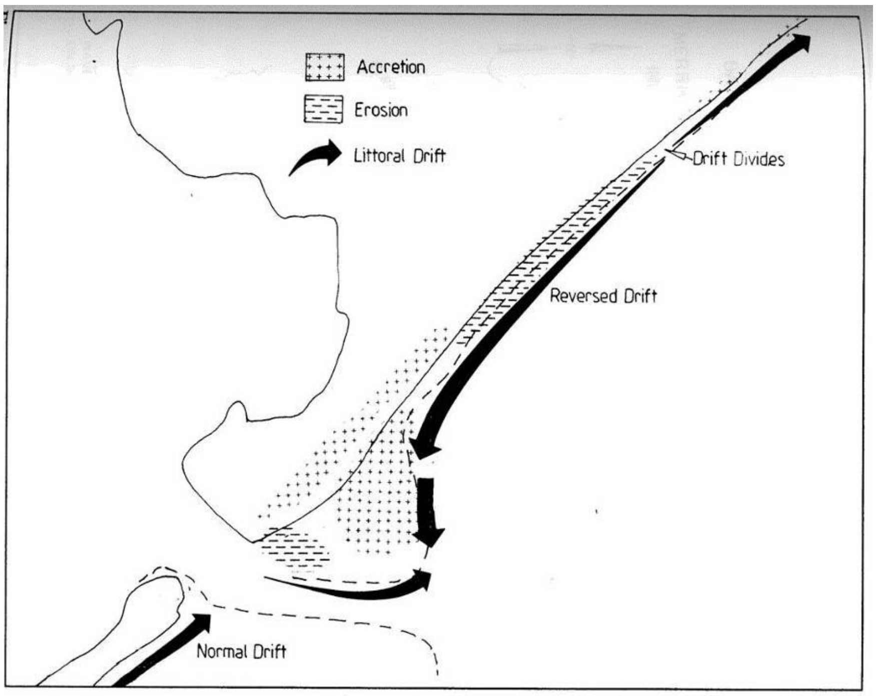
There are concerns that if Pagham Harbour continues its current trend of siltation it may eventually be naturally reclaimed. This would lead to closure of the Harbour mouth and impact upon the drainage and environment of the Peninsula.

4.9 Tidal flushing and the ebb tidal delta

According to the SCOPAC sediment transport study (2004), between 30-75,000m^3/year of sediment is potentially available at the entrance to the harbour, comprising convergent longshore transport from the south-west and north-east (see **Figure 4.5**). According to the Pagham Harbour BMP (2006), a local drift reversal occurs at the eastern boundary of the Pagham Beach frontage. Net direction of drift immediately east of Pagham Harbour inlet is considered to westwards over a 500-700m long frontage, as shown in **Figure 4.5**, at an approximate rate of 5,000 m^3/year. Drift convergence upon the inlet has formed the Church Norton and Pagham spits. Sand and gravel drifts along the spits to the inlet where it is flushed seaward by dominant ebb tidal currents and becomes stored within a tidal delta outside the harbour.

A proportion of this is stored temporarily in the beaches that make up Church Norton and Pagham spits, potentially leaving around 24-40,000 m^3/year to enter the entrance channel (Gifford Associated Consultants, 1997). Based on an assumption of bedload transport rate at the harbour entrance and calculation of the tidal prism, output to the delta by ebb current flushing is likely to be between 16-40,000m^3/year (Gifford Associated Consultants, 1997). However, a significant proportion of this quantity represents material introduced into the entrance channel by wave transport of gravel and coarse sand from landward migrating offshore banks that are already components of the tidal delta (Geodata Institute, 1994; Barcock and Collins, 1991). Sandy ebb tidal delta deposits extend shore parallel to Pagham Beach and are comprised of sediments that drift into the inlet channel and those that eroded from Pagham Beach prior to being flushed seaward.

Figure 4.5 Drift divergence north of tidal inlet



Taken from Barcock & Collins (1991)

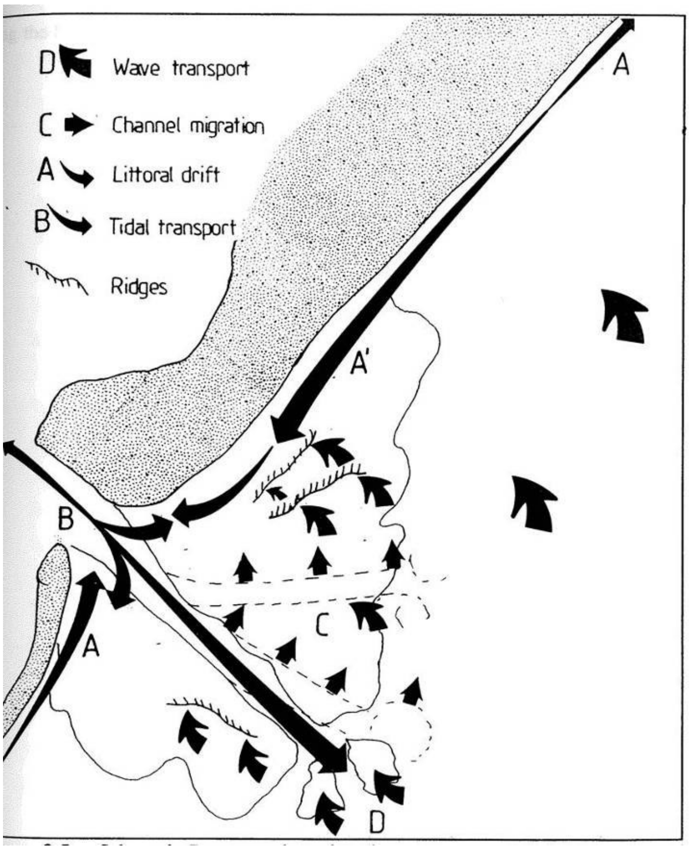
Ebb tidal currents are moderate and their influence does not extend very far seaward. Wave induced currents oppose seaward transport and tend to drive material back landward where ebb tidal currents are weak. A consequence of the aforementioned processes, historically the ebb tidal delta has been located close to the inlet and has been relatively small (SCOPAC, 2004). Sediment therefore had a short residence time within the delta and was liable to being driven back ashore within swash bars to the west and east of the inlet.

According to the Geodata Institute (1994), net seaward discharge that generates accretion of the ebb tidal delta at Pagham entrance is in the order of 16,000m^3/year representing the balance estimated between landwards (flood tide and wave-driven) input of 18,000 m^3/year, and seawards removal of 34,000m^3/year. Flushing processes and the ebb delta sediment budget have undoubtedly changed over the past four centuries due to reduction of the tidal prism of the harbour as a consequence of land claim.

Of importance is the fact that the mouth of the tidal inlet to Pagham Harbour and the tidal inlet channel itself also forms a barrier to bedload movement of shingle due to tidal flushing. The tidal inlet has been constrained and the estuary reclaimed, reducing the associated tidal prism and inlet flushing capacity. Tidal flushing still operates at the mouth of the river (being ebb dominant), but training walls inhibit gravel entering the inlet channel and transport mostly involves fine grained silts and sand. In the past the tidal ebb delta was consequently not as pronounced as it would be expected to be under natural circumstances but is apparent and serves to provide a degree of additional protection, particularly to the east of the mouth.

The Pagham Harbour ebb tidal delta and wide, accreting foreshore sets ups complex local wave refraction and provides protection against the dominant south-westerly waves and a very local dominance of south-easterly waves (Barcock & Collins, 1991). Barcock & Collins identified three principal transport pathways, labelled A, B and C in **Figure 4.6**.

Figure 4.6 Inferred sediment transport pathways in the vicinity of the tidal inlet and ebb tidal delta.



Taken from Barcock & Collins (1991)

Path A is normally orientated from the northeast to southwest but reverses near the tidal inlet. Drift to the south of the inlet causes material to be carried into the inlet mouth, which in turn is transported out onto the ebb tidal delta where it accumulates. Wave action sets up channel and bar migration to the north (path C). As the channel migrates towards the Pagham shoreline it becomes hydraulically unstable and a new, straighter channel cuts through causing bifurcation. According to the inferred sediment transport pathways envisaged by Barcock & Collins (1991), the old channel then infillls leaving a shingle bar/ridge which eventually migrates landward creating a considerable build up of material; on the western end of Pagham Beach.

At the distal end of the new channel material that is carried seawards is deposited within the newly formed ebb tidal delta. Wave action then gradually redistributes material to the northeast. The result is a highly dynamic and complex sediment transport regime which causes periodic accumulation of materials to the east of the inlet, with erosion further to the east producing a secondary sediment supply.

Drift convergence upon the inlet has formed the Church Norton and Pagham spits. Sand and gravel drifts along the spits to the inlet where it is flushed seaward by dominant ebb tidal currents and becomes stored within a tidal delta outside the harbour. As illustrated and discussed prior (see **Section 3.4** HTA), the position of the ebb tidal delta has maintained its position, with the channel experiencing periods of bifurcation and channel abandonment prior to returning to its previous location (west south-west) during the period 1969-1997, since which time it has migrated to the northeast, becoming fixed in its present location since 2005. Prior to 1997, wave action typically drove sediment onshore in the form of swash bars that migrated landward from the margins of the delta. The net effect was that the shoreline sediments arrived from the west, naturally bypassing the harbour inlet, with some being re-circulated up Pagham Spit and back toward the inlet. However, significant proportions are transported eastwards towards Aldwick Estate (Pagham Harbour BMP, 2006). However, since 1997, considerable quantities of littoral sediment have been stored within the ebb tidal delta and spits, with smaller quantities being stored within the flood tidal deposits located within the harbour immediately behind the inlet. The storage off significant quantities of littoral drift and offshore derived sediments since 1997 within the ebb tidal delta has resulted in the net effect that the shoreline sediments arriving from the west, no longer naturally bypass the harbour inlet, but are stored within the former tidal delta where they have contributed to rapid spit accretion as evident in **Section 3.4** (HTA).

This storage of littoral sediment within the former ebb tidal delta is important in terms of the littoral sediment budget and exerts a significant influence on the morphodynamics of adjacent shorelines. Such changes may contribute to changes in the spatial pattern of erosion and/or accretion which are linked to phases of ebb tidal delta growth and decay. The drift divide is marked by a zone of persistent erosion in the vicinity of Pagham Beach Estate, as is discussed further in proceeding section.

4.10 Changes in beach planform

This section of the study is concerned primarily with evidence of erosion and/or accretion at Pagham Beach and the resultant changes in beach planform and morphology. Data presented and interpreted include previous analysis of the measured cross-sectional profiles along the Church Norton and Pagham Beach frontages conducted by Atkins on behalf of the Environment Agency (1995-2007); Southeast Strategic Regional Coastal Monitoring Project (SRCMP) data (2003-2007); and, aerial photography (2001-2008).

Prior to this an overview of shingle recycling is provided to provide context for changes in beach planform. On an annual basis and if required, the Environment Agency recycle shingle from the foreshore to replenish that lost from the southern spit sea defence at Church Norton following winter storms/erosion. This is dome over an 8-week period between January and March. The Environment Agency has not undertaken any shingle recycling at Church Norton within the last 3 years, as this has not been required due to good rates of accretion.

The beach at Church Norton is composed mostly of flint shingle (Lewis and Duvivier, 1977; Wallace, 1990; Posford Duvivier, 2001). Barcock and Collins (1991) report that Pagham Beach (the north eastern shingle spit) consists of a steep upper beach, a shallower mid-beach, and an extensive low gradient foreshore. This beach is mostly flint gravel, but grades to coarse sand and granules on the lower foreshore.

Figure 4.7 presents the locations of beach monitoring stations from position 0 – 12, with station ID increasing in a northeast direction from station 1 at the southerly extent of Pagham Beach. **Figure 4.8** presents graphically trends in beach planform over the two monitoring periods of 1995-2001 and 2003-2007. The data display a marked spatial and temporal variability in the beach planform, which is directly related to changes in erosion/accretion rates. South of monitoring station 7, during the monitoring period 1995-2001, the frontage was characterised by a strong accretionary trend between, which since 2003 has dramatically reversed to one dominated by erosion in the period 2003-2007. On average each monitoring station along this section of the coastline has lost approximately 26m^2 of area above the 2m OD contour over the monitoring period 2003-2007 (4 yrs), equalling an annual average loss of approximately 6m^2/year. This trend is reversed north of station 7 with the period 1995-2001 being dominated by erosion and since 2003 being characterised as an accretionary environment. On average each monitoring station along this section of the coastline has lost an average of 11m^2 over the monitoring period 1995-2001 (6 yrs), equalling an annual average loss of approximately 2.7m^2/year.

