Climate change related sea-level rise and coastal erosion: a problem for the future? Hayle, Cornwall a case study.

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Abstract

Climate change induced sea-level rise poses a serious threat to the human population. Low lying coastal areas will be submerged and there will be extra pressure on finite resources, such as food, water, and housing. The rate of sea-level rise over the last century has increased markedly. Over the last decades the rate of global mean sea-level rise has doubled. Furthermore, the last 5 years has seen another increase in rate. Global mean sea-level is at present 5 mm y^{-1}. At Newlyn and St. Ives, UK, the rate of mean sea-level has almost quadrupled the rate of global mean sea-level rise over the same period to 19.4 mm y^{-1} and 17.9 mm y^{-1} respectively. This rate rise is equivalent to those predicted by Jevrejeva et al. (2012), who projects that the maximum rate of SLR by the year 2100 would be 17 mm y^{-1} (this is for the high emission scenario). They also predict that the maximum rate of SLR at around 2150 would be 20 mm y^{-1} in the high emission scenario. The rates for Newlyn and St. Ives are comparable to these figures now. To date there has not been a study that examines the erosion of a site that is experiencing the larger rates in sea-level rise. This study serves as a case model into how a coastline responds to the effects of increased sea-level rise. The effects of anthropogenic perturbations, such as dredging and sluicing are also examined against the historic cycle of erosion and accretion at Hayle, illustrating the need for sustainable methods of channel clearance to be implemented. The benefits of sluicing as a sustainable way to maintain a navigable channel in a working harbour has not been studied before. This paper provides a foundation for future research into sustainable methods of harbour maintenance.

(300 words)

Objectives

- Identify the rate of sea-level rise globally, and compare with both Newlyn and St. Ives data.
- Identify whether coastal processes that operate within the St. Ives Bay sediment transport system contribute to the erosion in the area, using published hydrodynamic modelling outcomes and projections (both globally and with a local focus).
- Assess the impacts of anthropogenic perturbations (dredging and sluicing), on both the study area and similar sites identified globally.
- Assess the cycle of erosion and accretion over the last 160 years with reference to the anthropogenic perturbations, and rising sea-level, using maps, tide gauge data, proxy sea-level data, and photos.

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1. Introduction.

Since the dawning of the Industrial Revolution, some 2 centuries ago, global temperatures have been rising, and are expected to continue to rise for several centuries, even if greenhouse gas emissions (CO_2, CH_4, N_2O, and CFC's), are reduced and their concentrations in the atmosphere are constrained (Kump et al. 2010). Sea-level (SL), is very sensitive to changes in global temperatures. Air temperatures warm the oceans causing the sea-water to expand, (thermal expansion), and consequently raise SL. Land Ice (e.g. mountain glaciers and ice sheets), melt as a result of the increase in air temperature, adding significantly to sea-level, (Meyssignac and Cazenave, 2012). Cazenave and Llovel (2009), state that approximately 30% of the rate of SL rise is due to thermal expansion and ~55% is a direct consequence of mass loss from land ice resulting from global warming.

Numerous authors suggest that the 20th century saw a rise in global mean sea-level (GMSL), of 1.7 mm y^{-1} with an increase in rate of SL over the last 2 decades of 3.2 mm y^{-1} (Meyssignac and Cazenave, 2012, Church and White, 2011). Cazenave and Llovel (2009) suggest a rate of 3.4 mm y^{-1} between the years 1993-2008, with a total rise in GMSL from Jan. 1880- Dec. 2009 of ~210 mm. In the future GMSL could exceed present day SL by 50-80 cm according to Meyssignac and Cazenave, (2012). Woodworth et al. (2009) suggest that the UK could see SL rise from present day values by up to 75cm, in a continued high emission scenario.

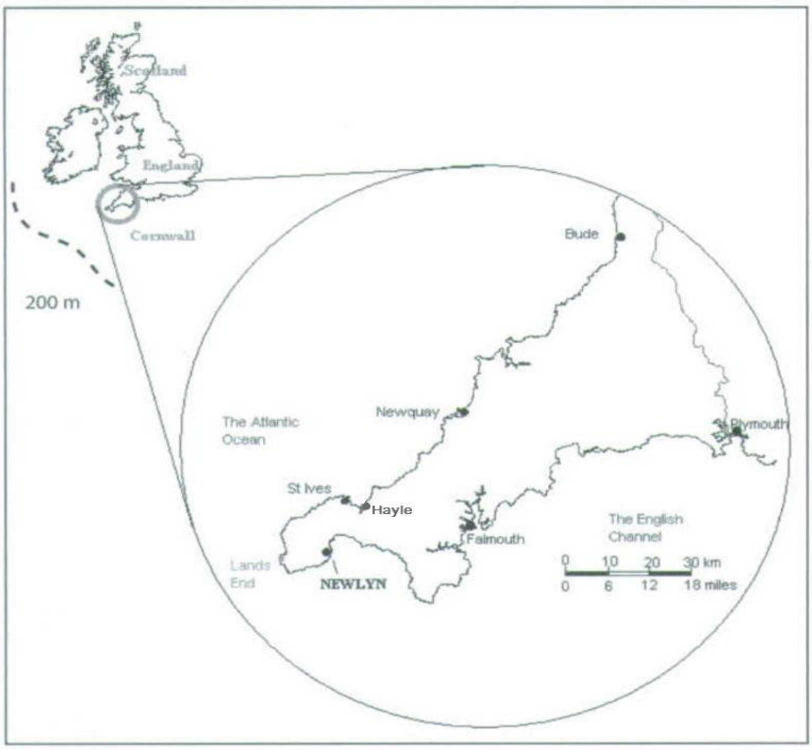


Figure 1. Map showing the location of Newlyn, St. Ives and Hayle in South west Britain. Adapted from Araujo and Pugh, (2008).

This study has found, and discusses the clear pattern of increase in the rates of SL rise (SLR), during the last century, from the beginning of the satellite altimetry records in 1993 up to the present day, and also in the last 5 years both globally, in the UK, and at Hayle, Cornwall (the case study site). See figure 1 for location of case study site. This SLR data will be examined alongside records of erosion and accretion in the case study area. The report will discuss causes of local and regional variability in SLR, such as salinity changes, meteorological conditions, Ocean-atmosphere circulation, and subsidence. It will also illustrate that it is essential to understand these causes of local and regional SL variability as well as global mean sea-level (GMSL), rise when predicting the potential impacts on the coastline and its communities. This report will illustrate how varied the amount of SLR can be from one side of the coast to the other.

This report examines, on both a global and localised scale, one of the longer term effects that will occur as the coast adjusts to the new sea-levels that prevail - coastal erosion. The particular motivation of this report is to illustrate how certain anthropogenic perturbations, such as dredging or sluicing can amplify or ameliorate the effects of SLR, by increasing or decreasing (respectively), the coastal erosion rates. To achieve this, the SLR data and the historic patterns of erosion and accretion, will be coupled with the timings of anthropogenic methods utilised for maintaining a navigable channel in to Hayle Harbour, (sluicing and dredging). Other examples of erosion, due to dredging and other anthropogenic perturbations, from around the globe will be discussed and compared with the case study site.

This report will discuss predicted global warming and the future large-scale SL changes that could result. It will also address the issues of projected SLR on the case study site in the year 2100 and 2500. There will be an evaluation of the most suitable coastal management schemes in the case study area to ameliorate SLR for both of the projections, (2100 and 2500).

2. Sea-Level Rise.

SL has risen by ~17.5 cm over the last century (see figure 2), and has been estimated to have risen by 20 cm since 1880. (Kump et al. 2010). The data used to calculate SLR traditionally came from tide gauges around the world's coastlines. This data was by no means constant, as some tide gauges have large gaps in their temporal coverage. Their relatively small number and restriction to shorelines (not the mid oceans) mean that their geographical spread is not uniform across the globe. This has made the estimation of historic GMSL unreliable. Since 1993 satellite altimetry has been providing a precise picture of near global SLR, however this record is quite short, (almost covering the last 2 decades). The altimetry record has shown that SLR is a dynamic value, and is not uniform around the globe, (Church and White, 2011). In fact it can vary widely from coast to coast. Many studies use detrended SL data.

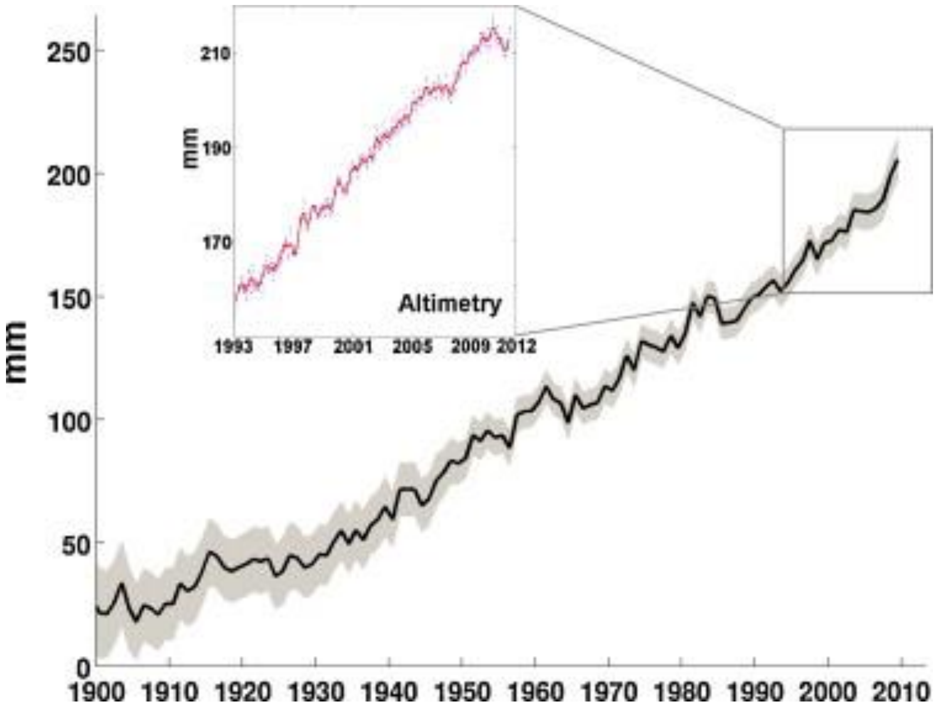


Figure 2. 20th Century Sea-Level Curve (sea-level curve in black, uncertainty in grey). The box shows the altimetry-based sea-level curve from when records began in 1993. (From Meyssignac and Cazenave, 2012).

Sea-level is one of the most difficult parameters to determine in climate models, because of the various interactions it makes with all other components of the climate system, (i.e. oceans, ice sheets, glaciers, atmosphere, and land water reservoirs). There are also the additional geological factors of volcanic and tectonics subsidence and uplift, as well as isostasy. Isostasy is a process where parts of the Earth rebound or subside as a result of the loss of a large mass. This can be as a result of the melting of the great ice sheets that covered parts of Canada and Europe some 11,000 years ago, or some areas are subsiding due to the increase of sediment loading. Many large deltas and estuaries are subsiding due to the increased load of sediment being deposited there, e.g. the Nile Delta, (Kump et al. 2010). All these factors have to be accounted for when trying to estimate future SLR and the likely impacts on the coast.

2.1. Causes of Global Mean Sea-Level Rise.

There are two main causes of SLR. The most significant of these is the introduction of freshwater to the oceans. This comes largely from the melting of land ice (ice sheets and glaciers). Only land ice is of importance to SLR. Ice sheets floating on the oceans displace the amount of seawater that precisely equals its mass (Kump et al. 2010). The other major contributor to SLR is from thermal expansion of seawater. This section will discuss all the relevant contributors to SL change, including salinity changes, and land waters.

2.1.1. Ice Sheets.

The most significant mass loss from ice sheets results from glacier flow into the oceans. There are two processes that promote glacier flow.

- Lubrification. Whereby the ice- bedrock layer is lubricated by summer melt water which has drained through crevasses.
- Break up and melting of the floating ice tongue or ice shelf. This part of a glacier acts as a buttress to the rest of the ice stream. (Cazenave and Llovel, 2010)

The latter process is favoured as the mechanism that has caused recent dynamic changes that have affected ice sheets. Once the buttress is lost the ice stream flows at a greater rate. This causes frictional heating at the ice-bedrock layer. This heating causes the base of the ice to melt producing a thin layer of water that allows the glacier to slide more smoothly over the bedrock, increasing the velocity of the glacier flow. This is termed a glacial surge. A glacial surge tends to be self perpetuating, creating a positive feedback loop, (Kump et al. 2010).

Over the past 2 decades there has been a rapid acceleration of outlet glaciers in both Greenland and Antarctica. For example the Jakobshavn Isbrae glacier on the western coast of Greenland has undergone rapid thinning and its flow velocity has increased since the early 1990's up to ~13 km y^{-1} in 2003, (Cazenave and Llovel, 2010).

The contribution to SLR would be substantial if all the ice sheets melted. Greenland alone would contribute approximately 7 m to SL if it melted completely. West Antarctica would contribute 3-5 m to SL (Cazenave and Llovel, 2010). However if the whole of Antarctica melted it would contribute 60-70 m to SL (Kump et al. 2010). Between the years 1993-2010 the glaciers and ice caps accounted for ~ 55% of the total SLR, (Cazenave and Llovel, 2010). If all of the ice sheets totally melted then SL would rise by ~70-80 m (Kump et al. 2010). This would submerge 20% of the present continents, and cause significant erosion to occur on the remaining land masses.

Greenland is much more likely to experience ice sheet melting than Antarctica as the Earth's climate warms. The reason for this is that Greenland extends to lower latitudes than Antarctica. The climate in South Greenland is considerably warmer than that of Antarctica, (Kump et al. 2010). Ironically as the climate warms Antarctica's ice sheets will likely grow. The increased warmth will promote greater precipitation, (snow fall) over Antarctica, thus increasing the mass of the ice sheets.

