Evaluation of coastal process impacts arising from nearshore aggregate dredging for beach recharge – Shingles Banks, Christchurch Bay

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Abstract

Although monitoring is a requirement of all aggregate production licences (within the UK), this generally relates to examination of physical or biological impacts within, or immediately adjacent to, the dredging area. Relatively few licences require detailed monitoring of the coastal zone, as aggregate dredging-areas are usually in relatively deep water (>20m) and some distance from the shoreline.

Post-dredging responses of the Shingles Banks dredging area; shoreline; and nearshore bathymetry of Christchurch Bay and Western Isle of Wight, are examined, in relation to a nearshore shallow water aggregate dredging programme for beach recharge of Hurst Spit. Data from an intensive 6-year programme of field monitoring and analysis has been compared with pre-dredging coastal process impact assessments, based largely on numerical modelling. Surveys have been integrated within best practice local and regional schemes of shoreline management and monitoring, to identify patterns of erosion and accretion. Changes have also been monitored at control sites, outside of the potential influence of the dredging area.

Conditions in the shelter of the offshore banks have been shown to be less severe than numerical modelling methods have previously suggested. Conversely, the offshore wave climate, to seawards of the dredging area, has been more severe than long-term statistical modelling methods have predicted; this suggests increased storminess over the analysis period. Shoreline responses demonstrate that beaches on the shoreline of the Isle of Wight have not been affected by dredging activity. Beaches have remained stable, despite increased storm activity. Offshore bathymetric surveys have demonstrated considerable movements and continued evolution of a dynamic offshore bank system, in response to wave and current action; this has remained in context relative to historical patterns of movement

Some of the risks, uncertainties and conflicts, associated with nearshore aggregate dredging for beach recharge purposes, are highlighted. The benefits of intensive aggregate-licence monitoring requirements, and co-operation between local authorities are demonstrated, providing a robust analytical approach to coastal process impact assessment of nearshore dredging.

Introduction

Aggregate dredging within the coastal zone may create a range of conflicts, uncertainties and opportunities. Demand for high quality aggregates from offshore sources is high, especially for beach recharge. There is considerable concern however, particularly from Local Authorities, that the dredging will have adverse impacts on the coastal zone.

Coastal process impact studies are required to inform aggregate production licence applications within the U.K. Numerical models are usually used as pre-dredging impact-evaluation tools, yet the results and robustness of these studies are often questioned by the coastal community at the time of application (Simons and Hollingham, 2001). When significant changes occur at the shoreline following dredging activity, it is difficult to prove or disprove that the impacts have arisen as a direct consequence of the dredging. Intensive pre- and post- dredging monitoring of: wave climate; dredging area responses; nearshore bathymetry and shoreline changes can provide the necessary tools to assess the validity of coastal process impact studies. In many instances post-dredging monitoring programmes are of limited value however, since lengthy pre-dredging control data sets are infrequently available for comparison.

This paper examines results from a monitoring programme, in compliance with licence conditions for the Shingles Banks dredging area. The results are examined in context with predictions derived from pre-dredging coastal process impact studies. Trends are examined by reference to control data sets, derived in conjunction with Local Authorities' best practice coastal zone management programmes. The significance of high quality baseline data, validity of modelling methods and appropriateness of measurement techniques are examined.

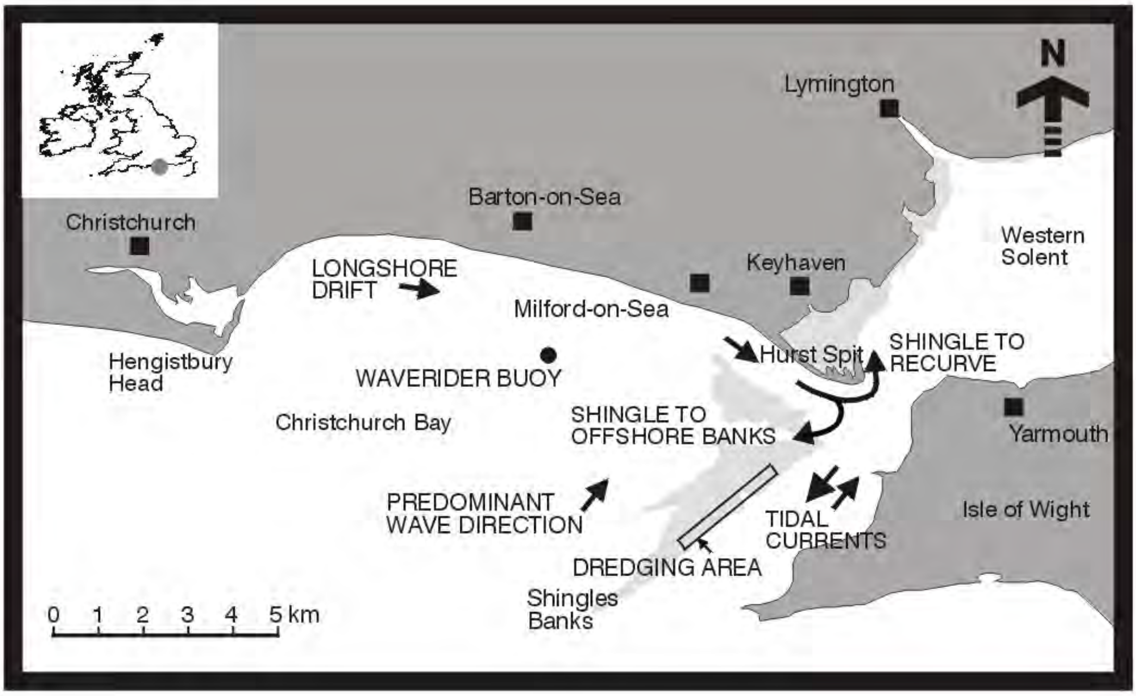

Figure 1 Location map – Christchurch Bay UK

Pre-dredging coastal process impact assessments

The conventional UK approach to pre-dredging coastal impact assessment was adopted for these investigations (Simons and Hollingham, 2001). Procedures included (a) assessments of potential changes in nearshore wave conditions, arising from the bathymetric changes caused by dredging, (b) the consequent potential impacts on the shoreline and (c) assessments of the impacts of dredging on sediment transport paths and seabed mobility.

Dynamics of the study area – historical evolution

The Shingles Banks system comprises mobile sand and shingle and is the major offshore sediment sink in Christchurch Bay. The total volume of the Shingles Banks system was estimated at approximately 42 million m^3, during prospecting investigations (Velegrakis, and Collins, 1991, 1992). A small surface emergent area of mobile sediment is exposed regularly; this represents a volume of approximately 15,000m^3. The local perception is that this surface emergent component is the most significant element of the Shingles Banks; in reality this area represents a tiny fraction of the total mobile bank volume (0.04%). A pre-dredging assessment of bathymetric changes in Christchurch Bay, based on historical chart analysis (1882-1988), identified that the Shingles Banks system was highly dynamic (Bradbury, 1992). Net growth of more than 3 million m^3 was measured for the analysis period, although large-scale spatial and temporal variations in patterns of erosion and accretion occurred, and the accuracy of surveys is uncertain. Field studies of seabed mobility, including sidescan sonar, have concluded that the system is highly mobile and that sediment is derived from the beaches of Christchurch Bay (Velegrakis, 1994). Trends were extrapolated forward, assuming that natural evolution would result in continued growth. The proposals for dredging from the Shingles Banks, for use as a beach recharge source, was essentially a recycling solution.