Figure 4.7 HR Wallingford beach monitoring locations 1995-2001 and 2003-2007.

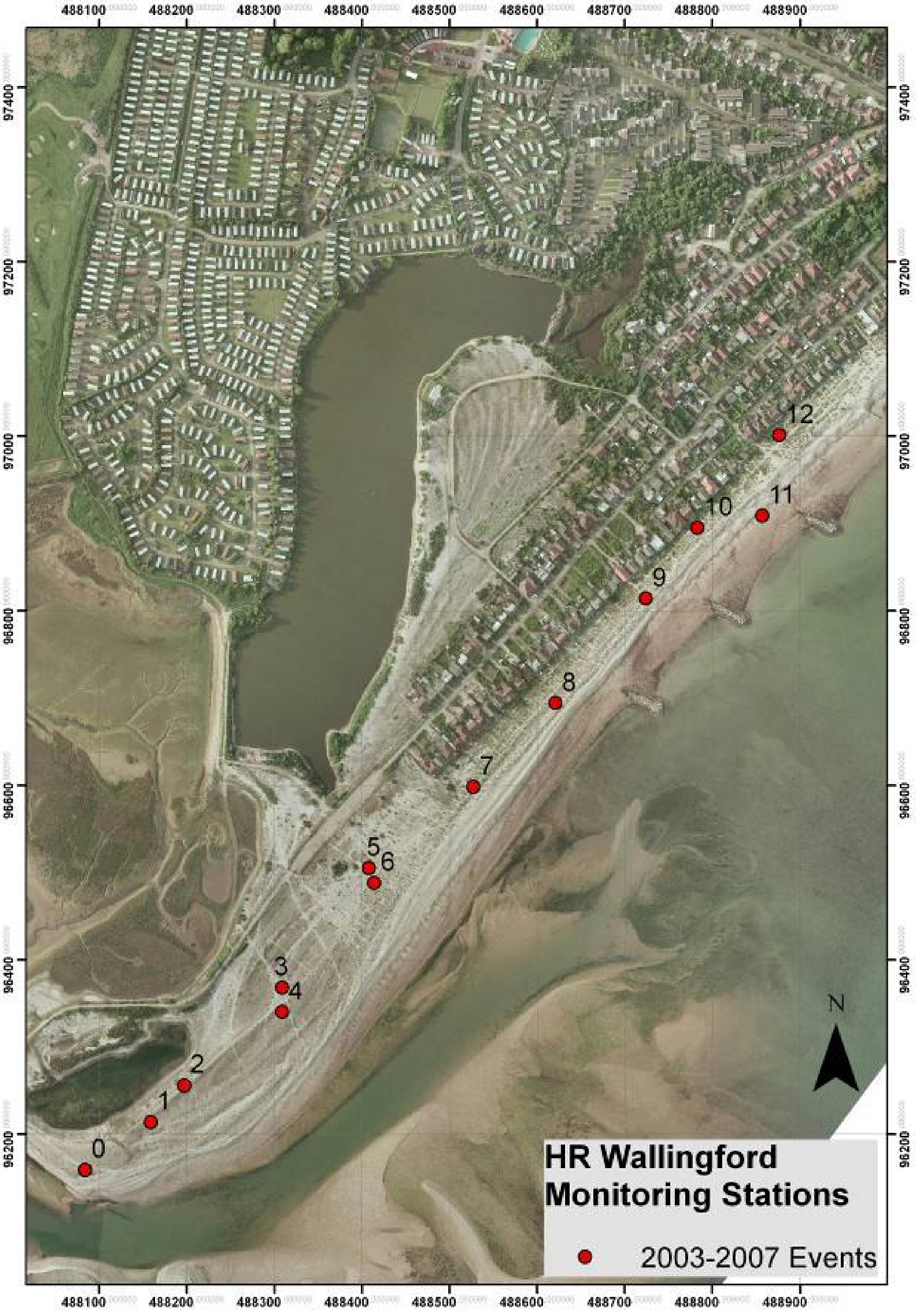


Figure 4.8 illustrates that north of station 17 that changes in coastal configuration attributable to either erosion or accretion are less pronounced, however, they illustrate change in the dominant trends from accretion to erosion since 2003 to monitoring station 40, some 2km north of the tidal inlet to Pagham Harbour. Further north the trend is one of predominantly accretion, though be it at a reduced rate since 2003.

Figure 4.8 Trends in beach area 1995-2001 and 2003-2007 (HR Wallingford, 2008).

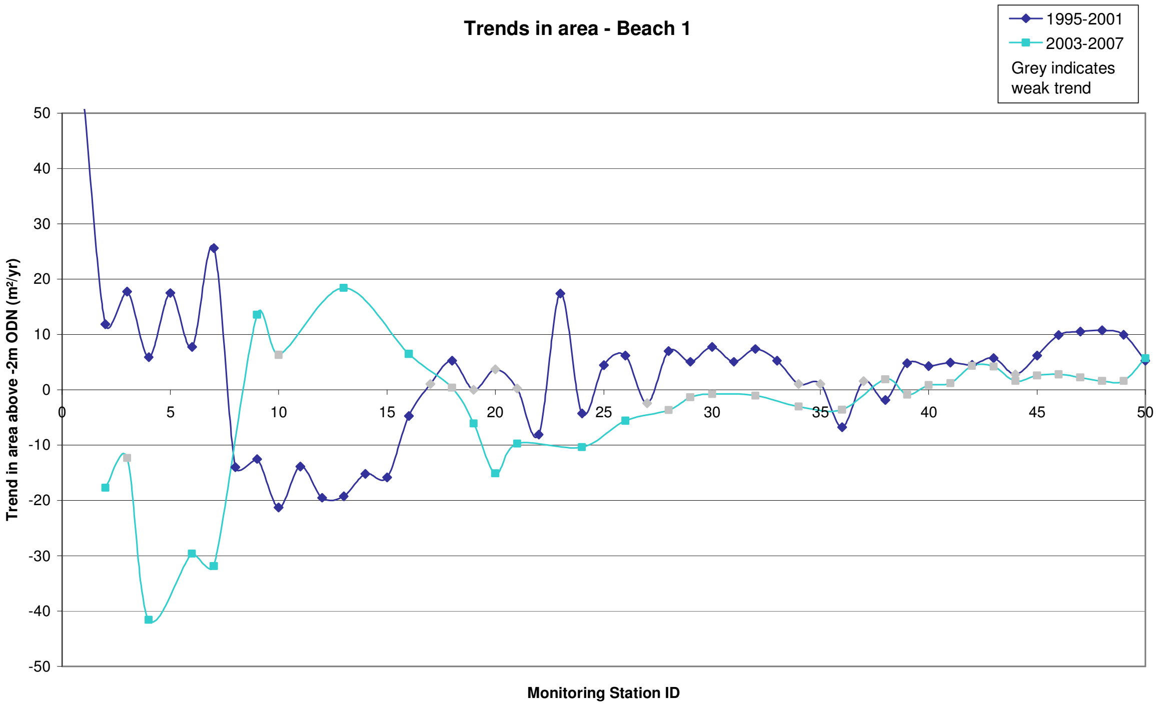


Figure 4.9 illustrates the spatial distribution and the quantification of trends in erosion (red circles) and accretion (green circles) over the monitoring period 1995-2001. Over the monitoring period, the area to the immediate north of the tidal inlet displays a marked trend toward accretion. To the south of Pagham Lagoon the frontage is characterised by a dominant trend toward erosion, which tends to increase towards the northeast, being most pronounced in the area fronting the houses. Northeast of the houses the trend again returns to one of accretion, though albeit at a rate that is not as pronounced as to the north of the tidal inlet. The delineation of erosion and accretion facilitates the mapping of a distinct drift divide, which occurs significantly closer to the tidal inlet during this period than its inferred 1991 location as suggested by Barcock & Collins (1991). This is discussed further in the summary and discussion section.

Figure 4.9 Spatial and temporal changes in accretion and erosion on Pagham Beach.

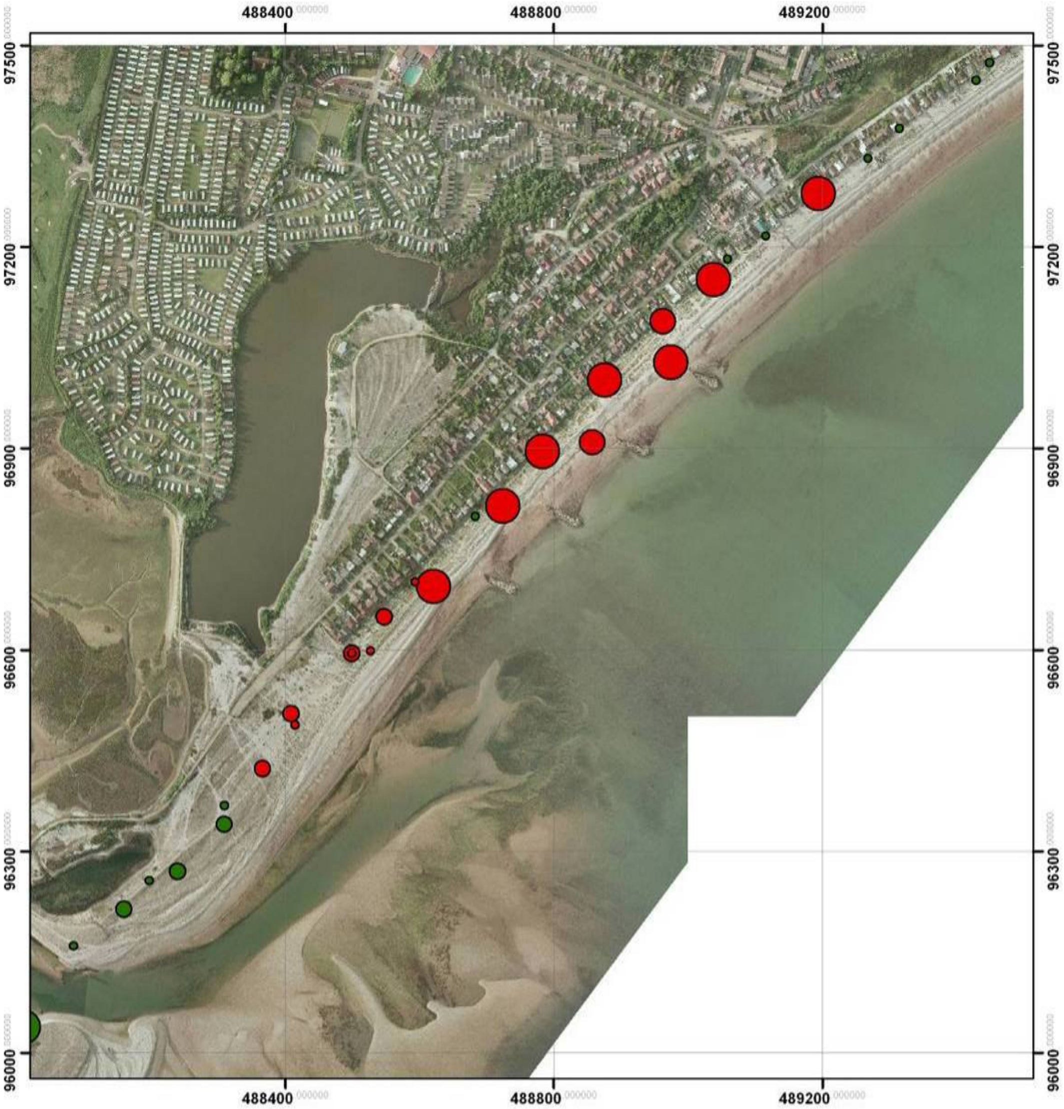


Figure 4.10 illustrates the spatial distribution and the quantification of trends in erosion (red circles) and accretion (green circles) over the monitoring period 2003-2007. Over the monitoring period, the area to the immediate north of the tidal inlet displays a marked trend toward erosion, which is a significant change to the previous monitoring period. To the south of Pagham Lagoon the frontage is characterised by a dominant trend toward erosion, which tends to increase towards the northeast, being most pronounced in the area fronting the houses. Northeast of the houses the trend of erosion continues further northwards than previously monitored (**Figure 4.9**). The delineation of erosion and accretion facilitates the mapping of a distinct drift divide, which occur in approximately the same location as documented prior.