2.1.2. Land Ice.

Mountain glaciers and small ice caps are particularly sensitive to climate change as they are often found at lower latitudes. The total amount of land ice has retreated worldwide during recent decades with a substantial acceleration since the 1990's, (Meyssignac and Cazenave, 2012). The total contribution to SL if all the land ice was melted would be 35 cm, (Cazenave and Llovel, 2010).

2.1.3. Thermal Expansion.

Like most materials water expands when heated, except between the temperatures of 0-4^{o}C when warming causes water to contract. It therefore stands that when the oceans warm as global temperatures increase the seawater will expand (thermal expansion), thus causing SL to rise. Thermal expansion explains about 30-40% of the observed SLR over the last few decades. Between 1993 and 2010 ~30% of the total SLR was attributed to ocean warming, (Meyssignac and Cazenave, 2012).

During the 20th century, atmospheric temperatures were raised by 0.8^{o}C. This would be expected to raise the temperature of the surface oceans by the same amount, which is equal to SLR of about 8 cm. An increase in temperature of 0.8^{o}C in the deep ocean would have a much greater effect on SLR, however this could take centuries to achieve as the thermohaline circulation is very slow. Ocean circulation operates on a timescale of hundreds of years. This factor gives the ocean a long-term memory. Patterns observed today can reflect not only modern forcing factors but also internal changes that would have happened in the past, (Kump et al. 2010). It is this fact that will sustain SLR even when greenhouse gas emissions are stabilized.

2.1.4. Land Waters.

Land waters are continuously exchanged between the atmosphere and oceans. This is indeed an integral part of the climate system. Global warming forces changes to the amounts of precipitation, evaporation, and river run-off. The freshwater contribution from land waters alters the salinity of seawater which ultimately leads to SL changes at a regional scale, (Meyssignac and Cazenave, 2012). See section 2.1.5.

Another contributor to SL change is land water storage. The building of dams and artificial reservoirs is estimated to have contributed to SL fall of 0.55 mm y^{-1} during the past 5 decades. In fact without dam and reservoir building SLR would have been larger, (Meyssignac and Cazenave, 2012).

2.1.5. Salinity Changes.

Changes to salinity values in the seawater column alter the density. This gives rise to SL variations. Salinity changes have no affect on GMSL, but do affect SL at a local and regional scale, (Cazenave and Llovel, 2010). Apart from the introduction of freshwater from land waters as mentioned above, ice mass loss from ice sheets and melting land ice, also provides a significant influx of freshwater to the oceans. The change in salinity, and therefore density, affects the ocean circulation, (Meyssignac and Cazenave, 2012). In the North Atlantic deep-water formation in the Norwegian and Greenland seas drives the thermohaline circulation. The highly saline and cold waters here subside and move southwards. The water here is then replaced by warm waters moving northwards. It is this process that drives the ocean circulation. Any large influx of freshwater would effectively slow or even prevent the North Atlantic deep-water being formed. This would effectively cut off warm water flow to the North Atlantic, (Kump et al. 2010). This would result in local and regional variations in SL as warmer waters would be replaced with colder waters, as the seawater would undergo thermal contraction rather than thermal expansion. This could have a major affect on areas like the UK that are kept anomalously warmer than their latitude would suggest.

The section of the thermohaline circulation that brings warm water to the coastline of the UK is the Gulf Stream. This additional warmth brings with it much milder weather conditions that would ordinarily prevail at that latitude. If this part of the thermohaline circulation was cut off, as suggest above, then the UK and other land masses further north would experience much colder weather. Paradoxically this would cause the growth and formation of glaciers and ice sheets. This scenario would eventually lead to a SL fall as more water was being stored in these ice masses. Not at all what would be expected from global warming?

2.2. Rate of Global Mean Sea-Level Rise.

There is a consensus of thought that GMSL rise has generally been at a rate of 1.7 mm y^{-1} throughout the 20th Century, (see table 1). The rate of SLR has however picked up the pace since satellite altimetry records began at the start of 1993. For the last 2 decades the rate has doubled. Cazenave and Llovel, (2010) suggest a rate of 3.4 mm y^{-1}, whilst other studies agree on a rate of 3.2 mm y^{-1}, (see table 1). The rate of 3.2 mm y^{-1} is near the upper end of SL projections for both the Intergovernmental Panel on Climate Change (IPCC), 3rd and 4th Assessment reports, (Church and White, 2011). Over the last 5 years of available records, global rates of SLR have risen again. From the period 2005-2009 (inclusive), the rate of SLR was calculated to be in the order of 5 mm y^{-1} (calculated from Meyssignac and Cazenave, 2012 figure 3).

Location	Rate of sea-level change in mm y^{-1}	Time period	Authors
Global	3.2	1993-2009	Church and white. 2011
		1990-2009	Meyssignac and Cazenave, 2012
		1990-2009	Merrifield et al. 2009
Global	3.4	1993-2008	Cazenave and Llovel, 2010
Global	1.7	1900-2009	Church and white. 2011
		1900-2000	Meyssignac and Cazenave, 2012.
Global	5.0	2005-2009	Own work using data from Meyssignac and Cazenave, 2012.
UK	1.4	1901-2008	Woodworth et al. 2009
Newlyn	2.0	1915-2010	Own work
	7.2	1993-2010	
	19.4	2007-2010	
St. Ives	17.9	2007-2011	Own work

Table 1. Comparison of global rates of sea-level rise with UK, Newlyn and St.Ives.

There is inevitably an aspect of internal variability of the climate system within these rates of SLR, (Meyssignac and Cazenave, 2012). These variables are related to ocean-atmosphere perturbations such as the North Atlantic Oscillation (NAO), the El Niňo-Southern Oscillation (ENSO), and Pacific Decadal Oscillation (PDO), (Meyssignac and Cazenave, 2012). Meyssignac and Cazenave, (2012) state that the detrended GMSL is significantly correlated with the ENSO, and the positive El Niňo and negative La Niňa SL anomalies. Kump et al. (2010) stress that the ENSO events are not just confined to the tropics. This perturbation to the atmospheric circulation can also influence the mid latitudes. The NAO will be discussed in more detail in the next section, as it is believed that this affects SL around the UK.

2.3. UK Sea-Level Trend.

The UK mean sea-level (MSL) change has been estimated at 1.4 mm y^{-1} since 1901, by Woodworth et al. (2009). From table 1 it can be clearly seen that the UK MSL change is slightly lower than that of GMSL change, by 0.3 mm y^{-1}. Care has to be taken when describing the UK MSL change in terms of a simple linear increase alone, (Woodworth et al. 2009). Taking the focus down to a regional level will always expose interannual and decadal variations in SL change. The observed variability can be caused by the oceans adjustment to meteorological factors, such as air pressure, winds, steric (density) changes and run-off, (Woodworth et al. 2009).

A number of studies have tried to link the NAO with the variability of the UK and indeed European mean sea-level (MSL), (Woodworth et al. 2009). The NAO is a major atmospheric circulation variability (Bojariu and Gimeno, 2003). It is a continual oscillation of the difference in atmospheric pressure between the Azores High and the Icelandic Low (Colling, 2002). It plays a significant role in winter climatic conditions in the North Atlantic Ocean and the Nordic Seas (Colling, 2002). Often the state of the NAO is described using the NAO Index. The NAO Index is normally expressed as the difference between the winter atmospheric pressure differences between meteorological stations on Iceland and the Azores. When there are higher than usual pressure differences, the NAO Index is considered to be positive, and for lower than normal pressure differences, it is deemed to be negative, (Colling, 2002). When there is a large pressure difference the NAO is considered to be strong. A small difference would result in the NAO being called weak. When the NAO is strong, westerly winds are stronger, and there are changes in rainfall patterns, winter storm paths, the strength of the North-east trades and the transport of heat and moisture between the North Atlantic and the surrounding land masses, (Colling, 2002). A strong positive NAO Index causes the paths of the Gulf Stream and the North Atlantic Current to move northwards and their flow is stronger (Colling, 2002). The warmer temperatures of the Gulf Stream cause SL to rise, due to thermal expansion.

Phillips and Crisp (2010), found, in their study of the Bristol Channel and Severn Estuary, that SL variation was strongly correlated to the NAO Index. Woodworth et al. (2007) also found that extreme sea-levels and storm surges around the UK were dependant on the NAO. Considering the changes to atmospheric patterns that the NAO can affect, it can be anticipated that there would be an effect on SL at a regional scale and this component should be factored into SLR model studies.

Apart from meteorological factors, there are also geological aspects to take account of in UK SLR. Since the end of the last ice age, the mass loss of the huge ice sheets that covered most of the land (11,000 years ago), have caused parts of the UK to rebound, whilst other areas subside, (isostasy). Typically Northern parts of the UK are rising, whilst southern parts are subsiding. According to Woodworth et al. (2009), the area of greatest rate of upwards vertical land motion in their study was Rosyth in South-east Scotland with 1.39 mm y^{-1}. The area with the greatest subsidence rate was Devonport in the South-west of England with a fall in vertical motion of 1.23 mm y^{-1}.

Evidence for a correlation between the geological data and tide gauge data is tenuous. Woodworth et al. (2009) agree with this. Their study showed that even with an additional decade of tide gauge data, there was little improvement in the correlation between the data sets.

This study examined 12 sites around the UK, (see figure 3). The sites were chosen to represent an even spread of geographical range and were selected for their consistent tide gauge data. Newlyn and St. Ives were chosen as part of this study as they are the nearest tide gauges to the case study site. Newlyn is on the south coast and St. Ives is on the north coast.

Figure 3. UK sites where tide gauge data has been used to calculate sea-level. Red dots show sea-level rise. Grey dots show sea-level fall. All data used was obtained from; http://www.bodc.ac.uk/data/online_delivery/ntslf/processed/ apart from the St.Ives data which was obtained from the Environment Agency on request. “Contains Environment Agency information © Environment Agency and database right”.

Figure 4 shows the amount of SL change in each of these sites over the last 5 years (2007-2011). Six sites show a significant rise in SL. The highest of these sites was St. Ives with an increase of 0.09 m. Milford Haven had a very minimal fall in SL of 0.001 m, and therefore could be considered as remaining at the same SL for the past 5 years. There were 2 areas of significant SL fall- Weymouth and Whitby. Weymouth was the greatest of these with a SL fall of 0.085 m.

Looking at figure 3, all of the areas north of Whitby are undergoing vertical uplift of land. All areas south of Whitby (Whitby included), are subsiding. The areas that are marked with a red spot have seen SLR and those marked grey saw SL fall. Using all this information there are only 3 sites which match SLR with land subsiding,-Newlyn, St. Ives and Holyhead. There is only one site which matches vertical uplift with SL fall, (Aberdeen). Therefore only 4 sites out of 12 match tide data with geological data. Therefore by comparing the tide gauge data with the geological data it appears that there is no correlation between the data sets.

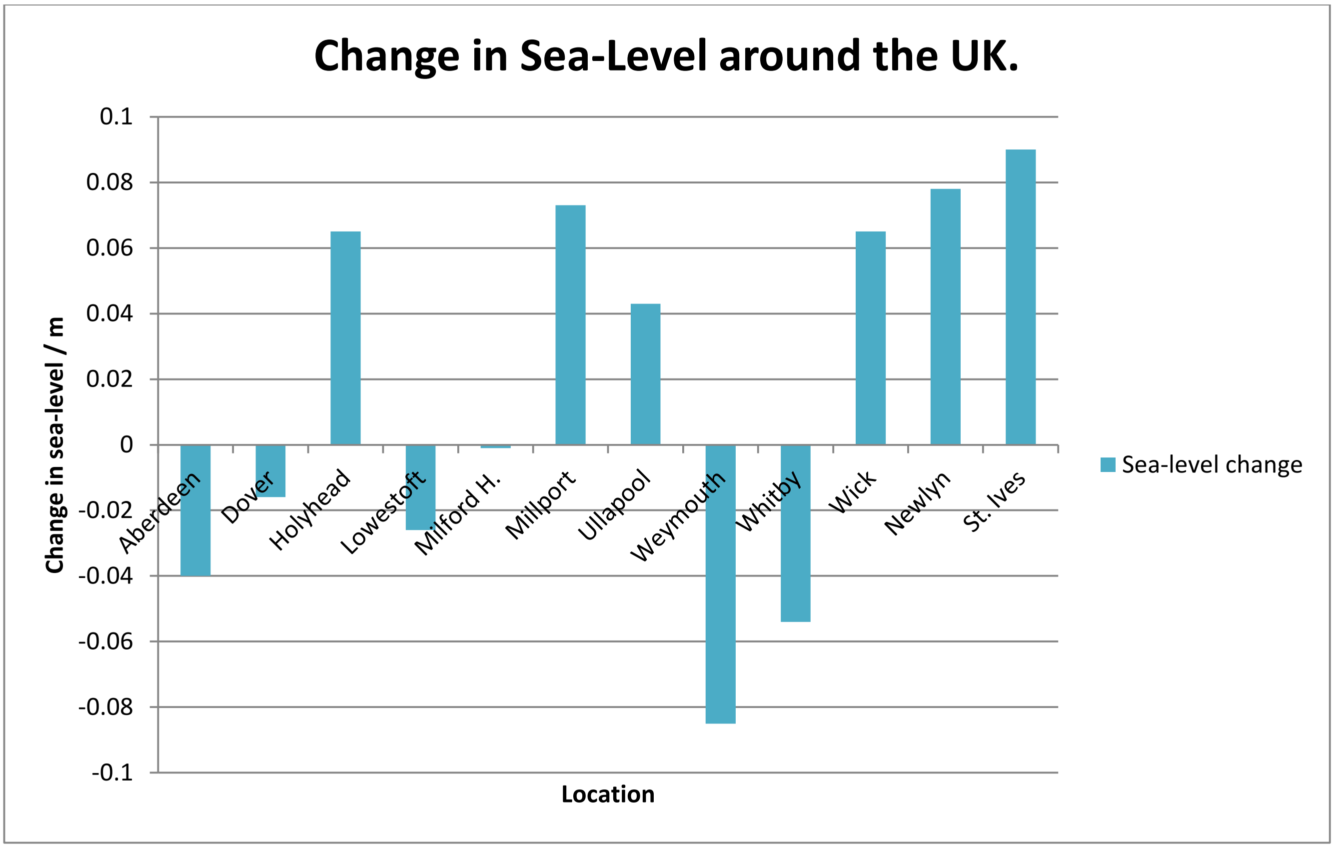


Figure 4. A graph to show the amount of sea-level change that has taken place from 2007-2011 inclusive. All data used was obtained from; http://www.bodc.ac.uk/data/online_delivery/ntslf/processed/ apart from the St.Ives data which was obtained from the Environment Agency on request. "Contains Environment Agency information © Environment Agency and database right".

