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Beach erosion and marine aggregate dredging: a question of evidence?

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Abstract

Coastal erosion is a global problem and a major concern for European Union Member States. In the UK, marine aggregate dredging is considered by many to be responsible for coastal loss and campaigns based on the 'precautionary principle' have been mounted to halt extraction. Two South Wales, UK coastal areas, where critical beach loss has been associated with dredging activities, were monitored to assess morphological change. In five years of beach monitoring along the Penarth coastline (September 1997 to September 2002) and six years monitoring Port Eynon and Horton beaches (January 2001 to October 2007), no qualitative or quantitative causal link was found between marine aggregate dredging and beach erosion. Conversely, many qualitative and quantitative relationships were established between beach erosion and forcing agents such as water level, wind and waves. Results from Port Eynon and Horton showed significant temporal variations in beach level and on-shore/offshore sediment movement was seen as significant in beach formation processes. At Penarth, changing wind direction and increased easterly storms were most significant. Furthermore, there were indications of recognised causes of coastal erosion such as increased water levels, storms and anthropogenic construction. Therefore, morphological changes on a relatively short timescale can be clearly attributed to influences other than marine aggregate dredging. Potential future work includes regular monitoring and analysis of shoreline changes in areas adjacent to dredging sites together with concurrent bathymetric surveys. As well as being a strategic approach, it would address stakeholder concern and reduce conflict.

Keywords

South Wales, morphology, processes, gradients, monitoring, beach variability.

Introduction

There is much controversy in the UK regarding offshore marine aggregate dredging. It is a commonly held public belief that dredging from sandbanks around the coastline has resulted in severe local beach erosion (Marinet, 2007; SOS, 2007; BBC, 2003). Two coastlines predominantly involved in this debate are Norfolk and South Wales. The argument is based on the Tanner model of source (beaches), pathway (sea) and sinks (sandbanks). For example, Happisburgh on the Norfolk coast is experiencing severe erosion and the problem is threatening many properties. Marinet (2007) identified from offshore marine aggregate dredging statistics that between 1989 and 2002, the total aggregate extracted from the Humber and East Coast areas, between which Happisburgh is situated, was 162,670,130 tonnes. Therefore, primed by reasonable argument, extracting sand from the sandbanks affected dynamic equilibrium which in turn led to critical beach erosion.

Campaigns in Gower, the first UK Area of Outstanding Natural Beauty (AONB), have included political lobbying and collections of old photographs to demonstrate sand loss from local beaches. Sand has been extracted from the Helwick Bank (Figure 1) since the 1960s and Llanelli Sand Dredging Ltd, who have been extracting sand since the 1990s, made an application in October 2000 to extract 300,000 tonnes of sand each year for 15 years. A public enquiry took place in 2006 and following the Inspector's report, which recommended allowing 150,000 tonnes each year for ten years, the Welsh Assembly Government decided that 150,000 tonnes year^{-1} should be permitted. However, this was for a restricted period of seven years and subject to stringent monitoring and review

(SOS, 2007). Both the Welsh Assembly Member and Member of Parliament were dismayed and surprised by the decision. They saw dredging as a threat to the coastal environment and visitor numbers. The impact on newly developing tourism markets, including specialist and lucrative surfing markets, had also been raised as a major concern (Turner, 2003; Collis 2003).

Nearly one in ten UK jobs is related to travel and tourism (9.3%) and in 2005, its contribution to the UK economy totalled 9.1% (WTTC, 2007). However, the construction industry is also a major contributor to the economy and in 2003 employed 6.6% of Britain's total workforce and generated around 10% of its Gross Domestic Product (GDP) (Concrete Centre, 2007). According to BERR (2007) statistics, construction contractors output for 2002 was £71.477 billion in England and £2.915 billion in Wales. For aggregates, including crushed rock, sand and gravel, the UK produces 99.99% of its annual requirement. The value of the concrete sector and related industries accounts for some 5% of total UK GDP (Concrete Centre, 2007) and the extraction of sand from the Severn Estuary and Bristol Channel has for a century, been vital to the construction industry and economy of South Wales and South West England. The Second Severn Crossing, Wales National Stadium and the Cardiff Bay Barrage are signature structures where marine sand dredged from the Bristol Channel/Severn Estuary was used. Almost 90% of the sand supplied in South Wales comes from marine sources (Bellamy, 1999) because of its high quality and the lack of viable and environmentally acceptable land based deposits. In March 2004 the Treasury's Barker Review of housing supply reported that 140,000 new UK homes a year were needed, in order to meet future demand (BBC

News, 2004). This is an example where central policy influences both aggregate demand and coastal decision-making processes.

Opponents of dredging recognise there is no definitive scientific evidence linking coastal erosion and aggregate extraction, but because of temporal associations, have proposed the ‘precautionary principle’ as a mechanism to stop dredging operations:

> *"Scientific evidence is still inconclusive, but we are worried by the implications. We think that the 'precautionary principle' should apply: no more sand should be removed until it can be proved that dredging is not harming our beaches. If we wait until dredging is proved to be harmful, it will be too late. Once the sand has gone, it has gone for ever."* (BBC, 2003)

The main objective of this paper is to examine the hypothesised link between beach erosion and marine aggregate dredging. This will be achieved by considering coastal erosion mechanisms and assessing two South Wales beaches where marine aggregate dredging was suggested as the erosion cause. From analysis and discussion, conclusions are drawn and management strategies suggested.