Figure 4.10 Spatial and temporal changes in accretion and erosion on Pagham Beach.

Figures 4.11 and **4.12** present the trend in erosion and/or accretion over the respective monitoring periods for all monitoring stations along the Pagham frontage. The black line within both figures represents a linear trend derived from the data and illustrates the change from the dominant process of erosion to accretion along the frontage. **Figure 4.11** (1995-2001) presents that this change occurs at station 17, with all areas to the south being characterised by a trend of erosion over the monitoring period, with all stations to the north being characterised by a trend towards accretion. **Figure 4.12** (2003-2007) presents that this change occurs at station 23, with all areas to the south being characterised by a trend of erosion over the monitoring period, with all stations to the north being characterised by a trend towards accretion. With both monitoring periods, the trend towards erosion increases toward the south of the Pagham frontage, with a corresponding increase in the rate of accretion toward the north.

Figure 4.11 Erosion/accretion trends in beach planform 2003-2007.

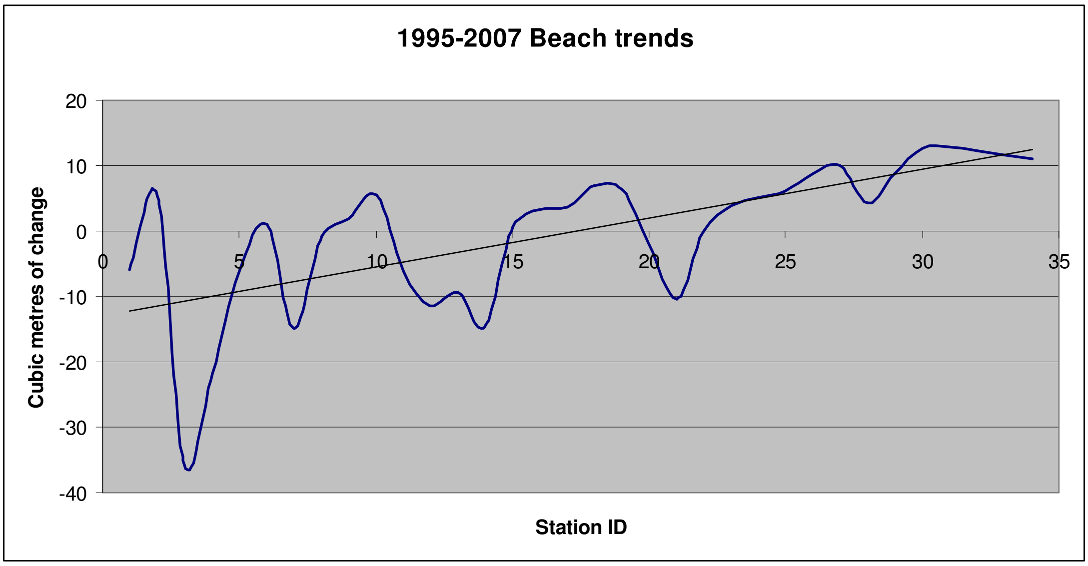
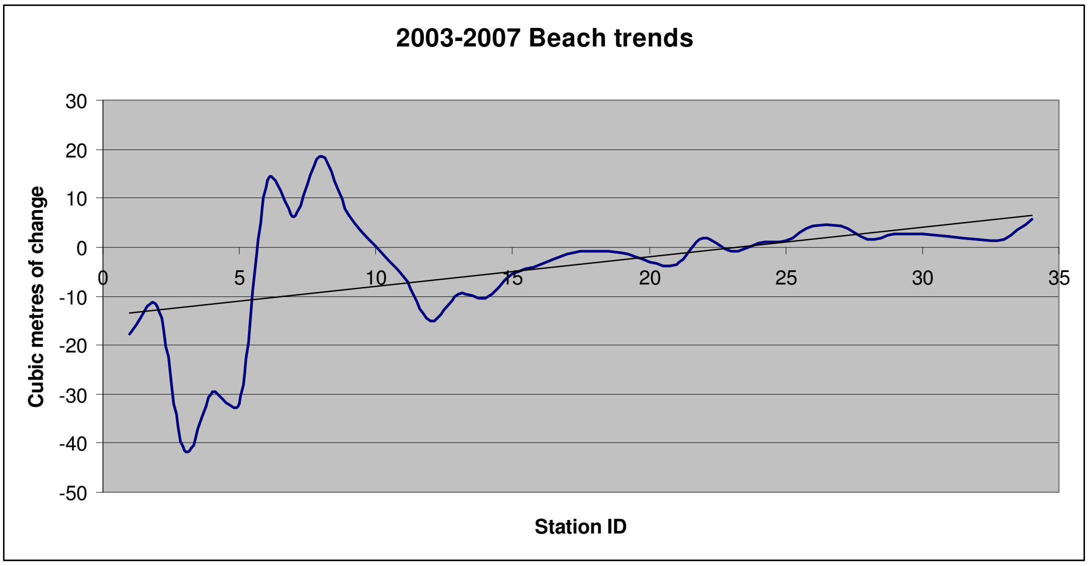


Figure 4.12 Erosion/accretion trends in beach planform 2003-2007.



As presented in **Figures 4.9** and **4.10**, the delineation of erosion and accretion facilitates the mapping of a distinct drift divide in the location of Pagham Lagoon which is presented in **Figure 4.13**. Analysis of data for the various monitoring periods indicate that the drift divide has migrated ~590m north-eastwards over the total monitoring period of 1995-2007. This migration north-eastwards is discussed further in the summary and discussion section of the EGA.

Figure 4.13 Drift divides along the Pagham frontage

Key to spatial and temporal changes with the pattern of erosion and/or accretion is channel evolution and how the channel has become fixed in its current position. This is presented diagrammatically in **Figure 4.14**. Since the tidal inlet has migrated and become fixed at its current location, increased erosion has been experienced along this section of the coastline (see **Figures 4.9** and **4.10**). A potential geomorphic explanation for the timing of the onset of this erosion phase is presented herein, and may go some way towards explaining the link between the rapid accretion of the spit from the south and the migration of an eddy formation north and landward, resulting in shoreline erosion/accretion by way of changing the position of the drift divide.

Since 2005 the tidal channel has been fixed in its current location, prior to which time (~2001) it migrated toward the Pagham frontage. Associated with this migration toward the Pagham frontage has been an associated rapid advancement of Church Norton spit to the northeast (see **Figure 4.15**). As the spit has advanced there has been a correlating retreat of the coastline along Pagham Beach. This correlates with changes in erosion and/or accretion presented prior.

Figure 4.14 Historic channel positions 2001-2008.

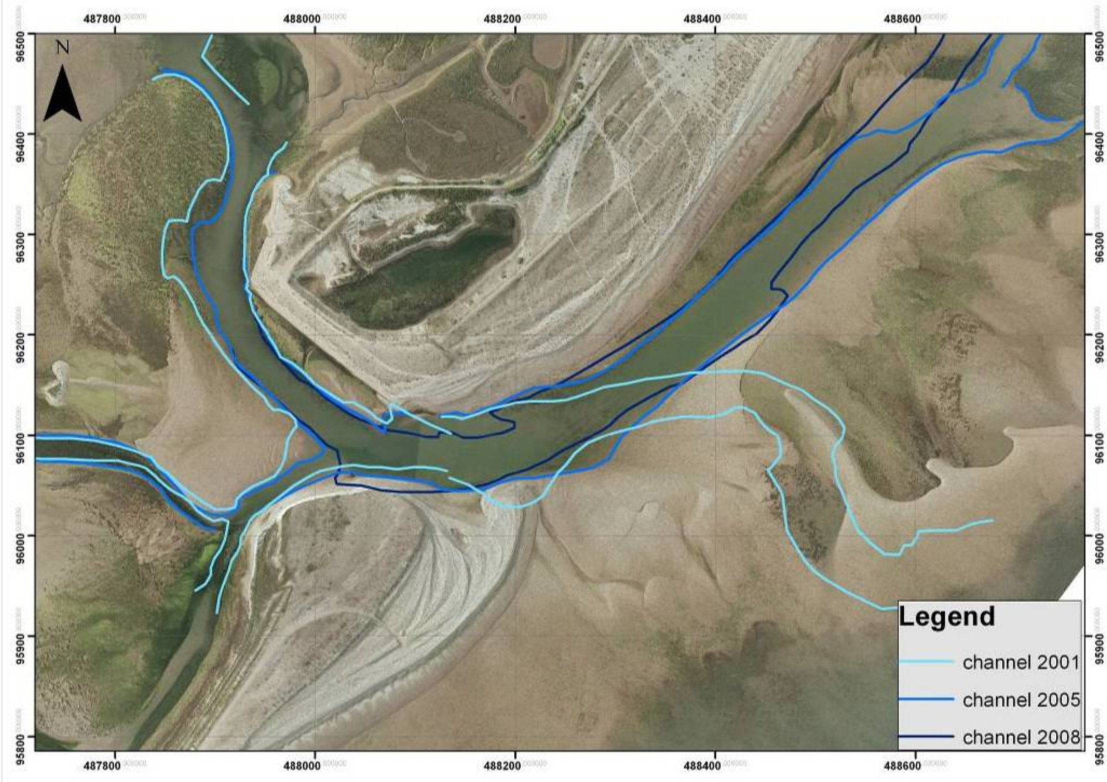
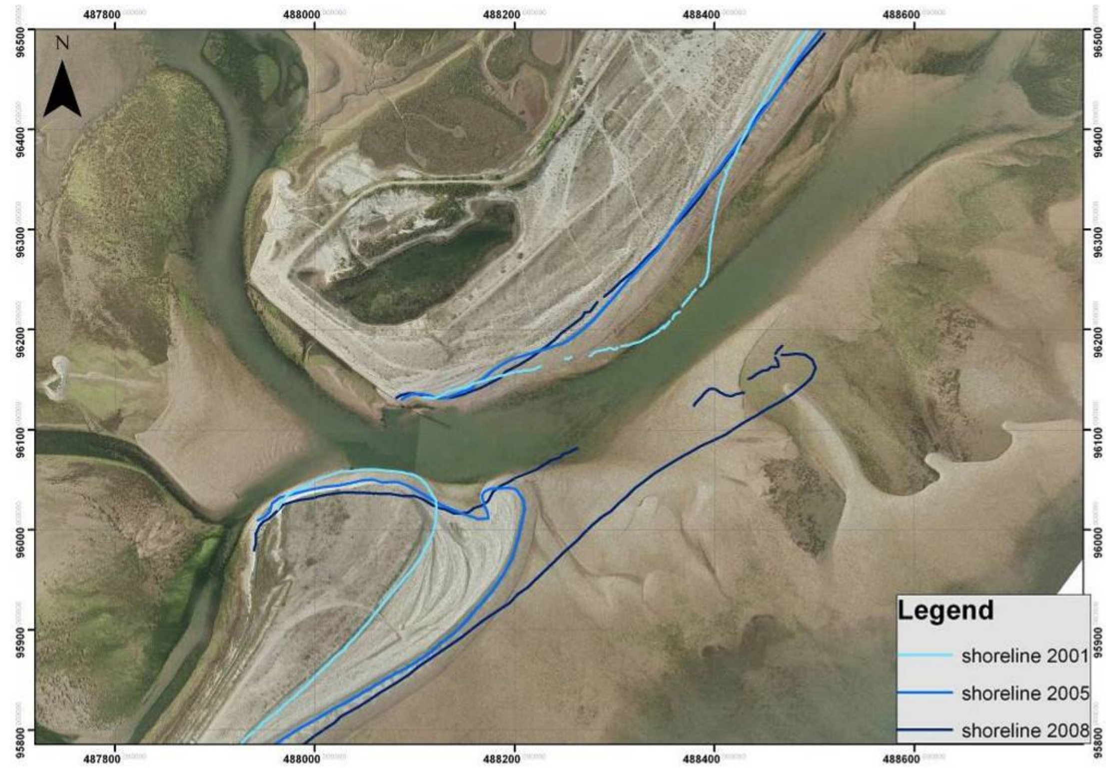