There does appear to be a pattern of SLR from the south western tip of England up to the North eastern tip of Scotland. A pattern such as this would most likely be attributed to meteorological causes. A regional variation in SL change such as this would appear to be a response to air pressure changes, strengthening of winds, and storm surges. There could also be a component of the SLR which could be a result of a northwards shift of the Gulf Stream and the North Atlantic Current. The pattern of SLR is probably a manifestation of how the NAO interacts with the UK coastline. Investigations into the reasons behind the distinct pattern of SLR around the UK would be beneficial. The information that would be gained from such studies would assist future climate models in projecting expected SLR at a local and regional scale. This would be of benefit for future coastal management plans.

2.4. Newlyn and St. Ives Sea-Level Trend.

Newlyn is the closest main tide gauge to the case study area, (Hayle). However it is located on the south coast and Hayle is located on the North coast. The data for Newlyn used in this study was obtained from the British Oceanographic Data Centre (BODC). As per Araujo and Pugh, (2008), the years 1982-85 have been omitted from the analysis as the tide gauge was being refurbished at this time. As the case study site was on the north coast of Cornwall, data from the coast was needed in case there were discrepancies between coasts. The St. Ives data was obtained by request from the Environment Agency. The St. Ives harbour tide gauge is station number 3154. Only the data from the last 5 years was received.

Between 1915 and 2010 Newlyn saw a SLR rate of 2 mm y^{-1}. As mentioned previously in section 2.2, global SL rose faster since the beginning of altimetry records in 1993. Newlyn saw its SLR rate increase to 7.2 mm $y^{-1}$from 1993-2010. The last 5 years of records have also shown a marked increase in SLR rate. Newlyn and St. Ives were no exception. They saw SLR rates of 19.4 and 17.9 mm y^{-1}, respectively. These latter figures are of enormous significance. The values have been calculated from a very short time period, however in later sections it will become clear that these figures have played a substantial role in the coastal erosion seen at the case study site and in the local vicinity. For example, headlines were made in 2011 when a large part of a cliff collapsed near Hayle. The video link is here http://benvironment.org.uk/post/11314475635/cliffcollapse . The reasons for this cliff collapse were thought to be related to an increase in SLR.

2.5. Global Sea-Level Compared to UK, Newlyn and St. Ives.

The pattern of SLR can clearly be seen in figure 5. The Global and Newlyn plots show a large increase in SLR rate at the end of the 1970's and the beginning of the 1980's. This is of the same order to the rise which has been observed over the last 5 years. Incidentally, one of the reasons for Araujo and Pugh,(2008) omitting the Newlyn data for the years 1982-85 was because they deemed the mean tidal values as being clearly outside the normal range. They put this down to the tide gauge being refurbished at the time. However in hindsight the abnormality of the data could well have reflected an abnormal rise in SL at the site. A link between the climatic impacts of the major ENSO event that occurred in 1982-3 may possibly be made. This would have to be investigated with other supporting evidence.

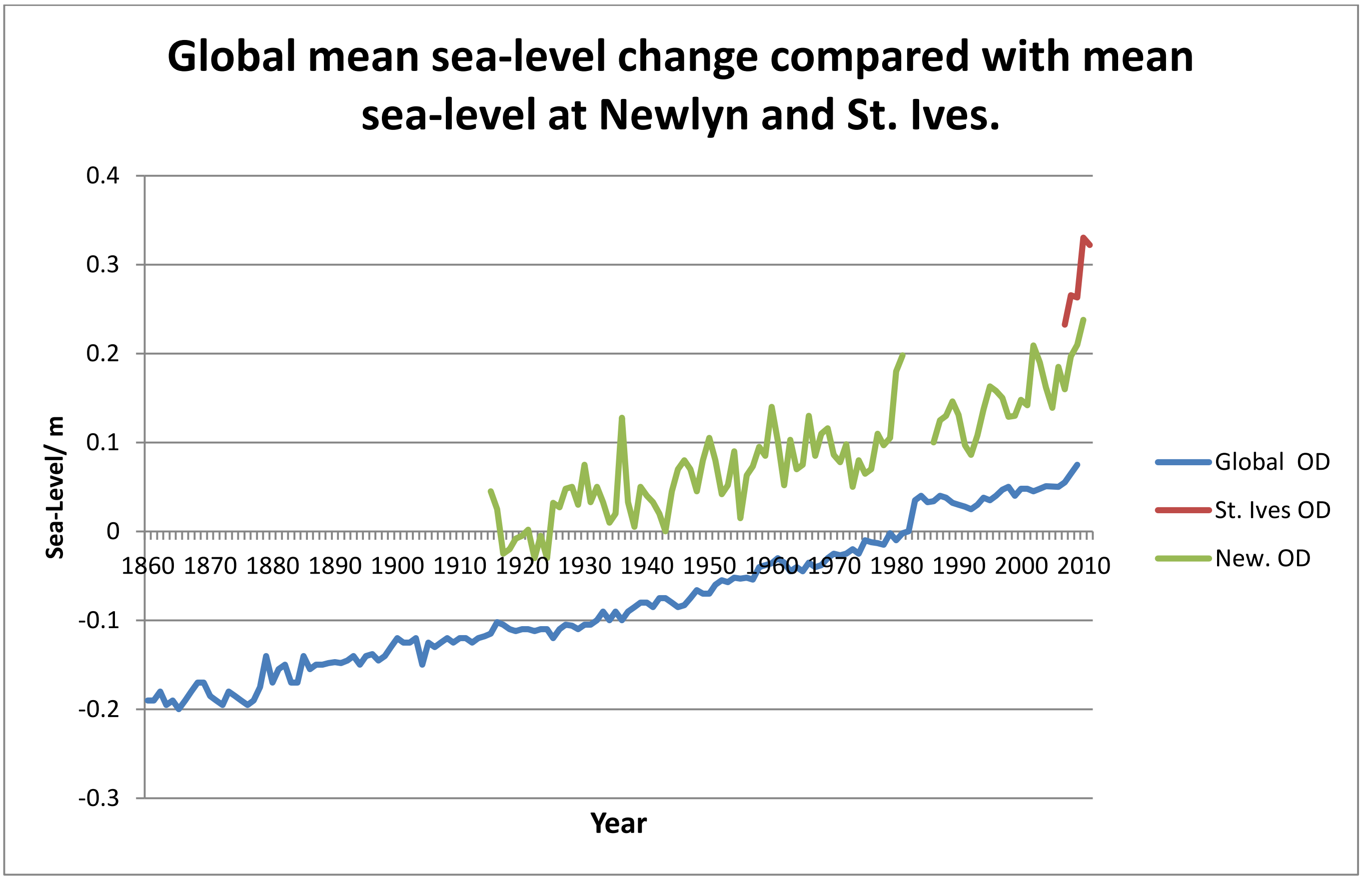


Figure 5. A graph to show global mean sea-level change compared with mean sea-level at Newlyn and St. Ives. Data expressed in terms of Ordnance Datum (OD). Newlyn data was obtained from; http://www.bodc.ac.uk/data/online_delivery/ntslf/processed/ . St.Ives data which was obtained from the Environment Agency on request. "Contains Environment Agency information © Environment Agency and database right".

In table 1 the rates of SLR can be compared. During the 20th Century the UK saw a SLR rate of 1.4 mm y^{-1}. Globally this was 1.7 mm y^{-1} and Newlyn was 2 mm y^{-1}. Both the UK and Newlyn were just outside the standard error margin of the Global rate (± 0.2 mm y^{-1}) at either end of the scale.

By examining the period since altimetry records in 1993, the SLR rates are markedly different. Globally the rate of SLR is 3.2 mm y^{-1}, but Newlyn sees a rate of SLR of 7.2 mm y^{-1}. Newlyn is more than double the rate of SLR seen globally.

The interesting figures come from examining the SLR rates from between the years 2007-2010. Globally this figure is 5 mm y^{-1}, at Newlyn it is 19.4 mm y^{-1}, and St. Ives is 17.9 mm y^{-1}. Both Newlyn and St. Ives SLR rate is almost 4 times as much as the global rate. These figures mirror the rates of SLR seen at the end of the 1970's and beginning of the 1980's in both Global and Newlyn data. Incidentally this period of time saw great erosion at the case study site. This will be discussed later.

The values of rate of SLR for Newlyn and St. Ives may seem anomalously high at first glance. However, Jevrejeva et al. (2012), project that the maximum rate of SLR by the year 2100 would be 17 mm y^{-1} (this is for the high emission scenario). They also predict that the maximum rate of SLR at around 2150 would be 20 mm y^{-1} in the high emission scenario. The rates for Newlyn and St. Ives are comparable to these figures now. These figures may seem alarmist; however the data from Newlyn and St. Ives undoubtedly contain a major local and regional SL variable. This probably relates to the NAO influence on the UK coastline. As this is a relatively localised variable this situation may not persist. The interest of these figures relate to how the coastline here adjusts to this rate rise. The erosion studied in this area can illustrate how other areas around the globe would react to a rate in SLR such as this. This could help to assess the various parameters that are needed to model future SLR. Future research into areas with high rates of SLR would therefore be beneficial. This is particularly true when assessing the suitability of various coastal protection measures, and their effectiveness in ameliorating the effects of SLR.

3. The St. Ives Bay Sediment Transport System.

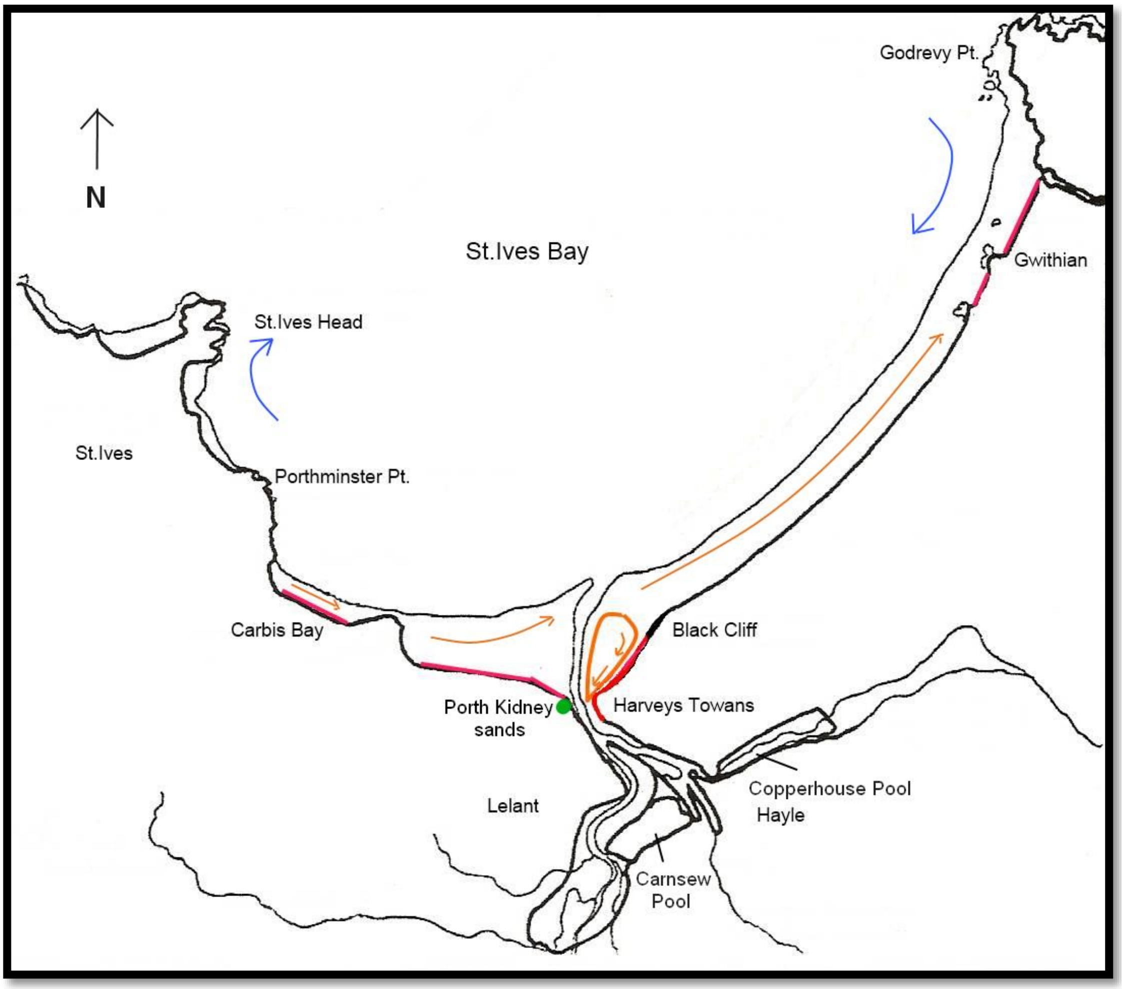
Before a study can look at how a perturbation can affect a system, there has to be an understanding into how that system naturally performs. In this chapter the dynamics of the St. Ives Bay sediment transport system will be explored.

