Sussex coast sediments and kelp

Coastal sediments

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Executive Summary

The coastal waters along the Sussex shoreline were once home to extensive kelp forests. In 1987, a report by Worthing Borough Council (cited in Williams, 2020) reported kelp beds covering 177 km^2, including 10 km^2 of very dense kelp cover. Since then, the kelp extent has decreased dramatically and is currently estimated to be 6.3 km^2, occurring in small patches, based on diver reports. Remaining kelp patches appear to be in shallower water compared to the historical extent (e.g. Williams et al, 2020).

To help reverse this decline, the Sussex Inshore Fisheries and Conservation Authority introduced the Nearshore Trawling Byelaw in March 2021 prohibiting the use of bottom towed gear (trawling) from over 300 km^2 of seabed with the aim for recovery of the lost kelp beds and protection of essential fish habitats.

Blue Marine Foundation is a partner on the Sussex Kelp Restoration Project (SKRP), a partnership of national, regional and local organisations set up following the introduction of the Nearshore Trawling Byelaw with a shared purpose to champion, study and facilitate the recovery of Sussex kelp to support a thriving and sustainable marine ecosystem.

To inform further work and appropriate targeted measures to reduce and mitigate the impact of sediment on natural kelp recovery and local fisheries, Blue Marine commissioned HR Wallingford (June 2022) to prepare a report on sediment sources, sinks and changes to these in Sussex waters.

One factor that could affect kelp recovery is the sediment regime. Sediment suspended in the water column decreases the light reaching the seabed and may therefore restrict the growth of kelp by impeding the rate of photosynthesis, especially in deeper waters. Mobile sediment on the seabed may reduce habitat suitable for kelp growth if it buries the rocky substrate to which kelp attaches.

This report includes a review of sediment sources to the Sussex coastline, including from coastal erosion, rivers, and human activities. In particular, fine sediments which are carried in suspension and cause turbidity and reduced light levels are considered. Potential future changes to the sediment regime caused by climate change or human activities are also considered.

The suspended sediment regime within the west Sussex area are set against a background of a large sediment flux moving through the English Channel (in the order of 20 M tonnes/year). Typical suspended sediment concentrations range from 5 mg/l to around 60 mg/l, and are likely to be higher inshore where wave interaction with the seabed is greater. During storms, suspended sediment concentrations may be in the order of ten times greater.

Increases in current speed and increases in wave action can lead to increases in suspended sediment within the water column. There is a typical spring-neap variation in suspended sediment concentrations associated with changes in tidal speeds and during storm conditions suspended sediment concentrations are typically elevated. Following large storm events fine material mobilised from within the seabed becomes more available for resuspension by currents and waves resulting in prolonged periods of elevated suspended sediment concentrations.

The sediment budget for the study area off the Sussex Coast exists within the wider scale of the sediment budget of the English Channel. The English Channel sediment budget is dominated by a flux of fine sediment moving eastwards. This flux has a magnitude in the region of some 2 to 70 M tonnes/year. The study area represents only a fraction of the cross-section of the English Channel through which this large flux passes and as a consequence it is important to consider a more local scale sediment budget for the area of relevance to the kelp beds.

In this local scale sediment budget the main source of fine sediment arises from the erosion of the cliffs and nearshore rock platform. On average about 290,000 tonnes of fine sediment is released each year as a result of erosion. The erosion tends to occur as frequent, low volume falls; however large cliff failures can occur. Most of this erosion occurs on the unprotected length of the shoreline close to Beachy Head.

Additional sources of fine material are from wash out from beach nourishment projects and from river inputs from the Sussex rivers. These inputs are small in comparison to the cliff erosion but may be of local significance. Whilst there are some offshore sources of fine material from nearby offshore aggregate dredging, or windfarm installation, these sources are also small in comparison to the continuous cliff erosion and, being offshore, are also being generated at locations less likely to directly influence the kelp beds.

The harbours and marinas along the Sussex coast trap and act as sinks for fine sediment (both sand and mud). However, this sediment is maintained in the nearshore system by removal and deposition at local nearshore disposal sites through licenced maintenance dredging. This may cause local disturbances to the fine sediment regime and localised increases in suspended sediment. Local disturbances to the fine sediment regime occur during maintenance dredging campaigns. The mass of fine sediment (sand and mud) recycled through annual maintenance dredging is comparable to the long term rates of erosion of the cliffs. It is possible that chemical contaminants present in the sediment will be released into the water column when the sediment is dredged.

Other sinks for fine sediment include the salt marsh and intertidal areas of the harbours, estuaries and managed realignment sites on the Sussex Coast. The likely scale of fine sediment trapping in these areas is small compared to the source.

Further afield the larger scale of offshore disposal of dredged material at the Nab Tower disposal site to the east of the Isle of Wight and the offshore aggregate dredging activity in the English Channel contribute fine material into the wider English Channel sediment budget but are generally too distant and too far offshore (in terms of tidal streams and residual currents) to significantly influence the historic Sussex kelp bed areas. With climate change rising sea levels can be expected to result in increased rates of cliff erosion. This can result in elevated nearshore suspended sediment concentrations increased turbidity and reduced light availability over the potential kelp bed areas. There may also be a need for increased amounts of maintenance dredging (sediment recycling) in the Sussex harbours and marinas, with increased local disturbance to the fine sediment regime from disposal activities.

Legislation, policies and guidelines that may be relevant to the management of sediment in the coastal zone include the Marine and Coastal Access Act (2009); the Water Environment (Water Framework Directive) (England and Wales) Regulations, 2017) and the Marine Strategy Framework Directive. Many activities, such as dredging, disposal and construction in the marine environment require a license from the Marine Management Organisation.

Trends in suspended sediment concentrations

In general, it has not been possible to identify historical trends in suspended sediment concentration:

- There are no direct, long-term measurements of suspended sediment or turbidity along the West Sussex coastline.
- The nearshore maintenance dredging records do show a slight increasing trend over the last decades, however this is influenced by increases in dredging and disposal at Shoreham since 2005 and the opening of Sovereign Harbour (Eastbourne) in 2000. Dredge disposal at the other sites shows no trend, so it is not clear that the increase in dredging and disposal at Shoreham represents an increase in suspended sediment or turbidity.
- The satellite monitoring data (CEFAS, 2016) shows no overall trend in annual suspended sediment concentration between 1998 and 2015, but does report a significant increase when looking only at the spring months. A longer dataset would help to confirm or dismiss this apparent trend.
- The release of sediment from coastal erosion may have decreased over the last centuries as the coastal defences have progressively increased.
- The evidence is insufficient to identify any long term trends in suspended sediment concentration that might impact on kelp.

With the data currently available, there is no clear evidence of long term changes in the suspended sediment regime off the Sussex Coast. However, there may be evidence for increases in suspended sediment concentrations in spring, which is an important time for sporophyte settlement and early growth for kelps found in Sussex. However it is not clear whether the increase observed in the dataset would be enough to have an impact on kelp growth.

The main driving force leading to a projected increase in sediment supply is the projected accelerated sea level rise leading to more potential sources of sediment in the nearshore / coastal area. Sea level rise brings the sea further inland and enables larger waves to impinge on the shoreline, potentially increasing erosion of undefended cliffs.

The study identifies a number of information gaps for which further investigation is recommended:

- An improved understanding of the residual flows over the kelp beds could be achieved using a fully coupled tide, wind and wave numerical model of this part of the English Channel.
- Improved understanding of the wider residual flows in the English Channel would enable an assessment of the significance of some of the offshore and more distant sources of fine sediment releases. Areas of flow recirculation may lead to accumulation of fine suspended sediment over time such that the significance of the larger scale offshore activities requires reconsideration.
- There are no long-term direct measurements of suspended sediment concentration, turbidity or photo-synthetically available radiation in the water column or at the seabed in the vicinity of the Sussex kelp beds. If suspended sediment concentrations and light availability are considered significant for the health or restoration of the kelp beds then a suitable programme of measurement should be instigated. During such measurements records of wave activity, larger scale cliff falls and harbour/marina sedimentation and dredging should also be obtained.
- Further investigations of more recent changes in saltmarsh coverage would help to understand the current situation and future trends and the rates at which fine sediment is being accumulated or eroded from these areas, however relative to other sediment sources and sinks the annual volumes of sediment involved are quite low.

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1 Introduction

1.1 Background

The coastal waters along the Sussex shoreline were once home to extensive kelp forests. In 1987, a report by Worthing Borough Council (cited in Williams, 2022) reported kelp beds covering 177 km^2, including 10 km^2 of very dense kelp cover. Since then, the kelp extent has decreased dramatically and is currently estimated to be 6.3 km^2, occurring in small patches, based on diver reports. Remaining kelp patches appear to be in shallower water compared to the historical extent (e.g. Williams et al, 2020).

To help reverse this decline, the Sussex Inshore Fisheries and Conservation Authority introduced the Nearshore Trawling Byelaw in March 2021 prohibiting the use of bottom towed gear (trawling) from over 300 km^2 of seabed with the aim for recovery of the lost kelp beds and protection of essential fish habitats.

Blue Marine Foundation is a partner on the Sussex Kelp Restoration Project (SKRP), a partnership of national, regional and local organisations set up following the introduction of the Nearshore Trawling Byelaw with a shared purpose to champion, study and facilitate the recovery of Sussex kelp to support a thriving and sustainable marine ecosystem.

One of the SKRP aims is to identify and minimize damaging impacts on existing and potential kelp habitat and there is growing concern that factors such as high levels of sediment may hinder natural recovery of the kelp beds and are directly impacting local fisheries.

Sediment suspended in the water column decreases the light reaching the seabed and may therefore restrict the growth of kelp, especially in deeper waters. Mobile sediment on the seabed may reduce habitat suitable for kelp growth if it buries the rocky substrate to which kelp attaches.

In response, Blue Marine initiated a programme of work in 2021 to review the sources and impacts of sediment in Sussex coastal waters and identify potential actions to mitigate and reduce sediment inputs:

- **Sussex Kelp Restoration Project Sediment Sources and Impacts Workshop** (September 2021) - Forty stakeholders from over 25 organisations shared information and identified opportunities for further research, collaboration and management interventions.
- **Sussex Sediment Sources and Impacts Report** – incorporating a desk-based literature review; personal communications with academics, benthic habitat specialists and fishermen; and the outcomes from the Sussex Sediment Sources and Impacts Workshop.
- **Sussex Sea Users Sediment Survey** – a survey of commercial and recreational sea users to gather observations of sediment type and location, and potential sources.

1.2 Study

To inform further work and appropriate targeted measures to reduce and mitigate the impact of sediment on natural kelp recovery and local fisheries, Blue Marine commissioned HR Wallingford (June 2022) to prepare a report on sediment sources, sinks and changes to these in Sussex waters.

This report includes a review of sediment sources to the Sussex coastline, including from coastal erosion, rivers, and human activities. Potential future changes to the sediment regime caused by climate change or human activities are also considered.

This review draws on publicly available information on sediment sources and impacts in Sussex waters, with a particular focus primarily on finer sediment fractions including fine sand, silt, clay and chalk particles which can be carried in suspension and therefore add to the turbidity of the water column.

The review has considered technical sediment reports as well as, where relevant to sediments, available management plans; known historical and future planned harbour/coastal developments, and policy and regulatory framework reports.

A summary of the legislation, policies and guidelines that may be relevant to the management of sediment in the coastal zone is provided as well as a high-level overview of the ecological impacts of sediments on kelp recovery.

1.3 Study area

The study area within which the impact of sediments are considered in this report stretches from Chichester Harbour to Beachy Head (Figure 1.1). Sediment sources that may influence turbidity levels or seabed substrate within this area are considered over a wider area, including licensed dredge disposal sites, aggregate dredging sites, land-based soil erosion and suspended sediment pathways through the English Channel.

The coastline is interrupted by estuaries and harbours, including Pagham Harbour, the River Arun, the River Adur (containing Shoreham Harbour), Brighton Marina, the River Ouse (the port of Newhaven and Newhaven Marina) and Cuckmere Haven. Further east, beyond Beachy Head, is also Sovereign Harbour at Eastbourne. The harbours and marinas are effective traps for fine sediment derived from marine and, to a much lesser extent, fluvial sources and require ongoing maintenance dredging to maintain navigable depths.

Further offshore are sand and gravel deposits that provide important supplies of aggregate for the construction industry (see Section 5.1.5).

Commercial fishing along the Sussex coast has a long history and is an important industry in the area. According to the Sussex Inshore Fisheries and Conservation Authority (IFCA; www.sussex-ifca.gov.uk): "*Most commercial fishing boats that operate off the Sussex Coast are under 10m in length and operate inshore, usually within six nautical miles (nm) of the coast…These smaller inshore vessels use a variety of static and mobile gears. Gill, trammel and entangling net fishing takes place widely in the region. Other methods include trawling, beam trawling, pair trawling, drift netting, and scallop and oyster dredging. There is also an important potting fishery for whelk, lobster, brown crab and cuttlefish.*"

Onshore, the coastline is heavily populated and a popular destination for tourists. In 2020, East and West Sussex had populations of 851,000 and 868,000 respectively, with the highest population densities generally near to the coast. Between 2002 and 2020, the combined population of Sussex grew by 14.6% (www.plumplot.co.uk). Much of the shoreline is defended by sea walls, embankments and groynes, with long and short sea outfalls.

Historical kelp distribution for West Sussex is shown in Figure 1.2 and Figure 1.3. Historically, kelp beds were found between Chichester Harbour mouth and Eastbourne, with the majority reported in the western part of the study area where the shallow coastal waters are wider. In particular, the coastline between Littlehampton and Shoreham had very high densities of kelp in 1987 (Worthing Borough Council, 1987).The historical kelp beds appear to have typically occurred in water depths of up to 10 to 15 m.

Figure 1.1: Location map showing the boundaries of the study area

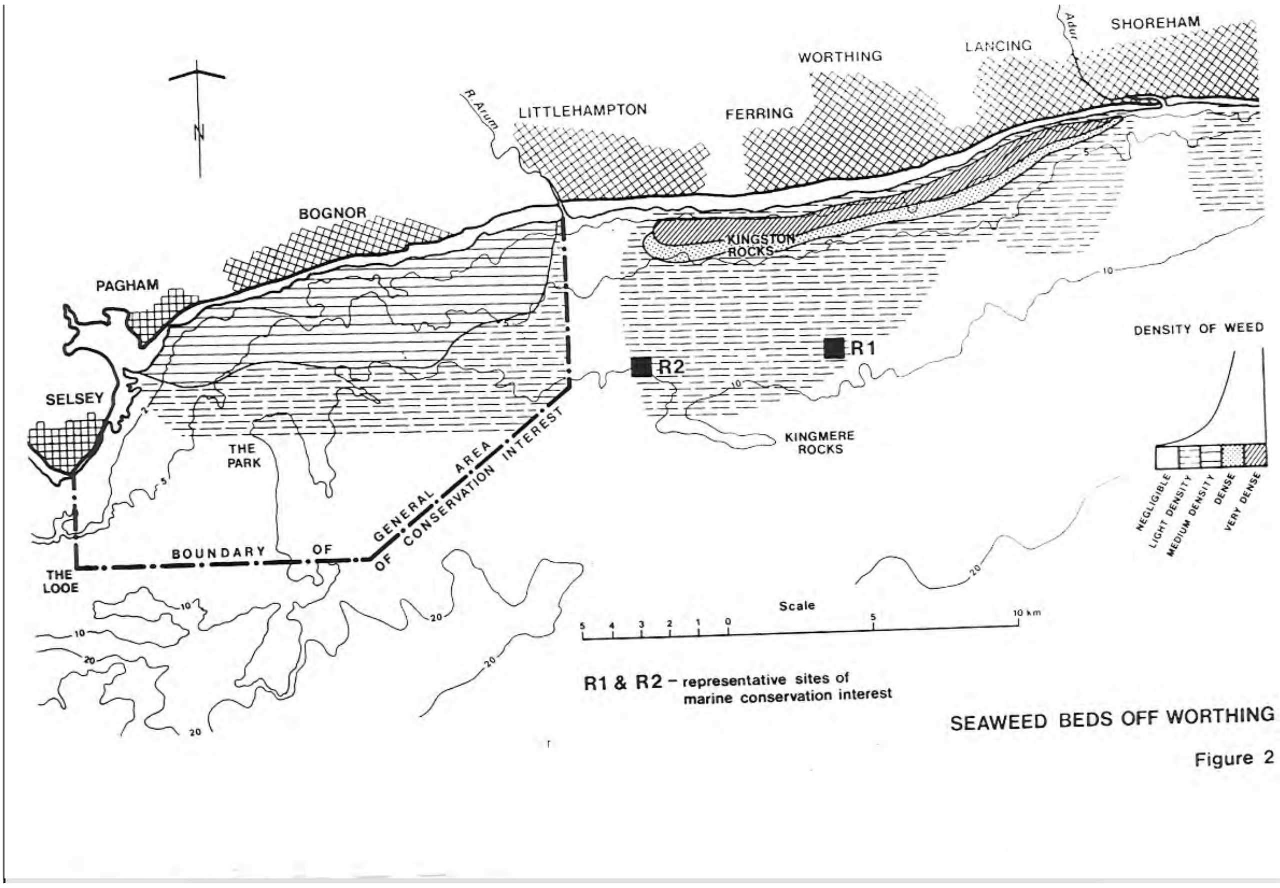

Figure 1.2: Distribution and density of kelp in 1987

Source: Worthing Borough Council (1987). Initial study of seaweed problem at Worthing and other related matters. Binnie & Partners Consulting Engineers report for Worthing Borough Council Report May 1987.

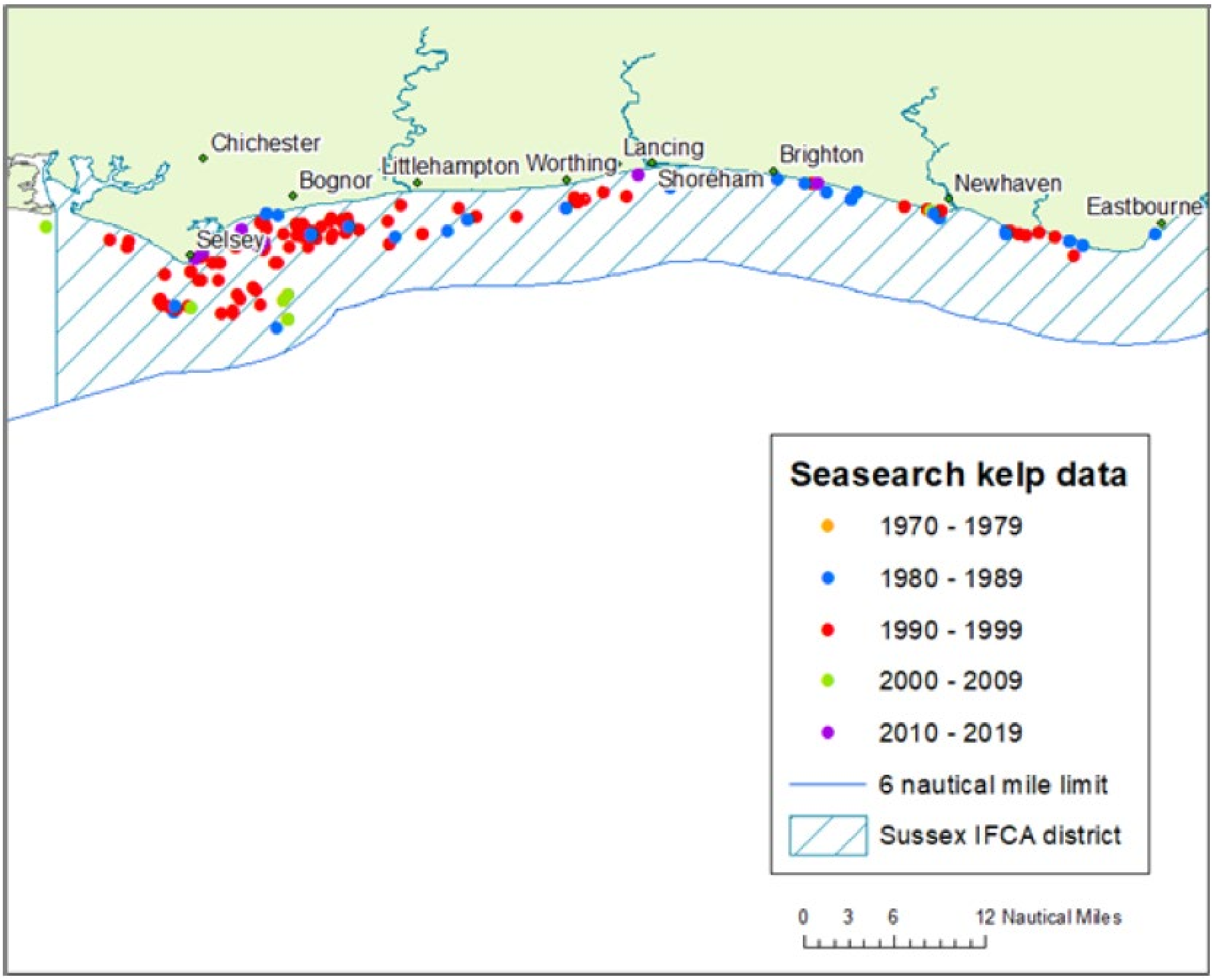

Figure 1.3: West Sussex kelp sightings by Seasearch divers, 1970 to 2019

Source: Williams and Davies, 2019

1.4 Key terminology

- Beach nourishment/renourishment – the placing of new sediment, usually at a beach to reduce erosion and increase beach width. This differs from sediment recycling as the source of sediment is not local to the nourishment site, and may be a distant marine or land based source.
- Bed load transport – the movement of coarser grained sediment (sands and gravels) along the sea bed by rolling, sliding or bouncing caused by tidal currents and wave action.
- Significant wave height (Hs) - the average wave height, from trough to crest, of the highest one-third of the waves.
- Sediment budget - the sediment inputs and outputs (sediment transport), sources (erosion) and sinks (deposition) for a given area. Usually these focus on beach material as this is important for coastal protection. For this study we are interested more in the finer sediment budget for the region encapsulating existing and historical kelp beds.
- Sediment cell – a stretch of coastline where the sediment transport is largely self-contained. Sediment cells may be separated by a littoral drift divide (a point from which littoral drift moves sediment away in

both directions) or a sediment sink. Changes to sediment processes in one cell would not affect adjacent cells.

- Sediment recycling – sediment (usually beach sediment) is moved locally from an area where it tends to accumulate (e.g. the updrift side of a groyne, harbour wall or channel) to an area of erosion. This may involve moving it back to the updrift beach, or placing it on the down drift beach to replicate natural bypassing that would occur without the structure.
- Sediment sub-cell – sediment cells may be further divided into sub-cells, which may be separated by partial drift divides. The majority of the study area lies within the sub-cell 4d, Beachy Head to Selsey Bill (HR Wallingford, 1993).
- Sediment grain size – the size of sediment particles is important for determining how sediment is eroded, transported and deposited in the marine environment and how it affects turbidity. The Wentworth Scale for classifying sediment is shown in Figure 1.4.

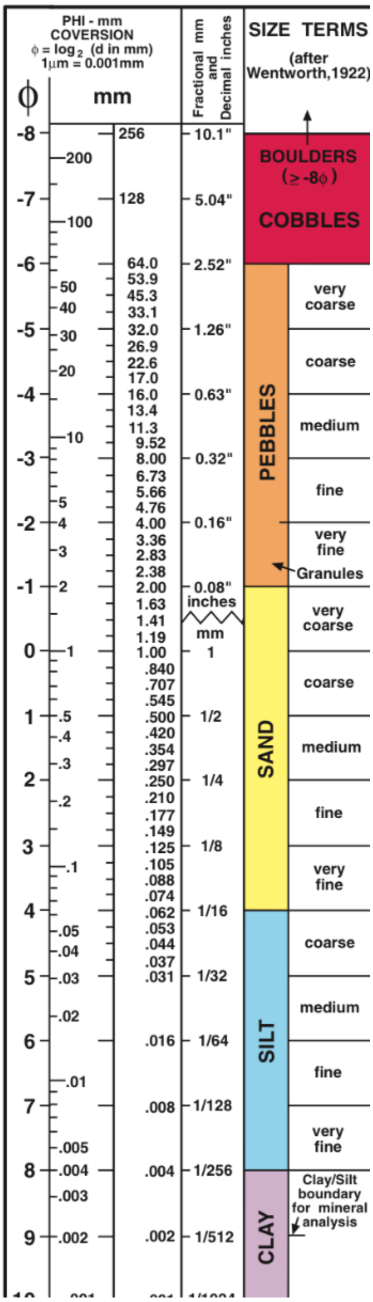

Figure 1.4: The Wentworth Scale of sediment classification

Source: Williams et al (2006)

Suspended sediment or suspended particulate matter– sediment carried in suspension in the water column. This is usually the finer particles, such as chalk, clay and silt, but may also include fine sand where wave and tides provide sufficient energy to erode sediment from the bed and carry it in suspension.