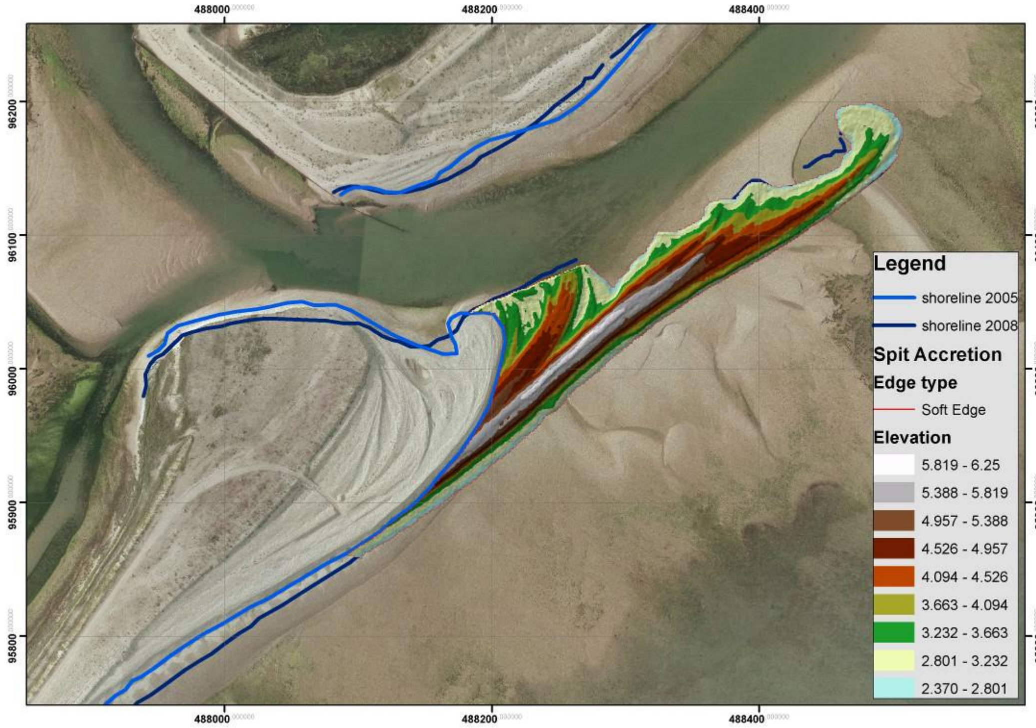
Figure 4.15 Historic shoreline positions 2001-2008.



4.10.1 Accretion 2005-2008

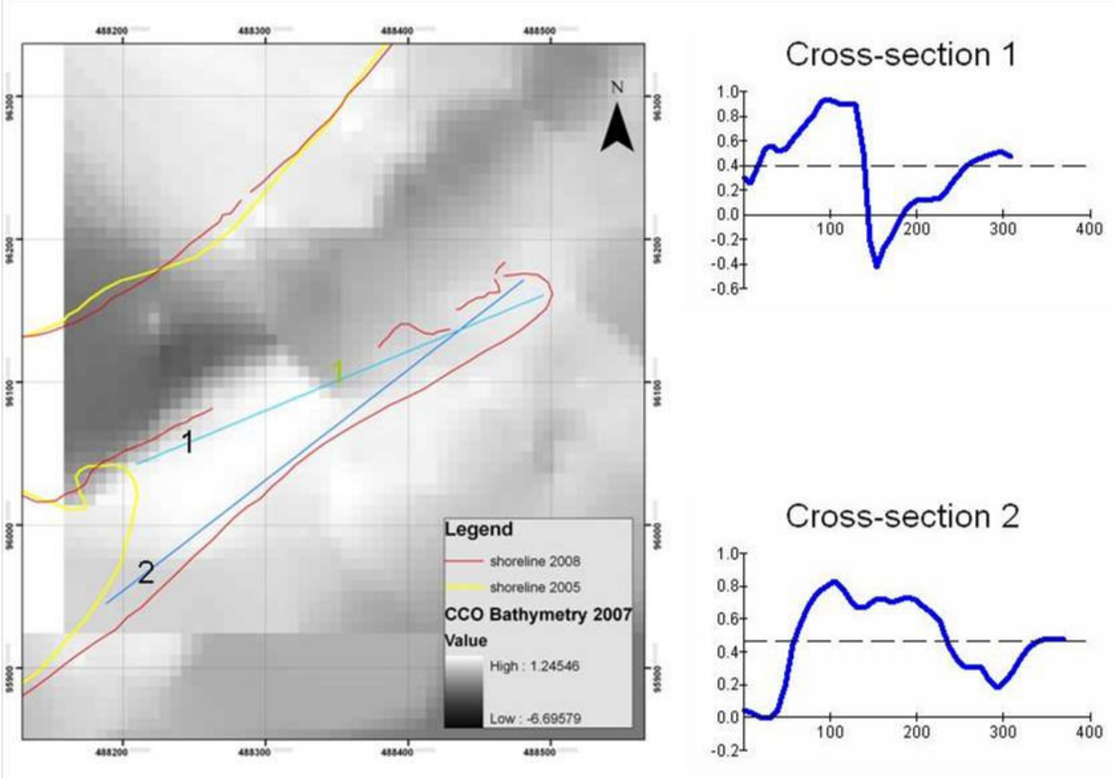
Figure 4.16 presents a TIN derived from 2008 Lidar data representing accretion of materials within Church Norton Spit during the period 2005-2008. Shoreline positions have been used to extract the required data for TIN creation prior to the calculation of volumes of material incorporated within the spit over the analysed period. The purpose of this exercise is to derive contemporary longshore drift rates for the period 2005-2008.

Figure 4.16 TIN representing accretion between 2005-2008 at Church Norton Spit.



To determine from which elevation from which the accreted materials were incorporated within the feature, bathymetry data were acquired for the period prior to landform genesis. Figure 4.17 presents a pre-accretion bathymetric surface over which Church Norton spit advanced during the period 2005-2008. Cross-section profiles obtained from a GIS analysis provide bathymetric variability and a mean elevation for the bathymetric surface. Mean surface elevation for cross-sections 1 and 2 are presented in **Table 4.5** along with volumes of sediment incorporated within Church Norton Spit during the period 2005-2008.

Figure 4.17 Cross-sections of pre-accretion bathymetric surface, Church Norton Spit.



(Derived from Channel Coastal Observatory 2007 Bathymetry data)

Table 4.5 Sediment volumes incorporated within Church Norton Spit 2005-2008.

Datum	Volume (m^3)	Inferred transport rate/year (m^3)
MHWS	32495	10,832
0.45	76434	25,478
0.4	77532	25,844

4.11 Summary and discussion of EGA

Barcock & Collins (1991) noted that over long periods of time the tidal inlet migrates to the northeast, although they noted that in 1989 that this process had halted due to the stabilisation of the channel. Previously, under wave action the outer channel migrated towards Pagham Beach until a position of instability was reached when a new channel breaches the old, causing bifurcation (see **Figure 3.2** 1979). The new straighter channel is then rapidly established and the old channel filled with sediment under wave action, and the process repeats. Barcock & Collins (1991) 5 year cyclic model illustrated a short period during which the channel was characterised by periods of channel avulsion and bifurcation and can not be taken as representing a cyclic model of tidal inlet migration that repeats, as it was based solely on a five year snap shot of tidal migration, that since its documentation has ceased to function accordingly. Should consideration be given to another 5 year period, then an alternative model of tidal migration could well be established. As with the documentation of coastal processes and their interaction with geomorphological units, it is fraught with difficulty and often not possible to take a short term process and scale it up to the medium-, long-term morphological development of the coastline.

A qualitative assessment of ebb delta area by Barcock & Collins (1991) suggests that prior to 1982 the delta area was decreasing. However, since 1982 the area has increased considerably. This he stated “may be linked to an increase in the littoral drift rate through this area”, though this is as yet un-established quantitatively. It should be noted that qualitative evidence of increased littoral drift into the area would be an increase in the extent of the ebb tidal delta and associated offshore bars and less pronounced channel movement as the channel becomes fixed in position due to the inability to breach through the accumulated sediments in the form of substantial offshore bars. Therefore, the fixing of the channel in its present location may be attributable to an increase in littoral drift.

The current trend towards erosion at Pagham Beach cannot be assessed without consideration of the stability of the tidal inlet to Pagham Harbour and its associated effect on the stability, or otherwise, of the adjacent shoreline. As highlighted prior (see **Section 4.10**) the temporal and spatial patterns of erosion and accretion are strongly linked to the position of the tidal channel and the spit. Furthermore, the position of the inlet’s ebb tidal delta also provides a considerable interruption to the north-easterly littoral drift with the submerged bars acting as a significant barrier to sediment transport and the ability of material to bypass these bathymetric irregularities. Such barriers have served to limit sediment bypass and as such they are acting as sediment sinks and facilitating the continued accretion of the spit due to the decrease in accommodation space to the north and east of the tidal inlet. The availability of significant accommodation space is normally a limiting factor in the evolution of many spits and gravel barriers worldwide.

As presented in **Section 4.10** (Changes in coastal configuration, 1938-1997) accretion and erosion at both Church Norton and Pagham Beach locations show a similar trend temporally in terms of erosion and accretion. However, since 1997 there has been a marked change in the correlation between erosion and/or accretion, which may be taken as indicating a shift in the previous dominant coastal processes and/or development of a feedback mechanism in and between the external forcing parameters of hydrodynamic regime, sediment supply and geomorphological development during this period of time. In support of such changes, since 1997 there has been a fundamental shift in the orientation in the seaward extent of the tidal inlet. As the tidal inlet has migrated to the northeast, driven by the dominant longshore drift system to this direction, the former ebb tidal delta has provided an elevated bathymetric surface over which Church Norton Spit has progressively advanced.

The rate of change in coastal configuration has varied both spatially and temporally over the analysed and presented period (1932-2008), with the most significant changes being associated with the rapid increase in accretion of Church Norton Spit since 2005, being negatively correlated with the rate of coastal erosion along the Pagham frontage. This change in accretion has been at a rate of approximately 106m per year over the 3 year period analysed (2005-2008) and is a significant change over the prior periods analysed, during which time coastal accretion varied between 4 and 22m/year, illustrating that the rate has increased towards the present, indicating a link between accretion and recent morphological development within the study site.

Analysis of changes in coastal configuration associated with accretion and erosion trends along transects 3 and 4 in particular, south and north of the tidal inlet, display a similar trend temporally in terms of erosion and accretion. However, since 1997 transects display a marked change in the correlation between erosion and/or accretion, which may be taken as indicating a shift in the previous dominant coastal processes and/or development of a feedback mechanism in and between the evolution of geomorphological units and the external forcing parameters of hydrodynamic conditions during this period of time.

The storage off significant quantities of littoral drift and offshore derived sediments since 1997 within the ebb tidal delta has resulted in the net effect that the shoreline sediments arriving from the west, no longer naturally bypass the harbour inlet, but are stored within the former tidal delta where they have contributed to rapid spit accretion. The incorporation of significant volumes of material (25,000m^3/year during 2005-2008) within Church Norton Spit has served to create a physical barrier to the ability of the tidal inlet to return to its preferred east-west orientation and shall continue to do so for the foreseeable future. However, better knowledge is required of how the ebb tidal delta came to expand rapidly since the 1997 becoming considerably larger in aerial extent, thus creating a wide inter-tidal area seaward of the coast which served to facilitate the accretion and rapid advancement of Church Norton spit. It is considered that the Inner Owers, a series of mobile nearshore gravel banks situated within close proximity to the Pagham Harbour inlet, which periodically migrate onshore are inextricably linked to this stage of morphological development of the ebb tidal delta and Church Norton spit.

The delineation of erosion and accretion along the Pagham frontage facilitates the mapping of distinct drift divides, which clearly illustrated a link in and between the growth of Church Norton spit and a corresponding shift in the locus of erosion along the Pagham frontage. This correlation can be assessed both temporally and spatially, initiating in the period post-1997 and continuing into the present. In summary, as Church Norton spit has accreted to the northeast, it has shifted the location of the drift divide in the corresponding direction due to the interplay of hydrodynamic conditions (predominantly waves) with changing bathymetric expression.

As highlighted in **Figure 3.2** (see **Section 3.3**), the tidal inlet during the period 1785-1843 occupied a similar position to that of today, in that it was orientated southwest to northeast. During this period extensive erosion of Pagham Beach occurred as the tidal inlet was deflected to this orientation. The advancement of Church Norton spit was fed by littoral drift from the erosion of cliffs at Selsey Peninsula. This contributed to the deflection of the tidal inlet, during which time the further accretion of the spit lead to the sealing of the harbour prior to the reclamation of the harbour in 1877. Episodes of breaching interrupted the spit extension in 1820, 1829 and 1840. As the spit extended and thinned during this 100 year period, there may not have been a significant supplementary supply from inshore sources (i.e. migratory bars associated with the tidal delta). This historic trend of similar orientation and spit accretion provides an important analogue for the contemporary and future development of the tidal inlet/spit system.