The St. Ives Bay area in Cornwall, UK, (Figure 1), used here as a case study, is considered to be a closed sand cell, (Buro Happold Limited, 2007). A closed sand cell system means very little or no sediment enters or leaves the system naturally; sediment is just circulated within the system. The reasoning behind the bay being considered a closed sediment cell is due to the fact that as sea-levels rose during the Holocene transgression, the shoreline moved landwards transporting sand and gravel onshore by wave action. This material now forms the beaches and dunes that front the bay. The sediment left offshore are larger grain size sands and gravels with thin, patchy distribution that under current conditions are largely immobile, (Wave Hub, 2006). The rivers which run into the bay do not supply sediment to the peripheral beaches. This is especially true for Hayle Estuary which acts as sediment sink, (Wave Hub, 2006). Hayle estuary is of a bi-lobate form. In figure 6, the two lobes are formed from the areas called Copperhouse Pool and Carnsew Pool. These pools act as the sediment sinks.

The coastal processes of St. Ives Bay dictate how the sediment flow and hydrological processes of Hayle Estuary will act. The Hayle Estuary forms a sub-cell (Buro Happold Limited, 2007), which acts, almost independently, from the St. Ives Bay sediment cell, (see figure 6). This littoral sub-cell will be discussed in section 3.1.

The littoral transport directions and littoral cells can be seen clearly on figure 6. The predominant flow is from west to east. The greatest manifestation of this flow direction is the eastwards build up of sand that fronts Porth Kidney Sands. This build up of sand actually shifts the direction of the channel out of Hayle Harbour by creating a bar, (Hayle Bar). Currently this channel points quite markedly to the east. This creates a shadow zone (Sea Sediments, 1983), where no sediment is received to the areas to the south of the channel. The reason for this is that the channel acts as a physical barrier to any material being brought in from the bay or from Porth Kidney Sands. Any sand that is brought toward the channel during high tide encounters the channel.

The natural geometry of an estuary means that a large volume of water has to flow through the restricted cross-section of the tidal channel (Wright et al. 2005). At Hayle this is an exceptionally narrow inlet. The channel is a deep, narrow feature which because of its shape causes the water within it to flow at higher velocities. When the seawater reaches the narrow channel a build up of water behind forces the water through faster. The speed of the water flowing through the channel removes the majority of sediment in suspension carrying it in the direction of tidal flow. The sand is deposited when the flow speeds reduce. The flow speed is reduced in areas where the flow of water is no longer constrained. This process usually occurs in the wider areas of Lelant Water, Hayle Harbour, and out in the bay near the area of Black Cliffs, depending on the state of the tide. Flood tide takes sediment to Lelant Water, and ebb tide takes the sand to the bay.



KEY: Littoral transport direction

Areas of erosion

Sediment transport direction in Bay

Chapel Anjou Point

Figure 6. A map of St.Ives Bay showing sediment transport directions, and areas of erosion.

Out in the bay the transport direction is from east to west driven by the flow of water out in the Atlantic Ocean. Taking all this information into account it can be seen that the sand is predominantly circulating through the system. There are exceptions to this which will be discussed in the section.

3.1. Hayle Estuary Sub-Cell.

Naturally estuaries are actively silting up. Hayle is no exception. The natural processes here lead to the steady infilling of the harbour and Lelant Water with sediment. At present this sediment is trapped. The ebb flow speed that would ordinarily carry sediment in suspension out into the bay is too weak. This is a result of the asymmetry of tidal flows. As mentioned previously the flood tide flows at higher velocities because of the restriction that is the narrow channel. However on the ebb flow, the water is flowing from tidal flats. These are the areas that are unconstrained and so the flow of water out of these areas is relatively slow. The slow velocity of the water means that any sediment deposited in the estuary is likely to remain there as it will not be drawn into suspension. Only will the ebb flow speed increase when it encounters the channel again. This results in sand being removed only from areas skirting the channel, i.e. Porth Kidney Sands and Hayle Beach. Table 2, in conjunction with Figure 7, shows that the ebb flow is considerably slower than that of the flood. Significantly more sand is transported landward than out into the bay. It is predicted that 232 tonnes is transported to, and remains within the estuary and harbour a year. This constant landward transportation of sand effectively chokes the harbour as it steadily infills. The channel if left would become treacherous and unnavigable. Later in this study the methods for addressing this situation will be discussed whilst taking into account the ongoing rise in MSL.

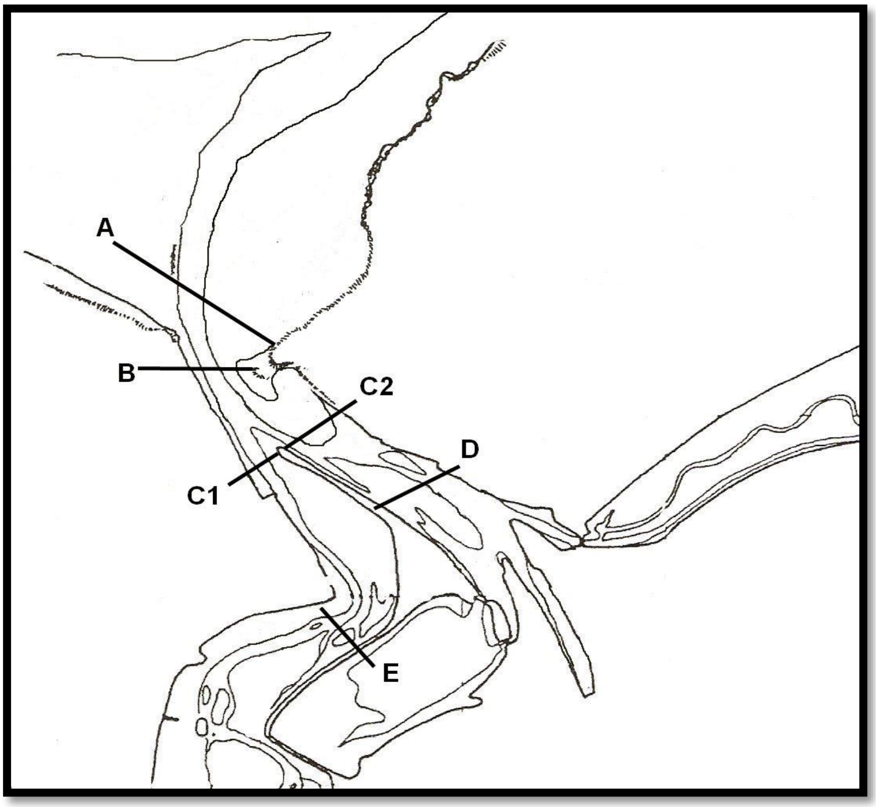


Figure 7. A map to show the cross-section areas for Table 2.

Cross section	Predicted Weight of Sand Movement in tonnes		
	Ebb	Flood	Net
A	61.9	-6.9	55.0
B	45.9	-27.3	18.6
C1	141.9	-179.9	-38
C2	47.3	-278.8	-231.6
D	25.7	-60.8	-35.2
E	4.3	-5.3	-1.0
Total	327	-559	-232

Negative value = Net transport is in a landward direction.

Positive value =Net transport is in a sea ward direction

Table 2. The potential sediment transport through Cross Sections on figure 7, during a spring tide. Adapted from Babtie Group (2002).

Another exception to the general circulation of sand within the St. Ives Bay is the Hayle Estuary sub-cell that is active in the location that fronts Harvey's Towans. This area is called Hayle Beach. From figure 6 the Hayle Estuary sub-cell can clearly be seen. This littoral sub-cell is at present acting almost as an isolated system. The reason for this is that the channel has curved to the east. As mentioned previously this creates a physical barrier to any sediment being brought in from Porth Kidney Sands and from offshore. The direction of littoral transport in this sub-cell is from east to west. This sub-cell can be determined from figure 8 where the transport directions diverge near the Black Cliffs area. Because of the flow direction in this sub-cell it means that sediment is taken towards the harbour and lost to the flow of water in the channel. Sand from this sub-cell can be transported to the harbour, Lelant Water or to the area just offshore from the Black Cliffs. Sediment is consistently lost and not replaced because the source and terminal areas of sediment transport are not connected. The source area of the littoral cell is at the furthest eastern extremity and the terminus is in the channel.

The natural state of the Hayle Beach area is not one of erosion. If there were no anthropogenic perturbations then the harbour would infill steadily reaching equilibrium. Once the estuary was full of sand, the removal of sediment from Hayle Beach would cease and the sand would just circulate in the bay. Due to the necessary harbour clearance measures taken, sand is consistently lost to the channel and beach levels are lowered. This allows the sea to encroach further inland, eventually undermining the toes of the dunes that skirt this area. The sand from the dunes feeds the beach, building up beach levels again, and the transport continues, until the beach is lowered enough for the sea to encroach to the dunes again. This is effectively a positive feedback cycle of erosion.

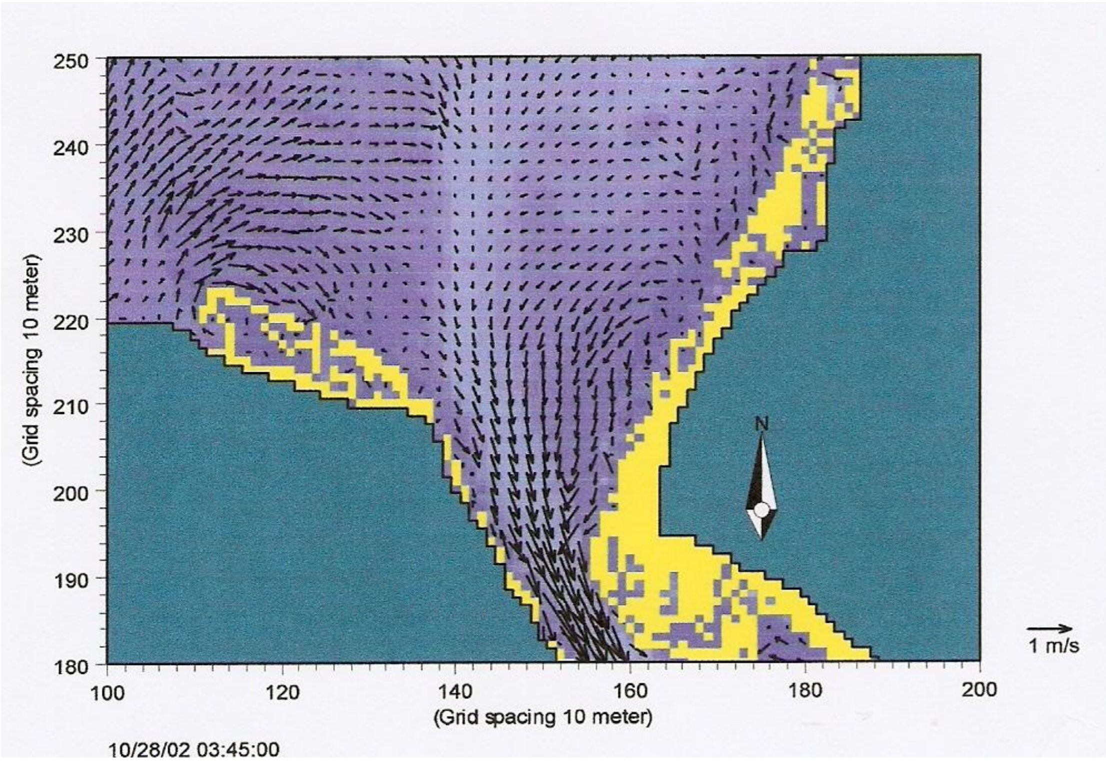


Figure 8. The magnitude and direction of tidal flows during mid flood state. Taken from Babtie Group, (2002), Hayle Harbour Hydrodynamic Modelling Report.

4. Anthropogenic Perturbations on a Sediment Transport Cell.

Estuaries do generally make good natural ports and harbours despite the fact that many are slowly silting up. Attempts are usually made to keep the navigable channel clear as long as possible. Anthropogenic methods of keeping the channel clear consist of training walls, dredging and sluicing. All methods disturb the natural state of the sediment transport cells that operate in the vicinity. Whether this results in a new pattern of accretion or erosion along the coast line is dependent on the method used.

4.1. Sluicing in Hayle and its effects.

Traditionally Hayle kept its channel clear and navigable by the use of sluicing. Sluicing is a process whereby on the flood tide seawater fills a large man made pool. This water is then impounded at slack water, withheld for 3 hours after high tide and then the water is released. This effectively increases the velocity of the ebb tide and thus scours out any build up of sediment brought in on the flood tide. Firstly, this operated from Copperhouse Pool in 1768/9, (Cahill, 2000), and then in conjunction with Carnsew Pool from the end of 1834 (Vale, 1966). Sluicing was used continually up until 1976. Sluicing effectively cleared the channel without removing sediment from the St. Ives Bay sediment system. It was so effective that large ships could bring in cargo to Hayle Harbour and also transport goods and people out of Hayle. Hayle developed into one of Cornwall's largest industrial ports. It served surrounding mines and foundries from at least the mid 18th century. The Cornish Copper Company and Harvey's of Hayle set up home here. These 2 companies were largely responsible for the growth of Hayle during the 19th century and for the creation of the sluicing regime in Hayle, (Cahill.2000)

Hayle continued to be a thriving port although the foundries ceased operations by 1903. Industry turned to ship building and breaking. In the Second World War Hayle Harbour served as a base for many war time related industries, such as ship building, gun manufacture and the production of bromide for aviation fuel. Post war saw a gradual decline in the activity at Hayle Harbour, however the transport of coal for the power station meant that commercial shipping continued until 1977 (Cahill. 2000).