Coastal erosion

Beaches constantly change in response to external environmental factors, such as tidal water level and storm surges. In practice the term storm surge is used loosely to include the astronomical tidal component and other meteorological effects, for example, variation in atmospheric pressures and subsequently generated winds (Simm, 1996). The roles of waves, tides and currents are therefore inextricably linked in determining the unique character of every beach while sea level is one of the principal determinants of shoreline position (Leatherman, 2001). There is international consensus amongst coastal scientists regarding predicted increases in storm activity and sea level rise; although depending on location, estimates of the latter vary between 2 and 9 mm year^{-1} (Warrick *et al.,* 1996; Crawford and Thomson, 1999; Jensen *et al*., 2001; Rivis *et al.,* 2002; Vilibic *et al*., 2000; Douglas, 2001a, 2001b). Storm surges contribute significantly to beach erosion, leading to considerable coastal infrastructure damage and such events will be exacerbated with current predictions of sea level rise.

Heyworth and Kidson (1982) highlighted errors in estimation of tidal levels with large tidal ranges such as the Bristol Channel/Severn Estuary and noted that in these circumstances, distribution of wave energy is as variable as tidal range. However, from analysis of sea-level curves they suggested that in the last 8000 years the rate and timing of sea level rise is comparable over the whole region. According to Allen (1991), from an analysis of deposits in active marshes of the inner Severn Estuary, the average rate of rise of sea level ranged from 0.4 mm yr^{-1} between the later Roman Period and the Medieval Period to 4.65 mm yr^{-1} since *circa* 1945. However, Haslett *et al.,* (1998) questioned previous models and found from clay deposition, that relative sea level change was 0.41-0.82 mm yr^{-1}. Although only based on a 10-year record, trends of 5.4 and 0.4 mm yr^{-1} (Phillips *et al.*, 2005) determined from tide gauge data at Mumbles (Bristol Channel) and

Newport (Severn Estuary) respectively (Figure 2), both agreed with some analyses of Holocene sea level rise.

One of the major physical impacts of sea level rise is beach erosion, particularly along the open coast and this will leave coastal infrastructure more vulnerable to storm waves (Titus *et al*., 1985). According to Leatherman (2001: 183):

> *"While many factors contribute to shoreline recession, sea level rise is considered the underlying factor accounting for the ubiquitous coastal retreat."*

A 0.3 m rise in sea level would cause an estimated 30 m erosion although the actual amount depends on wave climate and beach profile (Titus et al., 1985). Furthermore, a 0.1 m increase in mean sea level would contribute to an increased speed of tidal propagation and a potential 22% increase in tidal prism volume (da Silva and Duck, 2001).

Europe's coast is under increasing threat from erosion. A fifth of the enlarged EU's coastline is already severely affected (Table 1), with coastlines retreating by between 0.5 and 2 m year^{-1} and by 15 m in a few dramatic cases (Europa, 2007a). A worldwide tendency to coastal erosion (Cipriani *et al.*, 2004) has been locally aggravated by some of the very strategies implemented to reverse the pattern (Gillie, 1997; Weerakkody, 1997). Of the 875 km of European coastlines that started to erode within the past 20 years, 63%

are located less than 30 km from coastal areas altered by recent engineering works (Europa, 2007b). Natural beach changes usually involve erosive and sedimentary processes which are mainly a response to changes in incident wave regime and tidal range (Anfuso *et al.*, 2000). According to Bullen (1993), the Institute of Oceanographic Sciences concluded that human intervention including port developments and seawall construction, had been the main erosion mechanism along South Wales beaches. Cipriani *et al*. (1999, 2004) reported similar findings on downdrift beaches at other European locations. Therefore, many factors contribute to erosion, which further complicates the identification of specific causes. Importantly however, erosion is by no means unique to coastal areas in the vicinity of marine aggregate dredging operations and two locations where marine aggregate dredging has been promoted as the cause of severe erosion will now be examined.

Case Studies

Shoreline Management Plans (SMPs) cover 6000 kilometres of coast in England and Wales and provide a large-scale assessment of risks associated with coastal processes. It is a policy framework for sustainably managing the built and natural coastal environments. The coastline is split into sediment sub-cells which are managed by coastal groups made up primarily of coastal district authorities and other bodies with coastal defence responsibilities (Defra, 2007). Port Eynon and Horton, are located on the western limit of Shoreline Management Sub-cell 8b and Penarth is on the eastern limit (Figure 2) (SBCEG, 1999). Beach monitoring has been undertaken at these locations and will now be discussed.

Port Eynon and Horton

Physical Background The Gower Peninsula, South Wales, UK, is located in the Bristol Channel which has the second highest tidal range in the world (Figures 1 and 2). Its ragged outline comprises carboniferous limestone cliffs, sandy bays and headlands. The geology and mild climate have created diverse habitats and spectacular views leading to its designation in 1956, as the UK's first AONB. A proportion of the south Gower coastline and offshore waters are within the Carmarthen Bay Marine Special Area of Conservation (SAC). Although Gower is predominantly comprised of Carboniferous Limestone and is generally resistant to erosion, there are a number of beaches that overlie rock platforms and are subject to change. Some beaches exposed to the predominant south-westerly winds and waves are naturally unstable. Consequently, natural processes of sediment movement cause erosion and accretion along the coastline in a complex and sometimes unpredictable manner. It is estimated that the Severn Estuary/Bristol Channel carries over 30 million tonnes of suspended sediment on a spring tide (SES, 1997). Bullen (1993) stated that the main ebb tidal current carries material down channel and this is distributed along Gower beaches and onto the Helwick Bank. This sandbank is approximately 15 km long and up to 1.4 km wide and is approximately 2 km offshore from the southwest Gower coast (Figure 1). There is a circular (clockwise) sediment transport around the bank and wave-induced sediment transport may play an important role (Schmitt *et al.,* 2007). The macrotidal environment at Port Eynon and Horton, where beach surveys were undertaken, has a spring tidal range of 8.1 m while accepted longshore transport is weak and west to east in direction (SBCEG, 1999).