Again, in 1938, the coastal configuration was largely similar to that of today, with the exception of the extent of the Church Norton Spit, being volumetrically smaller, though similar in planform. The tidal inlet was also orientated roughly southwest to northeast and the inner harbour intertidal channels displayed a broadly similar configuration to those of today. This is of particular importance as it displays the role of inheritance in defining evolutionary pathways within the system by adopting prior orientations and locations.

The evolution and recent history of Pagham Harbour emphasises the highly dynamic nature of the area and the ability of the shingle spits to adjust and recover from extreme events. The presented information provides some insights into the formation and mechanisms controlling spit accretion. It is considered herein that the building of the shingle beach and growth of the spit is most likely the result of sudden onshore-directed storm waves, approaching directly onshore and carrying large amounts of shingle from a dominantly offshore source. Longshore drift of shingle then maintains and builds up the beach to form a spit which then tends to migrate towards the northeast under the dominant longshore drift regime.

Of importance in terms of future evolution and management options for active intervention to halt erosion along Pagham beach, is the historic tidal inlet position occupied close to Church Norton in 1947, after which time it gradually migrated northeast to its contemporary location. It is therefore justified that the tidal inlet could potentially occupy the same position again. The contemporary evidence for the successful functioning of the tidal inlet/intertidal channel creek system in this former position is the remnant intertidal channel and creek system within the southern extent of the present inner harbour.

As a consequence of sediment accumulation on the Church Norton Spit, the harbour entrance has extended to the northeast and in a landward direction. This is presently causing a thinning of the Pagham Spit, since it is deprived of material transported alongshore. However, it is considered that much of the material that has accumulated on the southern spit may be removed with the passage of the next large storm event. Such High-Magnitude Low-Frequency (HMLF) events have the capacity to transport substantial quantities of materials both on and alongshore. However, this capacity, in the form of energy to transport materials, is not readily available within Low-Magnitude High-Frequency (LMHF) events such as small changes to the predominant wave and tidal processes. Storm induced closure of the entrance would be a consequence of shingle being transported to block the existing entrance via ‘washover’ and ‘rollover’ mechanisms. This process is independent of siltation in the Harbour, which would serve to reduce the available tidal prism within the Harbour further reducing the potential for re-opening on the tidal inlet by natural means.

Until such times as the southern spit migrates landward under the process of barrier ‘rollover’, the tidal inlet shall become increasingly narrow. This shall serve to increase the speed of flow of currents in and out of the harbour which shall result in extensive erosion of Pagham Beach. This process has been demonstrated to be occurring at present and is expected to increase in severity prior to the sealing of the tidal inlet

Sediment accumulation within both Church Norton spit and the ebb tidal delta have the potential to grossly alter the position of the tidal inlet, which has cumulative impacts upon sediment transport patterns along the coastal frontage. While the inlet is in place, the ebb delta interrupts longshore drift by forming a physical barrier to the transport of materials shoreward. However, if the inlet were to close, this interruption would be removed. One of the major factors controlling this process is the future rate of sediment supply to Church Norton spit and the ebb tidal delta.

Currently the system is unbalanced morphologically with the available tidal prism. It is reasonable to assume that should current conditions continue into the foreseeable future, which is a reasonable assumption, the prism within the harbour will reduce, compared with present levels, as a result of continued sedimentation outstripping sea level rise.

Data has been presented regarding sedimentation rates within Pagham Harbour, which allow the conclusion to be drawn that the inner habour has been getting drier and is generally understood to be gradually silting up. This process will tend to reduce the overall competence of the mouth to be self-cleansing by reducing the available tidal prism. Indeed the channel at the mouth would probably be ephemeral now if not for the presence of control structures acting to constrain the position of the tidal inlet channel. This is further compounded by the natural rollover of Church Norton spit constraining the tidal channel, and in doing so increasing its length and decreasing its width. In conclusion, flushing processes and the ebb delta sediment budget have undoubtedly changed over the past four centuries due to reduction of the tidal prism of the harbour as a consequence of land claim.

Regime analysis may be required in order to assess the change in the tidal prism to the equilibrium form and then to calculate likely velocities within the mouth. This would facilitate an assessment on the stability of the current tidal inlet channel and whether the system shall become ephemeral without management of sediment and the presence of control structures acting to constrain the position of the channel.

The tidal prism in Pagham Harbour is small, and fluvial discharge into the harbour is relatively low. It is therefore possible that should the current regime of sedimentation within the inner harbour continue into the future, that the harbour could become infilled, leading to the closure of the entrance and subsequent creation of a lagoon. The issue of tidal prism is dealt with in the proceeding section.

4.12 Key points

- Barcock & Collins (1991) 5 year cyclic model illustrated a short period during which the tidal inlet channel was characterised by periods of channel avulsion and bifurcation and can not be taken as representing a cyclic model of tidal inlet migration that repeats, as it was based solely on a five year snap shot of tidal migration, that since its documentation has ceased to function accordingly.
- A qualitative assessment of ebb delta area by Barcock & Collins (1991) suggests that prior to 1982 the delta area was decreasing. However, since 1982 the area has increased considerably.
- The current trend towards erosion at Pagham Beach cannot be assessed without consideration of the stability of the tidal inlet to Pagham Harbour and its associated effect on the stability, or otherwise, of the adjacent shoreline.
- Temporal and spatial patterns of erosion and accretion are strongly linked to the position of the tidal channel and the spit.
- The position of the inlet's ebb tidal delta also provides a considerable interruption to the north-easterly littoral drift with the submerged bars acting

as a significant barrier to sediment transport and the ability of material to bypass these bathymetric irregularities.

- The storage off significant quantities of littoral drift and offshore derived sediments since 1997 within the ebb tidal delta has resulted in the net effect that the shoreline sediments arriving from the west, no longer naturally bypass the harbour inlet, but are stored within the former tidal delta where they have contributed to rapid spit accretion.
- Since 1997 there has been a marked change in the correlation between erosion and/or accretion, which may be taken as indicating a shift in the previous dominant coastal processes and/or development of a feedback mechanism in and between the external forcing parameters of hydrodynamic regime, sediment supply and geomorphological development during this period of time.
- There has been a rapid increase in the accretion of Church Norton Spit since 2005 at a rate of approximately 106m per year over the 3 year period analysed (2005-2008). This is a significant change over the prior periods analysed, during which time coastal accretion varied between 4 and 22m/year, illustrating that the rate has increased towards the present.
- It is considered that the Inner Owers, a series of mobile nearshore gravel banks situated within close proximity to the Pagham Harbour inlet, which periodically migrate onshore are inextricably linked to this stage of morphological development of the ebb tidal delta and Church Norton spit.
- The delineation of erosion and accretion along the Pagham frontage facilitates the mapping of distinct drift divides, which clearly illustrated a link in and between the growth of Church Norton spit and a corresponding shift in the locus of erosion along the Pagham frontage.
- As Church Norton spit has accreted to the northeast, it has shifted the location of the drift divide in the corresponding direction due to the interplay of hydrodynamic conditions (predominantly waves) with changing bathymetric expression.
- During the period 1785-1843 the tidal inlet occupied a similar position to that of today during which time extensive erosion of Pagham Beach occurred.
- This historic trend of similar orientation and spit accretion provides an important analogue for the contemporary and future development of the tidal inlet/spit system.
- Again, in 1938, the coastal configuration was largely similar to that of today. This is of particular importance as it displays the role of inheritance in defining evolutionary pathways within the system by adopting prior orientations and locations.
- It is considered that the building of the shingle beach and growth of the spit is most likely the result onshore-directed waves carrying large amounts of shingle from a dominantly offshore source. Longshore drift of shingle then maintains and builds up the beach to form a spit which then tends to migrate towards the northeast under the dominant longshore drift regime.

- As a consequence of sediment accumulation on the Church Norton Spit, the harbour entrance has extended to the northeast and in a landward direction. This is presently causing a thinning of the Pagham Spit.
- Storm induced closure of the entrance would be a consequence of shingle being transported to block the existing entrance via 'washover' and 'rollover' mechanisms. This process is independent of siltation in the Harbour, which would serve to reduce the available tidal prism within the Harbour further reducing the potential for re-opening on the tidal inlet by natural means.
- Until such times as the southern spit migrates landward under the process of barrier 'rollover', the tidal inlet shall become increasingly narrow. This shall serve to increase the speed of flow of currents in and out of the harbour which shall result in extensive erosion of Pagham Beach.
- Currently the system is unbalanced morphologically with the available tidal prism. This will tend to reduce the overall competence of the mouth to be self-cleansing.
- Flushing processes and the ebb delta sediment budget have undoubtedly changed over the past four centuries due to reduction of the tidal prism of the harbour as a consequence of land claim.

5 TIDAL PRISM ASSESSMENT

To calculate the tidal prism (the volume of water exchanged through the system through a single tidal cycle) a Geographic Information System (GIS) was employed. Input data, provided by Arun District Council, the Environment Agency and the Channel Coastal Observatory, comprised Lidar (2007) and bathymetry (2006) data and were amalgamated within a project specific GIS.

5.1 Tidal Data

The Mean High Water Spring (MHWS) and Mean High Water Neap (MHWN) levels as identified in the Beach Management Plan Report, Pagham Harbour (2007) were used for the analysis. The tidal levels are presented in **Table 5.1** for Management Units (MU) MU2 and MU2A (see **Section 4.5**) which are averaged herein to provide levels for analysis These water levels were taken to apply throughout the system, i.e. no adjustment for tidal resonance or stacking has been made and this should be recognised as a limitation in the analysis.

Table 5.1 Tidal levels along the Pagham frontage

	Tide height metres OD		
Tide level	MU2	MU2A	Average
MHWS	2.4	2.55	2.475
MHW	1.95	1.9	1.925
MHWN	1.5	1.25	1.375
MSL	0	-0.5	-0.25
MLWN	-1	-1.25	-1.125
MLW	-1.55	-1.9	-1.725
MLWS	-2.1	-2.55	-2.325
Spring range	4.5	5.1	4.8
Neap range	2.5	2.5	2.5

5.2 Tidal prism analysis

The tidal prism analysis is important as it provides fundamental data required for the Inlet Stability Analysis (ISA). Furthermore, the regime of the system has a relationship to this volume of water exchange (usually expressed to MHWS level) and its flow and sediment movement. As this is an in initial assessment, the work considered the inner harbour and the mouth of the system only. Results from the tidal prism assessment are presented in **Tables 5.2** to **5.5**.

Table 5.2 **Results of the tidal prism assessment MU2.**

	MU2	2D	Surface	Vol
MHWS	2.4	2722046	2735939	2958197
MHW	1.95	2305467	2317251	1797583
MHWN	1.5	1400016	1407101	1001176
MSL	0	147027	147447	40442
MLWN	-1	1	1	0
MLWN	-1.55	0	0	0
MLWS	-2.1	0	0	0

Table 5.3 **Results of the tidal prism assessment MU2A.**

	MU2A	2D	Surface	Vol
MHWS	2.55	2765063	2779256	3370144
MHW	1.9	2173267	2184581	1685495
MHWN	1.25	1153630	1158718	682428
MSL	-0.5	31606	31660	2879
MLWN	-1.25	0	0	0
MLWN	-1.9	0	0	0
MLWS	-2.55	0	0	0

Table 5.4 **Results of the tidal prism assessment average tidal levels.**

	Average	2D	Surface	Vol
MHWS	2.475	2747659	2761708	3163371
MHW	1.925	2243134	2254691	1740710
MHWN	1.375	1273603	1279608	834351
MSL	-0.25	70875	71036	15745
MLWN	-1.125	0	0	0
MLWN	-1.75	0	0	0
MLWS	-2.325	0	0	0

Table 5.5 **Results of the tidal inlet channel dimensions.**

	Average	2D	Surface	Vol
MHWS	2.475	823	832	2243
MHW	1.925	791	799	1796
MHWN	1.375	752	759	1372
MSL	-0.25	524	526	253
MLWN	-1.125	0	0	0
MLWN	-1.75	0	0	0
MLWS	-2.325	0	0	0

The lack of available prism at elevations below MSL suggests that the bed of the tidal inlet channel is sufficiently elevated above this level, that is to say the tidal water cannot enter into the inner harbour of Pagham on the flood tide until this elevation is attained. The elevation of bed level exerts a major control on the available prism within the inner harbour and the variance in water levels and their ability to enter and exit the system also helps describe the ebb dominance in the system near the mouth.