There were hidden benefits of using the sluicing process. Apart from retaining sediment in the bay, sluicing actually lowered the height of Hayle Bar and straightened the navigable channel. Straightening the channel is a key factor in making the Hayle Estuary sub-cell sustainable. For well over a hundred years the channel was kept pointing in a northerly direction from Chapel Anjou Point (marked on figure 6). When the channel is oriented in this manner it reduces the shadow zone. This allows the transport of sand from offshore reaching Hayle Beach at the source area, thus connecting the terminal and source areas. This regime results in the beach and dunes accreting. The straightening of the channel and increased velocity of the ebb flow also prevented sediment from Porth Kidney Sands and Hayle Beach from being lost to the harbour and Lelant Water. The sand was instead sent out into the bay to continue its flow around the whole of the St. Ives Bay sediment cell.

There have been no detrimental effects found globally or locally, of sluicing with relation to erosion.

4.2. Dredging in Hayle and its effects.

Dredging is a process whereby the build up of sediment in a harbour and its channel is removed to maintain a navigable channel. The methods used to dredge vary.

- Mechanical Dredging. This method consists of an excavator and dump trucks operating on the beach beside the channel. It does make works to the mid channel difficult.
- Cutter Suction Dredging. This involves a vessel removing sand from specific areas within the channel and off loaded using an excavator to the quay side.
- Grab Dredger. This involves a vessel that can load and unload using its own grab. The vessel used also has a split loader that can discharge the sediment to the seabed off shore.
- Plough Dredger. Plough dredging involves a vessel towing a plough along the sea bed. This draws up sediment into suspension which is flushed out to sea on the ebb flow.
- Injection Dredger. This involves the injection of a jet of water to the sand along the channel bed. This brings sand into suspension which is taken out to sea on the ebb flow.

The process of deepening channels to aid navigation, (by means of dredging), leads to an alteration in bathymetry. As mentioned previously the geometry of any estuary is such that, when the tide rises, a large volume of water is focused into a relatively small channel, causing flow speeds to increase. After dredging, the deepened channel and the new open volume of the harbour, increases the flood tide velocities and expands the capacity to trap sand. High flow speeds can transport large amounts of sediment, (coarse sand and even gravel), as bedload in a landward direction. When the water flows out of the restricted channel into the wider space of the harbour and estuary mud flats, the flood-tide velocities reduce and the sediments are deposited. Although this process is a natural one. Dredging speeds up the flood-tide flow to such a degree that the process is intensified, causing more sand to be bought in landwards. This situation is exasperated if the method of dredging removes the sand from the sediment transport cell. If the sand is removed it will just be replaced with more sand. Then this new build up of sand will need to be removed to maintain a navigable channel. Eventually more and more sand will be lost from the system. This will result in erosion along the coastline of the littoral cell that the sand is being drawn from. If the method of dredging retains the sand in the sediment transport cell then the sand removed will eventually end back in the channel but no new sand will be lost and the sediment will just circulate within the system.

Maintaining a navigable channel by dredging alone is unsustainable. Deepening the channel only serves to increase the amount of sediment being deposited in it, causing further dredging to be needed to maintain the channel. Effectively a positive feedback loop of sedimentation and removal is created (see figure 9). In the case of Hayle, the increased flood tide velocities are not just causing increased amounts of sediment to be drawn landward, they are also drawing in the Hayle Estuary sediment transport sub-cell into the harbour. The situation is analogous to a sand timer.

An additional factor that has to be accounted for at Hayle is the orientation of the channel. Natural processes curve the channel around to the east creating a shadow zone as mentioned before. Dredging and removal of sand from the channel when it is orientated in an easterly direction just serves to speed up the processes of erosion so it progresses at an extreme rate, as the source and terminal areas are maintained unconnected. Dredging would have to be repeated on a very regular basis to maintain a straight channel from Chapel Anjou Point as sluicing does. This is impractical as the costs to the harbour company would be enormous. These factors are leading to the extreme erosion seen on Hayle Beach.

Dredging in Hayle began in 1973, (Babtie Group, 2002), and took over from sluicing as the only form of channel maintenance from 1976. The method of dredging here was Cutter suction dredging until October 2001 when the method was changed to mechanical dredging (Buro Happold Limited, 2010). Both forms of dredging removed the sand from the cell for sale. This sale of sand paid for the operations to take place.

Maintenance dredging here has seen up to 30,000 tonnes, (15,000 m^3) of dredged material being removed from the system, and sold, annually since 1973, (Babtie Group, 2002). That equates to the removal of around 1 million tonnes of sand being removed since dredging began. The loss of this amount of sand is equal to a loss of depth of 110 mm a year from the Hayle Beach area alone, or 5 mm a year spread over the St. Ives Bay coastal cell up to the year 2002, (Babtie Group, 2002). Babtie Group (2002) stated that this could lead to the reduction of beach height on Hayle Beach by over 1 m in a decade (or almost 4 m since 1973), if no material was being supplied from the dunes in the area or by littoral transport. In 2010, some 16,200 tonnes of sediment was removed from Hayle Harbour in just 4 months (January-April), (Buro Happold Limited, 2010).Current Harbour owners ceased dredging at the beginning of April, that year, a few weeks before the last dredging license had expired. This was the highest amount of sand ever removed in Hayle's dredging history in a quarter. This was followed by an intense phase of erosion where a reduction of ~3 m in beach height resulted in the exposure of the Wave Hub export cable for the first time in June 2011. A significant section of dune frontage was also eroded in the order of ~65 m.

When the dredging process began as the only form of channel clearance in 1976, it was swiftly followed by a period of intense erosion which had not been seen in the area previously. 1977-78 saw the loss of a major extent of dune frontage and beach levels were lowered. The result of this loss was the destruction of a number of chalets along the coast at Harvey's Towans. These chalets ended their lives as mangled pieces of wood on Hayle Beach. This pattern of erosion will be discussed in section 5.2.

It was suggested by the Babtie Group, (2002), that in 2002 beach levels had dropped by ~1 m below the level seen in the survey undertaken by Sea Sediments (1983), in their hydrodynamic modelling report which was commissioned by Penwith District Council. The erosion of the dunes had prevented beach levels falling away too dramatically at this time.

In the last decade beach levels at the area of beach in front of Harvey's Towans have dramatically decreased even further. In modelling studies undertaken in 2002, a reduction in beach level of 1 m does affect the tidal current within Hayle Estuary, (Babtie Group, 2002). Flood tide velocities increase and ebb flow decreases in Hayle Harbour, leading to the sediment accretion within the harbour. This results in an increase in the landward movement of sand. These changes are a direct result of beach morphology and bathymetric alterations, as all other parameters have remained unchanged. A continued loss of sand from the sediment cell would act as a positive feedback mechanism, resulting in the continuing erosion of the beach and dunes (see figure 9). By permanently removing sand from the Hayle sub-cell, dredging is effectively sustaining the sediment transportation from Hayle Beach and Towans into the harbour. Gravity assists processes that redistribute sand. With less sand in the system, and increased trapping capacity (due to deepening of the channels), the highest points will become lower (erosion), and the lowest points will fill. The consequences of this include the loss of dunes and sand on the beach, (Montague, 2008). This fact has serious ramifications for coastal protection as the loss of beaches and dunes opens up Hayle to the effects of storms and climate change induced sea-level rise, (Vega-Leinert and Nicholls, 2007).

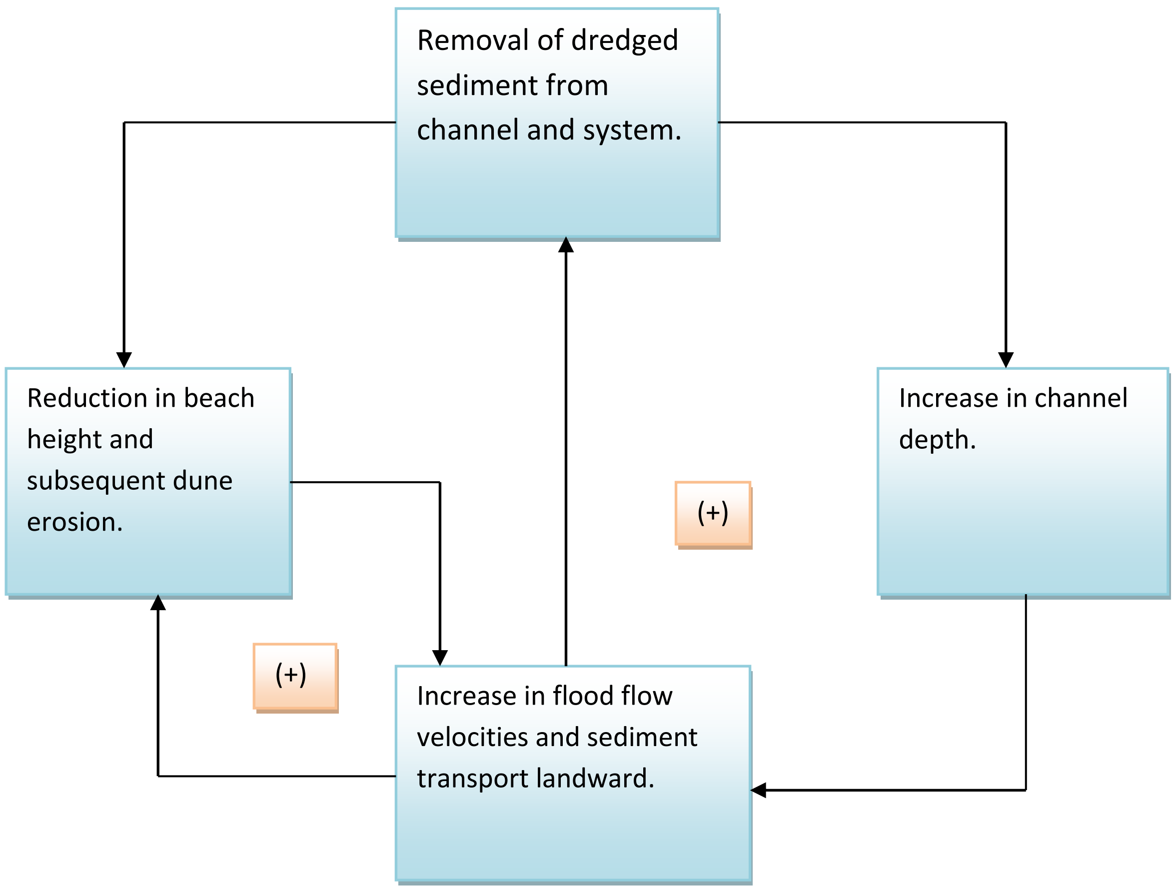


Figure 9. A flow diagram illustrating the positive feedback loop that is set up when dredging is undertaken in a harbour.

4.3. Global Examples of Dredging and the Effects.

Numerous cases of dredging and the resulting erosion that has been experienced on nearby coastlines have been found around the globe. This study has investigated a few of these cases. No literature has been found where dredging resulted in accretion.

To maintain navigation of the inlets of Florida's east coast, it has been dredged since 1903. Dredging has allowed increasingly larger vessels to navigate into the harbours, (Montague, 2008). Over the last century Florida's Atlantic coast saw these dredging activities remove a total of 160 x 10^6 m^3 of sediment over a century. 116 x 10^6 m^3 of this was removed from the sediment transport system permanently, (Montague, 2008). The sediment was deposited in deep water outside the sediment transport system and inland. The loss of this sediment from the transport system led to the reduction in the sand budget for that system. The deepening of the channels in Florida meant that more sediment could be deposited in the newly dredged areas. These areas effectively act as a sediment trap, which would require further dredging. This regime results in a positive feedback being set up. This feedback loop led to beach and dune erosion along the coastline. Montague, (2008) states that overall the loss of beaches and dunes could equate to 130x 10^6 m^3. The loss of the beach and dunes that skirt Florida leads to an increase in storm damage to the coastal communities. Beach and dune systems act as a buffer from the storms that come in off the coast. The beaches dissipate the wave energy protecting the towns and cities behind them. They effectively act as a first line of defence to the weather conditions that come in from the sea. Without them the coast is open to the meteorological onslaught.

In Dallas and Barnard (2011), study of the San Francisco Bay they discuss the erosion seen there and possible reason for it. The San Francisco Bay is connected to the Pacific Ocean by the Sacramento- San Joaquin River System. The river system consists of 3 internal bays, North Bay, Central Bay and South Bay. These bays are separated from the Pacific by the narrow Golden Gate inlet, (Dallas and Barnard, 2011). Once the ebb tide leaves the inlet the velocity of the flow decreases and sediment transported in the flow is deposited. This has led to the gradual build up of sand in the shipping channel, (Dallas and Barnard, 2011). This has resulted in the need for repeated maintenance dredging activities to maintain a navigable channel.

Dallas and Barnard, (2011), believe that the erosion seen along the coast is a result of a couple of factors. One such factor is that the sediment supply to the coast in this area has been markedly reduced by a number of anthropogenic means. These consist of dredging activities, damming and drainage. In the case of dredging a minimum of 2 x 10^6 m^3 of sediment has been permanently removed from the coastal system over the last century. A recent shoreline retreat of ~15.1 m has occurred since 1997 (Dallas and Barnard, 2011). Dallas and Barnard, (2011), suggest in their study that the deepening of the channel has also caused a reduction in the tidal prism which altered ebb-tidal morphology. The new morphology of the delta altered incident wave energy distribution and caused long-term shoreline change.

Goodrich et al. (2003), evaluate a proposed harbour expansion scheme at the mouth of the Savannah River System in Georgia. They examined anthropogenic impacts at the entrance to the Savannah River going back to the 18^{th} century. Maintenance dredging, construction of jetties and submersed breakwaters were all considered.