Methodology Considerable work has been undertaken investigating the depth of disturbance in beaches during a single tidal cycle (King, 1951; Williams, 1971; Greenwood and Hale, 1980, and Anfuso *et al.,* 2000). Following successful trials, it was decided that the variation used by Greenwood and Hale (1980) would be used in this research. Ten millimetre diameter mild steel rebar with loose fitting washers were arranged at 25 m intervals in a 50 m (longshore) by 75 m (cross-shore) grid (beach area 3750 m^2) located on both Port Eynon and Horton beaches (Figure 3). The grids were positioned shore parallel and normal with the back beach limit being Mean High Water (MHW). As recommended by Simm (1996), they were tied to independent control points inland of areas which might be subject to erosion during the course of the monitoring programme. Beach topography at the grid positions was measured using traditional levelling techniques. The washer settled as incoming waves lifted sand from the beach surface and was subsequently covered by sand settling on the beach surface during the ebb tide. Beach surface measurements were once again taken following the ebb tide and included the washer depth at each grid position. These measurements gave beach profile changes across the tidal cycle. Seasonal surveys were undertaken following the high spring tide, the first in January 2001 and the last in October 2007.

Results Fifteen surveys were undertaken. Depth of disturbance studies for incoming and outgoing tides showed variations in the amount of sand lifted from and replaced on the surface of both beaches. Minimum and maximum erosion on the incoming tides was 21.9 and 92.2 kg m^{-2} respectively (mean ± standard deviation: 51.2 ± 21.7 kg m^{-2}) while corresponding minimum and maximum deposition on the ebb tide was 13.5 and 94.5 kg

m^{-2} (mean ± standard deviation: 53.9 ± 20.4 kg m^{-2}). During the first two years of the study erosion on incoming tides had been less variable than deposition on ebb tides, but over the monitoring period standard deviations were similar.

Three significant surveys were chosen for analysis, as they recorded the highest and lowest mean beach levels at Port Eynon and Horton. The first survey in January 2001 (Time 0) was the baseline against which change was measured. In November 2002 (Time 22 months) and October 2007 (Time 81 months) Port Eynon recorded the highest and lowest mean beach levels respectively. Conversely, these surveys saw the lowest and highest mean beach levels at Horton. Table 2 presents the mean beach levels determined for these surveys and they are represented graphically in Figure 4. Between January 2001 and October 2007, mean beach level at Port Eynon fell by 1.022m (Table 2), which is approximately equivalent to a 3825m^3 beach loss over the survey area. At Horton during the same period the mean beach level increased by 0.520m, equivalent to a gain of 1950m^3. Therefore, results represented a total net sand loss of approximately 1875 m^3 (an overall average beach surface loss of 0.250 m m^{-2}) from the beach survey areas.

Paired t tests were carried out in conjunction with the first survey (January 2001) on the maximum and minimum recorded beach levels at both Port Eynon and Horton. Between January 2001 and November 2002, there was a significant increase in beach levels at Port Eynon (paired t test: $t = 7.887$; $df = 11$; $p < 0.01$) and significant decrease in Horton beach levels (paired t test: $t = -13.324$; $df = 11$; $p < 0.01$). Conversely, between January 2001 and October, 2007 there was a significant fall in mean beach level at Port Eynon (paired t test: $t = -21.392$; $df = 11$; $p < 0.01$) and a significant increase at Horton (paired t test: $t = 8.780$; $df = 11$; $p < 0.01$). This analysis demonstrates beach instability and as Port Eynon and Horton are at the western and eastern sides of the bay respectively (Figure 3), it shows beach formation processes are interdependent.

The beach levels at each location were further examined for differences in longshore and cross-shore sediment movement. Longshore and cross-shore gradients for the three surveys are shown in Table 3. There is a direct relationship between mean cross-shore gradient and mean beach level i.e., gradients steepen as beach levels rise and flatten as beach levels fall (Tables 2 and 3). Although longshore gradients generally behaved in a similar manner with increasing and decreasing beach levels, the relationship was not as strong (Tables 2 and 3). Interestingly, in October 2007, when Horton beach levels were maximum the longshore gradient was negative i.e., falling west to east (Table 3). Therefore, for Port Eynon and Horton, on-shore/offshore sediment movement is significant in beach formation processes.

Penarth

Physical Background The Penarth coastline is approximately 1.5 km of Triassic Marl and Rhaetic Limestone cropping out in the Severn Estuary where the spring tidal range is 11.1 m (SBCEG, 1999; Page and Oakley, 2002). Shingle beaches, rock platforms, eroding cliffs and seawalls make up the shoreline. Wallingford (1992) argued that the beach is largely supplied with material which erodes from the cliffs further south. Erosion of the cliffs north of the pier provides material for the beach between the pier and the

Cardiff Bay Barrage (Figure 5). The 1.1 km long barrage (Figure 6) spans the region between Queen Alexandra Head and Penarth Head and was built as the focus of waterfront regeneration. The main structural elements include: embankment, sluices, locks, harbour, fish pass and control tower. The embankment is a rock and sand fill structure, approximately 800m long, 100m wide at the base and 25m wide at the crest, with its seaward face protected from southeast wave action by rock armouring (maximum size: 5 tonnes). The barrage was completed in November 1999 and as two rivers, the Taff and Ely were subsequently impounded to form a freshwater lake, it has to accommodate a head difference in either direction.