The approach taken has considered the tide at the entrance channel. This is used to determine the prisms within the inner harbour and has used the range of tides as the volume of exchange for velocity calculations (see **Table 5.6**).

Table 5.6 Tidal prism calculations.

Tidal Prism Volumes	
MHWN (2.39m ODN)	**MHWS** (3.50m ODN)
834,351	3,163,371
MLWN (-1.82m ODN)	**MLWS** (-2.75m ODN)
0	0
Available Prism MHWN-MLWN	**Available Prism MHWS-MLWS**
834,351	3,163,371
Q_{max}	Q_{max}
6,248	9,354
Maximum velocity (m/s^{-1})	**Maximum velocity (m/s^{-1})**
0.56	2.13

The average channel velocity has been calculated using the prism and cross section at the relevant tide level (note that these calculations do not account for any influence of freshwater input). The assessment of the present harbour prisms shows a considerable variation between MHWN and MHWS tides. The prism is around 2.3 Mm^3 greater on a spring tide than a neap tide and sediment transport potential of shingle material, therefore, occurs on spring but not neap tides.

5.3 Implications of sea level rise to tidal prism

Applying the various scenarios on the rate of sea level rise to existing tidal levels, the prisms were calculated. These have been presented for Sea Level Rise (SLR) to 2080, after UKCIP (2005) (see **Table 5.7**).

Table 5.7 Tidal prism calculations for sea-level rise scenarios to 2080 (UKCIP 2002).

Low Emissions – Low Sea-Level Rise Scenario (15cm)	
MHWN (1.551m ODN)	MHWS (2.651m ODN)
Prism m^3	Prism m^3
1,073,996	3,650,288
High Emissions – High Sea-Level Rise Scenario (122cm)	
MHWN (2.151m ODN)	MHWS (3.251m ODN)
Prism m^3	Prism m^3
2,295,293	5,340,276

Applying the rates of sea level rise to the topography, the prisms were calculated. Of note is the lack of variability in the results which reflects the relationship between the sea levels identified and the (fixed) topography. The results neglect erosion and the associated increase in tidal prism associated with the erosion and subsequent removal of saltmarsh and intertidal mudflats.

The assessment of the Low Emissions Scenario prisms shows a considerable variation between MHWN and MHWS tides. The prism is 2.57 Mm^3 greater on a spring tide than a neap tide. The assessment of the High Emissions Scenario prisms shows a considerable variation between MHWN and MHWS tides. The prism is 3.04 Mm^3 greater on a spring tide than a neap tide.

5.4 Summary and discussion of Prism Assessment

The existing channel is prone to sedimentation by shingle (or larger) sediment on a neap tide and subsequent re-working of shingle or finer materials predominantly on a spring tide. The channel is presently fixed in its current position and will have some competence to move larger sediments. It is likely that the flows are sufficient to move the largest available sediments that may be driven into the mouth by wave action on a spring tide. However, further to sea these sediments are likely to remain as a lag deposit, effectively armouring the bed.

6 INLET STABILITY ANALYSIS (ISA)

6.1 Background

The south coast has a morphological response where the sediment transport along the coast has the potential to block, or partially block, the mouth of estuary systems. The available sediment in the system has changed over time as a result of management of the coast. In simple terms, this is a relationship between the amount of sediment transported along the coast and the competence of the tidal inlet to move the sediment from its mouth as it arrives at/in it form the coast.

The competence of tidal inlets on the south coast has been modified by reclamation within the estuaries which has effectively served to reduce the available tidal prism and hence the flushing/sediment movement potential. Where there are increases in prism, as a result of realignment or sea level rise for example, the prism will increase and hence the potential to move sediments also increases. It should be recognised that the longshore sediment drift can overwhelm this capacity to move sediments. In the extreme a tidal inlet can be completely blocked by longshore transport. There is also the potential for a more ephemeral situation to develop whereby blockage occurs irregularly with subsequent break-through of the blockage by marine storms. This situation is entirely natural but clearly limits the natural functioning of the tidal inlet and leaves an uncertain environment if certain management is required. At the other extreme a tidal inlet may have such a flushing capacity as to erode away the bed and banks and alter the morphology significantly.

The typical response to potential blockage and stability issues along the south coast in the past has been to build training structures, dredge channels, by-pass sediments at mouths, and restrict channel widths to increase the competence for flushing through hard engineering solutions. To ascertain the extent of potential problem of sediment blockage for the Pagham tidal inlet (and the potential to create a system that has the ability to function in an unmanaged or only partially managed way) an analysis of inlet stability (ISA) is needed.

The tidal inlet at Pagham has formed as a result of a spit enclosing a tidal channel that separated Selsey Island from the mainland some time after 2000 years BP (Barcock, 1989). Since this time the channel has generally migrated northeast under littoral drift until such times as storms have breached the spit forming a new channel. One of the key factors affecting the growth and processes associated with an inlet is the stability of the inlet channel. The stability of the inlet channel is a function of the flow through the inlet, its cross sectional area and the rate of supply of material into the inlet.

6.2 Method for ISA

Inlet stability is an issue of the balance between the accumulation of sediment and the ability to move or re-move that sediment out of the system. The following steps have been applied to assessing the inlet dynamics:

- A review has been undertaken of available techniques with respect to their applicability to the physical environment of the Pagham Harbour tidal inlet and coastline and the changes under consideration. The approach has also

considered the data requirements to apply the techniques and, in line with this initial assessment, discounted those methods where data is not readily available.
- Data and information required to input to the preferred tools have been collated and reviewed.
- The inlet stability tools have been applied directly to the parameters of Pagham Harbour and its associated tidal inlet, leading to improved understanding of the present inlet behaviour and providing a means of assessing the relative impacts and implications on the tidal inlet processes of initial management options.

This approach has led to the application of three out of eight potential techniques. The more techniques that are applied the more robust the conclusion can be, however, at this high level initial assessment stage, three methods can be applied to consider the potential stability of the mouth of the estuary. The first two of these were effectively combined in the analysis stage for efficiency. The methods applied were:

- Brown Method/Escoffier Curves – The development of Browns' 1928 method by Escoffier (1940) was to assess the degree to which velocity has potential to mobilise sediment. This uses the cross sectional area of the channel and mean velocity. As the cross sectional area increases so does velocity to a point where further cross sectional increases lead to velocity decreases. If the mean velocity exceeds the critical velocity for sediment motion then either an unstable or stable inlet may develop; the curves identify which this is.
- Maximum Velocity Criteria – The peak velocity can be applied to the sediment mobilisation assessment using the relationship between the peak velocity and the critical velocity for sediment transport. Thus if the peak velocity exceed the critical threshold sediment will be swept from the estuary mouth and vice versa for sediment deposition.
- K_c Criterion – Gao and Collins (1994) developed the Brunn and Gerritson 'r' Factor (a dimensionless parameter for sediment by-passing of inlets) to include the freshwater flows and tidal characteristics to produce a coefficient of inlet stability (K_c)

6.3 Data Collation and Review for ISA

To apply the methods identified for Pagham, the following data are required as input parameters:

- Scientific 'constants' (e.g. acceleration due to gravity).
- Plan areas flooded under different water levels.
- Estuary tidal prisms under different water levels.
- Tidal characteristics.
- Longshore drift rates.
- Freshwater flows.
- Grain sizes of sediments at the estuary mouth.

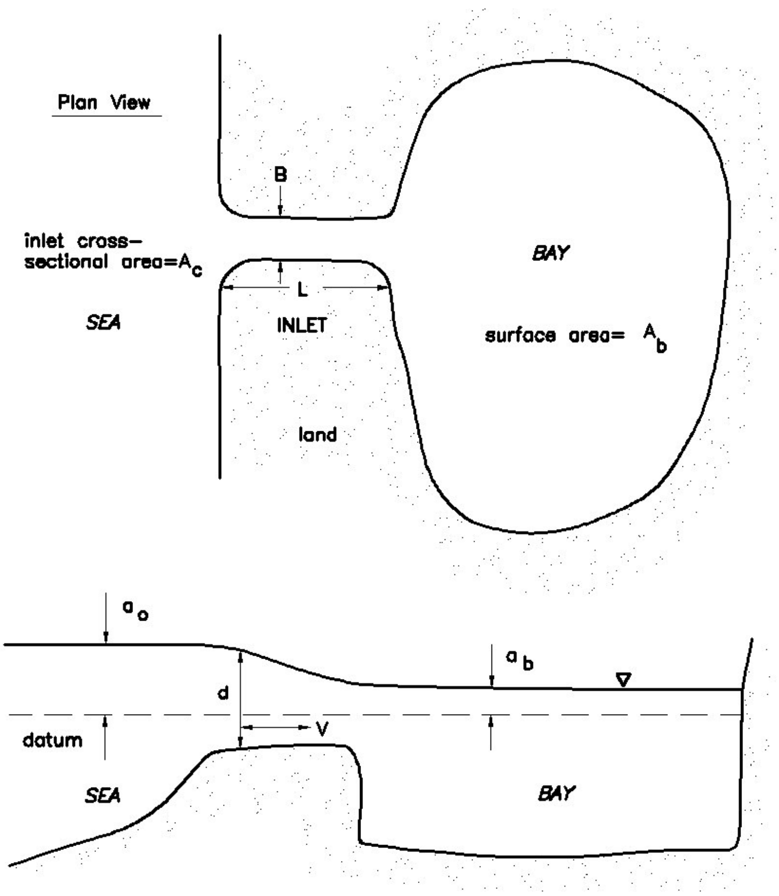
The plan form area and tidal prism assessment were undertaken as part of the Tidal Prism Assessment to inform the ISA (see **Section 5**). These assessments use the tidal characteristics and the same ones have been applied here. A review of the freshwater flow conditions has determined negligible input from this source.

Sediments at the inlet mouth are assumed to range in size from sand to gravel and cobbles. A D_{50} value has been applied of 5mm in diameter to the tidal prism assessment. However, gravel sizes of 50mm may also be commonly observed.

The variability in some parameters means that 'typical' values have been selected for application of the available inlet assessment techniques. This provides a feel for the differences that might exist but is not exhaustive at this stage. A sensitivity analysis around these results was applied to determine the relative importance of differences in these parameters. This is important for the inlet stability as larger sediment (cobbles) may remain as 'lag' deposits where finer material (sand and gravel) may be moved.

6.4 Application of Brown/Escoffier Method

Figure 6.1 Schematic layout of the assumptions underlying the Brown/Escoffier model of tidal inlet behaviour.



This inlet stability solution is that originated by Brown (1928) and subsequently expanded upon and more widely disseminated by Escoffier (1940). **Figure 6.1** shows the underlying physical assumptions of the method.

The system is assumed to consist of a bay, of approximately uniform depth, connected to the sea by a tidal inlet. The hydraulic characteristics of the inlet and the volume of the basin determine the behaviour of the system overall. There is a difference in water level between the basin and the sea outside the inlet, by virtue of the inlet constriction, which causes a time lag, and due to the bed roughness losses along the inlet channel. The bed roughness losses, which cause backwatering along the inlet channel, are a function of the length and cross sectional dimensions of the channel itself and upon the roughness characteristics of the bed.

In application of the method to the Pagham tidal inlet, it has been necessary to assume the system as a bay connected to the sea by a channel of nominal length. This allows the form and function between the available flood plain and mouth dimensions to be determined.

6.4.1 Application to Existing Channel

To understand more about how the system presently functions, the Brown/Escoffier method was applied to the existing channel situation. Resulting Brown/Escoffier curves are shown for present spring and neap conditions.

The critical threshold velocity (U_{crit}) for the mobilisation of 5mm diameter grain sizes is shown on all subsequent plots as a dashed horizontal line (1.005m/s^{-1}). The cross sectional area of the present inlet below MSL is taken to be 60.5m^2. **Figure 6.2** presents maximum velocity through the tidal inlet at spring tide, while **Figure 6.3** presents maximum velocity at neap tides.