Wave modelling

The basis for prediction of the impacts of pre- and post- dredging bathymetry scenarios on nearshore wave climate is numerical wave transformation modelling. Transformation of offshore wave conditions to a series of nearshore locations (Figure 2) identifies comparative changes in wave direction, period and nearshore wave height, arising from hypothetical modifications to the bathymetry. Comparisons of a range of dredging scenarios allowed an examination of the impacts for the removal of up-to 500,000m^3 of material (Wimpey, 1993). A factor of safety is included within these assessments, since only 300,000m^3 was to be dredged. A long-term synthetic offshore wave climate (Hydraulics Research, 1989a,b), extrapolated to determine a range of extreme conditions, has provided input conditions for wave transformation modelling (Bradbury, 1998). Extreme wave conditions are used, since these identify the greatest changes to nearshore wave conditions arising from modified bathymetry. If transformations arising from extreme conditions show no changes for alternative scenarios, then less severe events are highly unlikely to impact on near-shore wave climate.

Criteria for an acceptable impact at the coastline is such that any change in nearshore wave climate, predicted as a consequence of dredging, is considered of significance; in such an instance the licence will be refused. A nil effect is assessed by reference to the limitations of the modelling methodology, and scatter of data within the limits of model resolution (Simons and Hollingham, 2001). A threshold change of less than 3% is typically stated to identify limits of the accuracy and scatter of the modelling methodology, although this may be greater in situations where non-linear processes, such as bed friction and wave breaking, are significant. The complexity of the bathymetry across the Shingles Banks limits the precision of numerical modelling at this site. Modelled wave transformations, determined for pre- and post- dredging bathymetry scenarios, suggested that the dredging programme would have no significant impact on nearshore wave conditions. Many consultees view the modelling process with some degree of scepticism; this is perhaps not surprising since the wave transformation processes and modelling techniques are complex. The outputs of the numerical models and the real coastal impacts of post dredging are rarely tested, however. Transparent validation of the modelling techniques would provide greater confidence in the coastal process impact assessment procedures.

Pre-dredging shoreline evolution

Historical records of coastal evolution provide the basis for long-term predictions of coastal change, coupled with regional wave climate studies and modelling. Local practice within Christchurch Bay provided a solid monitoring baseline, dating back to 1987, against which future changes could be assessed. Analysis of Christchurch Bay beach-profile data identified declining beach volumes prior to dredging, hence the need for recharge at Hurst Spit. No such control data sets were available for the Western Isle of Wight, however.

Dredging licence monitoring programme overview

Intensive post-dredging monitoring was undertaken along the shorelines of both Christchurch Bay and the Western Isle of Wight, between 1996-2003; this programme followed a pre-dredging baseline survey, which took place in 1996. Dredging was conducted over a six-month period commencing in August 1996 (Bradbury and Kidd, 1998). Quarterly beach surveys and annual nearshore bathymetric surveys have been analysed together with detailed bathymetric surveys of the dredging area (quarterly) and Shingles Banks system (biannual). Measurements of morphodynamic responses have been supplemented with continuous tide and wave recording, further numerical modelling and biological sampling within the dredging area.

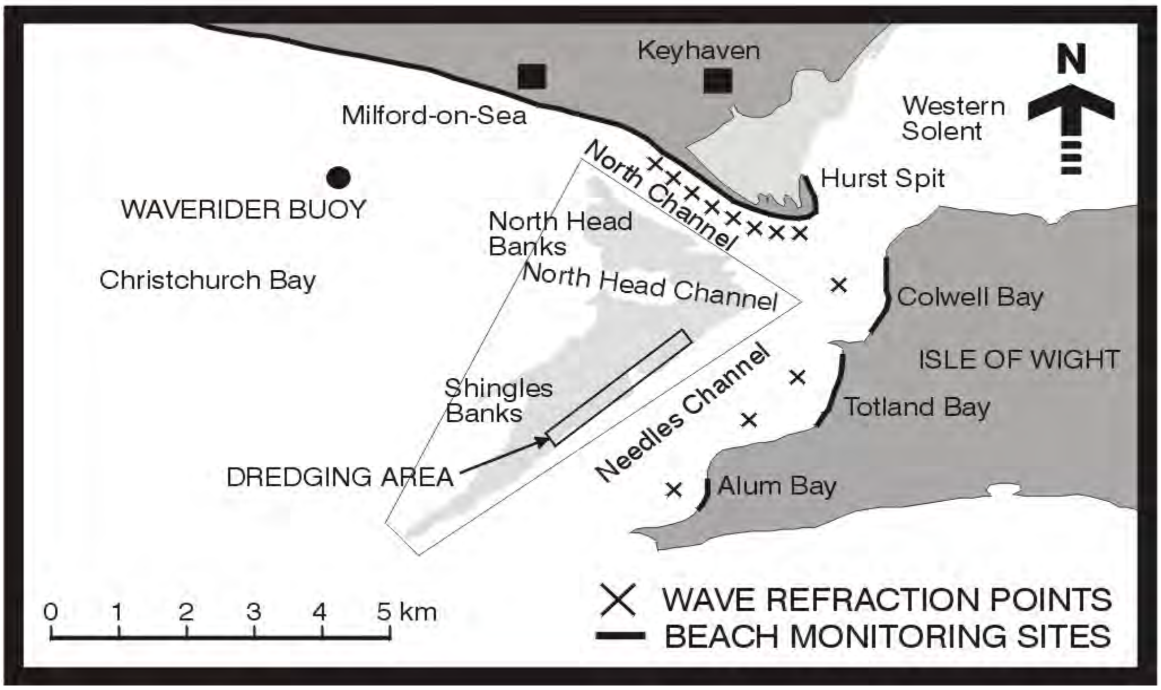

Figure 2 Layout of monitoring and modelling programme

Wave climate

A long-term waverider buoy deployment was sited in approximately 10-12m water depth, west of the dredging area (Figure 2); this is outside of the possible influence of the Shingles Banks dredging area, as the predominant wave direction is from the southwest. As such, the waverider is located at a local control site. Wave measurement has not previously formed part of a post-dredging coastal-impact monitoring programme. Data from the wave buoy site has been compared with synthetic offshore wave data that has subsequently been transformed to the wave buoy site, by numerical modelling. A comparison of a one-month sample of measured and synthetic data (Figure 3) indicates a strong correlation between measured and modelled conditions (Figure 4); this provides confidence in (a) the offshore synthetic wave data (b) the numerical wave transformation process and (c) the wave buoy measurements.