Turbidity - the measure of relative clarity of the water. Turbidity is a measurement of the amount of light scattered by suspended particles as the light passes through the water column. Higher concentrations of suspended particulate matter, particularly of the finest particle sizes, in the water column result in greater scattering of light and hence higher turbidity.

1.5 Legislation, Guidance and Planning Policy

This section provides a summary of legislation, policies and guidelines that may be relevant to the management of sediment in the coastal zone.

1.5.1 Marine and Coastal Access Act 2009

Under the Marine and Coastal Access Act 2009 a licence is required to carry out certain activities in the marine environment. Of relevance to the current review, this includes:

- Construction, alteration or improvement of works, in or over the sea and on or under the seabed;
- Aggregate dredging;
- Capital and maintenance dredging;
- Deposition of any substance or object in the sea or on or under the seabed.

Marine licence applications are assessed by the Marine Management Organisation (MMO) with decisions based on the policies outlined in the Marine Plan for the area (see Section 1.5.5). The Marine Works (Environmental Impact Assessment) Regulations 2007 requires that certain types of project with the potential to significantly affect the environment have an environmental impact assessment before a marine licence decision is made.

1.5.2 Water Environment (Water Framework Directive) (England and Wales) Regulations 2017

The Water Framework Directive (WFD) provides a framework for planning and implementing measures to protect and improve the water environment, including inland water bodies such as lakes and rivers, and coastal waters. Under the WFD Regulations, a river basin management plan must be prepared for each river basin district (see Section 1.5.6).

The area of sea from the mean low water mark to 1 nautical mile from shore is protected under the WFD which requires that the project or activity does not "cause or contribute to deterioration in water body status" or "jeopardise the water body achieving good status". For licence applications in this zone, MMO must make sure that the marine licence decision is compatible with the WFD and any river basin management plan.

1.5.3 Marine Strategy Framework Directive

The Marine Strategy Framework Directive is a framework for delivering marine policy to achieve "Good Environmental Status" and includes benthic habitats. Marine Plans should contribute to meeting the objectives of the Marine Strategy Framework Directive (DEFRA, 2019).

1.5.4 Marine Policy Statement

UK Marine Policy Statement (MPS) (September 2011) provides the framework for preparing Marine Plans and for the decision-making by marine planning authorities. The MPS notes in Section 2.6.1.3 that as a general principle, development should aim to avoid harm to geological conservation interests (including geological and morphological features), including through location, mitigation and consideration of reasonable alternatives.

The MPS further notes in Section 2.6.8.6 that Marine Plan authorities should seek to minimise and mitigate any geomorphological changes that an activity or development will have on coastal processes, including sediment movement.

1.5.5 South Inshore Marine Plan

Marine Plan policies that are directly relevant to sediment management include (MMO, 2014):

S-WQ-1

Proposals that may have significant adverse impacts upon water environment, including upon habitats and species that can be of benefit to water quality must demonstrate that they will, in order of preference: a) avoid, b) minimise, c) mitigate significant adverse impacts.

S-WQ-2

Activities that can deliver an improvement to water environment, or enhance habitats and species which can be of benefit to water quality should be supported.

Policy S-DD-2

Proposals must identify, where possible, alternative opportunities to minimise the use of dredged waste disposal sites by pursuing re-use opportunities through matching of spoil to suitable sites.

1.5.6 River Basin Management Plan

The South East River Basin Management Plan (Environment Agency, 2015) covers West Sussex and details the current ecological and chemical status of water bodies within the plan boundary as well as measures in place to prevent further deterioration and/or improve the current status. Sediments entering rivers from soil erosion, along with chemicals such as nitrates, are identified as an issue in some catchments. Many policies designed to reduce chemical run off into waterways may also reduce soil erosion and therefore sediment run off into rivers. For example, changing land use from arable to grass decreases the need for fertilizer and reduces soil erosion.

1.5.7 Shoreline Management Plan

A Shoreline Management Plan (SMP) provides a large-scale assessment of the risks associated with coastal evolution and presents a policy framework to address these risks in a sustainable manner. The West Sussex shoreline is largely covered by the Beachy Head to Selsey Bill Shoreline Management Plan (2006). The document includes details of current coastal processes and coastal defences and plans for the future. Coast protection options, from managed realignment to beach material recycling, beach recharge, and groynes / breakwaters, all have an impact on the transport of sands and gravels in the coastal zone.

1.5.8 OSPAR Guidelines for the Management of Dredged Material at Sea

The OSPAR guidelines (OSPAR Commission, 2014) provide a technical and scientific framework for assessing dredged material proposed for deposition at sea. These guidelines should be followed by member countries to inform permitting, monitoring and reporting associated with dredging and disposal. Dredged sediments are recognised as part of the natural sediment cycle. Therefore, when considering suitable management options, it is generally the preferred option to retain dredged material within the same aquatic sedimentary system from where it originated, if it is environmentally, technically, socially and economically feasible to do so.

2 Coastal processes along the Sussex coastline

2.1 Geological setting

The Sussex coastline is shaped by physical changes in sea level that occurred since the last ice age, referred to as the Holocene period (covering approximately the last 11,700 years). The English Channel was once low-lying land and inundation, as a result of rising sea levels, began around 8,000 years ago (Beachy Head to Selsey Bill Shoreline Management Plan: Appendix C (2016)). During periods when the sea levels were low (low stands) deeply incised river valleys were infilled with sediments. As sea levels rose, sediment deposited by these terrestrial processes was transported landwards, leading to the formation of shingle banks and barriers.

Between Chichester Harbour and Brighton Marina, the coastline is characterised by low lying coastal plain, backed, several kilometres inland, by the chalk cliffs of the South Downs. A shingle barrier extends along the shoreline from Selsey Bill to Brighton Marina. Offshore of Selsey Bill are a series of submerged shingle deposits, Inner Owers and Kirk Arrow Spit, which may provide an episodic shingle supply onshore to Selsey Bill. Offshore the seabed is boulder clay or chalk bedrock with a varying thickness of overlying sand and gravel deposits. In some areas the underlying bedrock is exposed.

East of Brighton Marina the South Downs chalk ridge meets the coast and the shoreline to Beachy Head is characterised by near vertical chalk cliffs and shore platform. Beach cover is variable along this section of coast.

The nearshore environment west of Brighton Marina is characterised by a wide coastal shelf, with the 20 m depth contour lying 15 to 20 km offshore (Figure 2.1). To the east Brighton, the coastal shelf narrows towards Beachy Head, where the 20 m contour is approximately 1 km offshore.

A wide variety of subtidal habitats have been recorded in the nearshore zone (Figure 2.2) (Sussex IFCA, 2020). In the region of the Sussex kelp beds, the predominant descriptions for the subtidal habitat are “moderate energy infralittoral rock”, “sublittoral macrophyte-dominated sediment”, “mosaic habitats” and “sublittoral mixed sediments”. Sandy habitats increase eastward and with distance offshore.

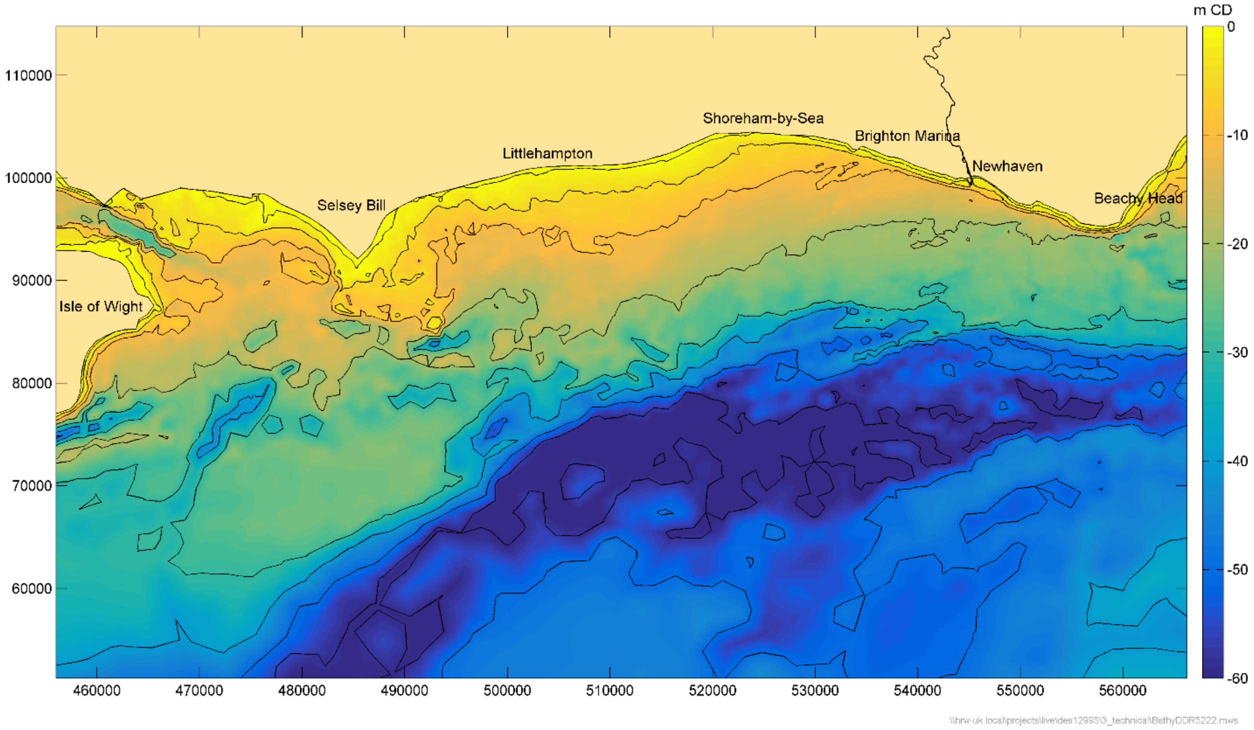

Figure 2.1: Bathymetry of the study area

Source: HR Wallingford

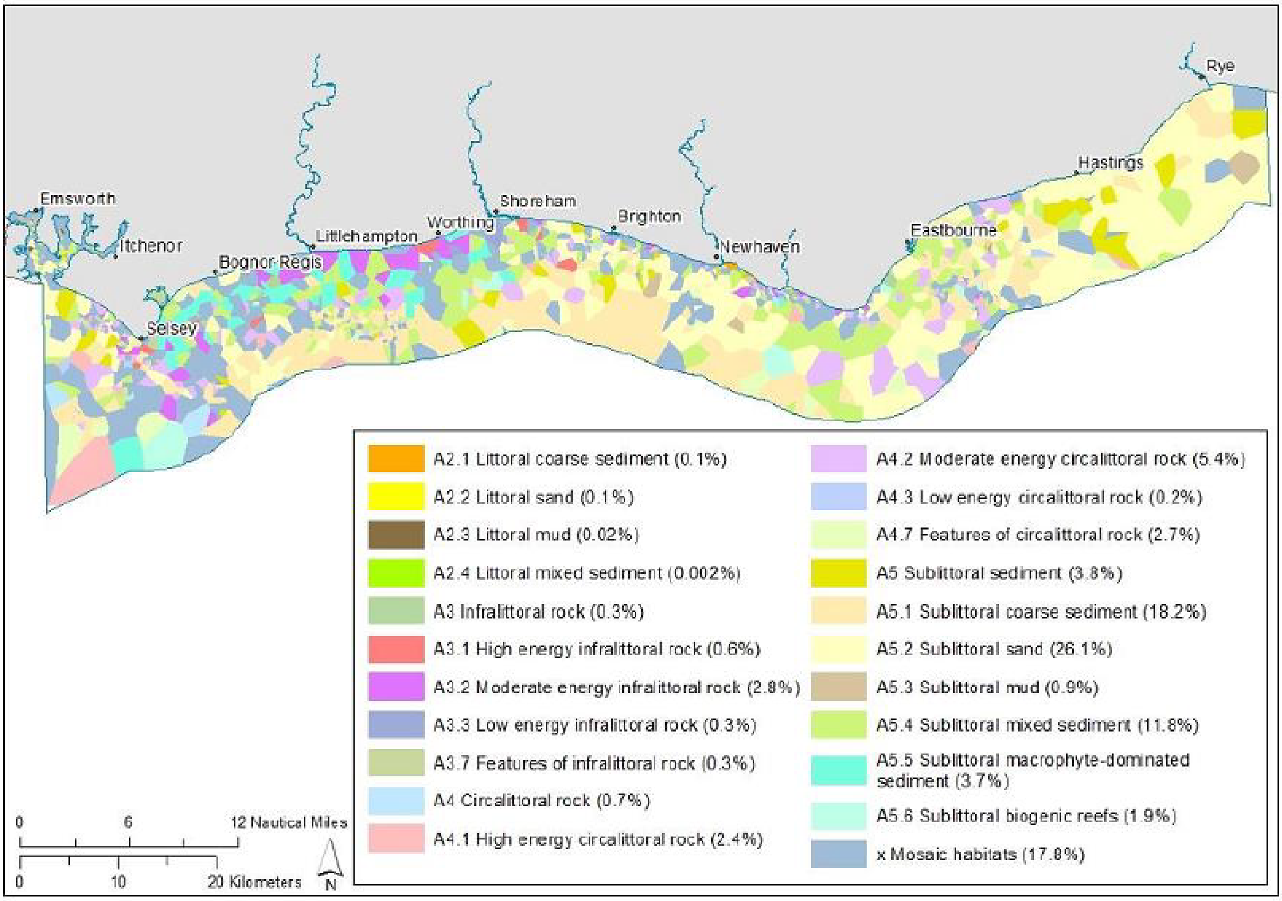

Figure 2.2: Indicative habitat map of Sussex District

Source: Sussex IFCA (2020)

2.2 Winds, waves, and tides along the Sussex coastline

Light levels (i.e. turbidity) in coastal waters such as the Sussex coast are governed to a large extent by the concentration of suspended particulate matter (SPM) in the water column, which in turn is influenced by the combined stirring effect of the tidal currents and waves. Winds also control the size of locally generated waves and can influence the residual patterns of tidal flows and hence may affect the potential sediment transport pathways and the potential locations of sources of fine sediment. In the absence of these driving forces, even the finest suspended particles, which settle through the water column very slowly (<1 mm/s), will eventually be deposited on the seabed to leave clear water with low turbidity. However, the perpetual twice-daily cycle of tidal currents, in addition to the twice-monthly lunar cycle in tidal range (i.e. the spring-neap tidal cycle), leads to time-varying suspended concentrations that continually vary in magnitude over timescales of hours to days. Seasonal differences in the wind and wave climate along the open Sussex coast leads to further, less predictable, variability in turbidity at seasonal and annual timescales, and natural atmospheric oscillations can cause variability over periods of several years, as will be discussed.

2.2.1 Winds

Like much of the UK, the prevailing wind direction in the Sussex coast regions is from the southwest. Figure 2.3 shows a wind rose produced using hourly mean wind speed and direction data (10 m above water surface) for the period 1979-2021, extracted from the freely available ERA5 global reanalysis model database (Hersbach et al, 2018) at a point 30 km offshore of Littlehampton. This shows that the wind is from a west to southwest direction for approximately 40% of the time. The long term average hourly mean wind speed at this location is 7.5 m/s, with a median of 7.3 m/s. The maximum hourly mean speed in the dataset was 28 m/s.

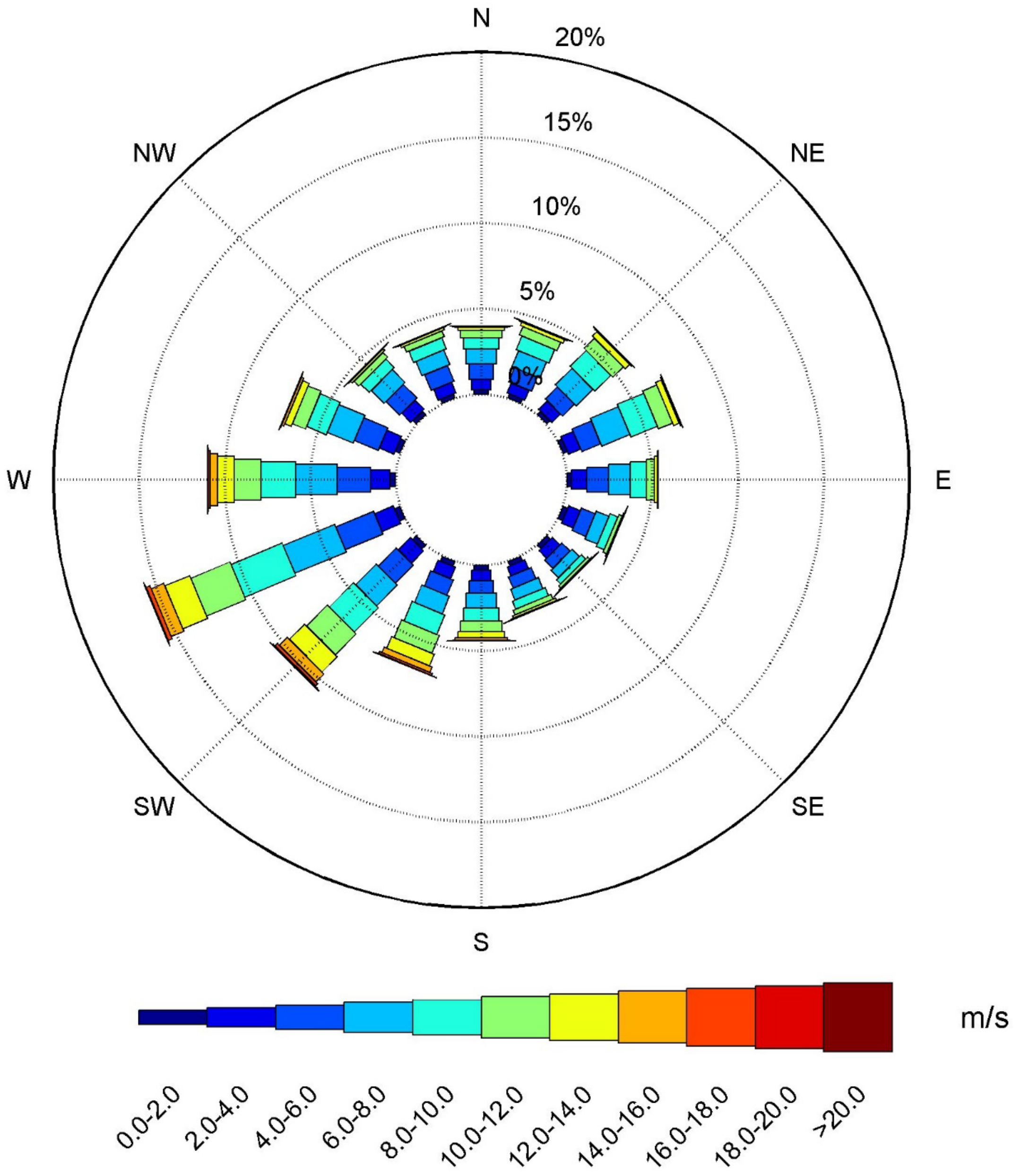

Figure 2.3: Offshore wind rose 1979 to 2021

Source: ERA5 global reanalysis model (50°30'N 0°30'W)

The wind rose plotted above shows that, although the direction of the wind tends to be from the southwest, there is a considerable spread in directions, with winds from the northeast also important at times. Previous studies have shown that the prevalence of south-westerly wind tends to be seasonal, with stronger southwesterlies generally during the winter months, but there is also considerable interannual (year to year) variability (Earl et al, 2013). The interannual variability has been previously linked to the North Atlantic Oscillation (NAO). The NAO is a measure of the difference in atmospheric pressure at sea level over the

North Atlantic between Iceland in the north and Gibraltar (Jones et al, 1997) or the Azores (Walker and Bliss, 1932) in the south.

A stronger than usual difference in pressures between north and south points is known as a positive NAO index. During positive NAO index periods, winds from the west tend to dominate, with more frequent storms travelling across the Atlantic to the UK. Conversely, during periods of negative NAO index (when the pressure difference is lower than usual), the wind in the UK is more frequently from the east and north-east with weaker and less frequent storms. The rate at which the NAO index changes between positive and negative can be the order of years (Figure 2.4) which means there can be relatively long periods during which either south-westerlies or weaker north-easterlies dominate. As an example, in Figure 2.4, it can be seen that the NAO index during the period between 1995 and 2010 was strongly negative, peaking in 2010 when recorded wind speeds were anomalously low which significantly reduced offshore wind power output for that year (Earl et al, 2013). Such interannual variability makes it difficult to predict longer term changes in wind conditions.

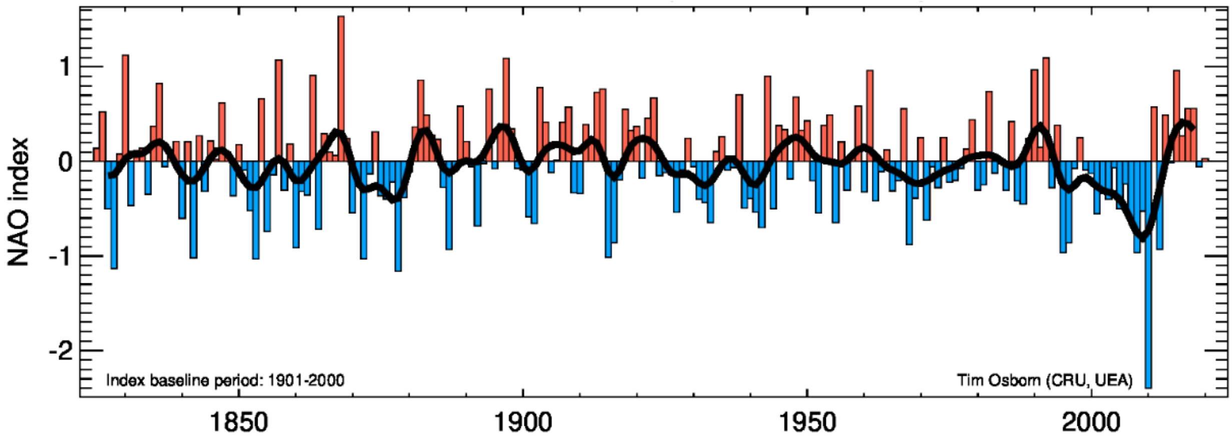

Figure 2.4: Annual NAO index (using Gibraltar-Iceland pressures)

Source: Climatic Research Unit, University of East Anglia

2.2.2 Waves

The waves, driven by the prevailing winds tend to be from the southwest and increase eastward due to the increasing fetch length (the term fetch means the distance of open water along which the wind blows, with larger fetches allowing larger waves to be generated). Offshore, at a point approximately 30 km offshore from the coast, significant wave height (Hs) and direction were extracted for the period 1979-2021 from the ERA5 global reanalysis and plotted as a wave rose (Figure 2.5). This shows that the waves are predominantly from the WSW. Further inshore, the incident waves vary depending on the bathymetry and shape and orientation of the local coastline. For example, at a point 8 km offshore from Rustington (which is 1 km east from the mouth of the River Arun), wave buoy data were available for the period 2003-2022. The wave rose at that point (Figure 2.6) shows that the waves in the shallower water here are refracted to be predominantly SW in direction. The long-term average Hs for this dataset is 0.8 m and the average wave period (Tp) is 6.7 s. In terms of exceedances, for 95%, 50% and 5% of the time Hs exceeds 0.2 m, 0.6 m and 2.0 m, respectively, with corresponding periods of 2.6 s, 5.6 s and 13.3 s. This shows that the wave climate in the region is energetic for much of the time.