Figure 6.2 **Maximum spring tide velocity, Ucrit 5mm**

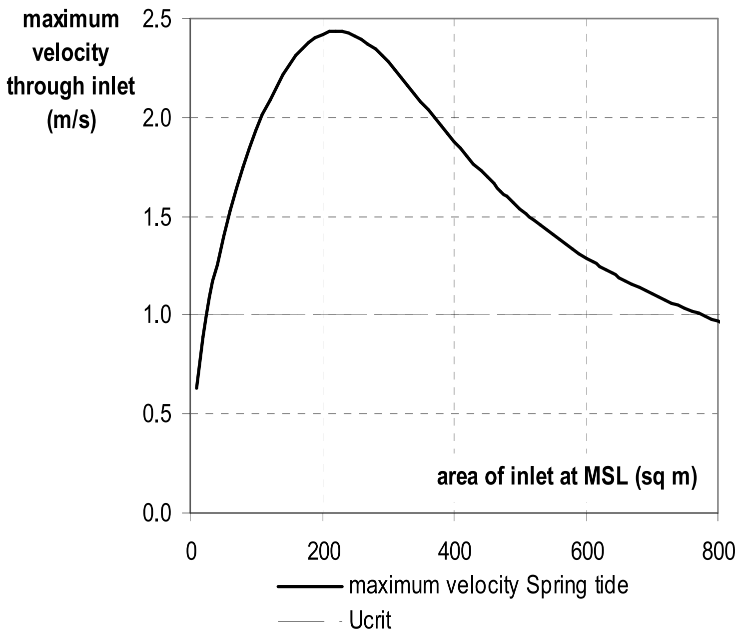


Table 6.1 presents critical threshold of velocity for sediment mobilisation (U_{crit}) for an increase in median sediment size to 10mm, 25mm and 50mm for both spring and neap tides.

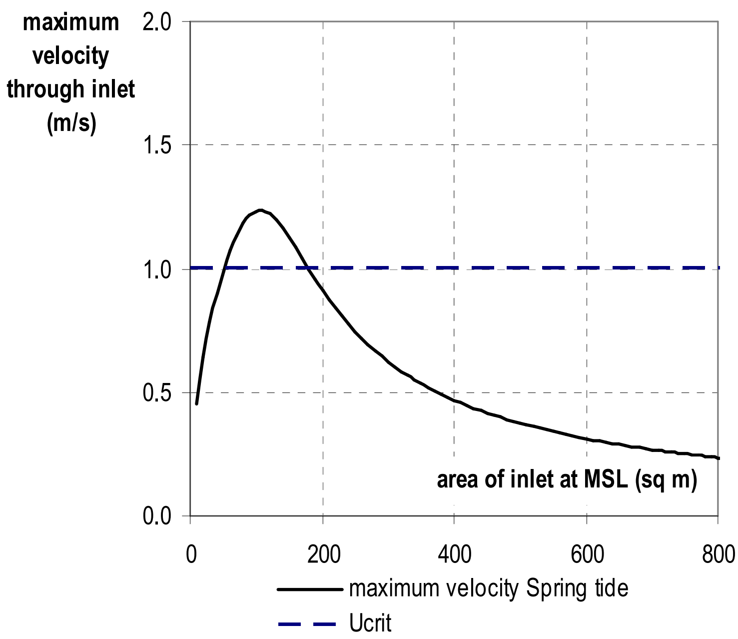
Table 6.1 **Median grain size variations and the critical threshold of velocity for sediment mobilisation.**

D50	Ucrit
1mm	0.436 m/s
5mm	1.005 m/s
10mm	1.331 m/s
25mm	1.843 m/s
50mm	2.357 m/s

From the plot (**Figure 6.2**), it can be seen that the maximum velocity created through the inlet is around 1.5m/s for a mouth cross-section area of around 60.5m^2 on a spring tide. This velocity is sufficient to mobilise sediment up to around 20mm in grain size and suggests that under existing conditions, spring tides help to keep the mouth from blocking with sediment.

If we consider the tidal exchange, the maximum velocities through the mouth remain sufficient to mobilise sand and gravels up to around 10mm or 25mm in size, respectively. The competence to move sediment smaller than 5mm in diameter would be maintained up to a cross sectional area of between 600 m^2.

Figure 6.3 **Maximum neap tide velocity, Ucrit 5mm**



On neap tides, however, the situation is very different. Assuming the maximum tidal exchange, for most of the time, peak velocities remain substantially below the critical threshold of motion for 5mm sized sediment. This suggests that there is insufficient competence in the system to self-maintain a channel on neap tides. The competence to move sediment smaller than 5mm in diameter would not be maintained if the cross sectional area was reduced further.

Based on these results, the tidal inlet has a tendency to infill at the mouth on neap tides and scour deposited material from the mouth on spring tides. Thus the existing system has a dynamic exchange on an on-going basis that has the potential to clear material away on spring tides. This is a logical result of the constriction to the mouth by the engineering works and highlights the natural variability inherent within the system.

6.4.2 Application to Existing Channel with Sea Level Rise to 2080

When factoring sea level rise estimates until 2080 into the above assessment (relating to increased tidal prism and plan area of the harbour within the present day defences), the inner harbour/tidal inlet becomes even more competent in its ability to self-scour during spring tides (see **Figures 6.4** & **6.5** for best and worst case scenarios respectively), with the average velocity now able to mobilise sediment up to around 10mm in grain-size diameter. The competence to move sediment smaller than 5mm in diameter would be maintained up to a cross sectional area of 800 m^2 under both scenarios.

Figure 6.4 Maximum spring tide velocity under a low emissions (best case) sea-level rise scenario until 2080

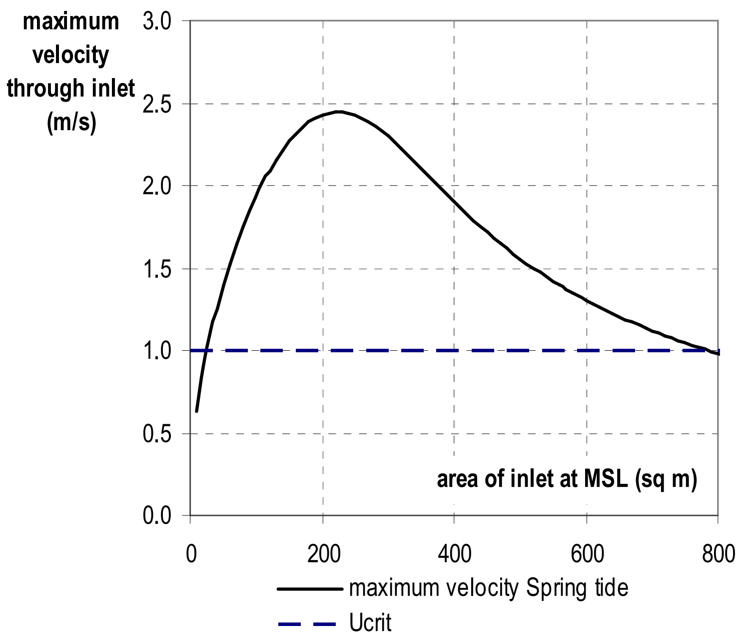
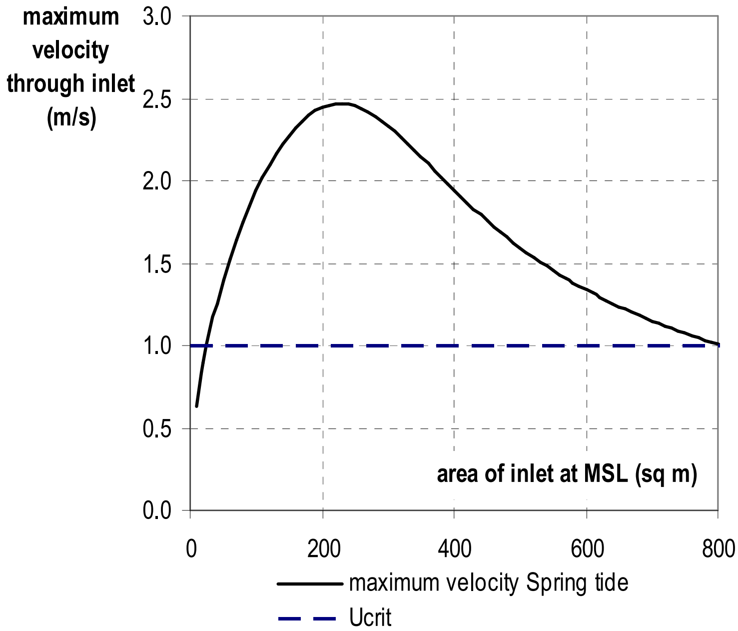


Figure 6.5 Maximum spring tide velocity under a high emissions (worst case) sea-level rise scenario until 2080



On neap tides the flushing potential of the estuary also improves, but only 10mm sized sediment can be mobilised and any increases in cross sectional area would mean deposition of sediment. There will therefore remain a tendency to infill on neap tides with sediment.

Figure 6.6 Maximum neap tide velocity under a low emissions (best case) sea-level rise scenario until 2080

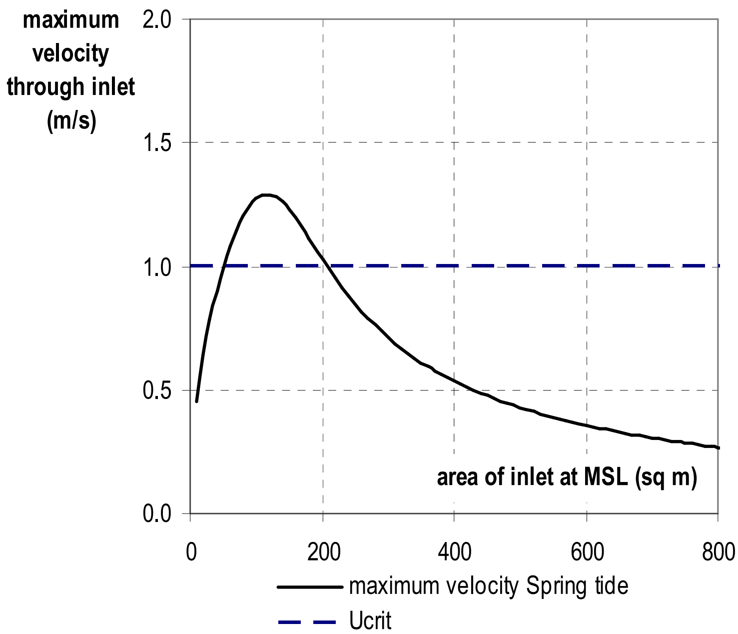
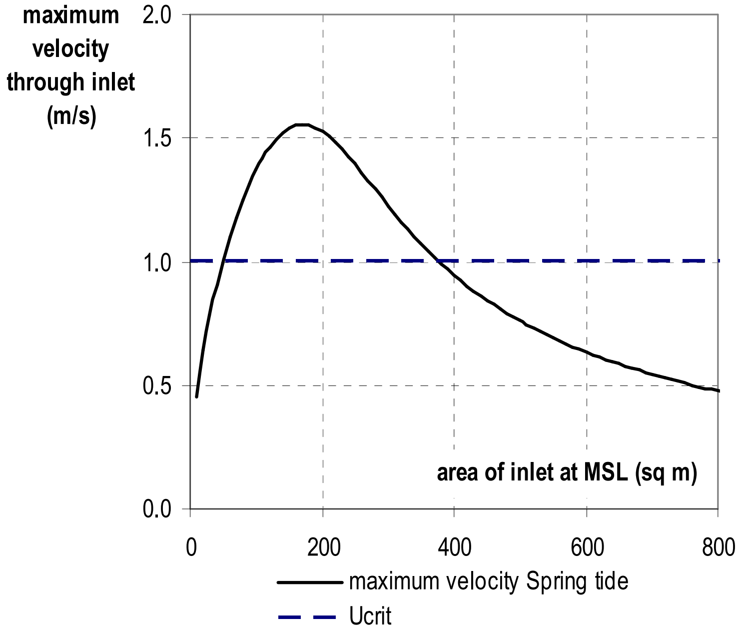


Figure 6.7 Maximum neap tide velocity under a high emissions (worst case) sea-level rise scenario until 2080



For the purposes of this assessment, it has been assumed that the mouth configuration under the various sea-level rise scenarios would, at least initially, remain as the present day. The spring tide conditions indicate the increase in prism would increase to the point that the existing mouth cross-sectional area would accommodate a flow of around 2.5m/s. This would not be possible and the mouth would become eroded, resulting in its deepening and widening until the velocities dropped to below critical thresholds and a new equilibrium, with a substantially different configuration, was established.