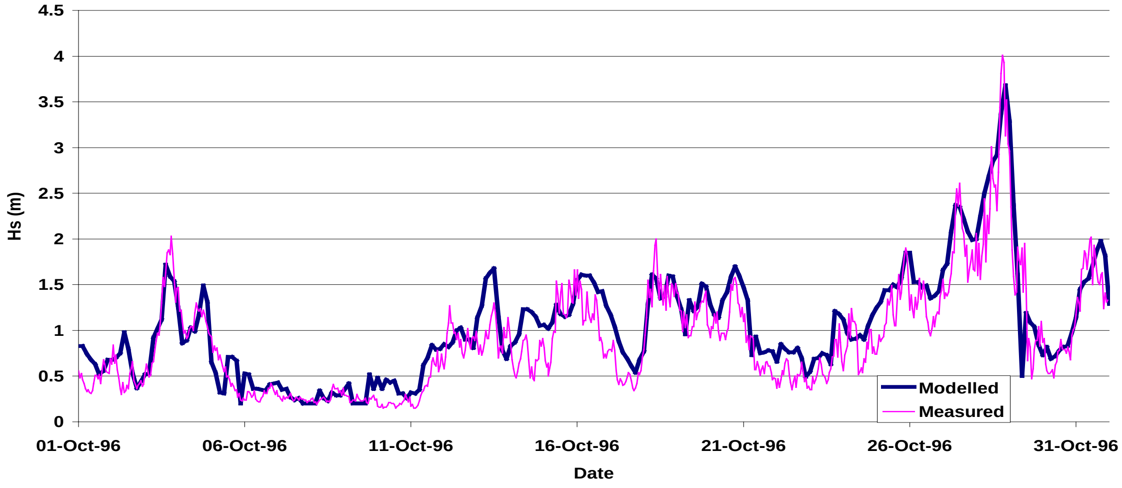

Figure 3 Comparison between modelled and measured wave heights at Milford-on-sea Waverider site

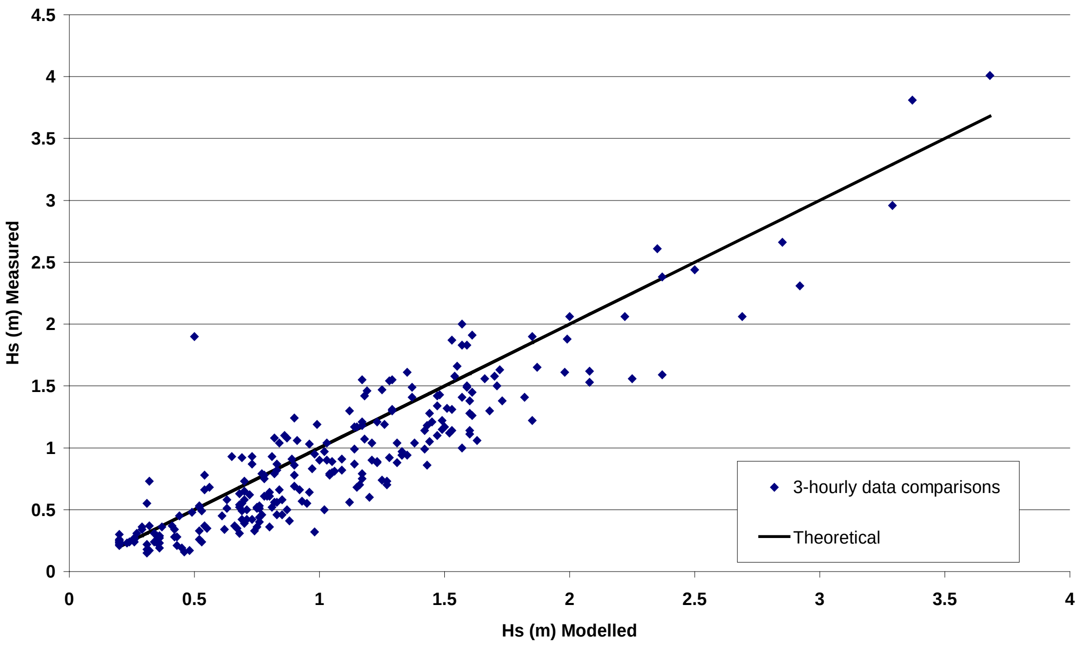

Figure 4 Correlation between modelled and measured wave heights at Milford-on-sea Waverider site

Pre-dredging wave climate studies were completed in 1989 on the basis of 16 years synthetic wave data (Hydraulics Research, 1989b). Extrapolation of a 3-parameter Weibull distribution provides extreme conditions; these were transformed to the waverider buoy site. Subsequently, the 1:100 year return period event (3.32m) calculated for this site (Hydraulics Research, 1989a), has been exceeded on 16 occasions (Figure 5); this demonstrates that either (a) the time series used for determination of extremes was too short, (b) the frequency of extreme events has increased locally during the past 13 years or (c) both. The increased severity of nearshore wave conditions implies that a higher degree of erosion might be expected under these circumstances, than during the pre-dredging control baseline period.

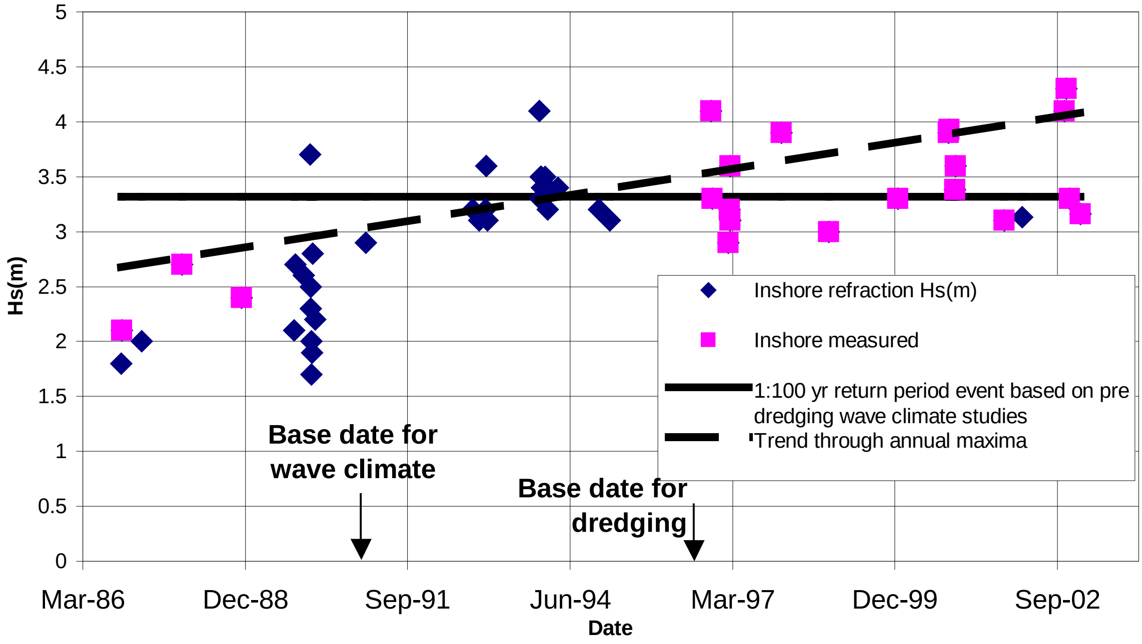

Figure 5 Temporal distribution of nearshore storm events resulting from storms with an offshore significant wave height >5m 1986-2003

A short-term pre-dredging deployment of the buoy, in the shelter of the Shingles Banks, adjacent to Hurst Spit demonstrated that the same numerical model provides a significant overestimate of nearshore wave heights at this site (Figure 6).