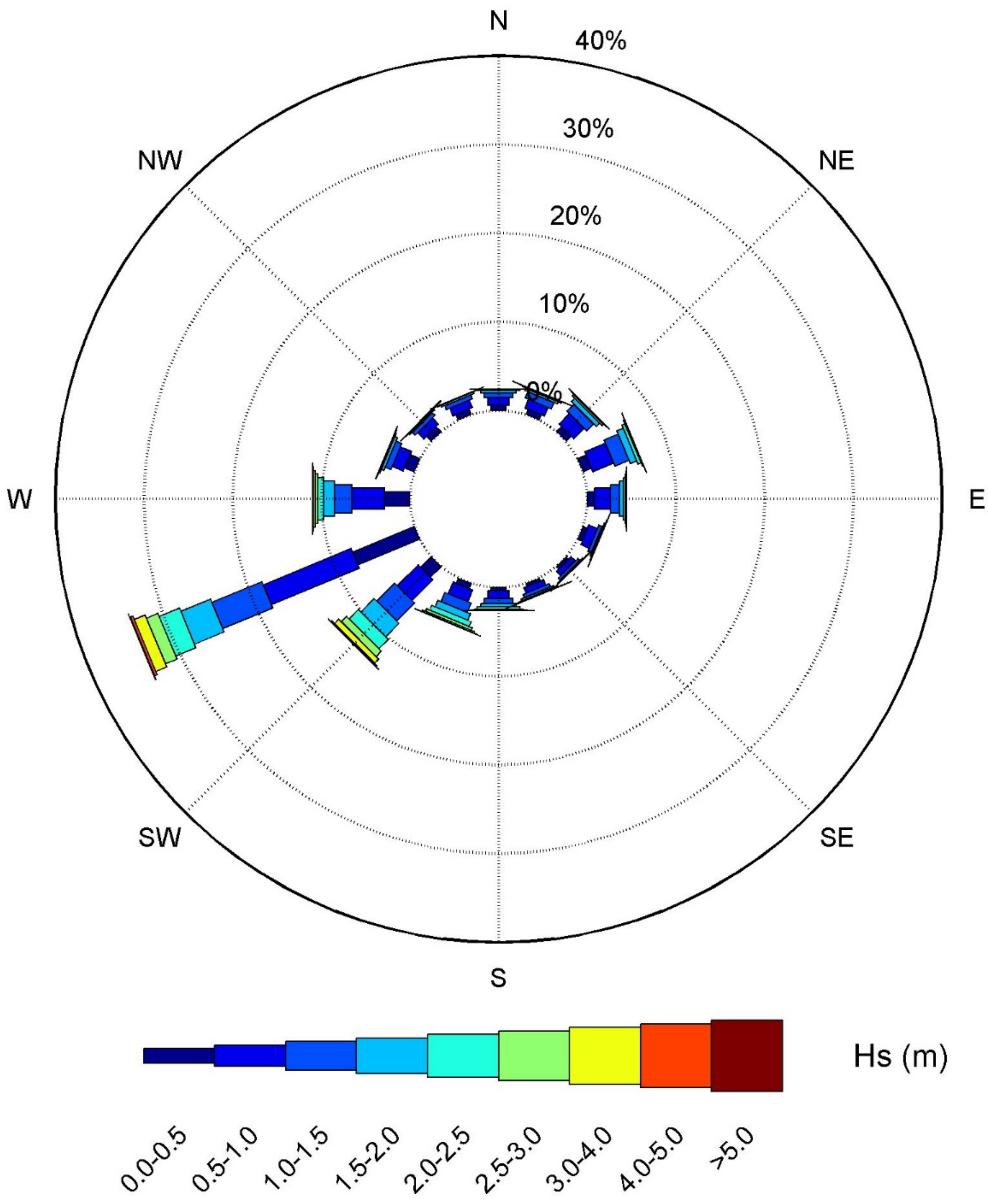

Figure 2.5: Offshore waves rose 1979 to 2021

Source: ERA5 global reanalysis model (50°30'N 0°30'W)

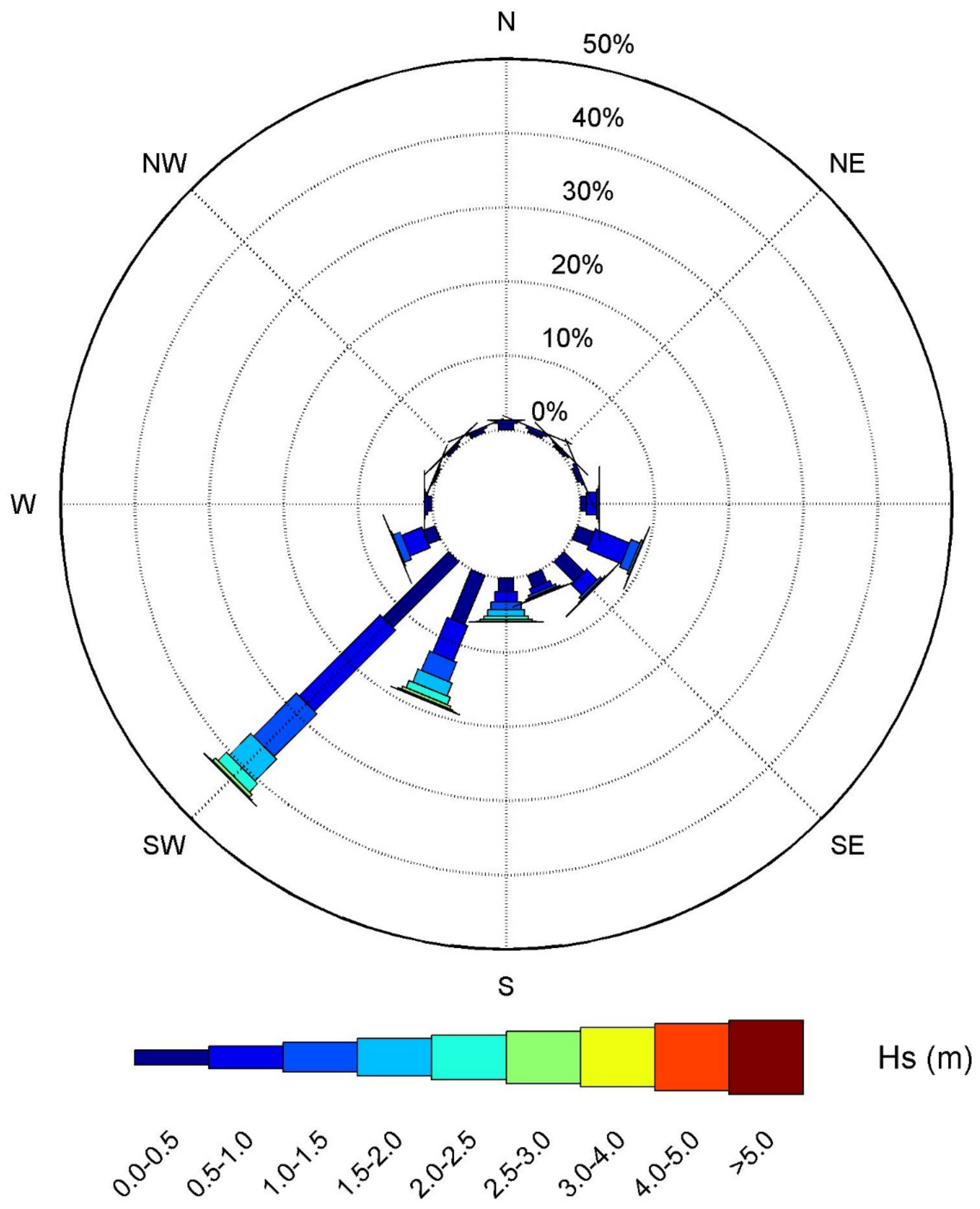

Figure 2.6: Nearshore waves roses along the Sussex coastline (Data period 2003 to 2022)

Source: CEFAS Wavenet data (Rustington Waverider buoy, 50° 44.06' N,: 00° 29.64' W)

The Rustington wave buoy data were previously analysed as part of a separate study investigating reductions in crab and lobster catch around Selsey Bill (CHASM; Channel Coastal Observatory, 2021) to investigate trends in storm occurrence. In that study it was observed that, for the analysed wave record period between 2003 and 2019, there appeared to be an increasing trend in wave height, with the largest number of storms (defined as periods when waves exceeded a significant wave height of 3.42 m at Rustington) recorded during 2013/14. However, this trend was found to be not statistically significant, primarily due to the short duration of the record which meant natural variability could not be ruled out as the cause. It is notable that throughout the period of the wave measurements (2003-2019), the NAO index was transitioning from strongly negative to positive values (Figure 2.4). There is therefore a strong possibility that the increasing trend could have been associated with the NAO oscillation. To check whether this was the case, as part of the present study, the ERA5 data used to generate the offshore wave rose (Figure 2.3) were analysed in a similar way to the CHASM data to determine the number of storm events per year (Figure 2.7). In this case, because of the more offshore location for the ERA5 data, a larger value of 4.1 m was used as the threshold for a storm event. The Rustington analysis carried out for the CHASM project is also plotted in Figure 2.7 for comparison. This highlights the lack of an overall clear trend since 1979 which corresponds with the UK Met Office report finding of no compelling trends in storminess over the last four decades (Fung et al, 2018).

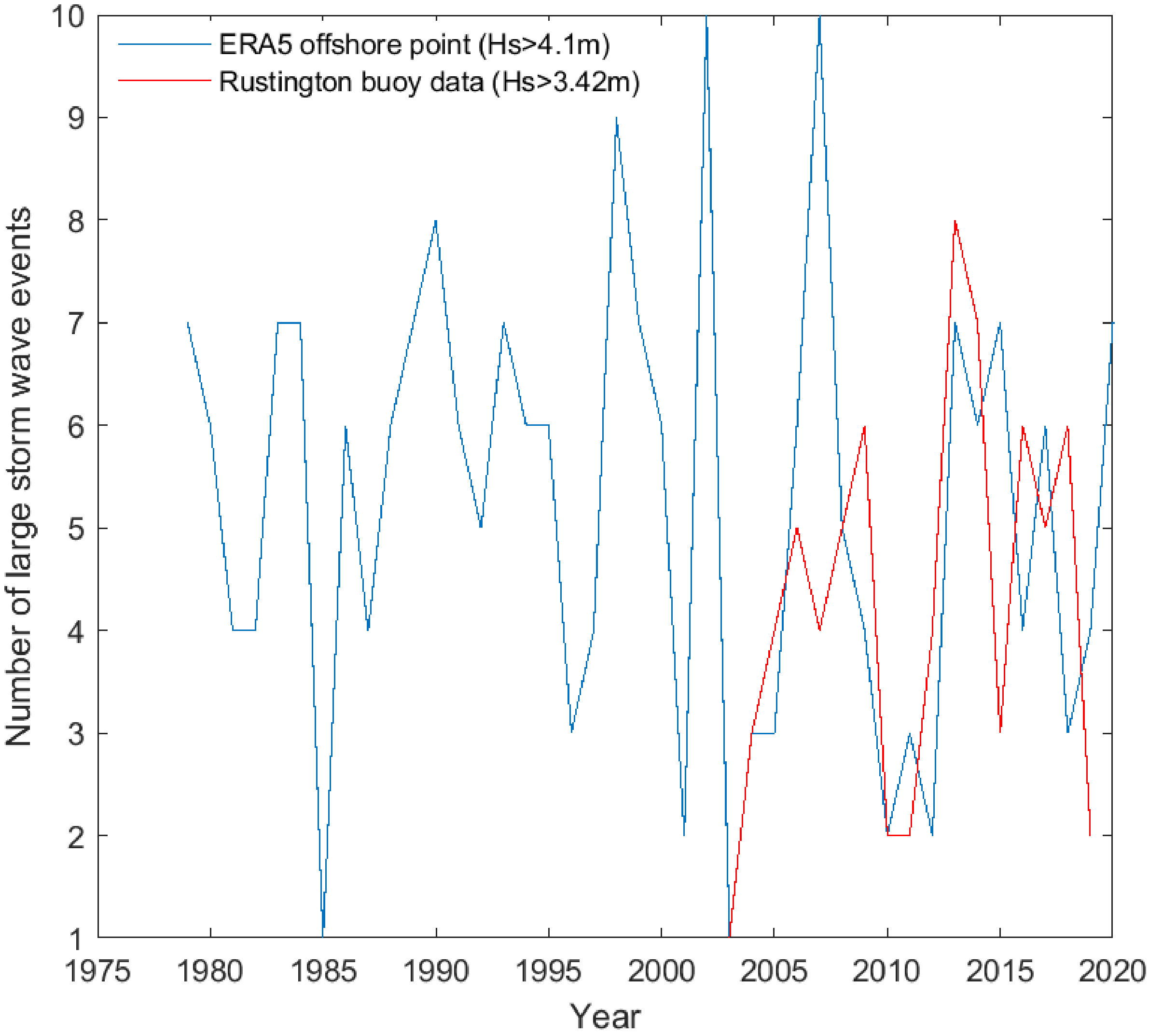

Figure 2.7: Number of storm events (Hs>4 m) per year determined using offshore ERA5 data (1979-2021) and previous CHASM analysis for Rustington

Source: ERA5 global reanalysis model (50°30'N 0°30'W)

2.2.3 Tides

The tidal range in the region is macro-tidal (i.e. in excess of 4 m) and increases from west to east (Table 2.1), whilst the inshore tidal current velocities, which are typically up to ~1 m/s during larger spring tides, decrease eastwards (SCOPAC, 2012). Spatial plots of the spring tide currents during peak flood and peak ebb are shown in Figure 2.8 and Figure 2.9 respectively. These plots highlight the regions of strong currents at the headlands of Beachy Head, Selsey Bill and south of the Isle of Wight.

Although not resolved in these model outputs, strong tidal currents (>2 m/s) also occur locally at the inlets (Pagham Harbour, Arun and Adur).

The *tidal excursion* is often useful for assessing potential sediment transport pathways. In Figure 2.10, a plot is shown of virtual floats placed in the tidal model at a spring tide low water and then tracked over a full tide to the following low water. The tidal excursion is the maximum length of the drawn elliptical track which, in this case, over the historic kelp beds is between approximately 5 km and 10 km, with the smallest excursions occurring nearest to the coast where flows are slower. Any fine sediment that is in suspension is likely to be dispersed over much of this excursion distance during a single tidal cycle. Where the tidal excursion is longest, such as offshore in the English Channel, the dispersion of fine sediment will be greatest. Also, it shows that any possible sources of fine sediment may be located at a considerable distance from the point of observation. Near to the Sussex coast, the tidal excursions are generally shorter (except at the headland of Selsey Bill where flows are squeezed) which indicates that the currents are generally slower and hence the suspended sediment will be carried over shorter distances per tide. However, the residual tidal flow (i.e. the rate of progression of a parcel of water over consecutive tides) is also important for the rate of dispersion or accumulation of suspended sediment, which will be discussed in the next section.

Table 2.1: Tidal levels for locations along the Sussex coastline

Location	MHWS (m MSL)	MHWN (m MSL)	MLWN (m MSL)	MLWS (m MSL)
Chichester Harbour mouth	2.0	1.1	-1.0	-2.0
Shoreham	2.9	1.4	-1.5	-2.8
Newhaven	3.1	1.5	-1.6	-2.9
Eastbourne	3.6	1.6	-1.7	-3.1

Source: Admiralty Tide Tables, Volume 1A, 2022 (UKHO)

Note: MHWS = mean high water of spring tides, MHWN = mean high water of neap tides, MLWN = mean low water of neap tides, MLWS = mean low water of spring tides.

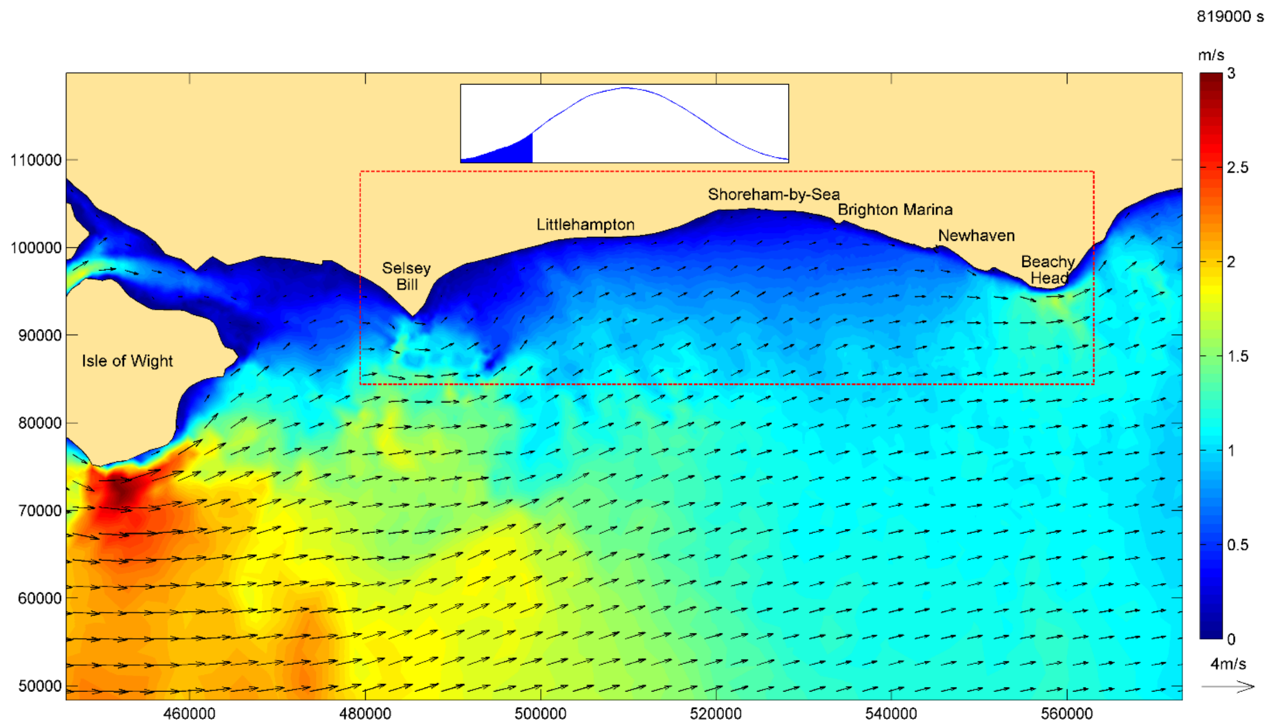

Figure 2.8: Peak flood currents on a spring tide

Source: HR Wallingford TELEMAC model

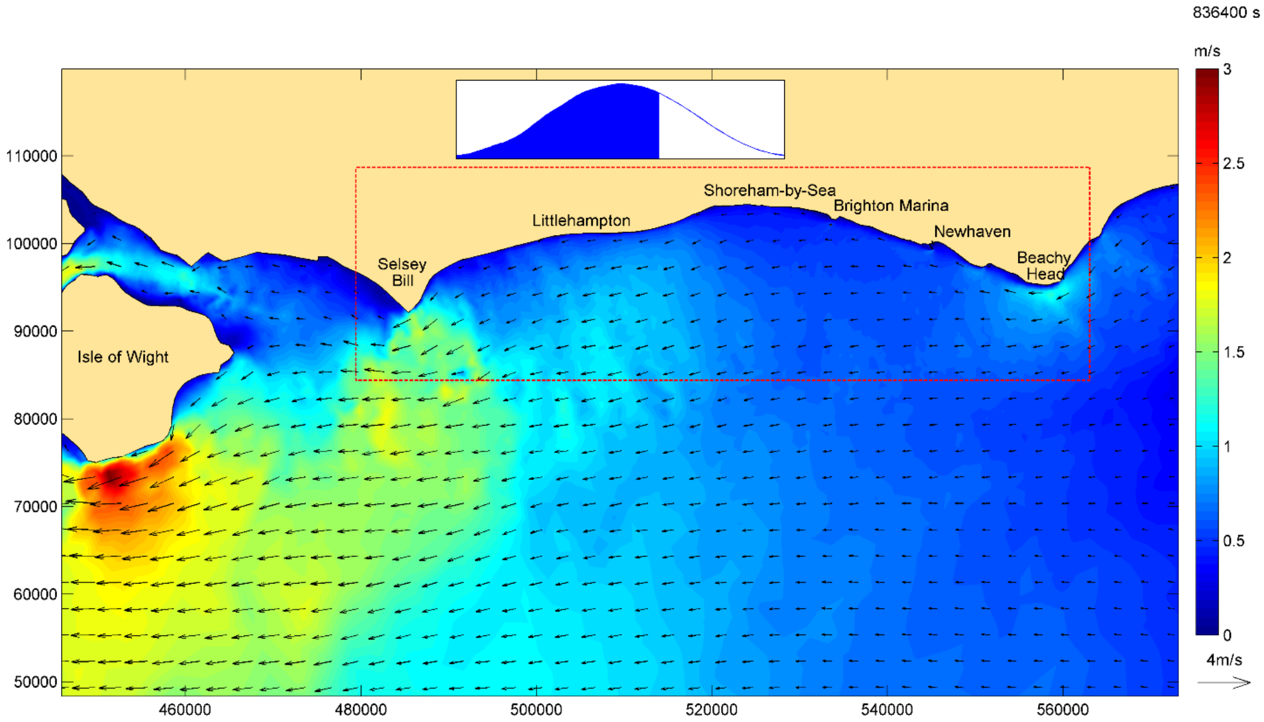

Figure 2.9: Peak ebb currents on a spring tide

Source: HR Wallingford TELEMAC model

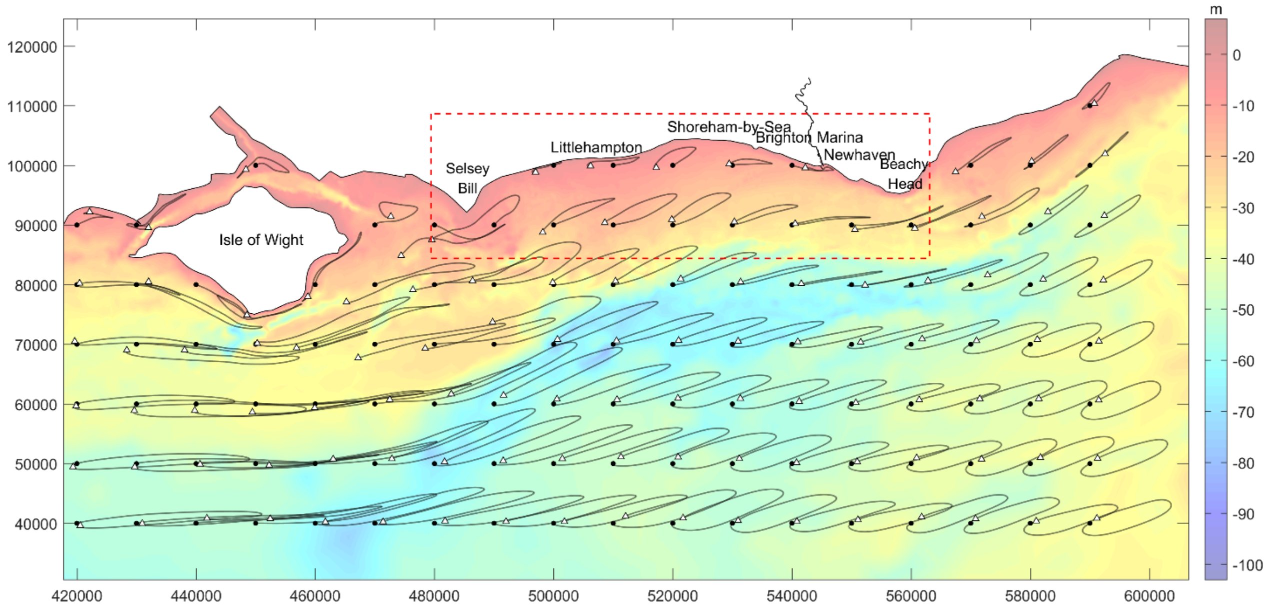

Figure 2.10: Tidal excursion tracks for a single spring tide starting at low tide (black dots) and finishing on the following low tide (white triangles). The bathymetry is also shown as coloured shading

Source: HR Wallingford

2.2.4 Residual currents

Previous studies have shown that residual currents, without wind effects, in the English Channel are generally towards the east (Guillou, 2015). Near to the coast however, headlands and islands cause recirculation of the residual tidal flow (Menesguen and Gohin, 2006). Using a tidal model with no wind effects, Salomon & Breton (1993) produced a map of tidal residuals which indicated a westerly residual circulation to the west of approximately Brighton that extended to the Isle of Wight before turning southwards then back eastwards in deeper water. Another clockwise circulation (15-20 km in diameter) was apparent within the east arm of the Solent offshore from Bracklesham Bay, west of Selsey Bill.