The area is protected from westerly and south-westerly waves that dominate much of the Bristol Channel. The relevant wave climate is generated from the east and southeast and shore parallel currents are important. Nearshore banks complicate the wave and tidal conditions and it is assumed that there is some interchange of material between the banks and the shore (SBCEG, 1999). The tidal currents are unusual in that there is an almost continuous southward flow offshore during the whole tidal cycle (Wallingford, 1992). This is due to a large eddy on the flood tide which is particularly strong during spring tides but it also occurs during neaps. According to Wallingford (1992) this predominantly southward flow will also tend to counteract wave-induced drift of beach material, particularly the finer grained material over the lower part of the inter-tidal foreshore. In 1997, Penarth beach had fallen to critical levels and following foundation undermining, sea defences required strengthening (SBCEG, 1999). Changes were characterised by beach loss, exposure of marl bedrock and consequent structural failure. The Cardiff Bay

Barrage construction was initially considered as the erosion cause, due to beach loss coinciding with the completion of two major structural components in December 1995 and January 1996. However, offshore marine aggregate dredging was soon deemed responsible (Penarth Times, 1998) but the erosion cause or causes remained unknown (SBCEG, 1999).

Methodology A 750 m longshore baseline (26 stations at 30m intervals) was established on the foreshore and positioned, at a minimum distance of 10 m on the seaward side of all structures (Section 1: Figure 5). Furthermore, a 0.72 Ha beach area (240m longshore by 30m cross-shore rectangular grid) and two cross-shore profiles from back beach to the Depth of Closure (DoC) were established directly in front of the main promenade. The 160 m groyned beach, immediately adjacent to the site of the Cardiff Bay Barrage, (Section 3: Figure 5), was concurrently monitored. The bearing of this part of the coastline is NNW and four groynes extend from the cliff face to form three bays which successfully retain beach material. Each survey comprised nine points per bay, three adjacent to each groyne and three in the centre of the bay. Between both sections, a 567 m link survey was positioned to assess changes along the two beach orientations, NNE and NNW, and this foreshore length is least influenced by anthropogenic construction (Section 2: Figure 5). To assess beach response and orientation influences, percentage gradients were determined for each survey along both headings. Therefore, the full 1.5 km frontage was monitored with beach levels determined each April and September, between September 1997 and September 2002, following the spring high tide, to assess summer and winter variations.

Results Evaluations of photographic evidence, maps and survey data in Section 1 (Figure 5) clearly showed that in September 1997, there had been a reversal of the accepted northerly longshore drift (SBCEG 1999). Temporal analysis of beach levels indicated variability in coastal processes between September 1997 and April 2000. However, between April 2000 and September 2002, all temporal models, significantly represented a trend of increased beach levels with time ($y = 0.0066x + 2.269$; $R^2 = 96.9\%$; Section 1: Figure 5). Furthermore, there was more uniformity in beach evolution over this time period and longshore drift had returned to the accepted northerly movement. Analysis of longshore gradients between September 1997 and September 2002 on the 0.72 Ha foreshore grid, showed significant differences ($t = 2.664$; $df = 6$; $p < 0.05$). Gradients in September 2002 were not as steep in a northerly direction and this was verified by a reduction in cross-shore gradients to the south and increase to the north. Variation in beach levels between September 1997 and April 2000 indicated variability in coastal processes whilst between April 2000 and September 2002 they indicated that coastal processes had become more consistent. Furthermore, it was demonstrated that there was a trend of increasing beach levels over the five years and that longshore trends were similar, irrespective of cross-shore location. Importantly, evaluation of the foreshore grid confirmed the change from a southerly sediment transport regime in September 1997 to a northerly direction in September 2002. In addition, this was shown to have occurred by April 2000. Furthermore, analysis of beach morphology showed that erosion induced a southerly movement of beach contours and vice versa.

The cross-shore position of the DoC was 50m seaward of the longshore profile, at approximately 5.5 m water depth (Phillips and Williams, 2007). Evaluation of the cross-shore profiles showed the greatest temporal variation in level was at the back beach, with little variation beyond the DoC. Temporal variations in cross-shore profiles further supported conclusions from the analysis of the longshore profiles and foreshore grid. By September 2002 beach levels had reduced to the south and increased to the north which corresponded to reductions and increases in the seaward edge of the pebble beach (Phillips and Williams, 2007). These results not only confirmed the change in direction of longshore drift, from a southerly to northerly direction by September 2002, but also the effects of cross-shore transport on the beach profiles. Significant temporal models represented the variation of the shoreline indicators MHW and DoC. Furthermore, there was significant correlation between the variations of both indicators. This model $y = 4.4167x - 53.963$ ($R^2 = 83.58\%$) combined with Whole Circle Bearing (WCB) DoC = $17.035 + \tan^{-1} (x_{14} - x_6)/240$ produced a simple tool to rapidly assess the health of the Penarth foreshore (Phillips and Williams, 2007). From an analysis of the temporal variation of longshore gradients between the two beach headings, NNE and NNW (Section 2: Figure 5), it was found that there was significant correlation between the two ($R^2 = 97{\cdot}4\%$). Therefore, irrespective of longshore transport direction and external factors such as storms and anthropogenic activities, beach responses to coastal processes along this section were inter-related (Phillips, 2008).