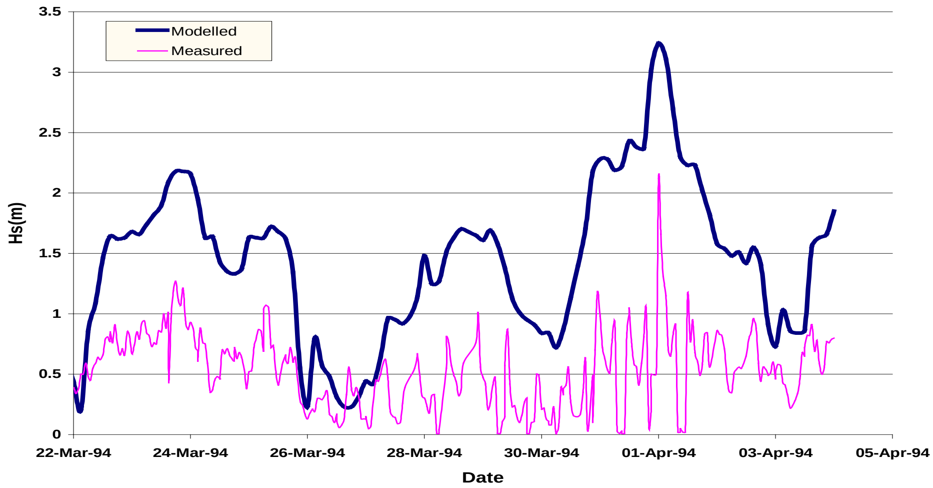

Figure 6 Comparison between modelled and measured wave heights at North Channel Waverider site

The poor correlation at the North Channel location is explained by the presence of non-linear wave transformation processes that are not well represented within the model. The complexity of the bathymetry and shallow water conditions across the Shingles Banks are such that bed friction and wave breaking are significant controls on wave height. A clear tidal signature is evident within the wave time- series, at the buoy site. Despite the limitations of the modelling methodology for this complex location, the modelling process provides conservative results.

Shoreline response

The mixed shingle-sand beaches of Hurst Spit and Milford-on-Sea (Figure 1) have been monitored since 1987, as part of a long-term beach management survey programme, thereby providing temporal controls on pre-dredging trends. Control sites at Milford–on-Sea are on broad unmanaged beaches that are outside of the influence of both the Shingles Banks and coastal structures. The control sites generally demonstrated a declining beach volume prior to dredging. Hurst Spit is a mixed shingle-sand barrier beach, whilst the fringing beaches of the Western Isle of Wight are backed by cliffs (Colwell and Alum Bays) and by a nearly vertical seawall with a recurve (Totland Bay). The shorelines of both Hurst Spit and the Isle of Wight are protected by the offshore Shingles Banks system. Regrettably no high quality pre-dredging beach performance data was available for the Isle of Wight shoreline. Beach cross-section changes were monitored relative to an initial master profile baseline survey, conducted immediately prior to the dredging programme (1996). The shoreline response data is compared with (a) Pre- and post-dredging beach trends; (b) Changes in the nearshore wave climate arising from dredging activity and (c) Changes in the patterns of nearshore wave climate adjacent to, but outside of the influence of, the dredging area.

Milford-on-Sea control beach site

Beach profile trends indicate that the control beach at Milford-on-Sea has continued to erode following dredging (Figure 6). There is no discernable increase in the rate of loss of beach material, despite the apparent increase in severity of wave conditions since 1990. Major departures from the trend line are indicative of storm events.

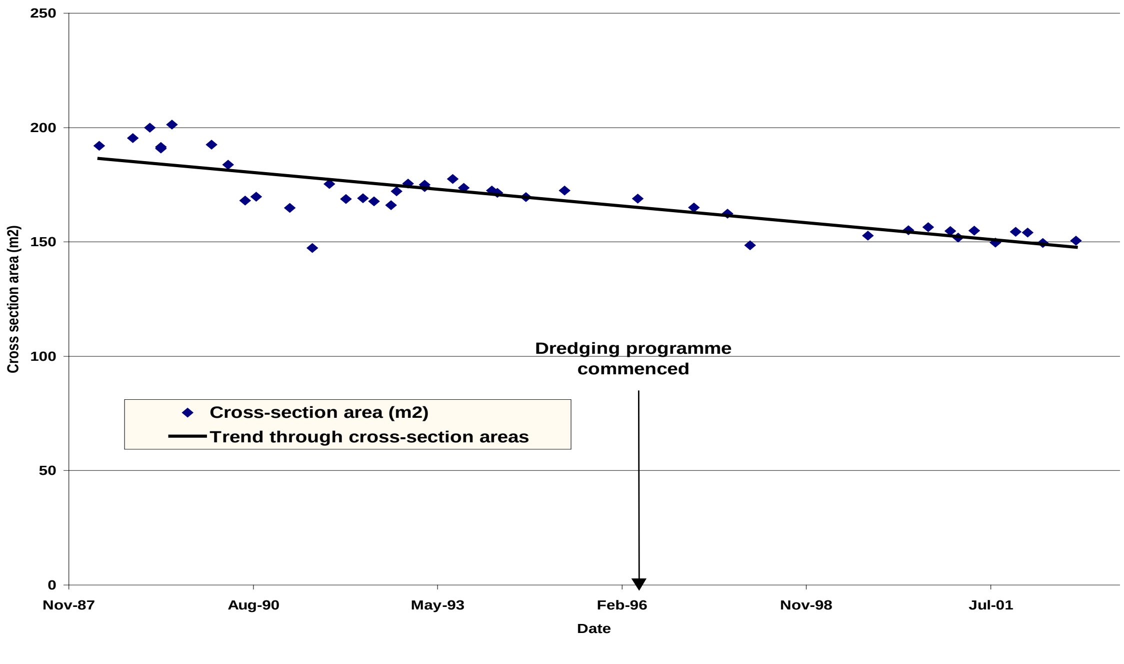

Figure 7 Beach profile trend analysis at Milford-on-Sea control site

Hurst Spit recharge site

Hurst Spit has been subject to major beach recharge and recycling, as part of a 50-year beach management plan, since 1996. Estimates of annual losses from the system have been made on the basis of (a) Pre-recharge numerical modelling (b) Physical modelling and (c) Long term field measurements. Comparisons between design stage projections of post-recharge losses, and measured responses are shown (Figure 7); these suggest that despite the increased severity of wave climate at the site, beach losses have been less than originally projected.