More recent and higher resolution tidal modelling of the English Channel (HR Wallingford, 2016) supports the presence of these recirculation patterns (without wind). A plot of the residual tidal currents averaged over a full spring-neap cycle clearly shows large residual gyres, particularly near to Selsey Bill (Figure 2.11). Key features of the residual circulation patterns (assuming no wind) are:

- A westerly residual over most of the historic kelp bed area to the west of Brighton which turns southwards at Selsey Bill.
- East/northeast residuals further offshore and to the east of Brighton.
- A north/northeast residual in the East Solent (to the west of Selsey Bill) turning clockwise and heading southwards from the tip of Selsey Bill where it meets the westerly residual from the Sussex coast.

The pattern of residual circulation in the East Solent (Figure 2.11) compares very well with radar measurements of surface currents within the same area carried out by Southampton University in 1995 and 1996 (Figure 2.12) as described in Guyard (2000), giving confidence that the modelled tidal residuals are real features.

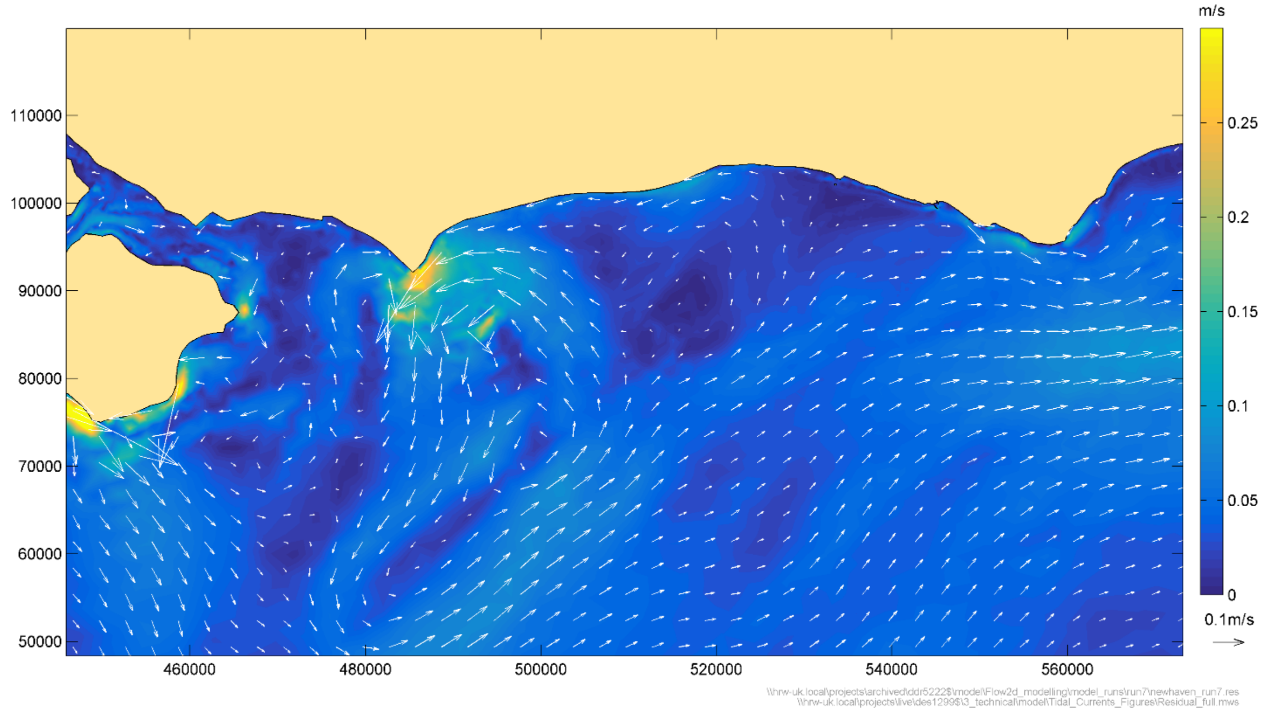

Figure 2.11: Modelled depth-averaged residual currents along the Sussex coast averaged over a spring-neap cycle (15 days)

Source: HR Wallingford TELEMAC model

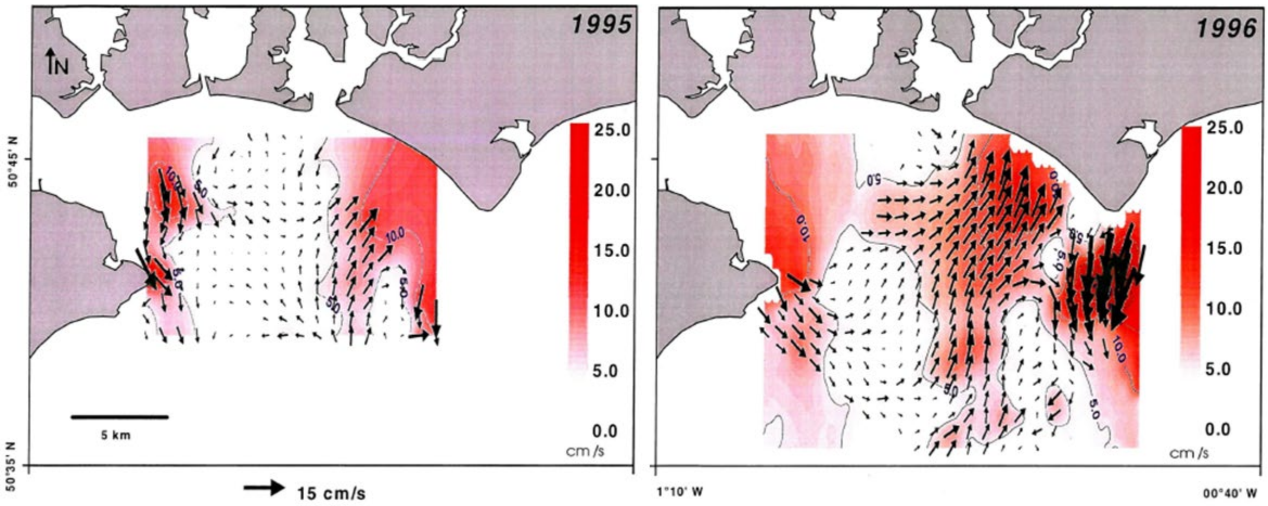

Figure 2.12: Surface residual currents in the East Solent measured using radar (OSCR) obtained during June 1995 (top) and July 1996 (bottom). Contours represent current speed isolines (cm/s)

Source: Guyard (2000) PhD Thesis

The residual tidal currents in the English Channel are generally rather weak, typically one to two orders of magnitude slower than the peak tidal flows (Salomon and Breton, 1993) and therefore the recirculation patterns are likely to be significantly influenced by the wind. Wind-driven currents in the Channel are slower than peak tidal flows, but can be greater than tidal residuals and therefore may play an important role in modulating their effects (Guyard, 2000).

Given that wind speeds are generally greater during the winter months (and generally from the southwest), it is likely that the strength and direction of the residual currents changes seasonally, possibly resulting in more eastward residuals during the winter. A better understanding of the residual flows would benefit from further investigations using a fully coupled tide, wind and wave numerical model of the English Channel.

2.3 Sediment transport

Sediment transport along the Sussex coastline primarily occurs by two mechanisms:

- Longshore drift caused by waves breaking obliquely to the shore is the main transport mechanism for beach sized sediment, such as shingle and sand. The rate of transport depends both on the wave height at the point of breaking and the angle of approach of the waves. The combination of this wave-induced longshore current and the wave action agitating the sediments is very effective at transporting sediment along the coast. Figure 2.13 shows an example of this process of longshore sediment transport.
- Tidal currents can transport fine sediments, especially silt, which can stay in suspension for longer. Tidal currents are likely to be important for sediment transport in the deeper water kelp bed areas.

Figure 2.13: Longshore sediment transport caused by oblique breaking waves

SCOPAC (2012) have summarised the sediment transport pathways along the south coast (see Figures 3.9-3.14) inshore of the existing / potential kelp beds. Between Chichester Harbour and Selsey Bill, the net littoral drift of sand and gravel is directed northwest, towards the mouth of Chichester Harbour. Selsey Bill itself forms a drift divide, with long term littoral drift on the east side of the Bill directed towards northeast towards Pagham harbour (Figure 2.14).

The net littoral drift continues to be towards the east along the majority of the Sussex coastline to Beachy Head, with the exception of a small drift reversal between Newhaven and Seaford. The tendency for sediment to move eastwards can be seen in the sediment accumulation updrift of beach groynes, and updrift of the harbours.

Cross shore sediment movement and onshore feeds

Cross shore movements of sediment to and from the coast are less well understood. It is thought that there is some onshore feed of gravel to Selsey Bill from Kirk Arrow Spit (SCOPAC, 2012). Kirk Arrow Spit is a mobile gravel bank which is exposed at low water and located 300-500 m offshore from Selsey Bill. Due to the interaction of waves and high current velocities in the area it is a dynamic feature. Large but infrequent pulses of sediment input to the Selsey Bill coastline occur when the spit extends landward and temporarily attaches to the shoreline (SCOPAC, 2012). Aerial photographs suggest this happens approximately once per decade, and this is the main natural supply of beach sediment to Selsey Bill. This sediment supply may average 5,000 – 10,000 m^3/year of shingle.

A further onshore feed of beach material comes from the mobile gravel banks of the Inner Owers which periodically migrate onshore between Selsey Bill and Pagham Harbour (SCOPAC, 2012). Further east, between Shoreham-by-Sea and Brighton, there is also evidence that sand and gravel may move shorewards in water depths less than 12-18 m.

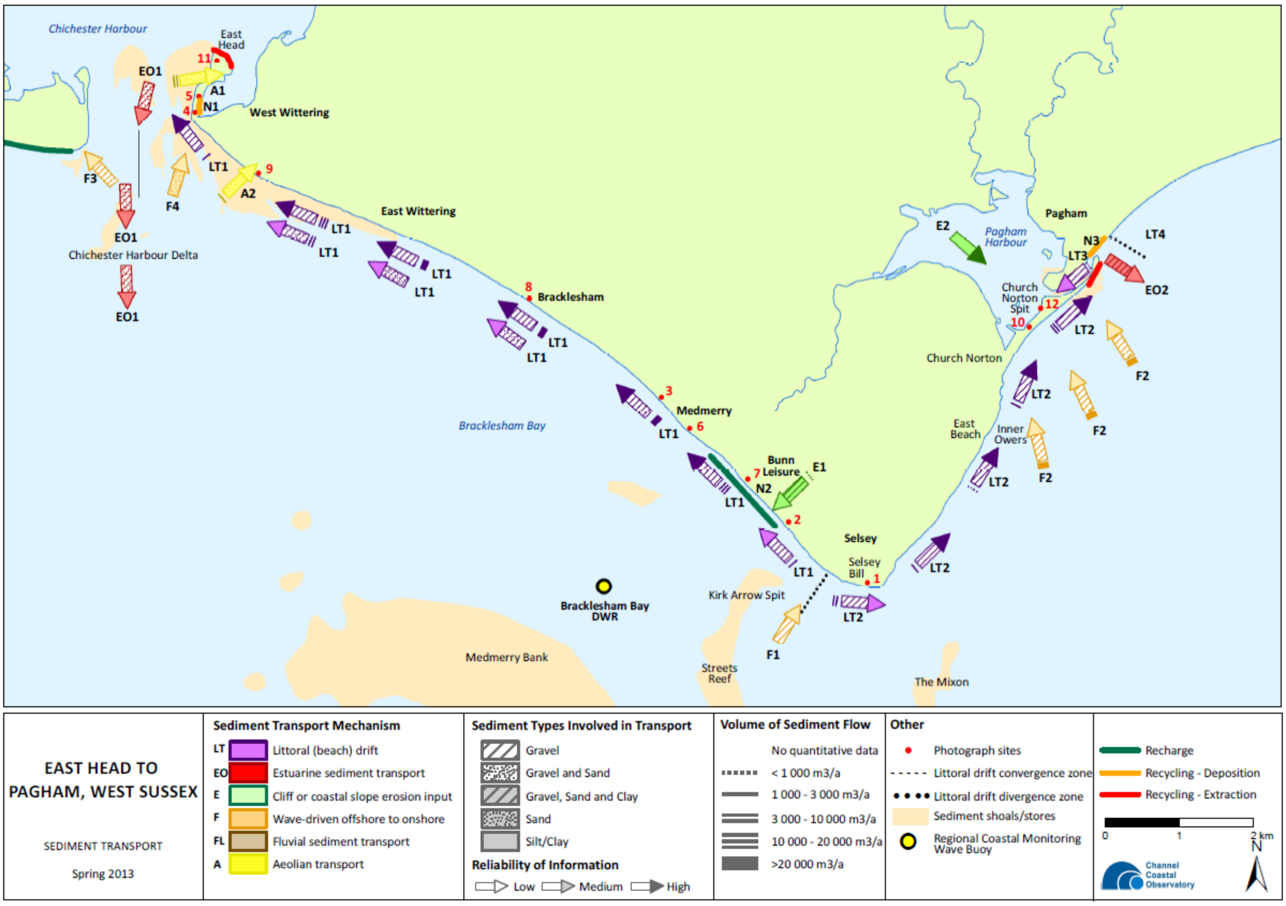

Figure 2.14: Sediment transport pathways between Chichester Harbour and Pagham Harbour

Source: SCOPAC (2012)

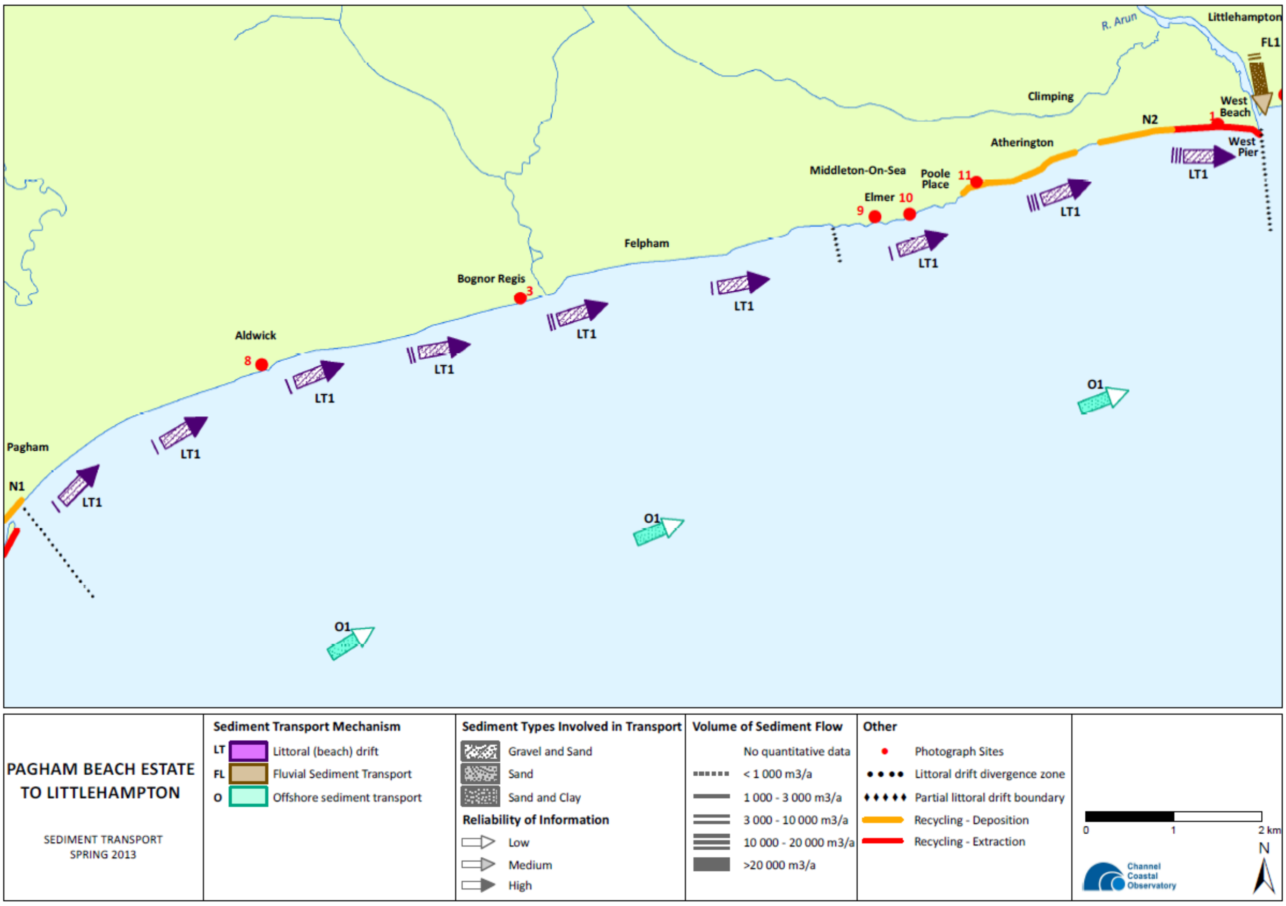

Figure 2.15: Sediment transport pathways between Pagham Harbour and Littlehampton

Source: SCOPAC (2012)

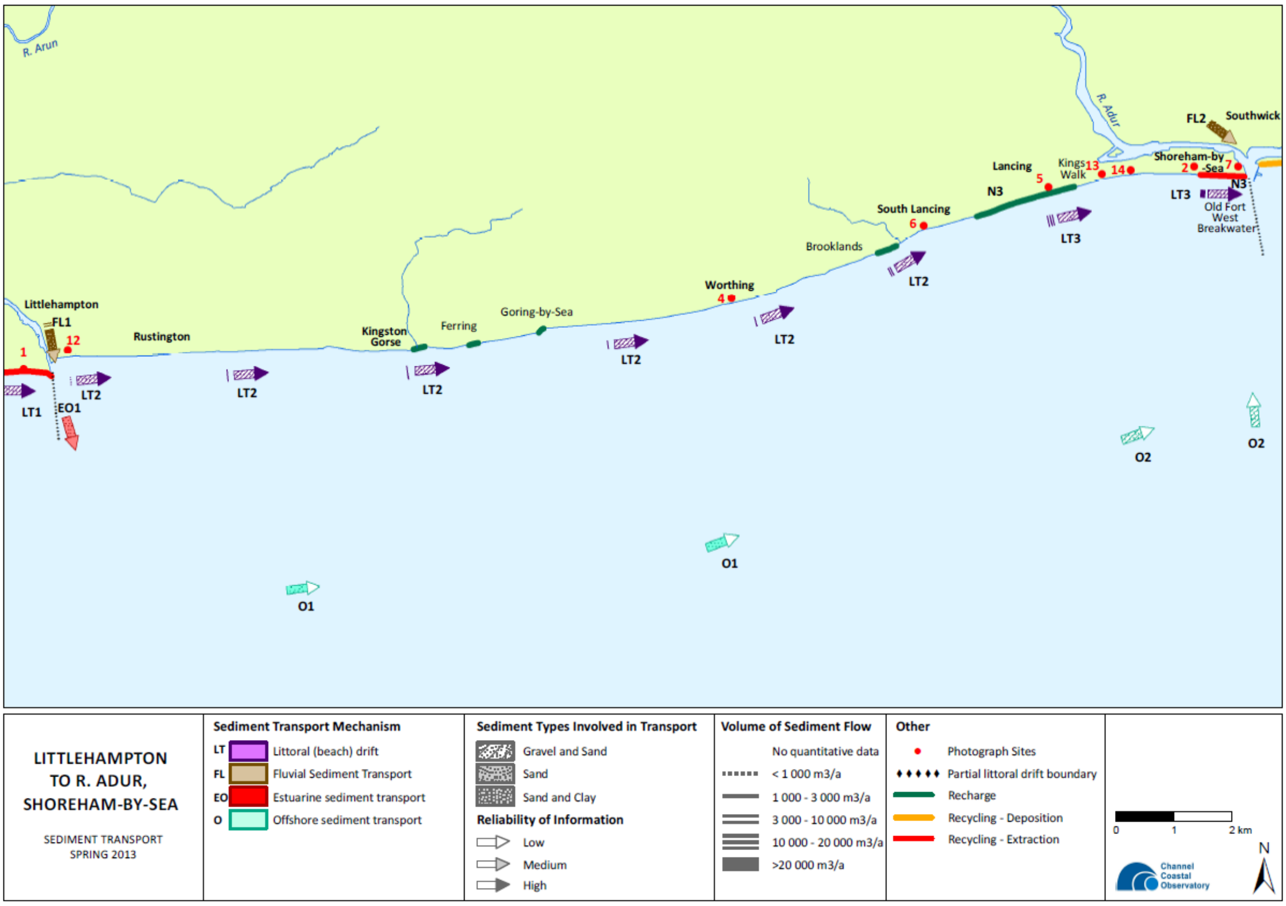

Figure 2.16: Sediment transport pathways between Littlehampton and Shoreham-by-Sea

Source: SCOPAC (2012)

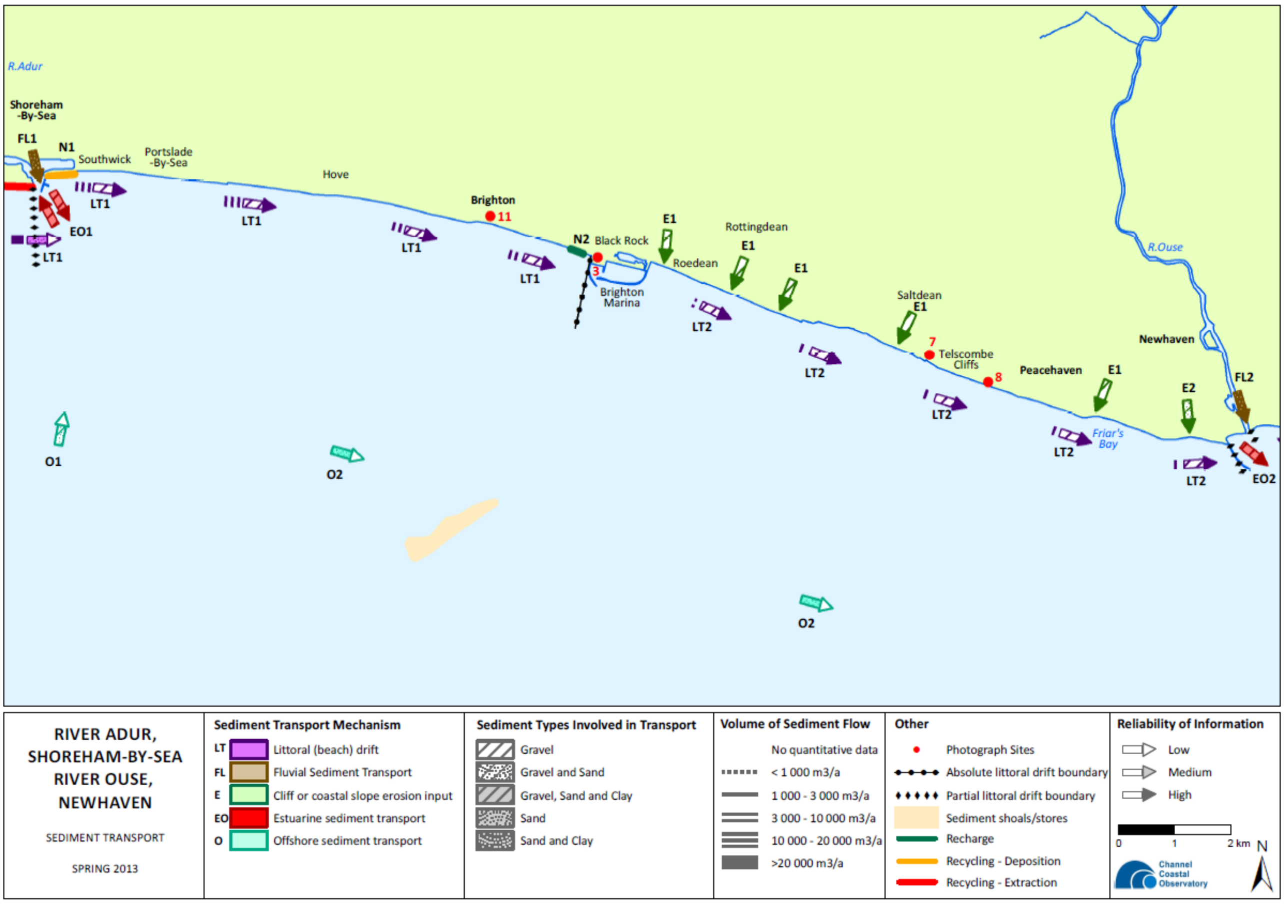

Figure 2.17: Sediment transport pathways between Shoreham-by-Sea and Newhaven

Source: SCOPAC (2012)