Mean beach levels for the groyned beach (Section 3: Figure 5) increased overall throughout the five-year monitoring period. Post completion of the barrage, both longshore and cross-shore gradients became less variable and increased beach levels adjacent to the barrage, prevented tidal action at the cliff toe. This was a significant change from the start of the survey programme and was verified quantitatively by parametric and non parametric tests at the 99% confidence level. Spatial analysis identified two highly significant longshore trends with respect to distance south of the barrage and showed its influence decreased with distance (Phillips, 2007).

Discussion

Work *et al.* (2004) argued that dredging alters waves reaching the surf zone and used wave model results to estimate longshore sediment transport and shoreline change. They subsequently produced a calibrated model to predict impacts of dredging on long-term shoreline change and stated that results reproduced observed trends of erosion and accretion along approximately 90% of the US Folly Island shoreline. Unfortunately, as identified by Pilkey and Cooper (2007), a prediction generated by hindcasting does not mean a model works and even if all parameters are fully understood, their intensity, frequency, duration and direction are not. However, Brampton and Evans (1998) suggested that although the marine environment is very difficult to predict, it is vital to fully consider potential impacts of near shore dredging on the surrounding coast. According to Butt and Russell (2000), erosion and accretion of the shoreline in response to dynamic wave conditions are functions of the overall sediment budget. ABP and Posford Duvivier (2000) stated that net sediment transport responds to the effects of wind and waves, seasonal variation and long-term climatic trends whilst, DOE (1995) recognised that sediment is linked by coastal processes to beaches and offshore sinks.

Dredging may increase total wave energy, reduce wave dissipating forces and shelter to the coastline (Brampton and Evans, 1998) and according to SBCEG (1999), the Helwick Bank provides some shelter from storm waves during low flow periods. Schmitt *et al.*'s (2008) bathymetric surveys reflected a simple circulation of sand around the eastern end of the sandbank and migration appeared to occur with little loss or gain of sand. The macro-tidal regime (8.1 m) means that higher flow conditions reduce the bank's influence. There are examples of erosion caused by waves affected by careless extraction of material from the sea bed including Hallsands, Devon, UK (in the early part of the 19th century) and more recently Grand Isle, Louisiana, USA (Brampton and Evans, 1998). Conversely, Lord and Brydon (2000) concluded that offshore dredging had little effect on wave height and mean wave direction at Owen Anchorage, Western Australia and that minor or no changes were observed or predicted at the coastline.

Beach erosion was identified as a major issue for the sustainable management of the Severn Estuary (SES, 1997) and poses a threat to all stakeholders. Along the Penarth foreshore, beach levels are increasing adjacent to the Cardiff Bay Barrage (Figure 6) because the structure interferes with longshore transport (Phillips, 2007). To the north of the barrage, the environment has been modified from a tidally flushed estuary to a freshwater lake. Increased storm activity and/or intensity, sea/water level rise and the interaction of both could and may have already contributed significantly to the erosion problem. Since at least the 1950's, monitoring has shown an increased frequency of abnormally high tides in the eastern Irish Sea (SBCEG, 1999). Along the South Wales coastline, Phillips (2008) showed that significantly higher water levels coincided with severe erosion of Penarth beach. The coastal environment is complicated and according to Simm (1996) locally generated waves which give rise to the largest wave heights at Newport, are uncorrelated with high water levels, whereas conversely in the outer Bristol Channel, swell waves from the west which give rise to the largest wave heights, are correlated to high water levels. Following five years of beach monitoring and analysis of ten years of environmental data, Phillips (2008) concluded that the critical erosion of Penarth beach between 1995 and 1997 was caused by increased wave attack from the northeast and southeast quadrants, generated by unique significant changes in wind direction, easterly storms and extreme sea levels.

At Gower locations, results showed significant changes in beach levels over the monitoring period. Highest recorded Port Eynon beach levels corresponded with lowest beach levels at Horton and vice versa. This relationship is to be expected, as the survey areas are located on the western and eastern sides of Port Eynon Bay respectively (Figure 3). If the Helwick Bank (Figure 1) protects these beaches from storm waves at low flow conditions (SBCEG, 1999), it is unlikely to affect back beach response. Furthermore, as the sandbank is to the west, this protection would only occur if storm waves approached from the southwest and Phillips (2008) had already demonstrated increased occurrences of easterly winds during the period of Penarth beach erosion. Survey analyses at both Port Eynon and Horton showed significant temporal variations in beach level despite aggregate extraction occurring at a constant annual rate. The beach is naturally unpredictable and it is logical from beach monitoring results that other coastal variables dominate beach formation processes. Granja and Carvalho (2000), highlighted problems of erosion on the northwest coast of Portugal and concluded that erosion processes along this coastline, had been on-going since the 1990s. Descriptions of erosion at one of the beaches, Bartolomeu do Mar, were very similar to conditions reported at Horton. Coastal aspects and Atlantic exposure of these Portuguese beaches are similar to Gower but there are no aggregate dredging operations to confuse issues. During monitoring of the Penarth and Gower beaches, no qualitative or quantitative causal link has been found between marine aggregate dredging and beach erosion. Conversely, many qualitative and quantitative relationships have been established between water level, wind and waves and beach erosion (Phillips and Williams, 2007; Phillips 2007, 2008). May (2007) observed that large-scale studies over the last decade have demonstrated no link between offshore aggregate extraction and coastal erosion. In the studied examples, morphological beach changes over a relatively short timescale can be clearly attributed to other influences.