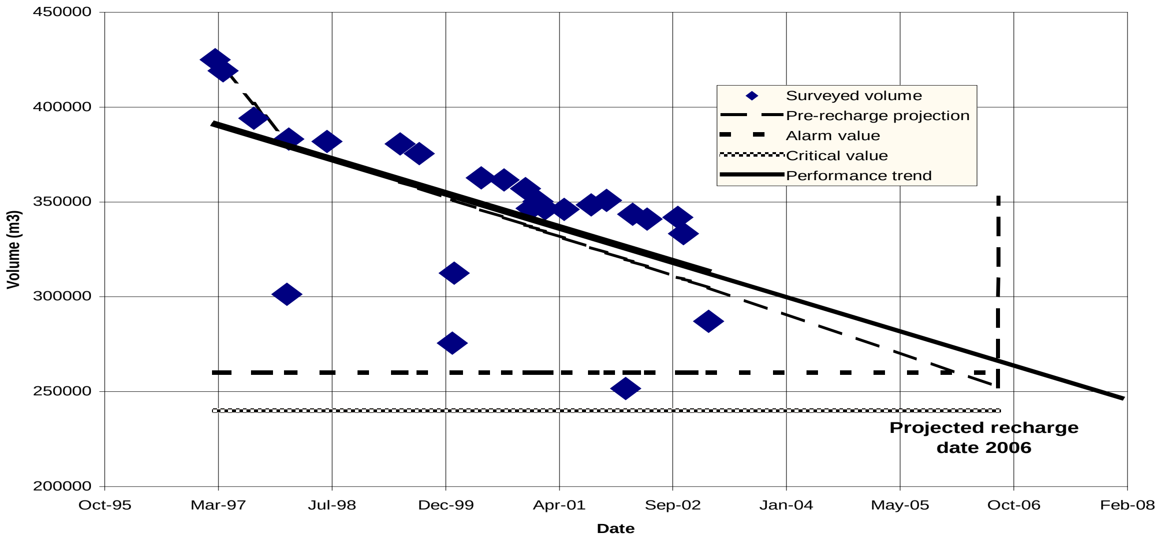

Figure 8 Comparison of surveyed and projected post recharge volumetric changes at Hurst Spit (above 0mODN)

Although extensive field data (since 1987) provided a pre-dredging historical baseline, the beach recharge activity has interrupted the natural processes and altered the system such that it is no longer in equilibrium. Beach responses are likely to be very different following recharge, whilst the beach adjusts to the new conditions. It is not reasonable to use this site for examination of either the influence of dredging, or increased storminess, due to the overriding impacts arising from beach management intervention.

Isle of Wight

Spatial analysis of 30 beach profiles indicates that accretion is the predominant post-dredging trend. Only three profiles measured exhibited a net downward trend. A longshore trend is evident from Alum Bay, through Totland Bay and Colwell Bay. Erosion is evident in the south (Alum Bay), whilst beaches to the north-east are either stable or accreting; however, there is net accretion throughout the system. Evidence of sediment transport to the north-east is demonstrated by patterns of change within groyne compartments of Totland Bay. Although the frequency of severe offshore wave conditions has increased, the beaches do not show any signs of a reduction in volume or performance. Overall the system appears remarkably stable.

As expected, seasonal variations in beach volumes are evident at all sites: higher volumes are evident in the summer months and lower volumes in the winter. Although the overall morphodynamic trends are similar, seasonal beach responses within Totland Bay are much more volatile than within Colwell Bay. Typical trend analyses for the two beaches are shown in Figures 9 and 10. Beaches of Totland Bay had a generally low initial beach cross-sectional area. Significant beach structure interaction is evident at this site; the shape of the post storm profiles and rapid changes in profile evidences this. Application of parametric profile models suggests that a dynamic equilibrium profile is unable to form anywhere within Totland Bay, even for frequently occurring conditions. It is suggested that the rigid seawall structures, in combination with the low beach volume, have restricted natural evolution of the beach.

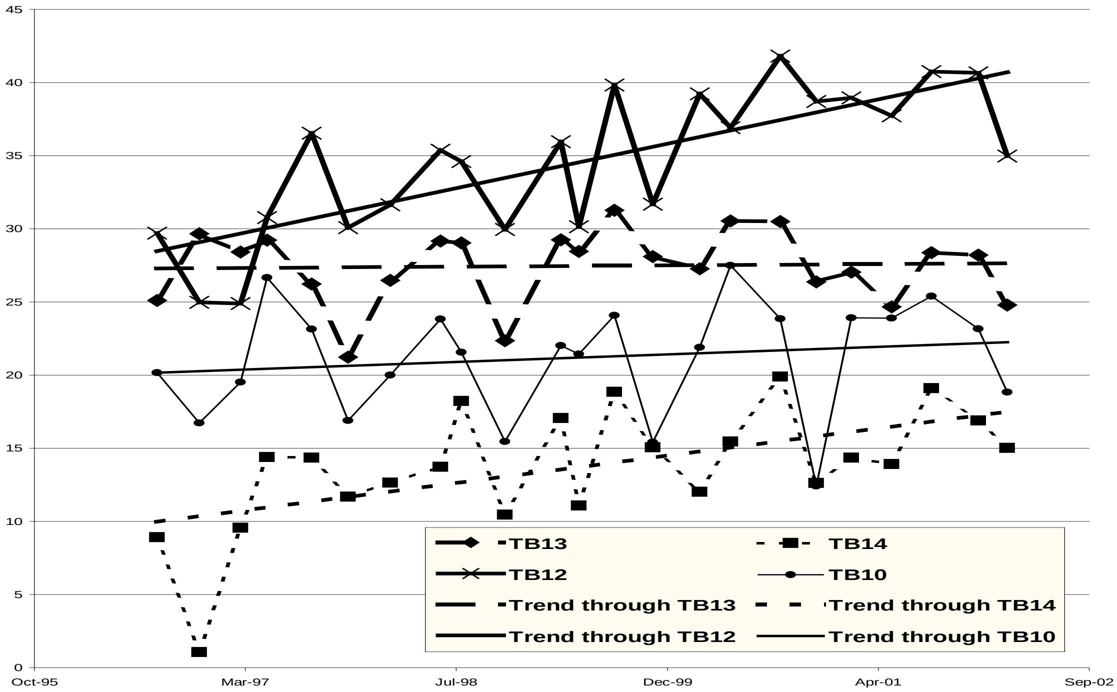

Figure 9 Example post-dredging beach profile trends in Totland Bay

By contrast, the initial beach cross section at Colwell Bay (Figure 10) is generally suitably large to enable a dynamic equilibrium profile to form under most conditions, without beach-cliff or beach-structure interaction.