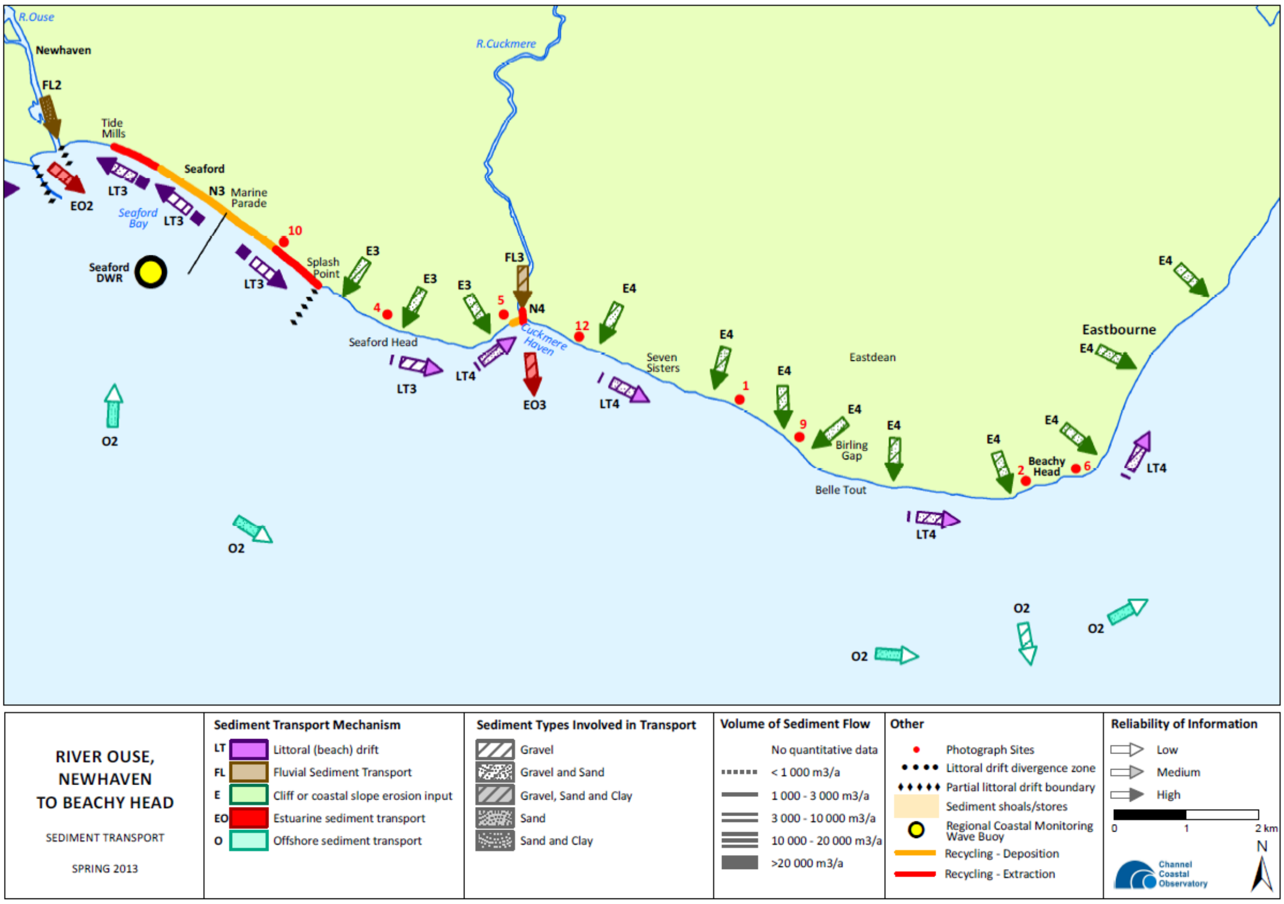

Figure 2.18: Sediment transport pathways between Newhaven and Eastbourne

Source: SCOPAC (2012)

2.4 Coastal defences

Much of the present day Sussex coastline is defended by a combination of seawalls, revetments and groynes (Figure 2.20, Figure 2.19). Between Chichester Harbour and Brighton, where the shoreline is characterised by the shingle barrier, the defences prevent the barrier moving landward with sea level rise. As a consequence, the shingle beach is steepening (low water retreats landward but highwater is prevented from retreating by the seawalls). The base of the chalk cliffs to the east are also defended in a number of locations (Figure 2.20). The main exception is the section east of Seaford to Beachy Head (approximately 13 km) where it is estimated that cliff erosion may release 7,700 m^3/year of beach material, in addition to 170,000 m^3/year of chalk (Dornbusch et al., 2006).

The input of shingle from natural processes (onshore feed and cliff erosion) is less than the sediment moved alongshore by littoral drift. As a consequence, there are areas where beach sediment is absent or occurs as a thin veneer over the shore platform. The beach is managed to maintain beach volumes by sediment recycling (moving sediment from an area of accretion to one of erosion) and renourishment (supply of new sediment from an offshore or land based source) (see Section 5.1.3).

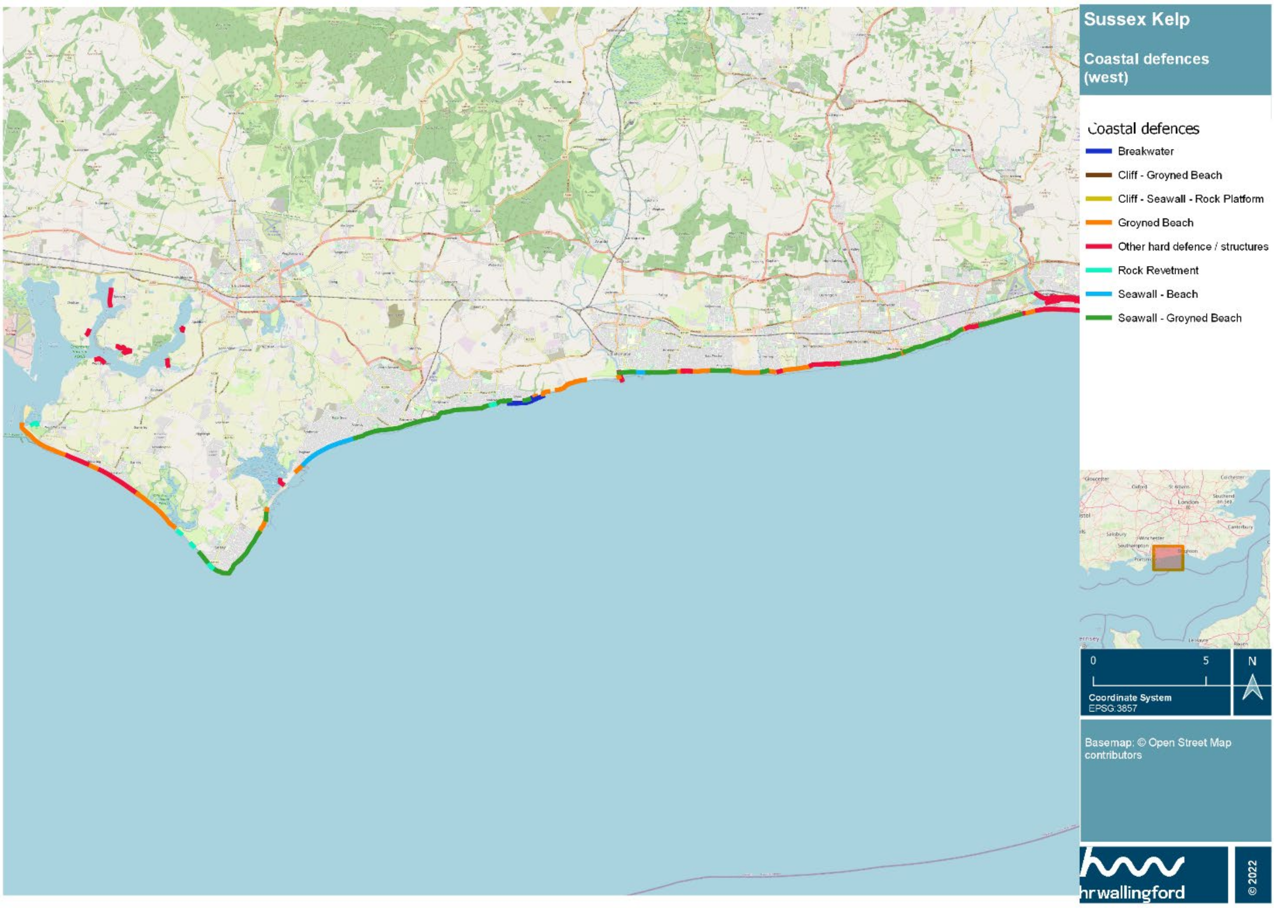

Figure 2.19: Coastal defences along the Sussex coastline (Chichester Harbour to Shoreham)

Source: Coastal Defences layer from https://www.coastalmonitoring.org/ccoresources/shapefiles/

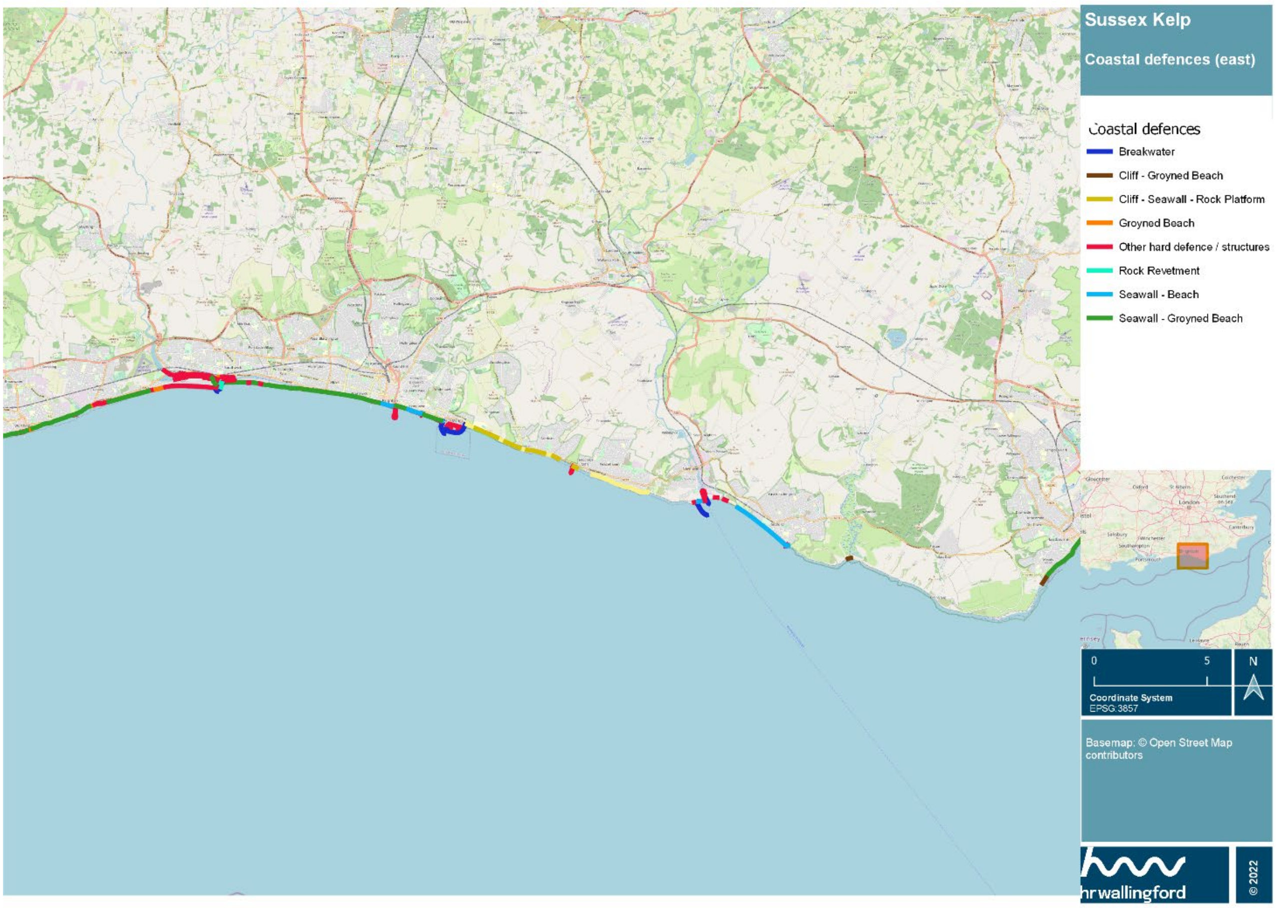

Figure 2.20: Coastal defences along the Sussex coastline (Shoreham to Beachy Head)

Source: Coastal Defences layer from https://www.coastalmonitoring.org/ccoresources/shapefiles/

3 Suspended sediment

In addition to the Sussex beach materials of shingle, transported as bedload, and medium or coarse sand, transported as both bed and suspended load, finer sediment fractions (fine sand, silt, clay and chalk particles) are also transported as suspended load in the water column. Waves and tidal currents can resuspend fine sediments in the nearshore zone, and there is also input of fine sediment from rivers and cliff erosion. The concentration of suspended sediment (turbidity) in the water column will vary depending on weather conditions and events such as cliff falls. Section 3.1 provides an overview of typical suspended sediment concentrations in the English Channel and Section 3.2 looks at possible historical trends.

The rate at which fine sediment settles through the water is related to the viscosity of the water. In the summer the water is warmer and the viscosity lower. As a result fine sediment may settle 25-30% faster than during the winter period. This has little impact on overall suspended sediment concentrations in coastal waters because typically in the winter the rates of input of fine sediment into the water column from wave agitation of the seabed or from river discharge are substantially higher than in the summer.

It is worth noting that, in the nearshore zone, suspended sediment concentrations may be higher than background levels further offshore as sediment is continually resuspended by waves in all but the calmest conditions. Furthermore, high current velocities around inlets will also contribute to increased sediment concentrations in the nearshore zone. Suspended sediment in the nearshore zone can be seen in historical aerial photographs of the Sussex coastline (e.g. Figure 3.1).

The different sediment types have differing impacts in terms of turbidity, with finer sediments causing greater turbidity. Chalk particles are smaller than silt and clay and therefore may have a greater impact on water turbidity (Traykovski et al., 1999). Chalk is made up of very fine particles much of which is smaller than 5 micrometres (µm). Clay minerals are similar in size, but electrostatic forces mean these tend to form “flocs” that are approximately 20-50 µm in size and sometimes up to several millimetres depending on hydrodynamic conditions. Since light scattering is greater for suspensions of smaller particles compared to suspensions of larger particles, the turbidity for a chalk suspension (at the same concentration as a silt or clay suspension) will be significantly higher.

Both increases in current speed and increases in wave action can lead to increases in suspended sediment within the water column. There is a typical spring-neap variation in suspended sediment concentrations associated with changes in tidal speeds, and during storm conditions suspended sediment concentrations are typically elevated. Following large storm events fine material mobilised from within the seabed becomes more available for resuspension by currents and waves, resulting in prolonged periods of elevated suspended sediment concentrations.

Figure 3.1: Aerial photo of sediment plumes along the coast around Brighton Marina in 2015

Source: Google Earth

3.1 Background suspended sediment concentrations

Salomon and Breton (1993) hypothesised that areas of residual recirculation of currents to the east of the Isle of Wight and near headlands cause retention of sediment to the south and east of the Isle of Wight (a few kilometres west of the kelp areas). This was supported by satellite derived (estimated) surface suspended particulate matter (SPM) concentrations which are generally higher in this region than the surrounding areas, and may exceed 30 mg/l on average during winter months and higher after storm events (Figure 3.3).

According to the tidal models (without wind) of Salomon and Breton (1993), Guillou et al (2015) and Menesguen & Gohin (2006) these recirculation patterns result in a residual direction of flow (and hence transport of fines) that is generally westwards from the Sussex kelp bed areas, west of Brighton, but eastwards further offshore. This is also supported by HR Wallingford's models of the area (e.g. HR Wallingford, 2016). However, there is conflicting evidence in the literature on the direction of residual transport in this area. The SCOPAC and MAREA reports (SCOPAC, 2012; HR Wallingford, 2012) both state that the sediment transport pathways are generally eastwards from Nab Tower towards the kelp bed areas. The influence of wind and associated waves is the likely explanation for this mismatch, especially close to the coastline due to the process of wave induced longshore drift. The complexity of the tidal recirculation and wind driven effects in the area would benefit from a detailed numerical modelling study. This would help to determine the likelihood of fine sediment from the Nab Tower dredge disposal grounds reaching the kelp beds (discussed further in Section 5.1.7).

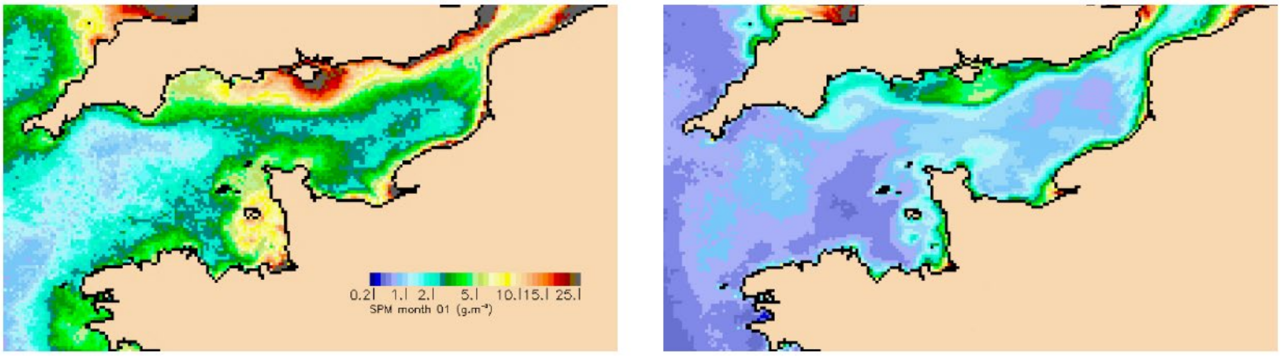

Figure 3.2: Averaged near-surface suspended sediment concentration (SSC) from MODIS satellite images over the period 2003–2009 for the months of (left) January and (right) August

Source: Guillou, 2015

Suspended sediment concentrations in calm conditions in the English Channel west of the Isle of Wight were reported in Velgrakis *et al*., (1999). These measurements relate to particles less than 63 µm in size (fine sediments) and do not take coarser particles into consideration, but suggest typical (calm, near bed) summer concentrations of a few mg/l rising to around 40 mg/l in winter. OBS (optical back scatter) measurements of suspended sediment concentration taken 0.5 m above the bed in January 2012 in 30 m of water to the west of the Isle of Wight (HR Wallingford, 2012) recorded concentrations varying between 5–60 mg/l. These measurements were derived from OBS measurements calibrated against collected water samples (standard error of calibration about 2.5 mg/l).

In the vicinity of the disposal sites east of the Isle of Wight (discussed later in Section 5.1.6; see Figure 5.8 for locations), Centre of Environment, Fisheries and Aquaculture Science (CEFAS) holds some monitoring data for winter suspended sediment concentrations just to the north of the Nab Tower disposal site, which lies within the region considered in this study. These indicate that concentrations range from 4–45 mg/l with a mean around 25 mg/l (CEFAS, 2001); unfortunately no corresponding summer data exists and it is not clear where and at what depth these measurements were taken or how they were taken.

Deployment of an OBS 0.5 m above the bed between November 2010 and February 2011 at locations 14-27 km east of Areas 453 and 488 (Figure 5.4) in water depths of 25–40 m for the Rampion Wind Farm EIA (ABPmer, 2012) found typical suspended sediment concentrations of 5–15 mg/l with maximum values of 50–100 mg/l.

HR Wallingford (2013) interpreted these measurements as providing evidence of background sediment concentrations of up to 45–60 mg/l under normal conditions for the sea area of coastline in the vicinity of Areas 453 and 488. Under storm conditions these concentrations can rise significantly to levels of about 300 mg/l.

As part of the CHASM project (Channel Coastal Observatory, 2021) measurements of turbidity have been made in the Medmerry realignment and in Pagham Harbour. These measurements show changes in turbidity with tidal cycles at both sites, with higher turbidity observed during spring tides compared to neaps. They also noted spikes in turbidity that were not related to the tidal cycles and differed between sites, which were likely related to localised wind or wave events.

Context

To give context to the amounts of suspended sediment involved, some estimates of sediment quantities involved in some simplified scenarios are presented below.

1. Assuming a storm eroded the top 10 cm of seabed across the study area and that 5% of the bed is fine sediment, how much fine sediment would be resuspended?

	Study area to 20 m contour	Study area to 10 m contour
Area	850,000,000 m^2	400,000,000 m^2
Depth of erosion	0.1 m	0.1 m
% fines	5%	5%
Volume eroded	85,000,000 m^3	40,000,000 m^3
Density	1,500 kg/m^3	1,500 kg/m^3
Mass of fine sediment	6,300,000 tonnes	3,000,000 tonnes

This scenario will overestimate the sediment brought into suspension because the whole seabed is not equally erodible, and the amount of erosion will vary with water depth. However, it gives an indication of the volumes and masses of sediment that could potentially be suspended by a storm event.

2. If the depth average concentration is 10 mg/l, how much fine sediment is the water holding over the study area?

	Study area to 20 m contour	Study area to 10 m contour
Volume	8,800,000,000 m^3	2,200,000,000 m^3
Concentration	10 mg/l	10 mg/l
Mass	88,000 tonnes	22,000 tonnes

These simplified scenarios give an indication of the mass of sediment typically in the coastal waters and the potential resuspension from a storm.

This analysis shows that a single large storm event has the potential to resuspend more fine material from the seabed than is derived from an average year of cliff erosion (289,000 tonnes per year, see Section 5.1.3). More typically observed suspended sediment concentrations of the order of 10mg/l are insufficient to maintain in suspension the mass of sediment released by a storm, so in addition to larger scale movements of suspended sediment by residual currents there must be resettlement of fine sediment back to the seabed after storms. This simple analysis helps to explain the variability that is observed in the suspended sediment concentrations.

3.2 Historical trends in suspended sediment

The aim of this section is to establish whether there has been an increase in suspended sediment concentration (SSC) in the Sussex coastal / kelp areas in the recent past.

In 2016, a report by CEFAS was commissioned to investigate whether the recent (and future) expansion of the offshore renewable energy industry on the UK continental shelf could potentially lead to increases in suspended solids, either by direct disturbance of the bed during construction and decommissioning or as a result of scouring during wind farm operations (CEFAS, 2016).

Using satellite ocean colour imagery covering the UK continental shelf area, the non-algal suspended particulate matter (SPM) concentrations in the surface waters were determined using a semi-analytical method described by Gohin (2011) for the period between 1998 and 2015. The maps of SPM were then averaged over time to provide spatial maps of monthly and annual mean SPM.