The area known as Bar Channel which extends from Fort Pulaski was of particular concern to Goodrich et al. (2003), because of the coastal processes there. Tybee Island was found to be particularly prone to erosion due to historic Savannah Harbour modifications and dredging.

All these articles illustrate that perturbations to the natural processes working in the coastal systems via anthropogenic means alter their dynamic equilibrium. Very often this can lead to irreversible damage to the environment, ecology and the coastal sediment transport system. All these studies show that the dredging process is unsustainable. This is an even more valid point when the dredged material is removed from a sediment transport cell. This type of activity results in a reduction in the sand budget of that system, inevitably leading to erosion. Once beach levels have been lowered via erosion then the bathymetry of the area, wave refraction, tidal prism and coastal protection are all altered. Once these components are perturbed the system has to find a new equilibrium. Often this is not a state at which the damage experienced can be reversed.

4.4. Comparison of Global Sites with Hayle.

The situation at Hayle is mirrored by all the studies in section 4.4. All of the sites saw dredging activities with subsequent removal from the sediment transport cell. All sites saw erosion along the coast from the port or harbour where the dredging occurred.

As in Hayle the global sites mentioned in this study had a substantial amount of sand removed from the system, and a positive feedback loop, (as seen in figure 9), was created. This led to the loss of beach and dune systems, and hence the loss of the main form of coastal protection along those shorelines.

During this study numerous examples have been found globally of dredging interfering with the natural processes seen at the site. However it has to be noted that in the case of Hayle dredging and removal of sand from the system actually speeds up and sustains the natural state of the system. Dredging, whether removing sediment from the transport cell or not, opens up new space which can be in filled with sand. This effectively prolongs the natural processes that are serving to silt up the harbour. If sediment is retained in the transport cell then the sand will just circulate back through the system eventually ending back in the harbour to be dredged out again. If the sand is removed from the system then the new open space will be filled with newly eroded sand that is drawn into the channel. This process enables erosion to be sustained.

Sluicing at Hayle was the process that actually interfered with the natural processes. Sluicing occurred for well over 100 years in Hayle. During its use, the area in front of Harvey's Towans built up from a spit of sand to a large beach and dune system. This was a result of the straightening of the channel and the reduction of the shadow zone that can set up in that area. Regular sluicing effectively clears the channel and allows the sediment that is flushed out of the harbour to remain in the system. This is a sustainable process of channel clearance. Dredging, and subsequent removal of sand, on the other hand is not a sustainable process in a closed sediment cell. Despite the fact that it speeds up natural processes, dredging of a finite resource is never sustainable. This is a sentiment that is echoed by all the literature.

There was no literature discussing the benefits or failings of sluicing, so in this respect sluicing is an unknown quantity. Further studies into channel clearance by means of the sluicing process, could be beneficial. Illustrating the effects of sluicing at Hayle could promote its uses around the globe, especially in the light of ever increasing SLR and resulting erosion.

5. Pattern of Accretion and Erosion in Hayle.

Over the past 160 years Hayle has seen a long period of accretion and more recently, erosion. Examining this cycle of accretion and erosion against global, Newlyn and St. Ives MSL data has created an interesting study.

5.1. Period of Accretion at Hayle- 1849-1960.

By examining figures 10 and 11 the gradual accretion and build up of the dunes at the mouth of the harbour can be seen clearly. Between 1848 and 1930 there was an increased accumulation of sand to the east of the channel. Between the 2 world wars the dunes at Harvey's Towans were used as a dump. Items such as metal signs and barbed wire were deposited here. This material acted as a nucleus for new sand dunes to build. Figures 10-11 illustrate succinctly the difference in beach and sand dune extent was very significant between 1848 and 1930. A large area of what was just a sand spit built out and become a well established, vegetated dune system.

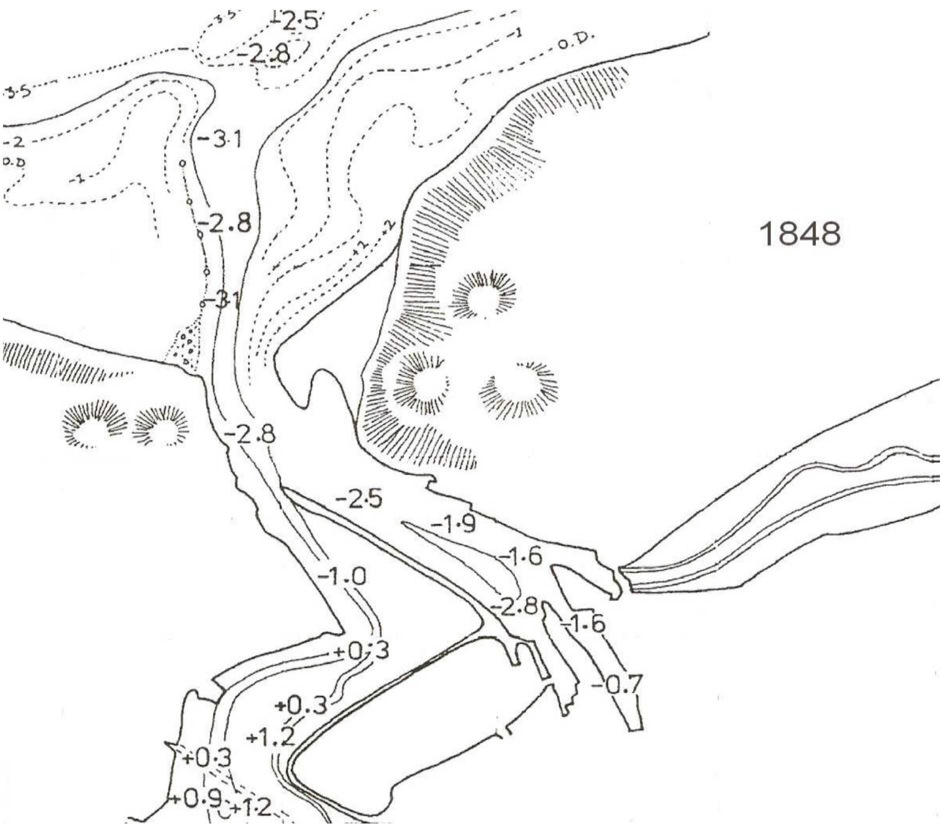


Figure 10. Map of Hayle Estuary in 1849. Adapted from Sea sediments(1983).

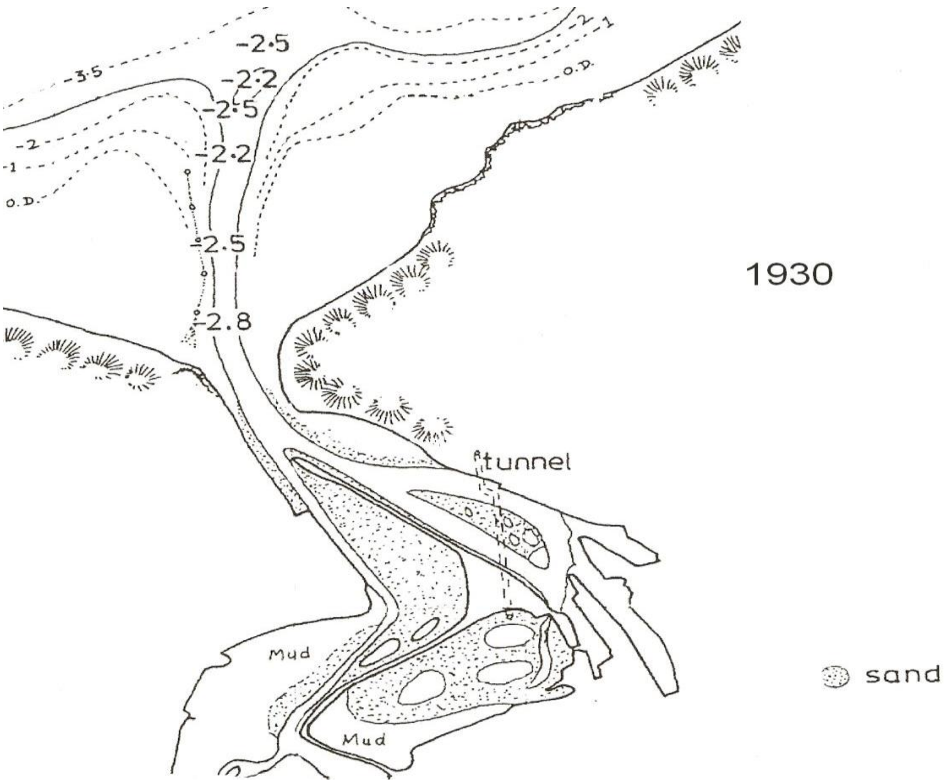


Figure 11. Map of Hayle Estuary in 1930. Adapted from Sea sediments(1983).

Sea Sediments (1983) state that at this time the beach area increased in height by 2 m. The authors also support the fact the dunes were well established in the area where previously there was a sandspit. All this is on a background of constant gradual SL rise (see figure 5). No erosion was noted during the period of a rapid rate rise in SL around the time of the late 1930's as seen on figure 5.

This pattern of accretion was consistent until around the late 1950's and early 1960's. This shall be discussed in the next section.

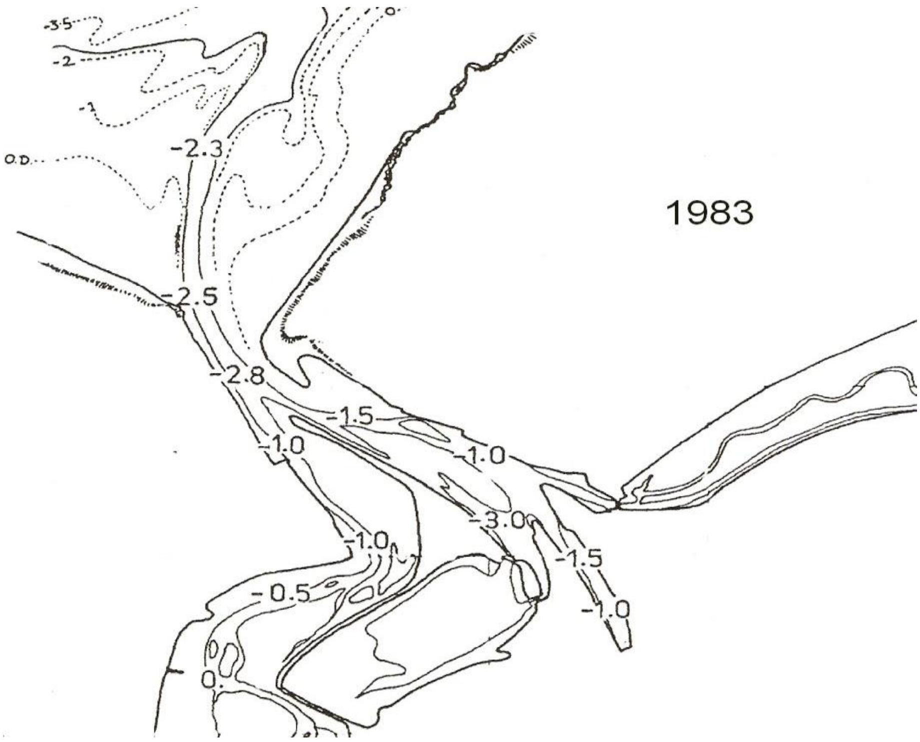


Figure 12. Map of Hayle Estuary in 1983. Adapted from Sea sediments(1983).

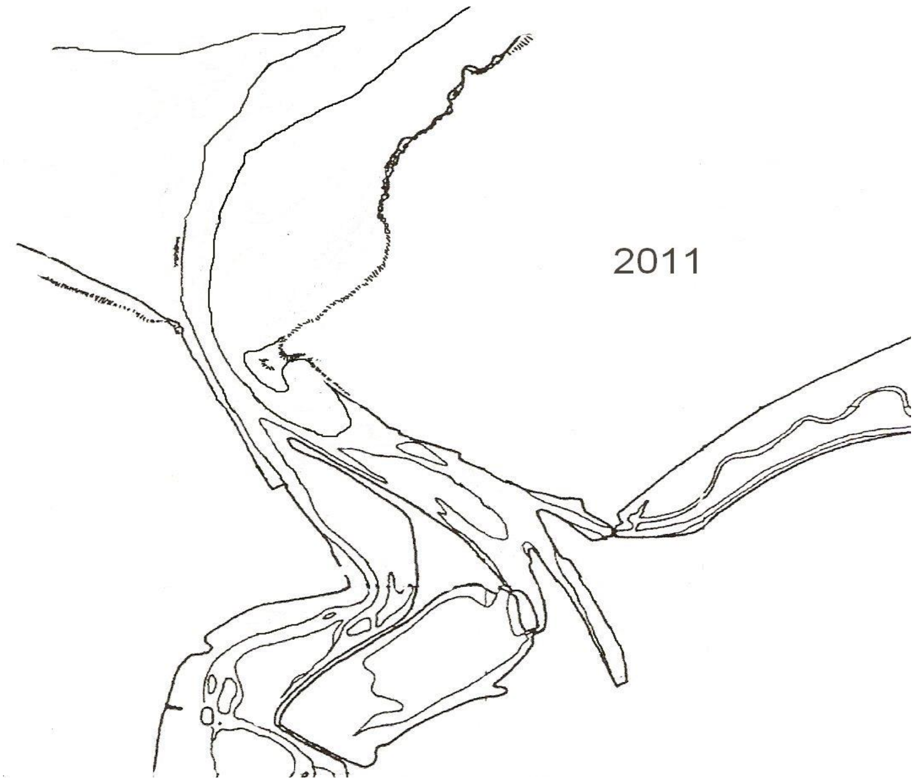


Figure 13. Map of Hayle Estuary in 2011. Adapted from Sea sediments (1983) using AA Maps (2011) aerial view and field trip data.