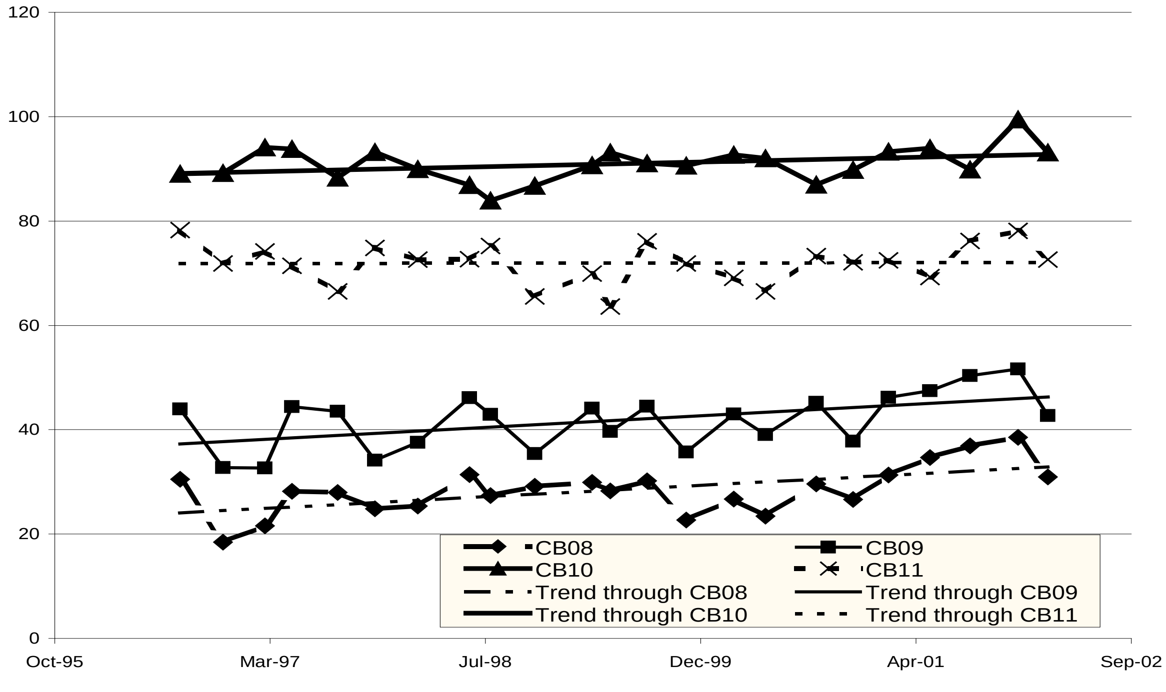

Figure 10 Example post-dredging beach profile trends in Colwell Bay

The small beach at Alum Bay has experienced a loss of beach volume. Interaction of the beach with the soft cliff geology and groundwater driven cliff failures complicates the patterns at this site.

Concerns that dredging would have an adverse impact on the beaches of the Isle of Wight cannot be supported by the beach profile evidence. In fact, the beaches exhibit remarkable stability for the wave climate conditions. Regrettably, no high quality pre-dredging beach performance data was available for comparison with the post-dredging programme, for any Isle of Wight beaches. On this basis, any post-dredging trends observed during the monitoring programme, (either coastal erosion or accretion) cannot be linked with earlier trends, or directly with dredging activity.

Offshore morphological changes

The Shingles Banks system consists of two distinctive areas, separated by the narrow and shallow North Head Channel: the main body of the Shingles Banks, and the smaller North Head Bank. The system is bounded to the east by the Needles Channel, with depths ranging from 15 to 60mCD, and is separated from Hurst Spit to the north by North Channel (Figure 2). Pre-dredging chart analysis demonstrated that the total volume of the system had generally grown since 1882. Subsequent bathymetric surveys (1996-2002) show that rapid changes have continued to occur.

The main body of the Shingles Banks exhibits an asymmetric morphology; it comprises a relatively gently sloping and stable western flank, highly mobile ephemeral shoal areas, evolving channels in the central section, and a steeply sloping eastern bank that faces towards the Needles Channel (Velegrakis, 1994). Analysis of historic charts and the recent bathymetric surveys have enabled evolution of specific morphological features of the Shingles Banks system to be analysed in detail.

Shingles Banks

Historic bathymetric charts and recent bathymetric surveys indicate that the central section of the Shingles Banks system is very mobile; the shoals and adjacent channel features are subject to large and rapid changes due to the local wave climate, tidal currents, and storm events. The location of drying shoals on the Shingles Bank system (see C Figure 10) has remained consistent, although their area varies. In particular, the shoals have accreted during storm events; they become surface emergent over the full spring tidal cycle on occasions.

A submerged-bar feature extending in a south-westerly direction (see D Figure 10) is clearly present on the western flank of the Shingles Banks system from 1882 to 1995. The feature was most prominent between 1945-1965, but had decreased in size and length by 1995. The bar feature was not evident in 1997, when an adjacent channel appears to have been filled with sediment. Disappearance of the feature coincided with dredging of the Shingles Banks. Surveys in 2001 and 2002 indicate redevelopment of the channel and bar with a similar form and extent to that measured in 1995. The short-term, localised morphological changes to this feature suggest that it is ephemeral and highly sensitive to hydrodynamic changes.

North Head Bank

The North Head Bank region (see A Figure 10) has declined in area and increased in depth since 1882. The 1882 Admiralty survey indicates that the North Head Bank was comprised of two areas separated by a channel that were joined along their western flank. The 1972 survey indicates that the Bank had evolved into a distinct single area, which had reduced in size.

Further reductions in area had occurred to the North Head Bank by 1997. Post-dredging monitoring has identified a continued reduction in size of the North Head Bank. This long-term evolutionary trend is indicative of continual adaptation to wave climate, tidal currents and sediment supply. Its location is distant from the dredging area and dredging processes are unlikely to have impacted upon the evolutionary trends.

North Head Channel

The North Head Channel (B Figure 10), demarked by the 5mCD contour, was a pronounced feature in 1882; this Channel gradually extended and lengthened eastwards, as indicated in the 1988 survey, although the North Head Bank remained connected to the Shingles Banks at the eastern end of the channel. The North Head Bank was completely separated from the Shingles Bank system, as a result of eastward extension of the North Head Channel, between 1988 and 1995. The 1995 survey indicates a narrow passage separating the North Head and Shingles Banks systems at its eastern end (Figure 11). The channel continued to widen and deepen until July 2002.