Opponents to South Wales offshore marine aggregate dredging, such as the Gower Society, do not state categorically that it is the cause of local beach erosion but until proven otherwise, they argue that the 'precautionary principle' should apply. The destruction of an AONB is their primary concern and they want to protect this heritage for future generations. However, the 'precautionary principle' was introduced to prevent developers using uncertainty as an excuse for not introducing appropriate measures to prevent environmental degradation (UK-ILGRA, 2007). Later interpretations attempt to use this principle to stop development. Applying the precautionary principle is essentially a matter of making assumptions about consequences and likelihoods to establish credible scenarios. As observed by May (2007), although beach loss has appeared concurrent with extraction, this does not mean that dredging is the only or contributory cause of erosion. Action in response to the precautionary principle should accord with the principles of good regulation (UK-ILGRA, 2007) requiring supporting evidence, which to date is unavailable. However, as May (2007) correctly identified, little attempt has been made to identify exactly what is causing the erosion. While the cause at Penarth has been established, for Gower it will take more time and survey effort to finally demonstrate cause or causes.

It is unlikely that Gower beaches will return to their former perceived well nourished state. Unfortunately, public perception of marine aggregate extraction as the beach erosion cause prevents a more strategic approach to the problem. Beach nourishment is a soft engineering solution used on eroded beaches worldwide and Phillips and Jones (2006) suggested this as a potential solution for Port Eynon and Horton beaches. Although arguably unsustainable in the long term, similar to other locations worldwide it would improve beach conditions, support tourism and enhance beach appearance. Another soft engineering solution, which has been used internationally to good effect on eroding coastlines, is beach drainage (Turner and Leatherman, 1997). Piccini *et al*. (2006) assessed its application in Ravenna, Italy while Bowman *et al.* (2007) showed beach accretion and shoreline advance at Alassio Beach, northern Italy. At Enoe and Hornbæk beaches in Denmark, beach drainage has been successful and at the former location, erosion has stopped and annual beach nourishment cancelled. Therefore, although it is uncertain whether beach drainage would be suitable for Port Eynon and Horton beaches, the feasibility of all management options to address the problem should be given due consideration. Such studies would help assure stakeholders that everything is being done to find solutions to the erosion problem.

Uncertainty and apparent lack of transparency contribute to stakeholder conflict. The Crown Estate and dredging companies' commission many sea bed and beach monitoring studies but results are not easily understood by stakeholders and there is mistrust of findings. Although reputable companies are appointed to undertake the work, because it is paid for by those who benefit financially from marine aggregate dredging, opponents view results with scepticism. Furthermore, studies are undertaken to support continuation of extraction activities and not to determine the cause or causes of beach erosion. To determine specific regional beach erosion mechanisms, regular monitoring and analysis of shoreline changes in areas adjacent to dredging sites should be undertaken together with concurrent bathymetric surveys of the dredge site.

Conclusions

Coastal erosion is a global problem and a major concern for European Union Member States. There is much controversy in the UK regarding offshore marine aggregate dredging, because of a commonly held public belief linking it to severe local beach erosion and campaigns based on the 'precautionary principle' have been mounted to stop operations. Two South Wales, UK coastal areas, Gower (Port Eynon and Horton) and Penarth, where critical beach loss has been associated with dredging activities, were monitored to assess morphological change. Results showed significant changes in beach levels over the monitoring period and highest recorded Port Eynon beach levels corresponded with lowest beach levels at Horton and vice versa. Between January 2001 and October 2007, there was an overall average beach surface loss of 0.250 m m^{-2} from the beach survey areas and on-shore/offshore sediment movement was seen as significant in beach formation processes. At Penarth, changing wind direction and increased easterly storms were most significant. No qualitative or quantitative causal link was found between marine aggregate dredging and beach erosion. However, many qualitative and quantitative relationships were established between water level, wind and waves and beach erosion. Furthermore, many universally recognised erosion causes were noted, including rising sea levels, increased storminess and anthropogenic construction. Therefore, it must be concluded that morphological changes on the studied beaches over a relatively short timescale can be clearly attributed to other influences. Future work recommended regular monitoring and analysis of shoreline changes in areas adjacent to dredging sites together with concurrent bathymetric surveys. As well as being a strategic approach, it would address stakeholder concern and reduce conflict.

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Table 1: Erosion in EU member states
(Source: Europa, 2007a)

Country	% of eroding coastline	Country	% of eroding coastline
Belgium	25.5	Italy	22.8
Cyprus	37.8	Latvia	32.8
Denmark	13.2	Lithuania	24.3
Estonia	2.0	Netherlands	10.5
Finland	0.04	Poland	55.0
France	24.9	Portugal	28.5
Germany	12.8	Spain	11.5
Greece	28.6	Sweden	2.4
Ireland	19.9	United Kingdom	17.3

Table 2: Temporal variation of mean beach level (m AOD)

Time (months)	Port Eynon	Horton
0 (Jan 2001)	2.685	2.802
22 (Nov 2002)	2.791	1.932
81 (Oct 2007)	1.663	3.322

Table 3: Average cross-shore and longshore beach gradients (%)
Note: Negative cross-shore gradients indicate falling beach levels from MHW towards the sea and negative longshore gradients indicate falling beach levels west to east (Figure 2)

	Survey Date		
	January 2001	November 2002	October 2007
Beach	**Cross-shore Gradients (%)**		
Port Eynon	-7.0	-8.1	-5.7
Horton	-3.8	-3.4	-4.9
	Longshore Gradients (%)		
Port Eynon	-0.2	-0.8	-0.5
Horton	0.4	0.1	-0.6