5.2. Period of Erosion in Hayle 1960 to the Present Day.

By 1960 there is evidence of a slight lowering of beach levels at the east of the channel, possibly as a result of lack of maintenance of Hayle Harbour as industrial activity ceases (Sea Sediments, 1983). The Sea Sediments (1983), survey revealed a significant change in the stability of the form of the estuary entrance and channel position that had persisted since the mid 1840's. By the early 1980's (see figure 12), the channel no longer pointed in a northerly direction from Chapel Anjou Point, but was curved to the east. However the depth of the channel remained the same. At this time Sea Sediments, (1983) notes that the beach levels at the east of the channel (Hayle Beach), had been lowered to such an extent that the measurements were comparable with those recorded in the admiralty chart of 1848. Therefore it was calculated that beach levels had dropped by up to 2 m. The survey also revealed that the high water mark along Hayle Beach in front of Harvey's Towans had retreated so significantly that it occupied a more landward position than in 1848. This landward movement of the high water mark resulted in a marked erosion of the dunes. In some areas a 70 m swathe of dunes had been lost from the seaward face of Harvey's Towans, (Sea Sediments, 1983).

The Sea Sediments (1983), paper concluded that, after examination of the changes in the area of the estuary mouth over the past 150 years, there was likely a single mechanism that had contributed to the erosion. Looking back at the tide data from Newlyn there appears to be little difference in SL between 1940 and 1977, (the date of major erosion). In total the difference in MSL was 7 cm from 1940-1977. This is a rate of 2.1 mm y^{-1}, which is marginally more than the rate of SLR during the whole period of Newlyn data (1915-2010), as seen in table 1. However it has to be noted that in 1976 the MSL was 0.07 m at Newlyn and in 1977 the MSL was 0.11 m (tide measurements are in OD). This was a rise in MSL of 4 cm in just one year. With this fact it can be argued that the erosion seen here was related to the cessation of sluicing and dredging operations coupled with the SL rise. However the largest rate of MSLR occurred in 1936. From the Newlyn data it shows a jump of MSLR of 10 cm from the previous year. No erosion was seen at this time. In fact Hayle Beach was undergoing a period of accretion. The figure of MSL in 1977 was actually less than that of 1936 0.11 m and 0.13 m (OD), respectively. The second largest rate rise was seen in 1980 and 1981. The data from Newlyn from the period 1982-5 was omitted from this study. However, as mentioned before, globally there was an anomalously high SLR which has been linked to and ENSO event. During these years the MSLR at Newlyn jumped 9.3 cm from the figure in 1979. This figure is comparable to the figure of SLR at St. Ives between the years 2007-2010, where MSL rose by 9.8 cm.

It has to be noted that the large SLR of 1936 occurred when the beach levels were significantly higher than today. This would have offered some protection to the dunes. The erosion in 1977-78 resulted in the loss of 2 m of beach height in the area (Sea Sediments, 1983). This fact means that from that period onward, the Hayle Beach and Harvey's Towans were more susceptible to future SLR. By 2002 the Babtie Group, (2002), reported that another 1 m of beach height had been lost. Examining the tides in this way helps to discover that the erosion in the past has probably been due to a single mechanism- dredging and removal of sediment- but the modern set up is now coupled with SLR because beach heights are so low. A tipping point has probably been reached in the Hayle Estuary sub-cell.

A period of cessation of dredging occurred from 2003-2008 due to local pressure. During this time beaches recovered and built out seawards, (Channel Coast Observatory, 2011). This period of accretion occurred during a period of MSL fall at Newlyn of 5 cm. The lowest MSL was in 2005.

From 2010 Hayle Beach and Harvey's Towans has experienced another significant episode of erosion. As mentioned in section 4.2 some 16,200 tonnes of sediment was removed from Hayle Harbour in just 4 months (January-April), (Buro Happold Limited, 2010). This was the highest amount of sand ever removed in Hayle's dredging history in a quarter. This was followed by an intense phase of erosion where a reduction of ~3 m in beach height resulted in the exposure of the Wave Hub export cable for the first time in June 2011. This can be seen on Figure 14, which compares the difference in beach heights in 1998, 2004, and 2011. A significant section of dune frontage was also eroded in the order of ~65 m. The shoreline retreat can be clearly seen in figure 13, and the photos in figures 15 to 19. This extreme erosion seen in 2010-11 falls into the anomalously high period of SL rise shown in table 1. As stated before MSL rise likely contributed in part to the damage seen in 2010-11, however the dredging and subsequent removal of sand from the system paid the most significant part in the erosion as the system had to find a new equilibrium.

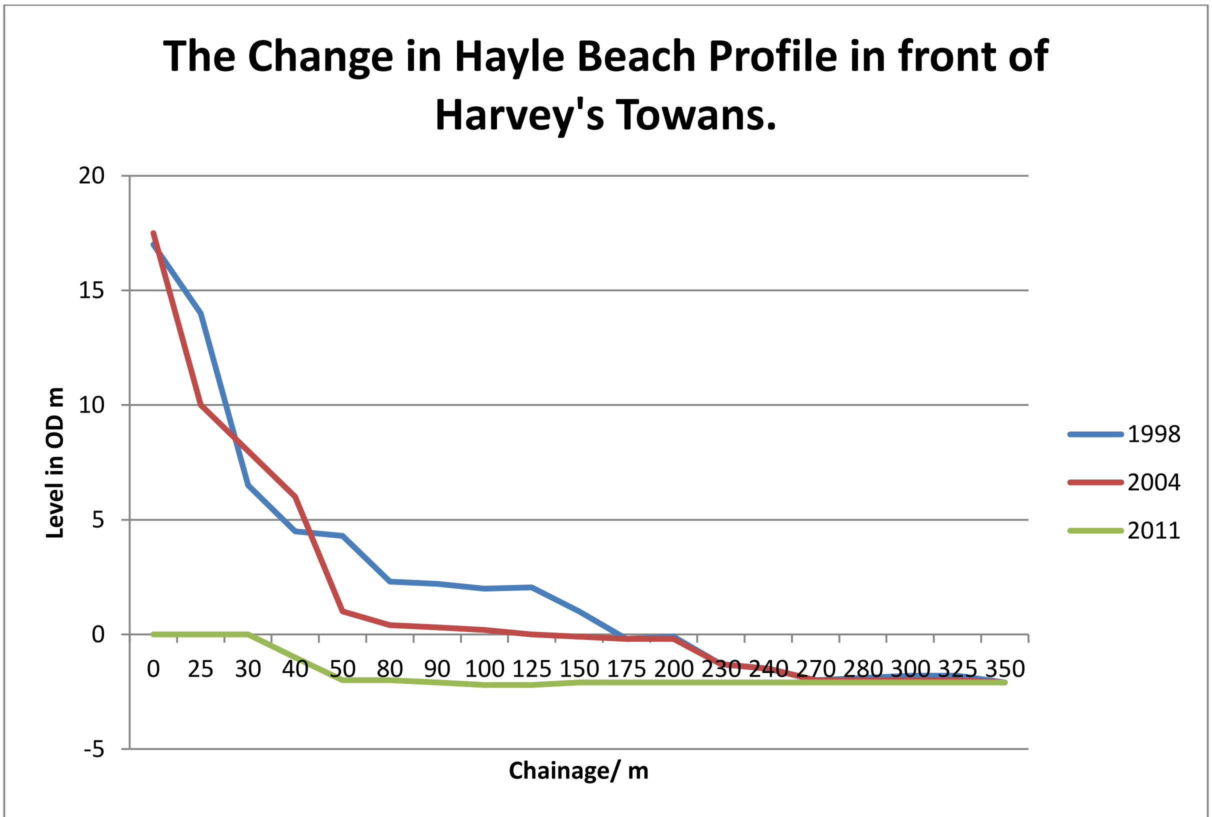


Figure 14. The change in beach profile at Hayle Beach in front of Harvey's Towans. Adapted from figure 5.111998 in Wave Hub (2006) using fieldwork data.

Figure 15. Hayle beach circa 1974. Photo kindly contributed by L. Gratton.

Figure 16. Hayle Beach 13th October 1977. Photo courtesy of Hayle Archive.

Figure 17. Hayle Beach 15th Nov. 1977. Photo courtesy of Hayle Archive.

Figure 18. Hayle Beach 20th December 1977. Photo courtesy of Hayle Archive.

Figure 19. Hayle beach with exposed Wave Hub export cable. Taken on 26/08/2011.

During 2012, Hayle Beach has stabilized. This is probably due to the collapsed dune system feeding sand into the beaches within the sediment transport sub-cell and the cessation of dredging since 2010. Storms that hit the coastline in November 2011 broke the beach's ridge and runnel set up, forming a curved barrier of sand which currently protects half the dunes along the beach. The Wave Hub export cable has been covered again by this sand.

6. Global Warming and Future Large-Scale Sea-Level Changes.

The human population has expanded and advanced their technological innovation to such an extent that we are now exerting a significant influence on our planet and its global environment, (Kump et al. 2010). The increase in greenhouse gases from anthropogenic activities such as fossil fuel burning and deforestation, have led to the modern global warming.

Projecting likely temperature rises for the future is complex. The IPCC have examined various greenhouse gas emission scenarios in their climate models, (low, medium and high) to calculate probable temperature rises.

Jevrejeva et al. (2012), suggest that by 2100 MSLR could be 57 cm for the lowest forcing and 110 cm for the highest scenario. They also project that by the year 2500 there would be a MSLR of 184 cm for the lowest forcing and 549 cm for the highest forcing.

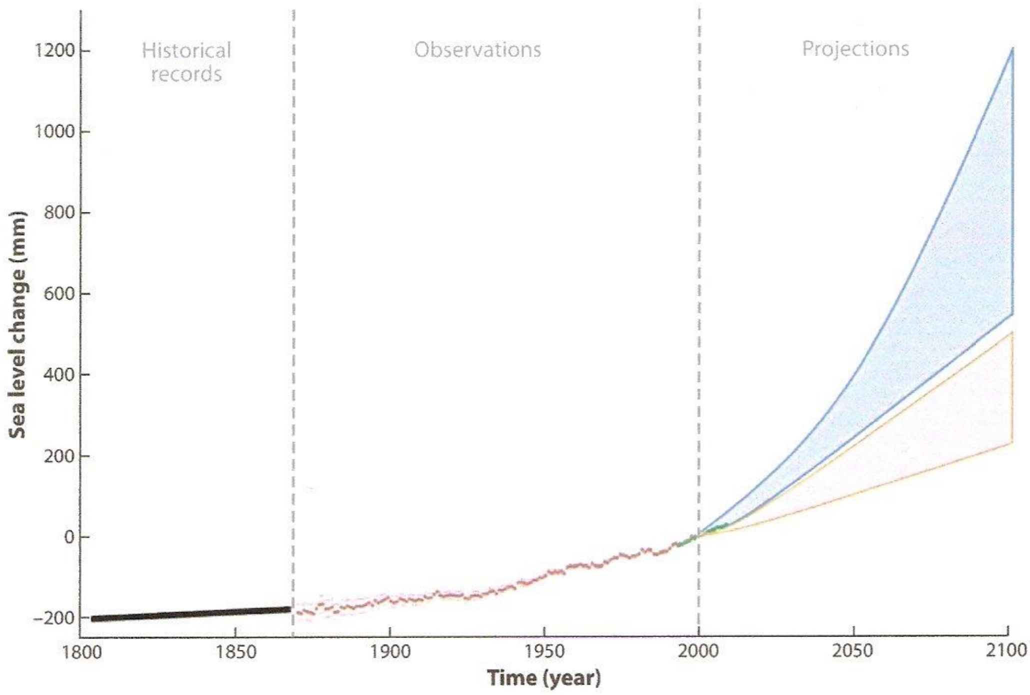


Figure 20. The evolution of global mean sea-level between 1800 and 2100 using observations for the 19th and 20th century and model projections for the 21st century. The black line is sea-level based on various observations. The red line is based on tide gauge data. The green line is based on the altimetry record. The pink shaded region includes sea-level projections from IPCC (2007) AR4. The blue shaded area includes projections from Rahmstorf (2007). Taken from Cazenave and Llovel, (2010) figure 11.

Cazenave and Llovel, (2010), state that the IPCC predict that the SLR will be ~35 cm above today's level by the year 2100. However they stress this is a minimum value as the realistic behaviour of the ice sheets have not been taken into account. Kump et al. (2010) also support the premise that the IPCC prediction is a minimum value as the models they use only account for a minimal contribution from ice sheets. Cazenave and Llovel, (2010), also mention Rahmstorf, (2007), study which directly reflects temperature projections. Rahmstorf, (2007), suggests that by 2100 the projected SLR would be between ~50 and ~120 cm. This is more in keeping with Jevrejeva et al. (2012), values for SLR in their study. Both the IPCC and Rahmstorf, (2007) SLR projections are shown on figure 20. Other authors have also undertaken studies into predicted SLR. Woodworth et al. (2009), suggest that SLR could exceed the present day figure by 75 cm. Meyssignac and Cazenave, (2012) suggest a SLR of between 50 and 80 cm.

Even if greenhouse gases emissions are stabilized the effects of global warming on SL will continue for several centuries. The deep water component of the oceans circulation results in SL having a long response time, (Jevrejeva et al. 2012). This means that for several centuries to come SLR will still be affected by changes that occurred in the past, and in the present day.

During the last interglacial period ~125,000 years ago (Eemian), it is thought that SL was about 6 m higher than today (Kump et al.2010). This figure is comparable to Rahmstorf, (2007), projected top end figure of SLR by 2500, (5.49 m). From palaeo-climatic data it is thought that the global temperature was only 1 ^{o}C warmer than today. A 6 m rise in SL similar to that seen in the Eemian would be devastating for low lying coastal communities.