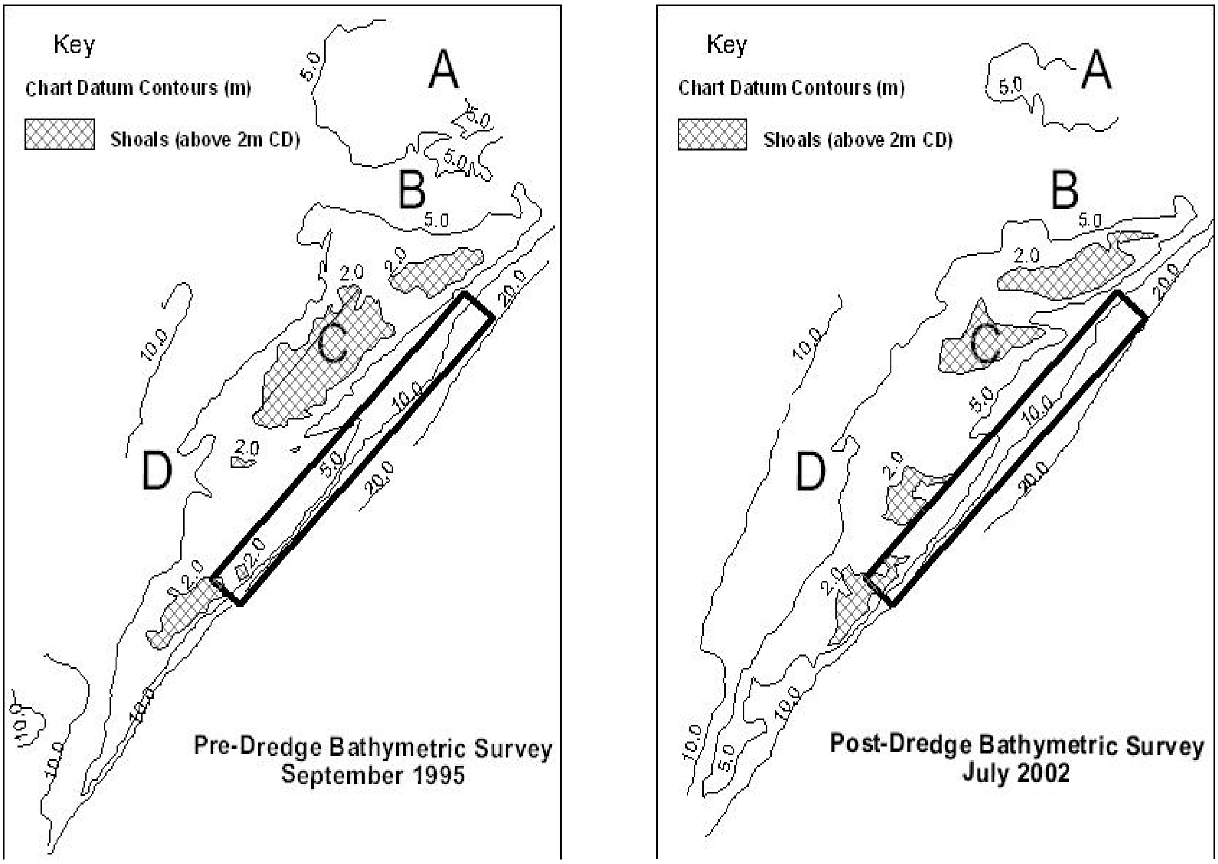

Figure 11 Evolution of the Shingles Banks system following aggregate dredging

Post-dredging volumetric changes

Beach recharge material was dredged from the eastern flank of the Shingles Banks, (August 1996 to January 1997). Dredging operations were monitored continuously by the onboard Crown Estates' Electronic Monitoring System (EMS), which indicated that most of the dredging activity occurred in depths between 5 and 15mCD. A total of 300,000m^3 sediment was dredged.

Unlike most aggregate dredging areas, the Shingles Banks are not a relic deposit. Storm events, particularly those from the southwest, rework and re-deposit the marine gravels within the system. Patterns of deposition are dependant on the occurrence, direction and, duration of storm events. Bathymetric surveys provide a series of volumetric snapshots of a highly mobile and dynamic system. The measured differences in volume between surveys need to be analysed in conjunction with regional wave climate data and tidal current patterns, therefore. Even with this data, interpretation of changes is extremely difficult. The potential accuracy of bathymetric survey techniques, typically +/- 0.15m vertical and +/-1m horizontal, is a significant issue in this environment. As the survey area is large (13 hectares), measured changes in volume of more than 2 million m^3 may lie within the expected scatter of survey error. Bathymetric survey line spacing for the dredging area is at 50m, whereas the line spacing for the surrounding Shingles Banks area (see Figure 2) is at 200m. The line spacing for the two areas provides sufficient information to describe plan shape changes of morphological features. The closer line spacing within the dredge area is more appropriate for volumetric calculations. Volumetric analyses of post-dredging bathymetric surveys (Colenutt, 1997-2001) indicates that the dredging area, and the Shingles Bank system as a whole have experienced substantial gains and losses of material (Figure 11). Wave conditions measured over the last 10 years, at a control site outside of the influence of the Shingles Bank system, suggest an increase in the frequency, intensity and duration of storm and wave activity.

The combination of intense periods of wave activity, strong tidal currents and the mobility of the coarse-grained sediment causes rapid and significant deposition and erosion of material within the dredged area. Patterns observed appear consistent with sediment transport pathways suggested by Velegrakis (1994). It is suggested that deposition occurs within the dredging area during periods of intense wave activity; this results as the shoals of the bank system roll north-eastwards. Ebb dominant tidal currents winnow out fine material and transport this to the south-west, resulting in losses from the dredging area, during calm periods.

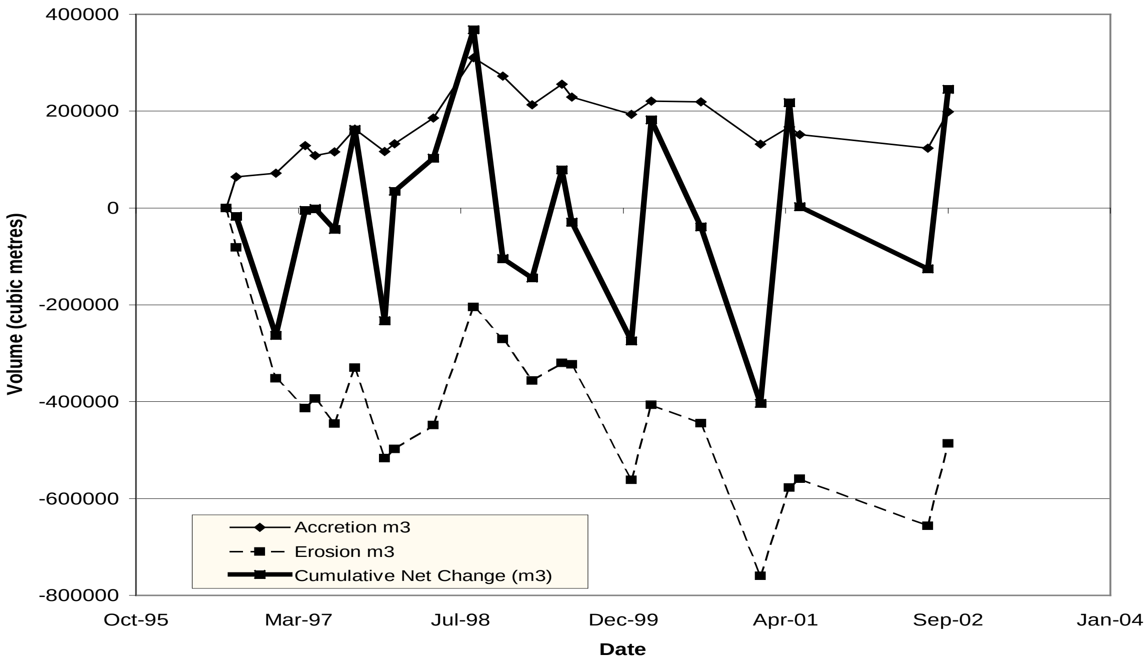

Figure 12 Volumetric Changes for Shingles Banks Dredging Area 406

Analysis of the post-dredging bathymetric surveys of the dredging area, plus a 300m wide bounding box of the surrounding area suggests that substantial fluctuations of accretion and erosion occurred within this area (Figure 12). Survey accuracy may also factor in the volumetric variations. Volumetric changes indicate both deposition and erosion, with no clear trend, although there is some evidence of deposition following stormy periods. The dredging area is part of a highly dynamic system and the mobile sediments respond rapidly to the prevailing hydrodynamic conditions, and storm events.