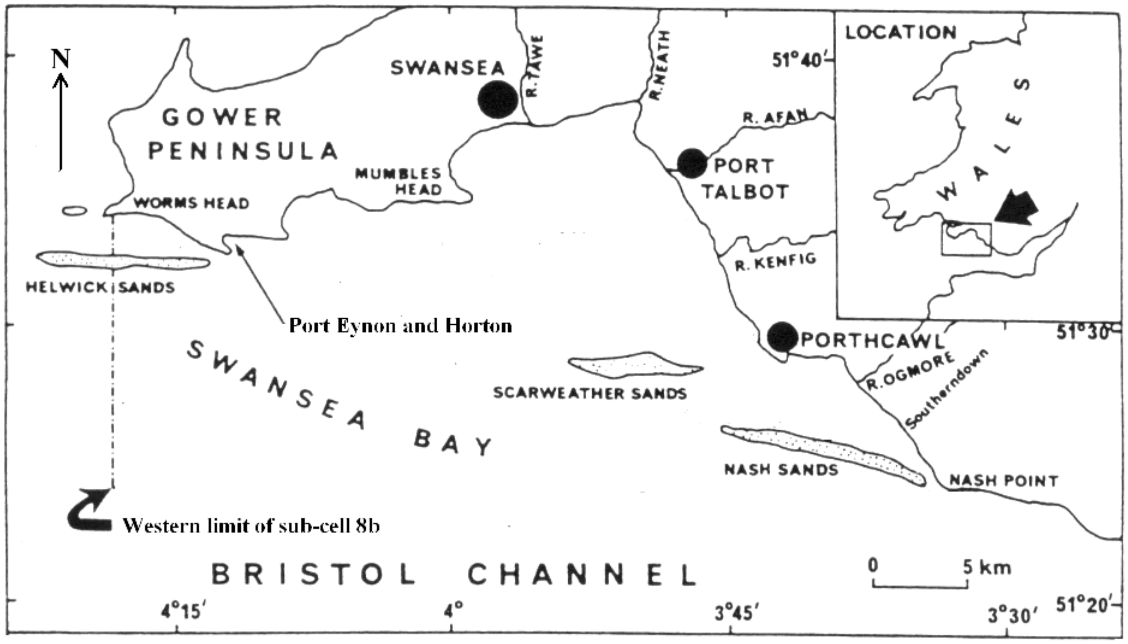

Figure 1: Gower location plan illustrating dredge areas

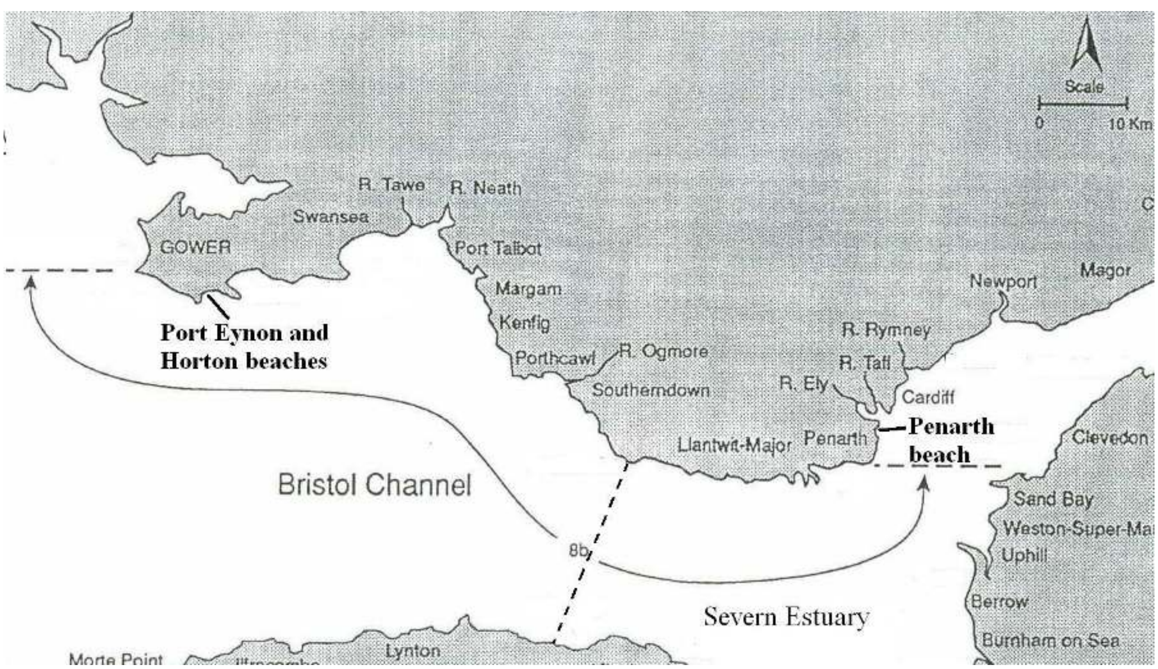

Figure 2: Location of study beaches (Source: SBCEG, 1999)