All the areas mentioned in this study have issues with erosion already, due to anthropogenic forcing factors. Steps would need to be taken to ensure that methods of clearing channels for navigation were sustainable. Coastal protection measures would have to be taken to protect communities at these sites and others like them. If this proved to be too costly, compared to the environmental, social, and economical benefits of protecting the land, then a managed retreat would have to be a serious option.

As mentioned before, if all the ice sheets totally melted then SL would rise by 70-80 m (Kump et al. 2010). This would submerge 20% of the present continents, and cause significant erosion to occur on the remaining land masses. This would place an enormous pressure on resources such as housing, food, water, health care etc. In this case protecting the land would be an unrealistic ideal.

6.1. Future Problems for Hayle?

To assess the likely problems that would be felt in Hayle in the year 2100,from SLR, this study will use a mean figure of the projected extreme ranges of SLR from Jevrejeva et al. (2012), Rahmstorf, (2007), Woodworth et al. (2009) and Meyssignac and Cazenave, (2012). These figures appear to broadly agree with each other. The IPCC figure of 35 cm was a bit of an outlier in all of the literature examined. The mean of figure for SLR is calculated to be 77 cm.

With the current state of the beach and dune systems that skirt the periphery of St. Ives Bay, a SLR of 77 cm could be devastating. This is especially true at Hayle. In total Hayle has lost ~6 m of beach height and ~135 m of dune extent since 1977. As the beaches and dunes are the main form of coastal defence in this area, this could spell disaster.

As mentioned at the end of section 5.2, during 2012 Hayle Beach has stabilized. However this system remains fragile, and is now very environmentally sensitive. Any slight perturbation to this system could result in far reaching consequences. It has to be noted that at present because of the severe erosion seen in the area during 2010-11, there are no plans for dredging and removal of sand. However a navigable channel has to be maintained to allow the harbour to carry on functioning. Plough dredging will be undertaken towards the end of this year to clear the channel. This will enable the sand to remain in the bay. The cost of the operation will be covered by the harbour owners. There are also firm plans to reintroduce sluicing from Carnsew Pool. A planning application has been passed which includes the renovation and reinstatement of the historic sluicing system. It is believed that sluicing from just one of the traditional sluicing pools will be effective at clearing the channel. The loss of 6 m in beach height since 1977, means that the increase in ebb flow velocity from just one pool will be sufficient, to clear the channel and bar.

When sluicing is reintroduced a navigable channel will be maintained, sediment will remain in the bay, the shadow zone will be reduced in size, and the Hayle Estuary sub-cell will have its sediment source and terminal areas reconnected. This will lead to the accretion of sand on Hayle Beach. This will be a slow process though, and the present increased rate of SLR could result in more erosion. Beach nourishment in this area could assist to ameliorate the effects of SLR in the short-term. Sluicing will address issues on a longer-time scale. These steps would assist Hayle to avoid the worse effects of SLR up to the mean value of 0.84 m. However with projected SLR of between 184 cm and 549 cm by the year 2500, (Jevrejeva et al. 2012), the measures suggested here will not persist in their effectiveness. Other methods would have to be found and implemented, or a managed realignment would have to be considered.

It is not just the beaches and dunes that could suffer erosion. Cliff faces that skirt certain areas of the bay could also be at risk from erosion. In section 2.4 a link to a video of a large cliff collapse near Hayle illustrates the power of erosion from SLR already in the case study area. Beaches dissipate wave energy but if the beaches have been lowered to such an extent that the cliff foot can undergo wave attack, then erosion will occur. Lee (2008), state that a cliff line is more susceptible to foot erosion if the beach levels in front are low. This is the case along much of the coast and especially in the Hayle Estuary sub-cell. By examining the dune collapse and newly exposed cliff faces seen in figures 16 and 17 it shows that a significant section of the cliff was once covered in dune prior to

1977. Lee (2008), states that future recession is critically dependant on what has, and what is happening at the site and elsewhere in the sediment transport system.

Like the erosion of beaches, beach nourishment can help cliff erosion too. Lee (2008) has found that if the beach wedge area in front of a cliff line is greater than 20 m^2 then the wave run up is restricted and the power of the wave attack is dissipated. The author also discovered that if the beach wedge area was greater than 40 m^2 then this led to cliff recession rates of almost zero. This method would only limit erosion in the relatively short term. As discussed before, the larger predicted SLR that could be seen in 2500 would be too much for this method of coastal management and other methods would have to be discussed and implemented.

Therefore it can be assumed that soft engineering problems will be beneficial in protecting coastlines, without interfering with the sediment transport cells at the lower SLR projections . If the high emission scenarios materialize and the larger projections of SLR occur then protection of some coastlines would be a futile exercise, and managed realignment would have to be undertaken.

7. Conclusion.

The Earth's climate is continuously warming, due to the build up of greenhouse gases in the atmosphere as a result of human activities such as fossil fuel burning and deforestation. Sea-level is very sensitive to these changes in global temperatures. Global sea-levels are expected to rise by at least 50 cm by the year 2100, and continue to rise for a couple of centuries. The most significant contributors to SLR are melting of the ice sheets and thermal expansion of sea water.

The rate of this SLR has increased in modern times. SLR increased two fold from the beginning of the satellite altimetry record up to 2010. The last 5 years of tidal data also show another jump in rate rise. Globally MSLR has almost doubled its rate again. At Newlyn and St. Ives this rate of MSLR is almost 4 times the global rate. This rate rise could be due to the NAO influence on the coast here. Dismissing this fact could be a mistake though. As the climate warms there will be more of these atmospheric-ocean circulation events such as ENSO, NAO, and PDO. This would have to be accounted for in any climate modelling with regards to SLR. Other factors would also have to be considered too. The IPCC have only included a minimal contribution from the melting of ice sheets. The present day is witnessing numerous glaciers and ice sheets reducing their size massively. This contribution needs to be factored into climate models sufficiently to reflect what is actually occurring now. By studying the erosion in Hayle, it has illustrated how other areas around the globe could react to a rate in SLR as large as the rate seen over the last 5 years. Future research into areas with high rates of SLR similar to this site would be beneficial. This is particularly true when assessing the suitability of various coastal protection measures, and their effectiveness in ameliorating the effects of SLR.

Any perturbation to the natural processes working in the coastal systems via anthropogenic means alter their dynamic equilibrium. This study has shown that it is necessary to understand the coastal dynamics of a site before an assessment of perturbations to it are made. This is especially true for future model studies of hard or soft engineering to ameliorate the effects of SLR and erosion, as well as the investigation into the most suitable method of channel clearance for a site.

In this study, the anthropogenic means used in the never ending quest to maintain a navigable channel have been examined. Numerous sites around the globe use dredging or other hard engineering schemes to achieve this. The study has found that dredging and subsequent removal of sediment is an unsustainable process. Deepening the channel only serves to increase the amount of sediment being deposited in it, causing further dredging to be needed to maintain the channel. Effectively, a positive feedback loop of sedimentation and removal is created. In all cases this has led to substantial coastal erosion.

Sluicing has been shown to maintain a navigable channel in a sustainable way. In the case of Hayle there was a pattern of accretion and not erosion. The beach and dune systems were able to build out significantly in size. This was beneficial with regards to Hayle's natural coastal defence as shown by the anomalously high SLR in 1936. The SLR in this year did not cause erosion; in fact Hayle was still actively accreting. The benefits of sluicing to other areas around the world could be great. More studies should be undertaken on sites such as Hayle, with the view of examining the use of sluicing as the sustainable alternative to dredging, in the constant war of channel clearance around the globe.

8. References.

- AA Maps, (2011). http://www.theaa.com/maps/index.jsp search term “The Towans, Hayle” select satellite view, click zoom once. [Acc. 4/7/2011]

- Araujo, I.B., and Pugh, D.T., (2008) Sea Levels at Newlyn 1915-2005: Analysis of trends for future flooding risks, Journal of Coastal Research. Vol. 24, No. 4C pp. 203-212

- Babtie group, (2002), Hayle Harbour Hydrodynamic Modelling Report, Final report, Revision R02, Penwith District Council. http://www.hayle.net/council/documents/20021128HayleHarbourHydrodynamicModellingReport-BabtieGroup.pdf [acc.16/11/11]

- BODC, British Oceanographic Data Centre http://www.bodc.ac.uk/data/online_delivery/ntslf/processed/ [acc. 20/08/12]

- Bojariu, R., Gimeno, L., (2003), Predictability and numerical modelling of the North Atlantic Oscillation, Earth-Science Reviews. Vol. 63, pp. 145-168

- Buro Happold Limited, Hayle Harbour Environmental Statement, Revision 01, November 2007, Section 13, Bath, UK.

- Buro Happold Limited, (2010), Hayle Harbour Dredging Protocol Document, Revision 03 Final, Job no. 022961, May 2010, Bath, UK.

- Cahill, N. (2000), Hayle Historic Assessment Report, Cornwall Archaeological unit, Cornwall County Council, Truro, Cornwall. www.historic-cornwall.org.uk/cisi/hayle/hayle_historic_assessment_report.pdf

- Cazenave, A., and Llovel, W., (2010), Contempory Sea Level Rise. Annual Review of Marine Science. Vol. 2, pp. 145-173

- Channel Coast Observatory, (2011) Southwest Strategic Regional Coastal Monitoring Programme. Interim report-Hayle 2011. Available to download from the South West Coastal Observatory. http://www.channelcoast.org/southwest/ [acc. 16/11/11]

- Church, J.A., White, N.J., (2011), Sea-Level Rise from the Late 19th to the Early 21st Century, Survey Geophysics, Vol. 32, pp. 585-602

- Colling, A. (2002), Ocean Circulation. Oxford. Butterworth-Heineman for the Open University.

- Dallas, K.L., Barnard, P.L., (2011), Anthropogenic influences on shoreline and nearshore evolution in the San Francisco Bay coastal system. Estuarine, Coastal and Shelf Science, Vol. 92, pp. 195-204

- Environment Agency, (EA), http://www.environment-agency.gov.uk/homeandleisure/floods/riverlevels/120724.aspx?stationId=3154 [acc. 20/08/12]

- Goodrich, M., Way, F., Liu, H. (2003) Evaluating Beach and Nearshore Sediment Transport Impacts from the Proposed Deepening of the Savannah Harbor. Proceedings of the 2003 Georgia Water Resources Conference, Held April 23-24, 2003, at the University of Georgia. http://www.gwri.gatech.edu/uploads/proceedings/2003/Goodrich,%20Way%20and%20Liu.PDF [acc.17/6/11]

- Jevrejeva, S., Moore, J.C., Grinsted, A. (2012) Sea-level projections to AD2500 with a new generation of climate change scenarios. Global and Planetary Change. Vol. 80-81, pp. 14-20

- Kump, L.R., Kasting, J.F., and Crane, R.G., (2009). The Earth System, (3rd Edn), New Jersey, Pearson Education Inc.

- Lee, E.M. (2008), Coastal Cliff behaviour: Observations on the relationship between beach levels and recession rates. Geomorphology. Vol. 101, pp. 558-571

- Merrifield, M.A., Merrifield, S.T. (2009) An anomalous recent acceleration of Global Sea-Level Rise. Journal of Climate. Vol. 22. Pp. 5772-5781

- Meyssignac, B., Cazenave, A., (2012), Sea Level: A review of present-day and recent-past changes and variability. Journal of Geodynamics, Vol. 58, pp. 96-109

- Montague, C.L. (2008), Recovering the sand deficit from a century of dredging and jetties along Florida's Atlantic Coast: A re-evaluation of beach nourishment as an essential tool for ecological conservation, Journal of Coastal Research, Vol. 24, no. 4, pp. 899-916

- Phillips, M.R., Crisp, S. (2010), Sea-level trends and NAO influences: The Bristol Channel/ Severn Estuary. Global and Planetary Change. Vol. 73. Pp. 211-218

- Rahmstorf, S., Perrette, M., Vermeer, M., (2007) Testing the robustness of semi-empirical sea-level projections. Climate Dynamics. Doi:10.1007/s00382-011-1226-7, in press.

- Sea Sediments of Chard (1983), An investigation of sediment dynamics in the Hayle Estuary, Cornwall. http://www.hayle.net/council/documents/SeaSediments.pdf [acc.16/11/11]

- Vale, E., (1966) The Harvey's of Hayle, Engine Builders, Shipwrights, and Merchants of Cornwall. First published 1966 by D. Bradford Barton Ltd Truro. Reprinted by The Trevithick Society, 2009 Short Run Press Ltd, Exeter. pp. 222

- Vega-Leinert, A.C., and Nicholls, R.J. (2007), Potential Implications of Sea-Level Rise for Great Britain, Journal of Coastal Research, Vol. 24, no. 2, pp. 342-357

- Wave Hub, (2006), Wave Hub Design & Development\ Coastal Processes. Study Report- June 2006. www.wavehub.co.uk/wp-contact/uploads/2011/06/Appendix-A-Coastal-Processes.pdf [acc. 18/3/12]

- Woodworth, P.L., Flather, R.A., Williams, J.A., Wakelin, S.L., Jevrejeva, S., (2007) The dependence of UK extreme sea-levels and storm surges on the North Atlantic Oscillation. Continental Shelf Research. Vol. 27. Pp. 935-946.

- Woodworth, P.L., Teferle, F.N., Bingley, R.M., Shennan, I., Williams, S.D.P. (2009) Trends in UK mean sea level revisited. Geophysical Journal International. Vol. 176, pp. 19-30

- Wright, J., Colling, A., Park, D., (2005) Waves, Tides and Shallow Water Processes (2nd Edition). Oxford, Butterworth-Heineman for the Open University. p. 168

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