Under neap tide conditions, no significant changes would occur and the tidal inlet, assuming its present dimensions, would experience velocities of around 1.25-1.5m/s (**Figure 6.7**). These flow velocities would not tend to erode the tidal inlet mouth configuration, and there would be no corresponding increase in its cross-sectional area to accommodate the small increase in flow.

The Brown/Escoffier curves show that the existing channel has excellent competence to move sediments on the spring tides but insufficient competence on the neap tides. This suggests that the bed bathymetry would be variable between these tidal states but flushing is achieved using the defined cross section. It is likely that as the tidal range varies through the year, greater or lesser accumulations occur on neap tides. The channel would respond to neap tides by sedimentation in the channel and narrowing of the channel width (potentially down to 10m) through the formation of shoals. These may persist for some time where tidal ranges are generally lower. Above mean high water spring level this sediment is likely to be flushed out. It should be noted that this relates to sediment of a size of 5mm and hence sediments of greater size may accumulate and remain as a lag deposit in the channel, potentially armouring the bed and finer sediments beneath and leading to the need to dredge the channel.

The introduction of a tidal prism associated with sea-level rise to 2080 makes a marked effect to the functionality of the system and would see excessive velocities through the existing mouth. Spring flows are high enough to maintain a very wide mouth. This is still balanced with the neap flows where there is a relatively lower competence where 5mm sized sediment would be transported. This suggests a highly variable system where dynamic changes to channel position and size would occur between spring and neap tidal cycles.

6.5 Application of Gao & Collins Method

The stability criterion developed by Gao and Collins (1994) defines the relationship between longshore sediment transport and volume of tidal exchange and freshwater discharge over time. Gao and Collins categorised stability according to the value of a stability factor termed K_c. Ranges of K_c are used to define stability classes (presented in **Table 6.2**) which describe both the nature and degree of the inlet stability. This approach does not relate to stable channel widths as in the prism assessment and Brown/Escoffier methods but, rather describes the morphological stability that can be expected to develop.

(The colours used for each class in this table have been applied consistently to subsequent tables for ease of reference. Stable forms are shown in green. The moderate to low stability are shown in yellow and orange. The very ephemeral and changeable condition of an unstable mouth is highlighted in red).

Table 6.2 - **Gao and Collins' K_c values and stability classes**

Kc range	Stability Class		Stability
150 < Kc	Good conditions, good flushing. Minor bar	Extremely high stability	↑
100 < Kc < 150	Bar usually more offshore	High stability	
50 < Kc < 100	Large bar by entrance, but usually a channel through bar	Moderate stability	
20 < Kc < 50	Typical bar-bypasser – storm events provide flushing	Low stability	
Kc < 20	Very unstable inlets, mainly just outflow channels	Highly unstable	

6.5.1 Application to different changes

Table 6.3 presents results for a variety of longshore drift rates (see **Table 4.4** in **Section 4.6**), applied to the the Gao & Collins Method using readily available data and that generated through this project. **Table 6.3** shows the results for the change situations considered and applies the contemporary as well as 'best' and 'worst' case sea-level rise scenario 2080 spring and neap conditions. This matrix helps to understand the range of variation that might occur and indicate which factors may have more or less control on the spread of results.

Table 6.3 **Gao & Collins Kc values and stability classes for various longshore drift rates under a range of tidal prism scenarios.**

Scenario	Tide	Longshore drift rates (m^3 per year)					
		10,000	20,000	30,000	42,000	50,000	76,000
Existing	Spring	316.34	158.17	105.45	75.32	62.27	41.62
	Neap	83.44	41.72	27.81	19.87	16.69	10.98
SLR 2080 Low emissions Scenario (best case)	Spring	365.03	182.51	121.66	86.91	73.01	48.03
	Neap	107.4	53.7	35.8	25.57	21.48	14.13
SLR 2080 High emissions Scenario (worst case)	Spring	534	267	178	122	107	70
	Neap	229	115	77	55	46	30

These results demonstrate that, presently, the tidal inlet is not stable on neap tides, but becomes more stable on spring tides. The tidal inlet displays low to moderate stability under contemporary neap tide conditions. High stability only occurs under a spring tidal regime supplemented with a sediment drift rate to the lower end of the range presented (10 – 20,000m^3). This situation is proven to improve slightly under the best (low emissions) sea level rise scenario and improve considerably under the worst (high emissions) scenario (when only considering its effects on the available tidal prism). Increased tidal prism helps to maintain a more stable inlet, as the system is typically ebb dominated.

6.5.2 Sensitivity test to Longshore Drift Rates

To test the sensitivity of the system to a variety of longshore drift rates further application of the Gao & Collins method was undertaken. The results, shown in **Table 6.4** presents required increases in longshore drift rates required to attain contemporary stability under spring and neap tidal conditions by 2080 under low emissions and high emissions scenarios. The table presents calculated Kc inlet stability factors for different longshore drift rates (Kc (2).

Table 6.4 Changes in longshore drift rates (kc (2)) to reach currently stability class under future sea-level rise scenarios.

Regime		Kc (1)	P	Tp	Qf	M	Kc (2)
Existing	Spring	41.6	3163371	44712	0	76,000	14.16
	Neap	10.9	834351	44712	0	76,000	10.9
Required changes to longshore drift rates to attain similar scenarios to the present regimes							
Low Emmision scenario	Spring	48.03	3650288	44712	0	**87,500**	41.72
	Neap	14.13	1073996	44712	0	**98,000**	10.96
High Emmision scenario	Spring	70	5340276	44712	0	**130,000**	41.08
	Neap	30	2295293	44712	0	**210,000**	10.93

If we consider that longshore drift rates could also increase (with future management options of the coast potentially liberating sediment and sea level rise/climate change affects) we can see that we need to increase the longshore sediment transport to 210,000m^3 to reduce the stability to present day (existing channel) levels for a worst case scenario and to some 87,500 m^3 for a best case scenario.

If longshore drift rates are confirmed to be nearer the 20,000 m^3/year end of the range, then the proposed scheme would create an extremely highly stable inlet (more stable than the present day). If, on the other hand, the rates are confirmed to be nearer to 100,000 m^3/year, then the inlet would remain incompetent on the neap tides (although the situation will be improved slightly compared to the present day) and would rely on spring tides to maintain an inlet.

6.5.3 Assessing prism size for a stable inlet

The Gao & Collins' equation can be re-ordered so that a tidal prism can be defined for a given *Kc* stability parameter and longshore drift rate. **Table 6.5** present the results from such an assessment for an extremely highly stable, highly stable and moderately stable tidal inlet respectively.

Table 6.5 Tidal Prisms required to generate various tidal inlet stability scenarios.

Stability	Longshore Drift Rate (m^3/year)		
	10,000	42,000	76,000
Extremely highly stable (Kc >150)	1,500,000 m^3	6,300,000 m^3	11,500,000 m^3
Highly stable (Kc >100 <150)	1,000,000m^3	4,250,000 m^3	8,250,000 m^3
Moderately stable (Kc >50 <100)	525,000m^3	2,125,000 m^3	4,000,000 m^3

These results indicate that, for an inlet of the highest order of stability to be created (Kc >150) in the face of no freshwater flow and longshore drift rates along the coastline of 76,000 m^3/year, a tidal prism of 11,500,000 m^3 is necessary. Under similar input conditions, an inlet of moderate stability (Kc > 50) could be created through the introduction of a prism of 8,250,000 m^3. The present harbour has a tidal prism on spring tides of 3,163,000 m^3.

6.6 Summary and discussion of ISA

Material entering the tidal inlet will have a choking effect, restricting flow through the channel. To regain stability, the channel must move this material via tidal currents towards the ebb tidal delta. The ebb tidal delta size will therefore be dependant upon the ability of the system to move this sediment seaward and the rate of littoral drift. As historically the main source of material has been from littoral drift, the channel has migrated in the direction of this predominant drift system. The ISA presented herein has demonstrated that the harbour/tidal inlet is currently characterised as being of low stability as it does not have the required competence to transport littoral drifted materials towards the contemporary ebb delta.

Given the physical setting of Pagham Harbour and its associated tidal inlet, and the data availability, the Brown/Escoffier and Gao & Collins Methods of inlet stability analysis are best suited to this study. Both methods are semi-empirical tools used to assess the sensitivity of inlet behaviour to changes in tidal inundation capacities and longshore drift rates (Gao & Collins Method) or mouth dimensions (Brown/Escoffier Method). By using the two tools in combination, a good overall picture of inlet stability can be obtained from two independent methods.

Under the present day configurations, it is estimated using the Brown/Escoffier Method that mean velocities through the estuary mouth at time of peak tidal discharge are around 1.5m/s on a spring tide. This velocity is sufficient to mobilise sediment up to 50mm in grain size diameter.

At spring tides the average velocity at peak tidal discharge remain sufficient to mobilise sediment typically characteristic of the estuary mouth (5mm in grain size diameter) and will still mobilise 20mm sized granules. On a neap tide, however, the present day situation is very different and mean velocities at time of peak tidal discharge are insufficient to mobilise sediment of 10mm in grain size diameter. These findings indicate that at present the inlet has a tendency to start to infill on neap tides, but scour sediment from the mouth during spring tides.

When considering the effect of sea level rise until 2080, the self-scouring effect during spring tides becomes even more pronounced and this may, if left to natural processes, result in enlargement of the cross-sectional dimensions of the mouth to accommodate the increased velocities at time of peak tidal discharge. During neap tides, however, there would remain a tendency to infill with sediment (albeit to a lesser extent).

Through use of the Gao & Collins Method, assessments of inlet stability can incorporate consideration of longshore drift rates of sediments along the open coast to the inlet mouth. Results for the present day base case (assuming a mid-range rate of longshore drift) support the Brown/Escoffier findings in that the tidal inlet is relatively incompetent and unstable on neap tides, but improves in stability during spring tides.

The effect of sea level rise on tidal prism alone results in an improvement in stability conditions up to 2080, but sea level rise could also result in increased longshore drift rates, meaning that the future system is likely, overall, to behave similarly to the present day in terms of conditions at the mouth. If there is no additional sediment then increased stability will result.

The system is relatively sensitive to longshore drift rates. If the longshore drift rate is assumed to be 20,000m^3/year (the lower end of the range of rates in published literature) the present day configurations are typically moderate to low (neap tide) to high (spring tide). If a drift rate of 12 - 50,000m^3/year is assumed (the higher end of the range of rates in published literature) the present day configurations range from highly unstable (neap tides) to moderate stability (spring tides). This variability in longshore drift rate has implications for the proposed approach as the system would be dependent on spring tides to maintain the channel at the mouth.

The tidal prism required to create a ‘moderately stable’ inlet in the face of a longshore drift rate of 76,000m^3/year and no freshwater flow is of the order of 4.0Mm^3. The present day spring tidal prism lies just below this value, but the neap tidal prism is considerably below.

6.7 Key points

- The Inlet Stability Analysis (ISA) has demonstrated that the harbour/tidal inlet is currently characterised as being of low stability as it does not have the required competence to transport littoral drifted materials towards the contemporary ebb delta.
- Material entering the tidal inlet will have a choking effect, restricting flow through the channel.
- These findings indicate that at present the inlet has a tendency to start to infill on neap tides, but scour sediment from the mouth during spring tides.
- When considering the effect of sea level rise until 2080, the self-scouring effect during spring tides becomes even more pronounced and this may, if left to natural processes, result in enlargement of the cross-sectional

dimensions of the mouth to accommodate the increased velocities at time of peak tidal discharge. During neap tides, however, there would remain a tendency to infill with sediment (albeit to a lesser extent).

- Results for the present day base case (assuming a mid-range rate of longshore drift) support the Brown/Escoffier findings in that the tidal inlet is relatively incompetent and unstable on neap tides, but improves in stability during spring tides.
- The effect of sea level rise on tidal prism alone results in an improvement in stability conditions up to 2080, but sea level rise could also result in increased longshore drift rates, meaning that the future system is likely, overall, to behave similarly to the present day in terms of conditions at the mouth. If there is no additional sediment then increased stability will result.
- The system is relatively sensitive to longshore drift rates.
- The tidal prism required to create a 'moderately stable' inlet in the face of a longshore drift rate of 76,000m^3/year and no freshwater flow is of the order of 4.0Mm^3. The present day spring tidal prism lies just below this value, but the neap tidal prism is considerably below.

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