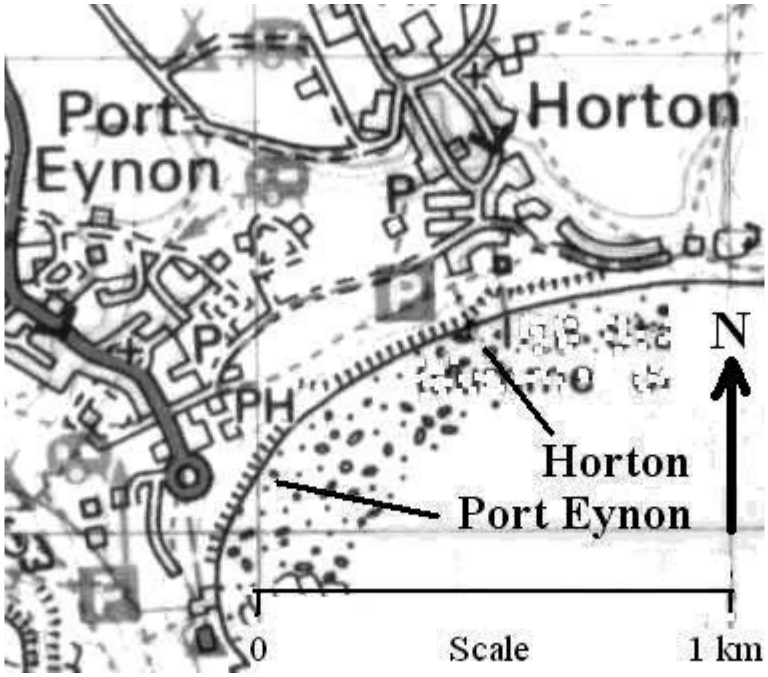

Figure 3: Location of Gower surveys (Reproduced by kind permission of Ordnance Survey, Crown Copyright. All rights reserved.)

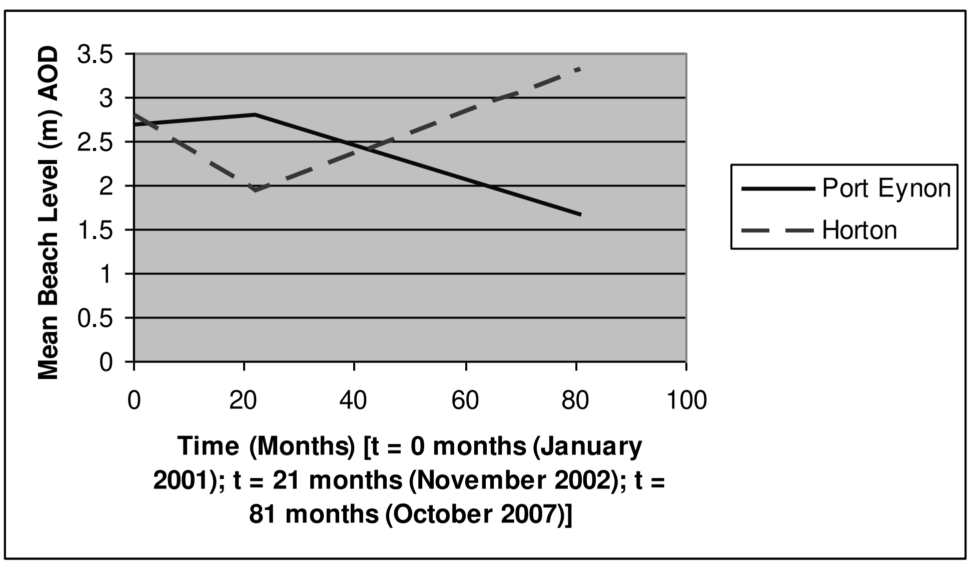

Figure 4: Temporal variation of mean beach level

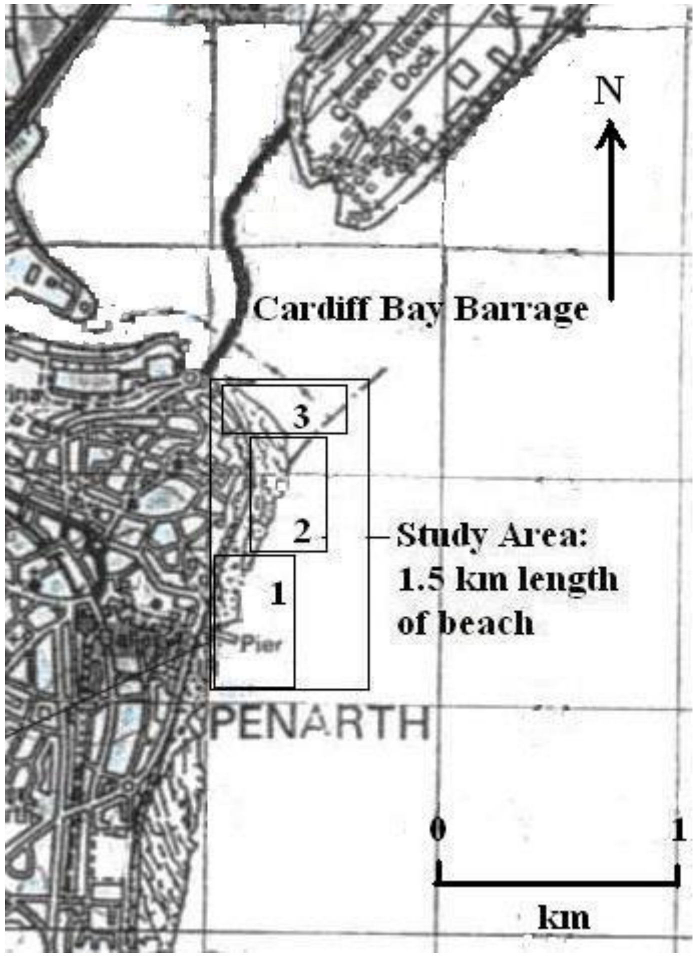

Figure 5: Location of Penarth surveys (Reproduced by kind permission of Ordnance Survey, Crown Copyright. All rights reserved.)


Figure 6: Cardiff Bay Barrage (Reproduced by kind permission of Balfour Beatty)