Statistical analysis of the SPM maps identified increasing trends in the annual average SPM in 5 out of 10 regions (Figure 3.3). However, the Eastern English Channel (which includes the Sussex coast) did not show a statistically significant increase for the annual average. Seasonally however, a statistically significant increase in SPM was found in the Eastern English Channel during spring time.

It should be noted that the period 1998 to 2015 is relatively short in terms of assessing climate change effects and shorter term variability in wind and waves due to other factors, such as the North Atlantic Oscillation, mean it is not possible to say for certain whether SPM along the Sussex coast is increasing. However, it is worth noting that where the CEFAS study found statistically significant trends in SPM levels, they were all related to increases in concentrations over time.

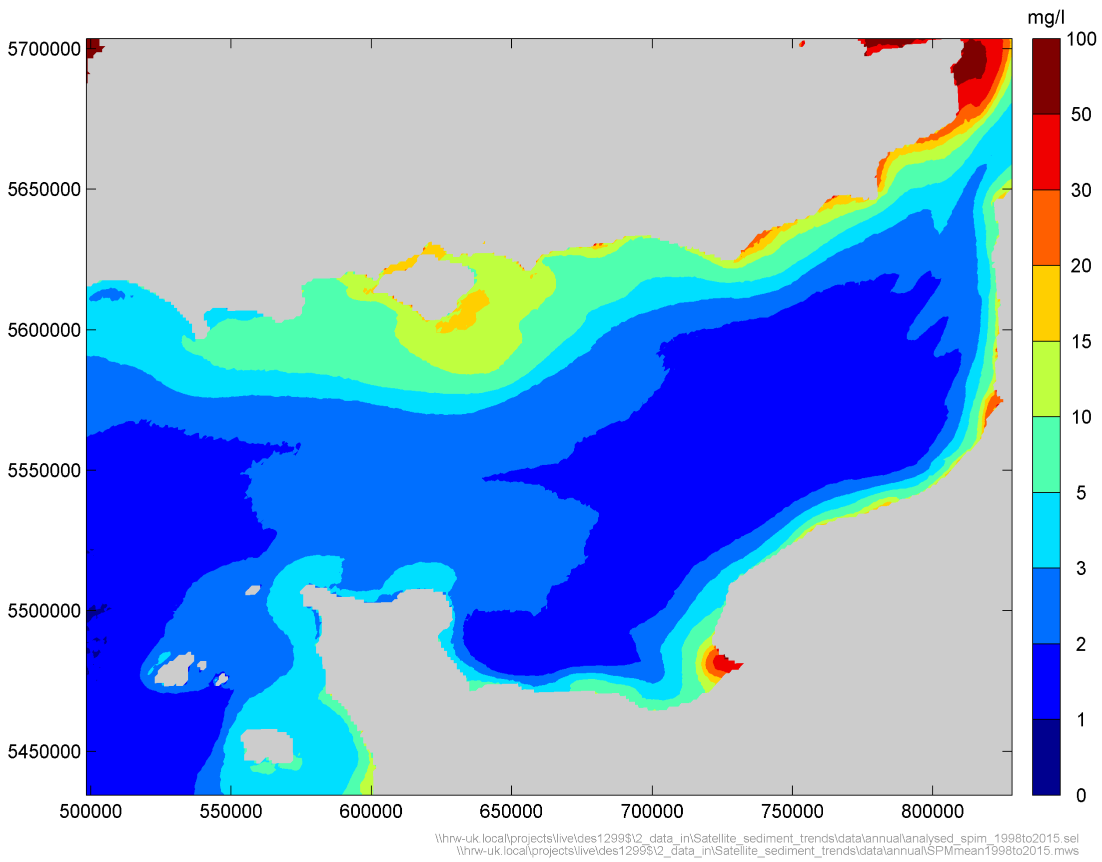

Figure 3.3: Average satellite derived sea surface Suspended Particulate Matter (SPM) for the period 1998-2015

Source: Adapted from CEFAS data (2016)

4 Factors affecting kelp

The health of kelp, like many algae that are present within the UK's coastal waters, will depend on a wide range of abiotic (physical) and biotic (biological) factors. A detailed review of factors that affect kelp is being provided by another part of the kelp restoration project. This section of this report provides a high-level commentary on factors that can affect kelp and kelp bed health, with a note provided where factors may be directly, or indirectly affected by changes to levels of suspended sediment within the water column, or by the settlement of suspended sediments.

Factors listed below are not in any order of relevance and/or importance, and are simply provided in alphabetical order.

4.1 Abiotic Factors

4.1.1 Abrasion

Kelp can be affected by abrasion. The cause of abrasion can be natural, such as scour caused by wave action and storms, or manmade, such as caused by fishing activities. Low levels of abrasion are tolerated by mature kelps, whereas younger individuals are likely to be more susceptible.

Fishing activity in kelp areas, especially those methods that employ bottom towed gear, can directly remove kelp from the substrate they are attached to.

Both natural scour, caused by waves and storms, and manmade abrasion can lead to increases in suspended sediment within the water column, which may contribute to additional impacts further from the location of the activity.

4.1.2 Currents and wave action

A degree of current movement is important for the distribution of propagules (see Biotic factors - Life Stages), as well as the supply of nutrients from land and sea sources. Currents and wave action impact kelp differently in the different life stages. Gametophytes and sporophytes are more susceptible to increased flows, unlike adults, which may have implications for the development of new kelp beds from sparsely populated groups in areas exposed to stronger wave action (M. Glascott pers comm. to S. Fanshawe). In regions where light and nutrients are sufficient, the growth of *Laminaria digitata* is found to benefit from fairly energetic flow conditions, with optimal growth rates in areas with currents speeds of between 0.5 m/s and 1.5 m/s (Kregting et al, 2016).

Kelp are generally found in areas that receive a moderate amount of wave action. However, kelp will be negatively affected by high velocity currents and/or higher wave action such as during storms, where either parts of the fronds are broken off the plant or the whole kelp is removed from the substrate. Whilst healthy beds of most UK macroalgae, including kelps, can withstand some levels of high wave exposure, more prolonged or more frequent high wave and storm intensity may cause uprooting of kelp, preventing growth to maturity. An increase in local wave height may increase local sediment mobility and scour, potentially increasing dislodgment of kelps (Birket et al., 1998).

Waves are also important for structuring of the populations. For *Laminaria hyperborea* the density, biomass, morphology and age of the kelp population is generally greater in sites exposed to wave action (Smale et al, 2016).

4.1.3 Depth

Kelp species will have a depth range which is limited by levels of light penetration. Different kelp species are able to tolerate different levels of light penetration, which is one of the factors that influence zonation in kelps around British shores. For example, *Saccharina latissima* will grow at depths between 5-20 m whereas *Laminaria digitata* can grow at depths of up to 40m. Smith et al (2021) shows that shifts in kelp population structure along depth gradients are strongly driven by light availability, although regional variability in the strength and nature of these relationships may be promoted by other factors such as temperature.

The depth at which kelps can survive can be affected by the level and nature of suspended sediment concentration that are within the water column. Greater suspended sediment concentrations and higher proportions of the finest sediment particles will reduce light penetration and hence the depth at which kelps can grow.

4.1.4 Light

The amount of light that a kelp receives will affect its ability to grow. Different kelp species have different ranges of light in which they can grow. Sustained light levels below the lower limit is likely to be detrimental. Additionally, levels of light above a certain level are also likely to cause growth impacts due to photoinhibition.

Suspended Particle Matter (SPM) concentration has a linear relationship with subsurface light attenuation (Kd) (Devlin et al., 2008). Devlin et al studied the relationship between suspended sediment (SPM) concentrations and light attenuation (K_d) in coastal waters around the UK. A number of linear relationships are shown from that study in Figure 4.1.

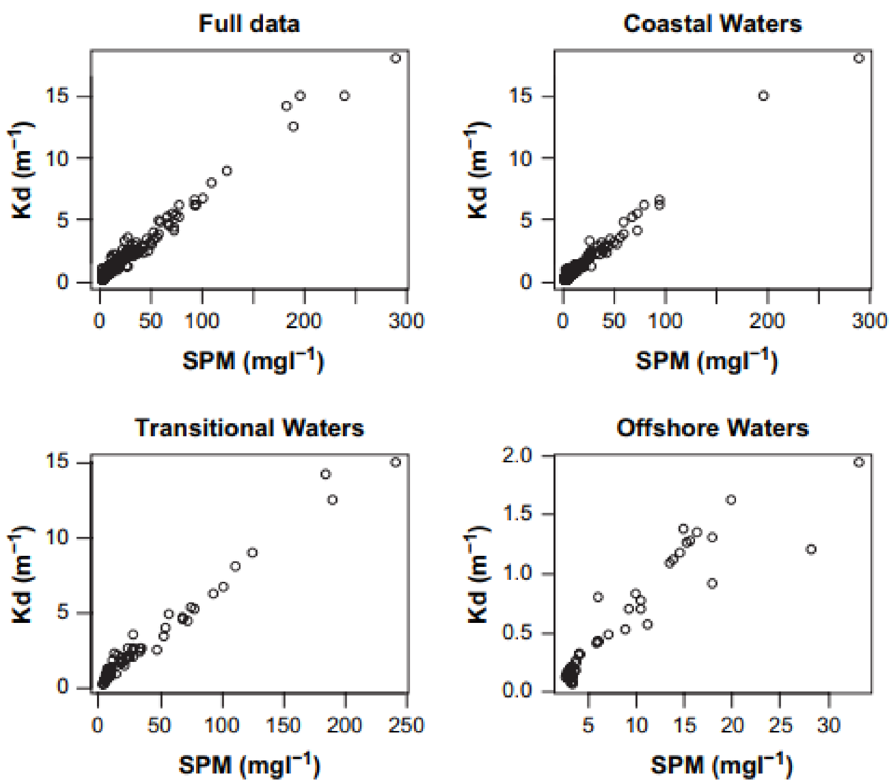

Figure 4.1: The relationship between Kd and the concentration of suspended particulate matter (SPM) for the full data set and the coastal, transitional and offshore waters based on data - collected between August 2004 and December 2005

Source: Devlin et al., 2008

Light penetration influences the maximum depth at which kelp species can grow and it has been reported that laminarians can grow at depths at which the light levels are reduced to 1 percent of incident light at the surface (Luning, 1990; Birkett et al. 1998). As such, increases in fine suspended matter will reduce the levels of light that is available for kelp to grow.

4.1.5 Nutrients

Like most plants, the availability of nutrients will affect kelp health and growth rates, particularly nitrates and phosphates. The source of nutrients can be both marine or terrestrial.

Terrestrial sources can include run-off from agricultural land. An excessive amount of nutrients can also lead to increased growth of other algal species, especially those that cause algal mats, which can grow over available substrate, inhibiting attachment and growth of kelps (Johnston & Roberts, 2009). Excessive nutrients may also lead to algal blooms, which may in turn block light from reaching kelps.

Although nutrients will not directly cause increases in suspended sediments, the process of run-off from land may also bring increases in terrestrially derived fine particulate matter, which will also reduce light levels. The potential to indirectly cause/increase algal blooms will also indirectly increase suspended particulate matter.

4.1.6 pH

Algae species will have an optimal pH level at which growth and health is best achieved. For kelp species in Sussex this is noted as a pH of 8.1 (Sussex IFCA, 2020).

There is no direct or indirect link between pH and levels of suspended sediments in the water column.

4.1.7 Salinity

Due to the near coast environments in which kelps are found, they are able to tolerate a wide range of salinity as nearshore waters are exposed to varying degrees of freshwater inputs. A range of between 20-35 ppt is suitable for most of the kelps found in Sussex (Sussex IFCA, 2020). Salinities outside of this optimal range will start to reduce growth.

There is no direct or indirect link between salinity and levels of suspended sediments in the water column in the coastal waters offshore of the Sussex coast. However It has been reported that increases in suspended sediment can have an effect on the ability to measure salinity effectively (Sun et al. 2018), as measurements in waters with greater suspended sediment may result in a lower measured salinity.

4.1.8 Smothering

Levels of suspended sediment in the water column can settle and cause degrees of smothering, caused by the build-up of sediments on either the available substrate, or over zoospores that have just settled.

Smothering by fine sediment is unlikely to cause significant damage to semi-mature and mature kelps, although species that form a mucus layer on the blade may attract and adhere sediment which could block light and weigh the blades down. Accumulation of fine sediments on rocky substrate may block the settlement of zoospores and therefore negatively impact the recruitment process (Moy & Christie, 2012), especially if the smothering event is prolonged, or during the recruitment period of a particular kelp species.

4.1.9 Substrate

Kelp species require a hard substrate on which to settle. This can be in the form of bedrock, stable boulders, pebbles and even on large gravel. Hard substate can also be found within manmade structures, such as moorings, slipways and pontoons (Stamp et al, 2022).

Increases in suspended sediment within the water column can increase levels of sedimentation (settlement) of finer material. Increases in sediment deposition over the available hard substrate may reduce the ability for kelps to attach, which may be more important during settlement of zoospores (See Abiotic factors – Smothering). In areas of high wave or tide energy such sediment deposition is likely to be transient and readily remobilised.

4.1.10 Temperature

Water temperature, such as increases in summer water temperatures and length of time at higher temperatures are potentially damaging or even fatal for kelp species adapted to cooler waters (Kerrison et al, 2015). The three species previously found in Sussex have optimum water temperatures of 15-18^{o}C. Temperatures higher than this may cause stress which will also reduce productivity and the ability to reproduce. Increased frequency of high summer temperatures and marine heatwaves associated with climate change are therefore a direct threat to kelp survival. CEFAS (2022) report that sea surface temperatures in the summer of 2022 broke records at several locations.

Temperature, in addition to waves, is cited as an important controlling factor on where kelp grow around the world (Smale et al, 2016; Copping et al, 2020). Increasing ocean temperatures as a result of climate change is therefore likely to affect the distribution of kelp.

Other than influencing water viscosity and hence settling rates there is no direct relationship between temperature and the amount of suspended sediments in the waters offshore of the Sussex coast. Temperature may directly reduce the amount of light that is available to kelps. Growth of phytoplankton can proliferate in warmer temperatures, which can in turn cause algal blooms. These blooms directly utilise some of the available light to grow, and reduce light attenuation by increasing particulate matter within the water column.

4.1.11 Water quality

Alterations to water quality will affect the health and ability of kelps to grow and reproduce. Effects to water quality can include non-point and point source pollution including sewage outfalls, storm overflows, industrial disposal, and coastal runoff. Alterations to water quality can be caused by natural processes, such as algal blooms that can alter water chemistry, although along a developed coastline are more likely due to anthropogenic activities that introduce waste, contaminants and toxins into the marine environment.

There is the potential for release of contaminants as part of the dredging process, which may affect water quality. Chemicals can be associated with marine sediments, particularly the finer, more silty sediments, especially from areas with historical industrial use. Chemicals that are bound within the sediments can be disturbed during the process of dredging. If sediments are then disposed of at sea, these contaminants can also be transported to and may disperse at the disposal site. Although not all chemicals associated with dredged material will become available, a proportion of them have the potential to alter water quality. Sediment quality is considered by the MMO when granting a licence of sea disposal of dredged material and only material with acceptable quality is permitted.

4.2 Biotic factors

4.2.1 Competition

Changes to the structure of kelp beds may happen due to competition from other kelp species. The golden kelp (*Laminaria ochroleuca*) is common in northern Europe and benefits from generally warmer sea temperatures. The golden kelp has been seen to compete with and replace native kelps in the southwest of England, which is likely due to increasing sea temperatures as a result of climate change.

Competition may also occur with non-kelp species. Increases in nutrients (see Nutrients – abiotic factors) may favour other algal species which in-turn will outcompete kelps in terms of available substrate on which to attach. This can also include invasive non-native species (INNS). *Sargassum muticum,* a now common invasive algae within British waters*,* was shown to replace and out-compete leathery, canopy-forming macroalgae such as *Saccharina latissima*(Staehr et al., 2000; Engelen et al., 2015). *Sargassum* has been reported off Selsey Bill (M. Peck, pers comm. to S. Fanshawe)

Competition for light may also be increased indirectly due to increases in nutrients (see Nutrients – abiotic factors) which may cause algal blooms to develop, leading to reduced light levels.

Suspended sediment in the water column may affect competition as it may favour other species, that are able to cope with lower light levels, that are in competition with kelps for space and resources.

4.2.2 Disease

Although information is scarce for the effect of disease in kelps, it is likely that diseases will play a role in the health of kelps and kelp beds. For example, the marine fungi *Eurychasma spp* can infect early life stages of kelps, however the effects of infection are unknown (Müller et al., 2006).

Like most organisms, stresses caused by alterations to other factors that affect kelps, such as increased temperature or decreased salinity etc, may make kelps more susceptible to diseases.

4.2.3 Life stages

Kelp zoospores, the reproductive units released from mature kelps, are thought to have a large dispersal range, however the density and the rate of successful fertilisation decreases exponentially with distance from the parental source. Replacement of lost kelp following a period of disturbance will be affected by the proximity of mature kelp beds, and the availability of viable, fertilised zoospores. Recruitment following disturbance will be influenced by the proximity of mature kelp beds producing viable zoospores to the disturbed area (Kain, 1979; Fredriksen et al., 1995).

Saccorhiza polyschides, although not classed as a true kelp, is termed as an annual and can reach maturity in 8 months, although young kelp that do not reach maturity within the first growth season can overwinter and have a life expectancy of 16 months during which time fronds can reach a length of 3-4m. Whereas *Saccharina lattisma* is a perennial kelp which can reach maturity in 15-20 months and has a life expectancy of 2-4 years (Birket et al., 1998; Fernández, 2011).

Saccorhiza polyschides sporophytes (settled, attached small kelps) appear from March-April, beyond which is a period of rapid growth. *Saccharina latissima* recruits appear in late winter and early spring beyond which is a period of rapid growth, in late summer and autumn growth rates slow and spores are released from autumn to winter (Stamp et al., 2022).

Laminaria digitata zoospores may be released all year round with peaks in July/August and November/December. Zoospores are in the plankton for approximately one day and generally settle 200-600 m from the parent plant. Settlement close to the parent plants highlights the importance of a sufficient stock of adult kelps in recolonisation, following disturbance events (Birket et al., 1998; Marlin, online).

As such, perennial kelps may be less resilient to disturbance due to the longer time taken to reach maturity than annual kelps. Disturbances, such as higher levels of suspended sediments in the water, leading to reduced light availability and potential smothering during recruitment periods, may be detrimental.

4.2.4 Predation

Kelp are predated (grazed) by several types of animal, including sea urchins, snails and small crustaceans. In parts of the world, kelp beds can be significantly reduced by urchin predation, following removal of urchin predators from the food chain.

While its less likely that such significant impacts occur within British waters, predation of the zoospores and early settlement stages (sporophytes) by grazing molluscs may be of greater significance (Veenhof et al, 2022).

4.3 Feedback mechanisms

The presence of kelp itself, once it has become established, can have marked effects on the local marine environment. From a biotic viewpoint, kelp forests provide a habitat and nurseries in which other species can grow (Teagle et al, 2017). From an abiotic (physical) viewpoint, kelp can influence the hydrodynamics in the area due to drag forces generated by the kelp fronds and stipes which act to attenuate waves and decrease currents (Morris et al, 2019). The reduction in waves and currents will promote deposition of material from suspension and lead to reductions in suspended sediment concentrations (and hence turbidity). These positive feedback mechanisms are likely to increase the resilience of kelp beds once they have become established and, conversely, make it harder for kelp to become re-established after it has diminished.

4.4 Potential Impacts for Sussex Kelp

Understanding how physical and biological factors influence the distribution of organisms and the structure of populations is a fundamental goal of ecological studies, and a prerequisite for effective management and conservation of biodiversity (Bremner 2008; Kaiser et al. 2011).

Improved understanding of how environmental factors influence the distribution and population structure of foundation species therefore contributes to management and conservation of entire ecosystems (Smith et al, 2021).

A high-level commentary on abiotic and biotic factors that may affect kelp was provided in Section 4 of this report. Interactions between only a small number of these factors can be complex. Various studies have been conducted to provide a better insight into these complex interactions. For example:

- Diehl et al (2020) looked at the interaction of salinity and temperature on the survivability of polar *Laminaria solidungula* sporophytes in laboratory tests, concluding that the combined effect of increased temperature and reduced salinity caused significantly more stress than either factor in isolation.
- Traiger (2019) looked at the effect of elevated temperature and sedimentation on grazing rates of the green sea urchin. In this experiment it was considered temperature and sedimentation may have synergistic negative effects on urchins. It concluded that this scenario may be partially beneficial to kelps, as urchins were unable to feed as effectively and some warming increased frond growth.
- Bekkby et al (2019) looked at the combined impact of depth, waves and currents on kelp abundance, finding that high abundance of kelp occurs mainly in moderately exposed and exposed areas, and that kelp abundance decreases down to a single or few kelps per m^2 in very wave sheltered areas.

There are available studies for nearly all combinations of factors that affect kelp, including some larger scale projects that look at active disturbance of kelp beds, including Norderhaug et al (2020), which show the likely effect of increasing anthropogenic disturbances, including kelp trawling and increased storm frequency caused by climate change and how it may alter ecosystem structure and function.

Some interactions, in the factors that are described in Sections 4.1 and 4.2 may work synergistically to provide a positive benefit for kelp health within a certain range, however when this range is further increased, the same simple two factor pairing may be detrimental to the health of the kelp. An example of this is the interaction of light and temperature. An increase in light and heat from a baseline may result in positive benefits for some kelp species, whereby growth and reproductive effort increases. However past a certain threshold, which differs for different species, further increases in light and temperature may have negative effects on the kelps ability to grow and on reproduction.

Due to the range of factors that may affect kelp health and the complex nature of the interactions between each factor, it is difficult to determine the route cause for losses and lack of recovery in kelp beds, as it is likely the combined effect of a number of factors, especially those that occur during an important life stage, either before reaching maturity, or during development and settlement of sporophytes.

This report has highlighted the potential increases in suspended sediment concentrations in spring, which is an important time for sporophyte settlement and early growth for kelps found in Sussex. However it is not clear whether the increase observed in the dataset would be enough to have an impact on kelp growth.

5 Sources of suspended sediment to the Sussex coastline

5.1 Marine sediment sources

5.1.1 Suspended sediment flux in the English Channel

In the English Channel, the net residual flow towards the east (see Section 3) leads to the assumption that a proportion of the fine sediment in the region must be sourced from the Atlantic. Velegrakis et al (1999) used in situ measurements of the SPM concentration from samples taken at the surface, mid-depth and near-bed to estimate the annual flux of suspended sediment across a transect between the Isle of Wight and the Cotentin (or Cherbourg) Peninsula (Figure 5.1) in Normandy, France. They concluded that the flux of SPM was between 2 and 71 million (average 20 million) tonnes/year which is similar in magnitude to earlier estimates of the SPM flux eastwards through the Dover Straits (2 to 44 million tonnes/year).

Whilst the flux of suspended sediment from the west through the English Channel is large, it is thought to be balanced by the flux out through the Dover Straits.