Post-dredging volumetric analysis of the whole Shingles Banks system demonstrates a volatile response of the system. Accumulation appears to be evident following more energetic periods. No obvious trend is evident however, with cumulative volumetric changes swinging from erosion to accretion between surveys. Trend analysis of the data sets shown in Figure 13 suggests that there is no statistically valid trend. A cumulative net loss of 1,625,000m^3 of material arising as a balance from 4,034,000m^3 of erosion and 5,660,000m^3 of accretion was evident on the occasion of the last survey. The net change is the equivalent of a 0.12m thickness over the entire Shingles Banks area; this quantity can be consumed by the expected error of a hydrographic survey. Although the measured volumes are subject to some considerable uncertainty, evolutionary trends are clearly evident within the system.

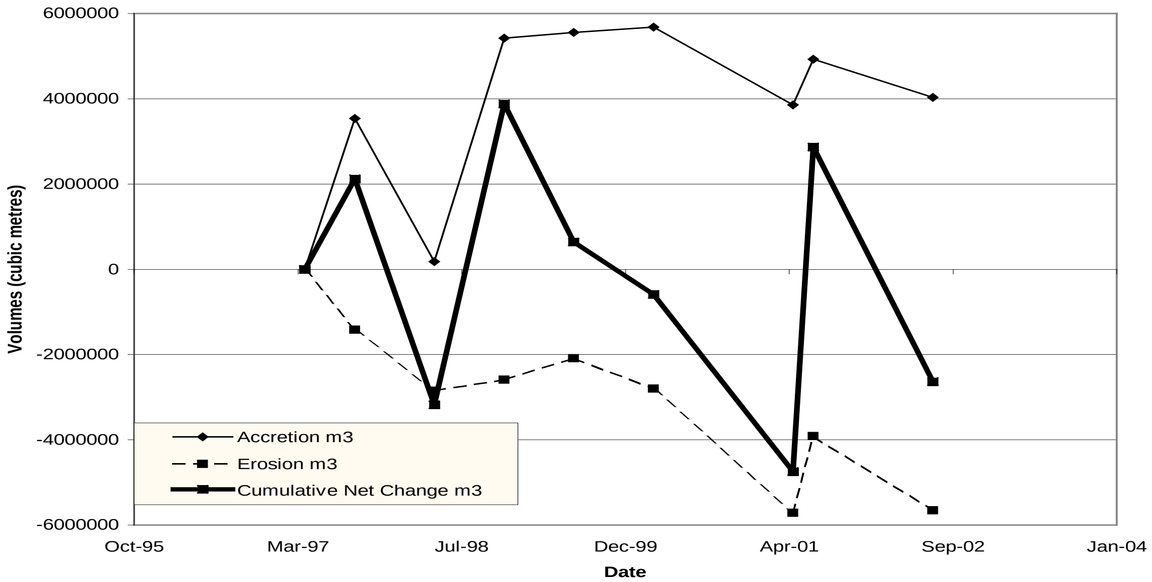

Figure 13 Volumetric Changes for Shingles Banks Whole Area

Benthic Surveys

A pre-dredging benthic survey was conducted in August 1996, and post-dredging benthic surveys conducted in March 1997 and September 1997 (Serpell-Stevens, 1996,1998). The two summer surveys are directly comparable, whilst the March 1997 survey shows significant seasonal mortality of the indigenous species. The frequency of individuals and diversity of species, measured on each survey, were not significantly different. Although the post-dredging survey indicated a significant reduction in both count and diversity of species, this may reflect the impacts of seasonal mortality as well as disturbance by dredging. A rapid recovery of species is evidenced by the September 1997 survey. The dredging operation appears to have had a short-term impact on the benthos of the dredging area, but recovery has been rapid.

Discussion

Despite the fact that local wave conditions have been significantly more severe, and storm conditions more frequent than anticipated at the environmental assessment stage, there is no evidence of a decline of the beaches on the shoreline of the Isle of Wight. The control site in Christchurch Bay has exhibited similar trends to those prior to dredging. Beach monitoring at Hurst Spit demonstrates a declining beach, in line with pre-recharge prediction. However, the influence of the beach recharge operation has been overwhelming at this site. Large-scale post-dredging evolution has continued within the offshore bank system although there is no evidence of changing patterns.

The Milford-on-Sea wave buoy data provides some confidence in the numerical modelling methodology used for coastal process assessments. Whilst its location is ideally suited to a validation exercise for the modelling, it cannot be used to prove whether wave conditions have become more severe in the shelter of the Shingles Banks, since post-dredging measurements were not made at these sites.

These observations collectively imply that the nearshore dredging area has not had an adverse impact on the shoreline. This cannot be shown conclusively however, because of the lack of suitable controls at either Hurst Spit or on the Isle of Wight. Significant improvements to the understanding of causal linkages can be made only when long-term pre-dredging control data is present at appropriate locations.

The coastal manager has a responsibility to conduct monitoring routinely, as part of best practice shoreline management, and to understand natural coastal evolution and changes arising from the introduction of coastal defences. This responsibility has been addressed within the south-east of England by the introduction of a strategic regional coastal monitoring programme. Only when comprehensive baseline programmes are in place at appropriate locations, can additional monitoring data relating to dredging activity be put to best use. Conclusive linkages with dredging activity cannot be made unless adequate temporal control baselines are in place. The responsibility for achieving this approach lies with both the operating authorities and with the organisations responsible for dredging.

Conclusions

- Beaches on the Western Isle of Wight have been stable or accreted since dredging on the Shingles Banks.

- Large-scale morphodynamic changes have continued within the Shingles Banks system. Patterns of change are consistent with those observed since 1882.

- The benefits of the integration of best practice long-term coastal monitoring, arising from coastal management initiatives and dredging licences, are demonstrated.

- The occurrence of severe nearshore wave conditions has increased within Christchurch Bay. Regular exceedence of the predicted 1:100 year wave height condition has occurred.

- Regular reviews of wave climate statistics are required, to identify temporal trends in extreme conditions, particularly during periods of perceived climate change.

- Comparisons of modelled and measured wave data have indicated a strong correlation for the Milford on sea wave buoy site, but a poor correlation with the North Channel site.

Dedication

This paper is dedicated to the memory of Darren Hume, a revered colleague of the authors, who died tragically in summer 2002.

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