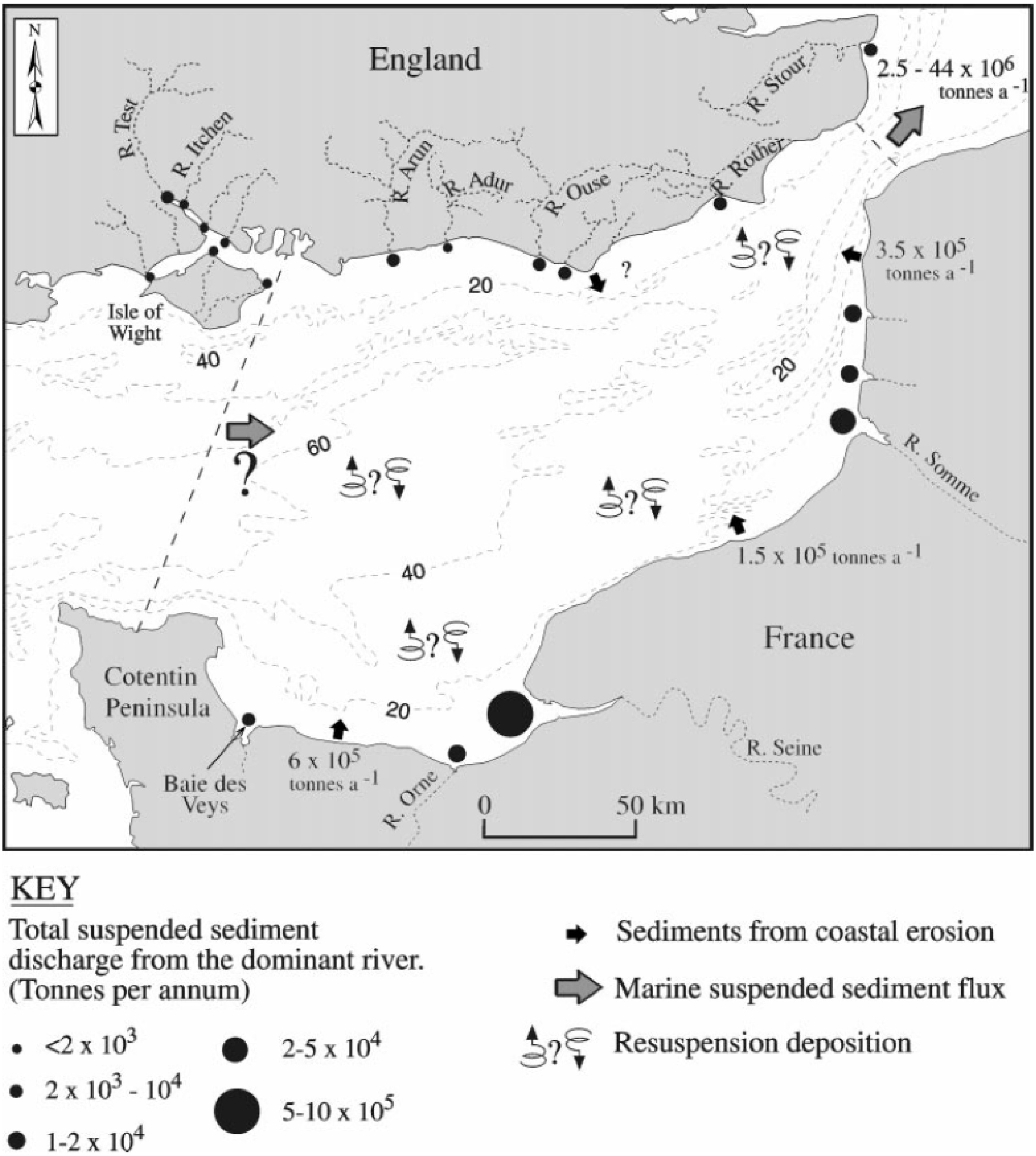

Figure 5.1: Schematic of sediment inputs the English Channel and output via Dover

Source: Velegrakis et al (1999)

5.1.2 Coastal erosion between Chichester Harbour and Brighton Marina

The coastline between Chichester Harbour and Brighton consists of raised shingle beaches overlying sandstone and clays. Low cliffs form the headland at Selsey Bill and the backshore areas are low lying. Historically this coastline has been retreating, with shingle barriers rolling back over the coastal plain as sea-levels rise. The coast is now largely prevented from retreat by extensive defences, comprising of seawalls and groynes and is therefore steepening.

Undefended stretches of coastline occur at Medmerry and around Pagham Harbour. At Medmerry, historical sediment yields were estimated to be up to 10,000 m^3/year from coastal erosion, supplying a mixture of gravel, sand and silt. As defences increased this volume has reduced and the current input is negligible (SCOPAC, 2012). Selsey Bill also has a history of retreat of the low cliffs and shoreface, however the construction of hard defences at Selsey Bill in the 1960s has halted coastal retreat and therefore sediment supply.

Posford Duvivier and the British Geological Survey (BGS) (1999, in SCOPAC 2012) have calculated that vertical wave erosion of the shoreface zone between Bognor and Rottingdean yields between 1,900 and 4,000 m^3 per year of coarse material and 2,000 to 7,000 m^3 per year of fine sediment (3,400 to 12,000 tonnes/year). Most of the fine sediment is presumed to be lost to the coastal transport system as suspended load and therefore adds to the coastal turbidity.

With the exception of intertidal areas inside the harbours, the shoreline is shown to be relatively stable. However in some locations this is only possible due to sediment recharge and recycling.

Medmerry realignment

In November 2013 the shingle barrier at Medmerry was breached allowing a 340 ha area to be tidally inundated. The aim was to stop the need for sediment recycling to maintain the barrier and to provide 184 ha of new intertidal habitat. This was considered to be compensatory habitat for losses predicted in the Solent over the next 20 years (Channel Coastal Observatory, 2018). Channel Coastal Observatory (2018) monitoring of the breach shows that the remaining shingle barrier width decreased rapidly during the 2013/2014 winter storms that followed the initial breach. The barrier beaches were continuing to retreat in the 2018 survey. The retreat of the barrier beach has led to the exposure of the former land surface, including historical groynes and sea defences, on the shoreface. The exposed land is resistant, compacted mud that was previously beneath the barrier and is believed to be more resistant to erosion (Channel Coastal Observatory, 2018).

Channel Coastal Observatory (2018) report a net loss of sediment (mostly shingle/gravel) from the Medmerry breach and adjacent barrier beach between the rock armoured sections to the east and west. This totalled 318,500 m^3 between 2013 and 2018. From 2016 onwards, the Channel Coastal Observatory (2018) report highlights erosion of the compacted mud that has been exposed by the movement of the barrier.

It is estimated from arial photography that 50,000 m^2 of compacted mud has been uncovered by the retreat of the shingle barrier. If this eroded by 10 cm each year, this could yield 5,000 m^3/year of fine sediment (approximately 5,000 tonnes/year). Dale (2018) studied the realignment site and concluded there was net import of sediment, with sediment only exported from the site during periods of high freshwater input. Littoral drift is north westward from Medmerry towards Chichester Harbour, however the residual tidal circulation may carry eroded mud in the opposite direction. Long-term, the Medmerry realignment site might be expected to act as a sediment sink. However, it appears that adjustments in hydrodynamic and sediment regime following the breach are ongoing.

5.1.3 Erosion of chalk cliffs and shore platform (Brighton Marina to Beachy Head)

English coast

From the Black Rocks at Brighton, eastward to Beachy Head, the Sussex coastline is characterised by chalk cliffs, a wave cut shore platform, and varying amounts of beach sediment. These cliffs are eroding, releasing chalk and flints into the marine environment (Figure 5.2).

The cliffs from Brighton to Rottingdean, Saltdean and Peacehaven are protected from wave attack by concrete seawalls. In these sections, cliff falls of relatively small volumes still occur, caused by weathering processes such as freeze/thaw and wetting and drying. Cliff falls from the protected coast were quantified by examining the amount of cliff material deposited on the seawall at Peacehaven over the period of a year. Although some material may be lost due to wave action, the volumes deposited were small and suggested horizontal erosion of the cliff face equivalent to fractions of a mm per year (Moses & Robinson, 2011).

Where the chalk cliffs are unprotected there is ongoing erosion. Mean annual retreat rates between 0.11 m/year and 0.57 m/year have been reported between 1873 and 1999 (Dornbusch et al., 2006). Much of this retreat occurs as frequent, low volume falls; however large cliff failures also occur. In one cliff collapse near Beachy Head during 1999, an estimated 150,000 m^3 of chalk was deposited, extending 130 m across the shore platform (Shadrick et al., 2022). In 2022 another large cliff collapse removed the footpath to Belle Tout lighthouse.

Moses & Robinson (2011) report that time scales for the removal of cliff fall debris range from days to decades, depending on the volume of the fall and the size of particles within the debris. Large falls typically take longer to be removed from the beach by wave action than small falls.

Figure 5.2: Aerial photograph imagery (3D rendered) of cliff and chalk platform erosion looking west from Beachy Head (August 2015)

Source: Google Earth imagery

Dornbusch et al., (2006) used historical maps to calculate that on average 170,000 m^3/year of chalk and flint fell from the cliffs between Saltdean and Beachy Head over a 124 year period up to 1999. Between 1 and 5 % of this volume was flint, the remainder chalk. Platform down-wearing was reported to be up to 7 mm/year, and contributed approximately 10% of the total flint volume released from the cliff and platform. Based on this, it is inferred that the chalk released by platform erosion is in the order of 17,000 m^3/year.

Based on map surveys and aerial photography, Dornbusch et al., (2008) suggest that the average rate of cliff retreat has reduced from 0.37 m/year between 1873 and 1925, to 0.27 m/year between 1973 and 2001. They conclude that this reduction in retreat rate resulted from a decrease in beach volume over the same period – smaller beaches contribute to cliff and platform erosion due to abrasion when shingle is resuspended by waves, whilst large beaches can protect cliffs from wave attack by absorbing wave energy before it reaches the cliff foot.

Assuming a dry density for the chalk cliffs of 1,700 kg/m^3 (Mortimore et al, 2004) then 170,000 m^3 equates to 289,000 tonnes of chalk per year being released along the coast from Saltdean to Beachy Head.

French coast

To understand the total sediment budget for the Sussex coast, it is also necessary to consider the amount of sediment entering the Eastern English Channel from cliff erosion on the French coast. Velegrakis et al (1999), cite various previous studies that estimate the total rate of cliff erosion to be 1.1 million tonnes/year (Clique, 1986; Lafite, 1990; Dupont, 1996), which is attributed by Dupont et al., 1993 to be largely due to erosion of the chalk cliffs.

Whilst sediment inputs at the French coast are important for the wider English Channel sediment budget, they are unlikely to affect the local sediment budget around the Sussex coastline.

5.1.4 Beach recharge and recycling schemes

To compensate for the loss of beach material caused by longshore and cross-shore sediment transport, sediment recycling and renourishment are undertaken at various locations along the coast.

1. Sediment recycling – sediment is taken from one area of the beach, usually the west side of a groyne or harbour wall, where it has accumulated due to littoral drift, and is then relocated to a place where beach volumes are lower. No new sediment is added to the coastal system through sediment recycling. There may be some local increase in turbidity caused by the physical process of moving sediment around, but this will be localised and temporary.
2. Beach renourishment or recharge – sediment is placed on the eroding section of beach to increase beach volume and width. The sediment used may be sourced from offshore sediment deposits by dredging and placement by pipeline discharge or extracted from inland gravel pits and placed by truck. For beach nourishment there is therefore an input of fresh sediment to the coastal system.

For the Sussex coastline, beach recharge and recycling schemes are summarised in SCOPAC (2012).

Beach recharge schemes do introduce new sediment to the coastal system and may contain a fine component. However, screening and cleaning of the source material means this is likely to be minimal. For example, there is a licence for recharge at Selsey of 6,000 m^3/year of pebbles from an inland source. If 1-5% of this were fine sediment, that would introduce 60-300 m^3 of fine sediment into the coastal zone each year. The fines content of beach material sourced from offshore aggregate license areas is likely to be less than this because of the nature of the offshore deposits (typically with in-situ fines content of less than 1%) and the dredging process itself that tends to wash a significant proportion of any fines away as a dredge plume during the extraction process.

Between 1982 and 2012, beach recharges totalling an estimated 2,800,000 m^3, were conducted along the Sussex coastline. Whilst this is an estimate (some may have been recycling activities rather than placement of new material) this gives an average of 94,000 m^3/year of new sediment. The majority of this will have been pebbles, shingle or coarse sand. It is possible some fine sand or silt was also added to the beaches. Assuming this was between 1 and 5 %, then the average annual addition of fine sediment could be between 940 m^3/year and 4,700 m^3/year (about 1,000 to 8,000 tonnes/ assuming a density of 1000 to 1700 kg/m^3).

5.1.5 Aggregate dredging

There are several licensed offshore aggregate dredging sites along the south coast (Figure 5.4). The closest is Area 453, approximately 8 km offshore from Littlehampton at a water depth of 12 to 15 m. Other sites are further offshore and tend to be in water depths of at least 20 m. The majority of the sediment targeted is sands and gravels for the construction industry, with a small proportion being used for beach recharge schemes (The Crown Estate, 2018). In the south coast region, there has been a decrease in the area used for aggregate extraction between 1998 and 2017. Since 2017, the area dredged in the south coast region has remained approximately the same, at about 15 km^2 (The Crown Estate, 2021), and around 10% of the total area that is licensed for dredging. In 2021 the area licensed for aggregate dredging increased by 10 km^2.

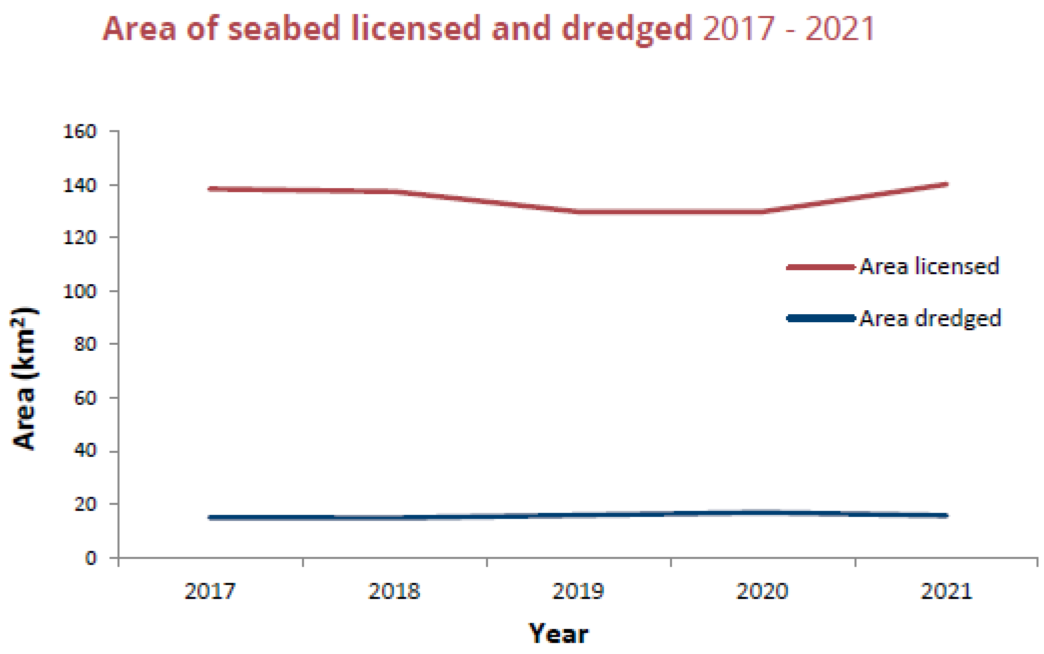

Figure 5.3: The area of seabed licensed for aggregate dredging and actually dredged over the 5 years to 2021

Source: The Crown Estate (2021)

The aggregate dredging tonnage for the south coast region are shown in Figure 5.5. The amount varies between years, but is typically around 4 million tonnes per year of sand and gravel. Assuming 1% of the total dredged is fine sediment (Section 5.1.3) aggregate dredging could release 40,000 – 50,000 tonnes/year of fine sediment into the water column. This release will contribute to the overall sediment budget of the English Channel, but is unlikely to have a significant affect in the nearshore zones where the kelp beds are located.

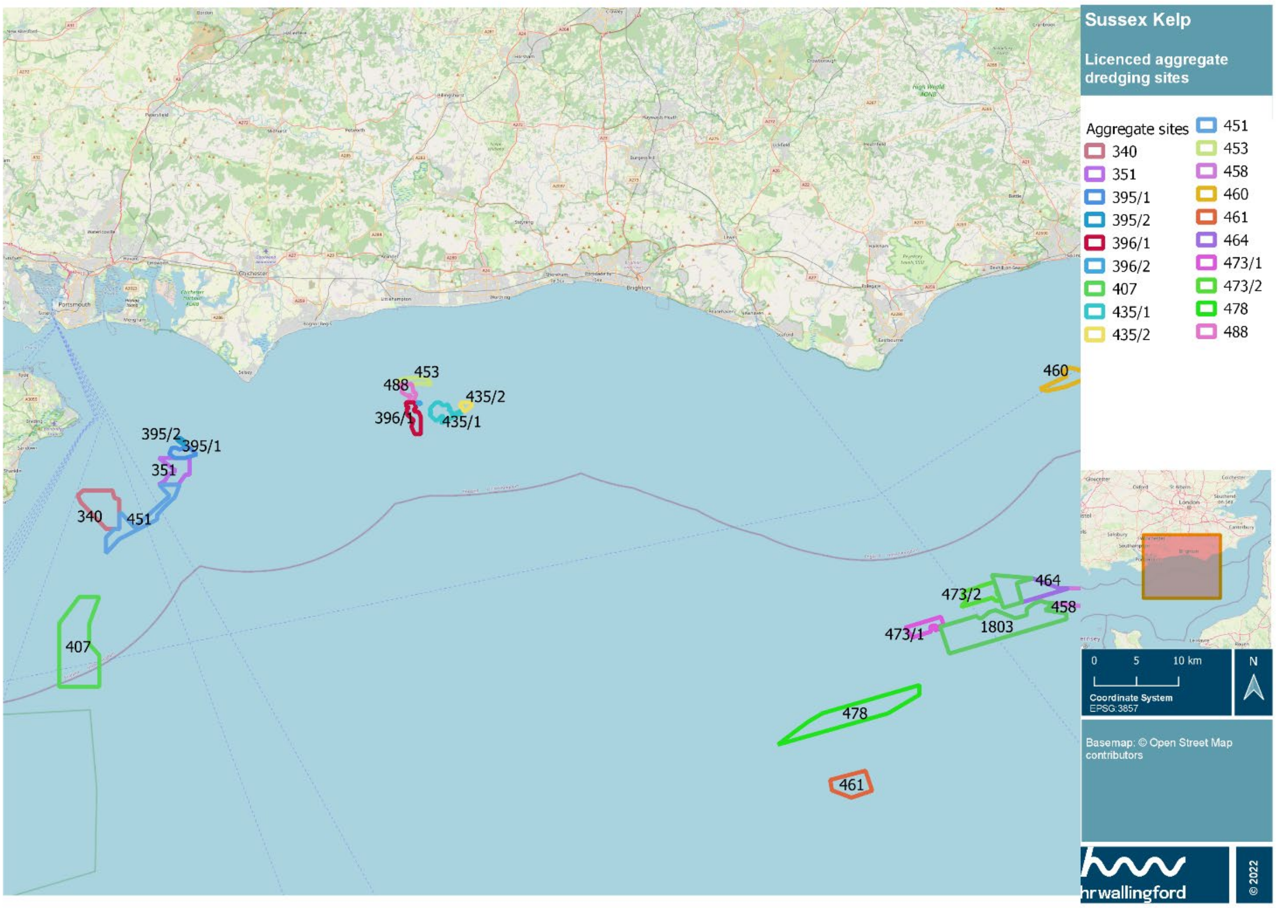

Figure 5.4: Map of licensed offshore aggregate dredge areas around Sussex

Source: The Crown Estate

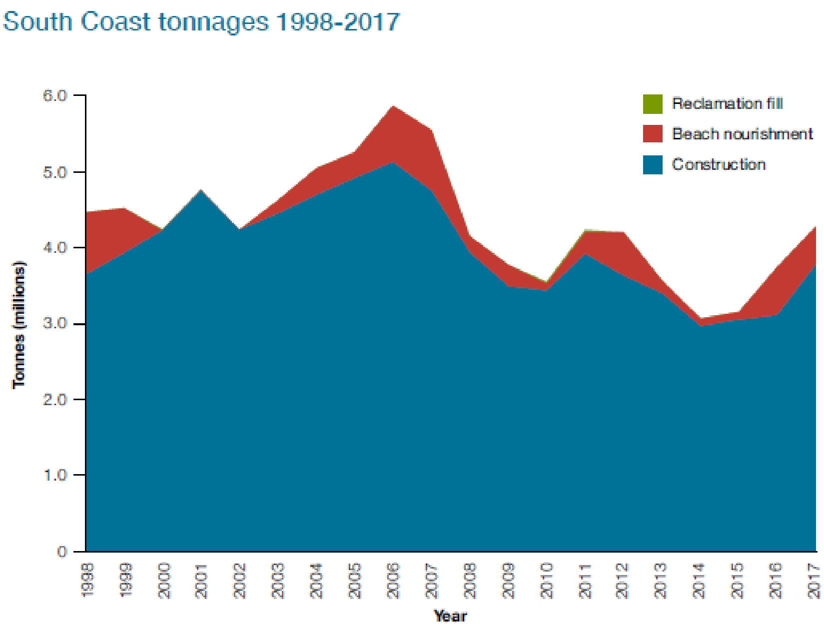

Figure 5.5: Aggregate dredging in the south coast region between 1998 and 2017

Source: The Crown Estate (2018)

Figure 5.6 shows the dredging intensity within the licensed dredge areas during 2021. The majority of the licensed areas are un-dredged. Limited areas had high intensity dredging in 2021.

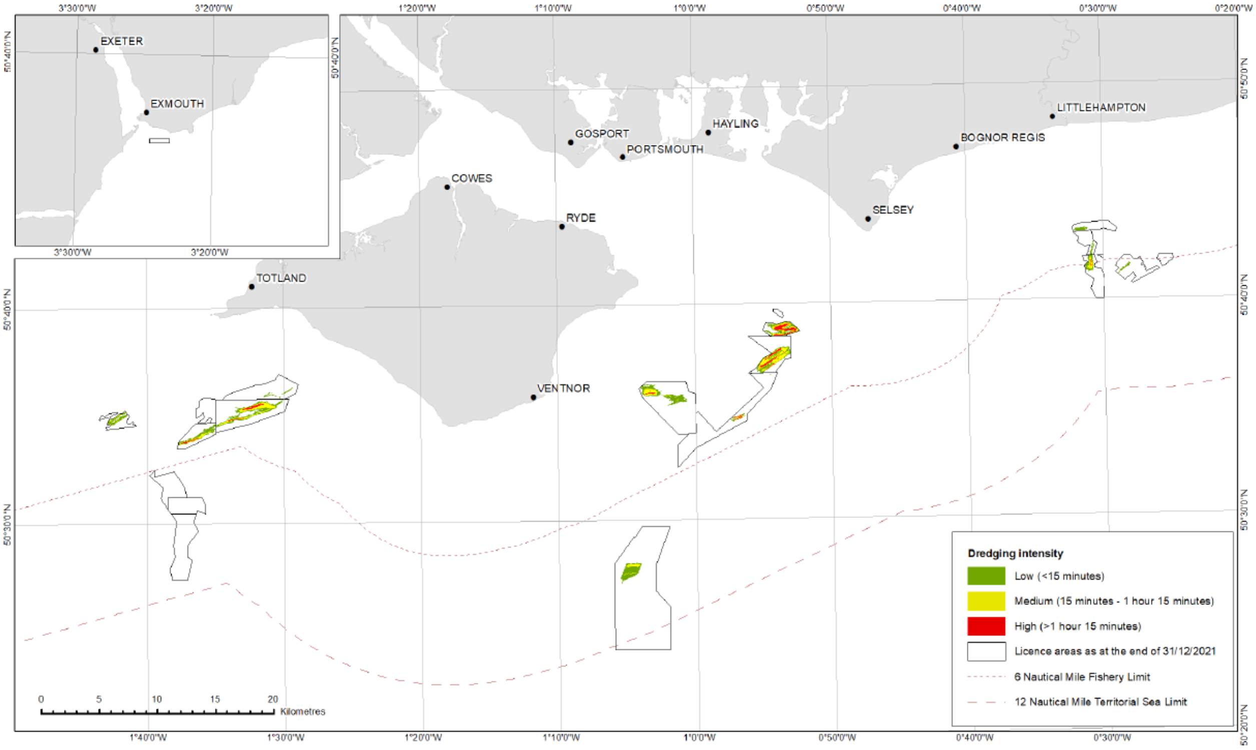

Figure 5.6: Dredging intensity at south coast dredging areas in 2021

Source: The Crown Estate (2021)

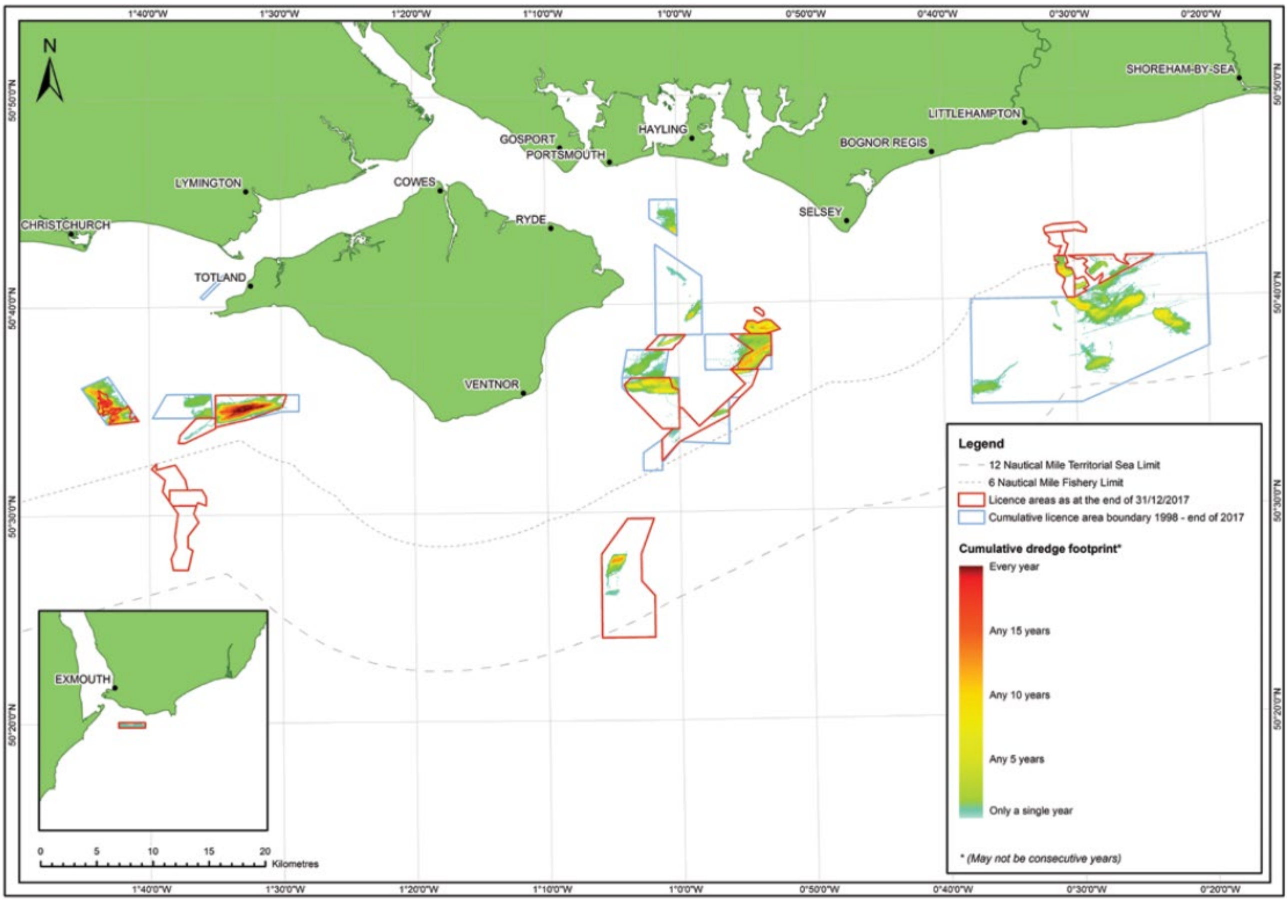

Figure 5.7: 20 year dredging effort

Source: The Crown Estate 2018

Spearman (2015) reviewed several studies recording the extent of suspended sediment plumes and changes to bed sediments and benthic species relating to aggregate dredging at sites around the UK. The size of the impact area varied depending on the size of the dredger, the degree of sediment screening and the prevailing currents at the site. In the worst case, the increase in suspended sediment caused by the aggregate dredging could be detected up to 3 km from the dredging activity. Typically however, plumes were distinguished from background concentrations over much smaller areas (e.g. up to 600 m from the release point) and plumes observed over larger distances related to higher current speeds. For two dredgers operating at Owers Bank (offshore from Littlehampton) increases in suspended sediment were observed up to 300 to 500 m from the release point.

Potential changes in bed substrate were usually limited to within a few hundred metres of the dredge location, but could extend further where screening was more extensive, there was strong net sediment transport potential away from the site, and when background sand transport was low.

In a previous HR Wallingford plume dispersal study for marine aggregates sites along the Sussex coast (HR Wallingford 2013) it was predicted that there would be no permanent deposition of fine sediment caused by dredging with typical dredgers for the region. Some temporary deposition may occur on neap tides. For sand transported as bedload, no significant changes in sand content were predicted outside of 600 m from the dredging.

HR Wallingford (2012) undertook a high-level plume study looking at potential plumes from current and proposed licensed dredging sites as part of a Marine Aggregates Regional Environmental Assessment (MAREA) for the South Coast Dredging Association (SCDA). HR Wallingford concluded that:

"*the predicted increases in suspended sediment concentration that will be experienced outside each of the proposed Licence Areas will be less than 20 mg/l above background except when dredging occurs close to the boundary of a Licence Area. Even when this does occur suspended sediment concentrations more than 50 mg/l above background are only likely to be experienced within 200 m of the Licence Area boundary and concentrations more than 20 mg/l above background are only likely to be experienced within 1.5 km of the Licence Area boundary. These concentration increases will be experienced only while dredging occurs and only in the streamline of the dredger. As a result, for the vast majority of the time over the licensing period at any given point in the study region, there will be no increases in suspended sediment concentration above background. Even when concentration increases, which can be characterised as a few tens of mg/l above background, occur, these concentrations are less than the increases which occur naturally as a result of variation in tidal conditions and waves*."

Changes to sediment from aggregate dredging, both in suspension and on the seabed, are generally localised and/or temporary and are unlikely to be affecting kelp recovery outside of licensed dredging areas.

5.1.6 Maintenance dredging at local harbours

There are several licensed dredge disposal sites within or close to the study area (Figure 5.8). Material from capital and maintenance dredging may be disposed of at these sites. Historically, sewage sludge was also disposed of at Nab Tower (WI060) (last reported in 1998). The smaller sites, WI010 (Newhaven), WI020 (Brighton/Rottingdean) and WI031 (Shoreham) are disposal sites for harbours located nearby. The Nab Tower site (WI060) is a large disposal site taking material from several different capital and maintenance dredging schemes.

Dredge disposal volumes are reported each year and appear in annual OSPAR reports (OSPAR Commission, 1999 to 2015). These are usually reported as dry weight in tonnes.

Maintenance dredging of the harbours and marinas located along the Sussex coast (including areas to the east of the study area) moves around 225,000 dry tonnes/year of recently deposited fine sediment from the temporary sinks to the nearshore disposal sites.

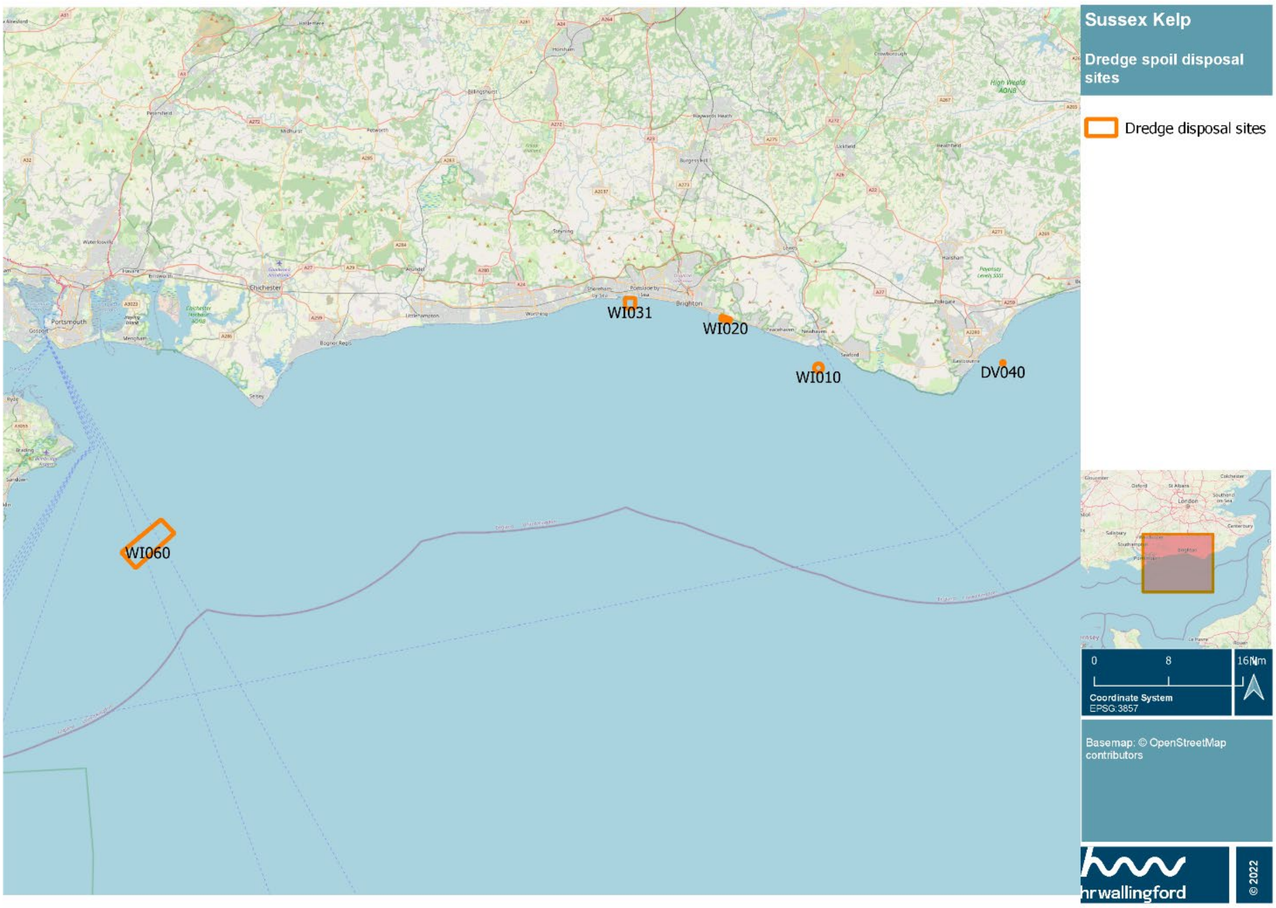

Figure 5.8: Map showing dredge disposal sites within or adjacent to the study area

Source: CEFAS - Contains public sector information licensed under the Open Government Licence v3.0

An annual timeseries of the amount of sediment disposed of at each site is shown in Figure 5.9. The disposal at each site varies considerably through time. There is a slight increasing trend for disposal, driven largely by relatively high disposal at WI010 (Newhaven) between 2007 and 2014. All of the nearshore disposal sites had a peak in disposal volumes in 2014, probably reflecting the higher sedimentation following the large storms in the 2013-2014 winter.

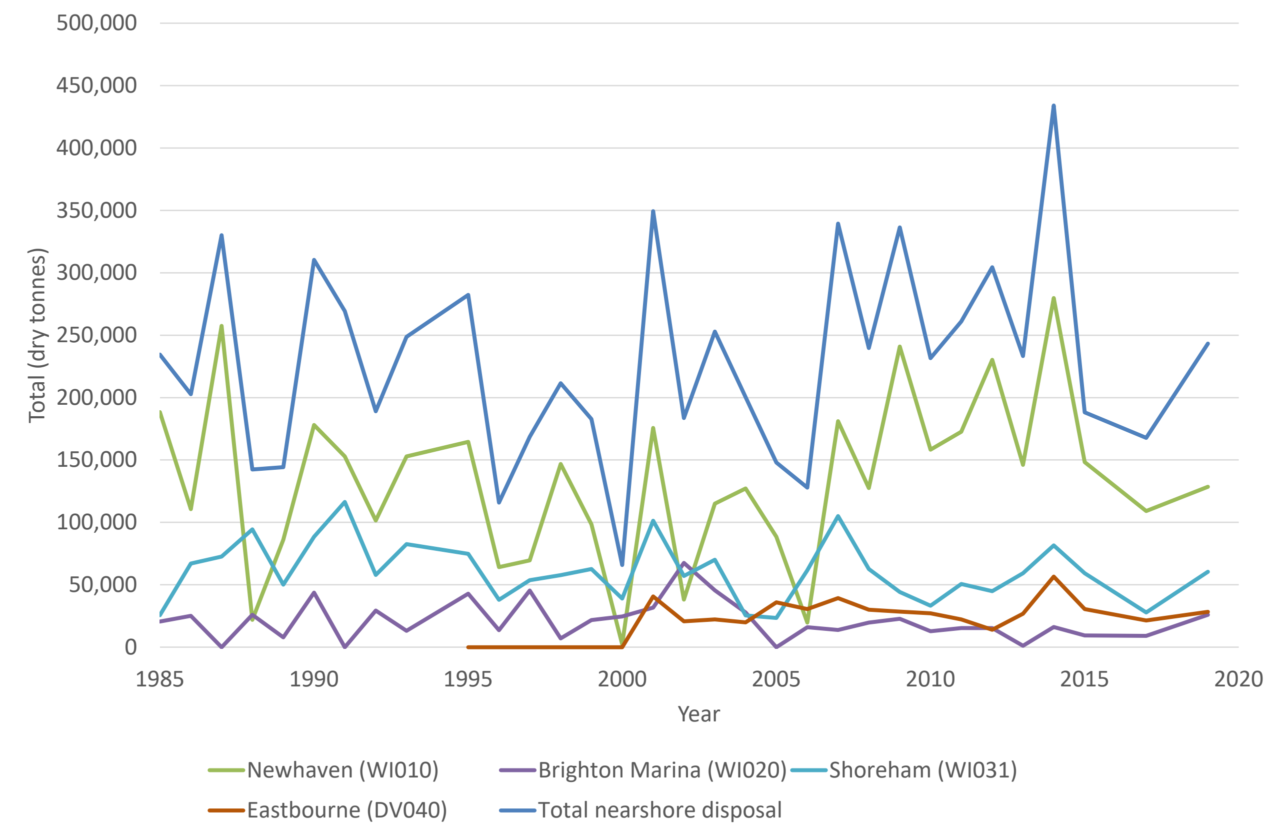

Figure 5.9: Time series of disposal at sites along the Sussex coastline

Source: OSPAR disposal records

Eastbourne (DV040)

Although located to the east of the main kelp areas, it is possible that sediment placed at DV040 could be transported westward, into the potential kelp zone if there were strong easterly winds, but generally the sediment from this disposal site is likely to be carried eastwards. Dredging of Sovereign Harbour and disposal at DV040 began in 2000. Sovereign Harbour (Eastbourne) suffers from relatively high rates of sedimentation. The latest dredge disposal licence allows for the deposition of sand and silt at DV040. Monitoring of benthic sediments and species is carried out as part of the licence conditions.

Newhaven (WI010)

Newhaven Port has a license to dredge the harbour to maintain navigable depths and to dispose of the material arising at disposal site WI010. WI010 is located approximately 2 km offshore from Newhaven with depths of 12 to 15 m below Chart Datum (CD). Dredging at Newhaven Port has been ongoing for decades.

In 2012 and 2018 Royal Haskoning carried out an assessment of the likely impacts of increased disposal of sediment at WI010 on Water Framework Directive objectives as part of a licence application. Increasing volumes of dredging (and therefore disposal) are noted between 2003 and 2010, particularly highlighting the high level of disposal in 2009, which was due to a storm event. Royal Haskoning (2012) suggested that material from the disposal site is transported back into Newhaven Harbour over time, and especially under storm conditions. It was concluded that the ongoing dredging and disposal at Newhaven Port would not be detrimental to the WFD 2015 objectives.

Royal Haskoning (2018) reported the presence of kelp in the lee of the west breakwater. Plume modelling for dredging activities suggested that the kelp should not be impacted because the sediment was carried away from, rather than towards the kelp beds identified.

Rottingdean (WI020)

Brighton Marina opened in 1978. The disposal site at Rottingdean (WI020) is used for material dredged from Brighton Marina and approaches. Dredging is presently undertaken by both back hoe dredger discharging into a split barge and by a suction dredger discharging directly to the disposal site via an underwater pipe (MMO, 2014).

The sea user survey results (Sussex Kelp Restoration Project (2022) show that dredging and disposal at Brighton Marina is perceived as a concern by sea users. A number of respondents mentioned silt in rock pools and visible plumes relating to disposal at Rottingdean. The disposal site is 200-700 m offshore and therefore visible from the beach and cliff top. There have also been reports of spills from the pipeline disposing of silt from the suction dredger (The Argus, 2021).

The Water Framework Directive Compliance Assessment (Jan Brooke Environmental Consultant Ltd, 2014) submitted with the licence application suggests that the disposal site is dispersive in nature, with no significant build-up of sediment seen in post-disposal surveys for the preceding years.

Ecological monitoring of the disposal site suggested changes to mussel beds in the disposal zone were in line with those at the control site (Ocean Ecology, 2020) and therefore unlikely to be impacted by dredge disposal. No changes in species richness or composition of chalk habitat were observed through time or in comparison with the control site. In addition no significant changes in the extent of chalk habitat and sediment habitats were found. Small variations in the extent of chalk habitat may be caused by natural changes in the distribution of the overlying sediment (Ocean Ecology, 2020).

Shoreham (WI031)

The disposal licence for Shoreham Port allows for silt and sand dredged from the Port to be disposed of at WI031 (MMO, 2019). The disposal site is approximately 700 m east of the harbour entrance and 200 m to 1300 m offshore. However the draft of the vessel used for disposal means that the shallowest, nearshore parts cannot be used (Shoreham Port, 2014). Shoreham Port (2014) suggest that 85% of the maintenance dredging requirement comes from longshore transport of sand being trapped by the harbour. They estimate that 50,000 m^3 per year is trapped, representing 25% of the fine longshore transport. They suggest that disposing of this sediment elsewhere (e.g. beneficial use) would be detrimental to the downdrift shoreline because it would effectively remove 50,000 m^3 per year of sediment that would result in seabed lowering to the east.

Discussion of nearshore dredge spoil disposal from maintenance dredging

Maintenance dredging at the harbours and marinas in the study area largely reflects the amount of fine sediment being transported in the nearshore zone by natural processes. The estuaries and harbours make effective sediment traps. Fine sediment is transported into the harbours and marinas by tidal exchange and settles where currents and wave agitation are lower. Maintenance dredging recycles sediment trapped in the harbours and marinas back into the nearshore zone when the sediment is placed at the local disposal sites, but does not add new sediment to the study area.

Whilst maintenance dredging does not cause sediment to be added to the system, it may cause higher concentrations and deposition locally for short periods because dredge disposal typically occurs as discrete events, during dredging campaigns, rather than the more continuous process of natural sediment transport.

Disposal of dredged material is licensed by the MMO. The tonnages that can be disposed of are set in each individual license.

Disposal of dredged material was identified as a sediment source by approximately half of the respondents to the Sea User Survey (Sussex Kelp Restoration Project, 2022), with about 20% selecting it as the greatest source.

5.1.7 Nab Tower Disposal Site (WI060)

The Nab Tower disposal site is further offshore and includes both maintenance and capital dredging from sites around Southampton Water, Portsmouth, Langstone and Chichester Harbours and the Isle of Wight. In some years (but not all) capital dredging is recorded separately, as detailed in Table 5.1 and Figure 5.10. In 1997 and 2014 sediment from large capital dredge campaigns was deposited at Nab Tower, these were an order of magnitude larger than dredging disposal in more typical years. Capital dredging can be considered as introducing "new" sediment to the marine environment. The annual average maintenance dredging was 359,000 dry tonnes/year between 1985 and 2019. Capital dredging averaged 370,000 dry tonnes/year averaged over the same period. It is noted that, whilst capital dredging can introduce large volumes of new sediment, the disposal from capital dredging is likely to be less erodible than that from maintenance dredging (CEFAS, 2021).

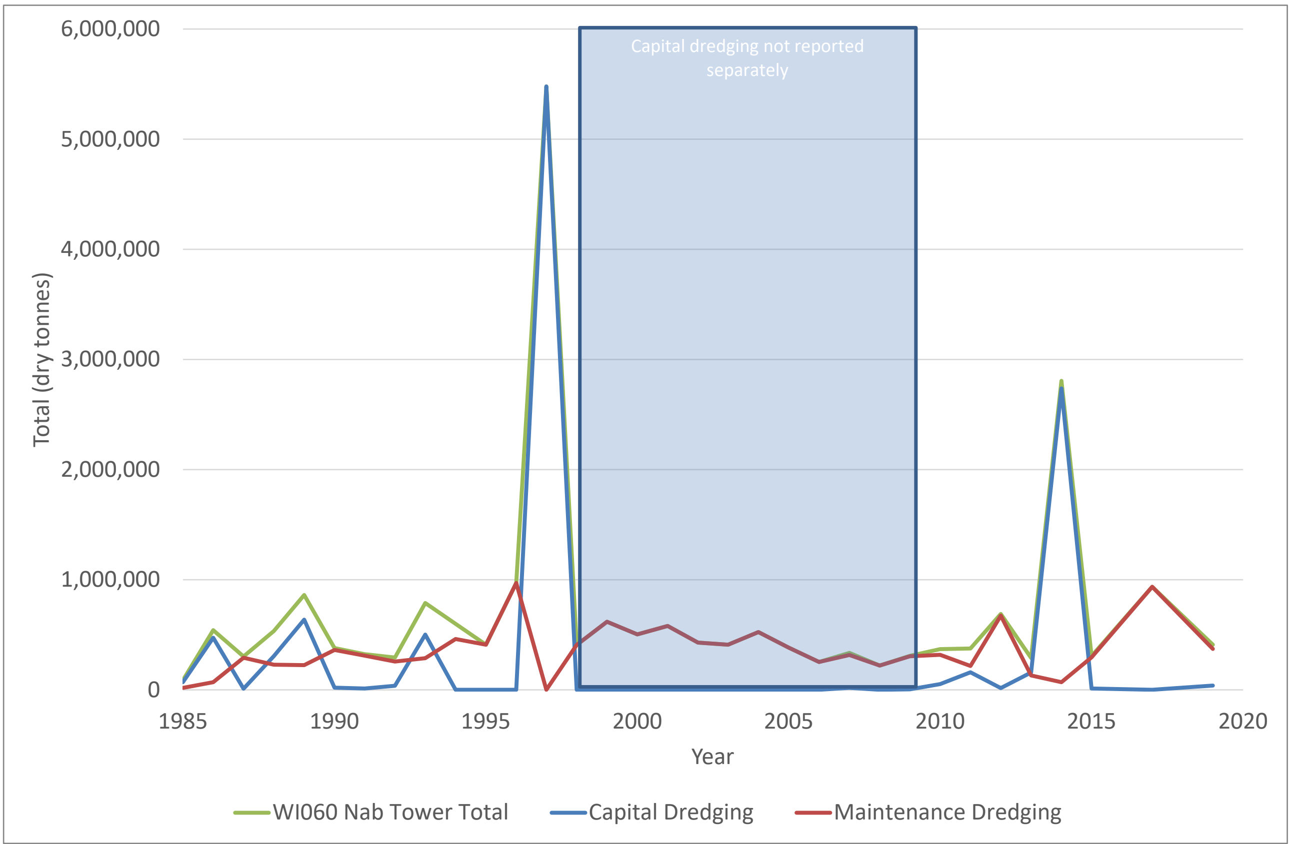

Figure 5.10: Time series of disposal at Nab Tower (WI060)

Source: OSPAR disposal records

Table 5.1: Capital dredge sediment disposed of at Nab Tower

Year	Source	Mass (dry tonnes)
1985	Portsmouth Harbour	68,529
1986	Chichester Harbour, Langstone Harbour, Portsmouth Harbour, River Test	472,830
1987	Chichester Harbour, IoW	10,770
1988	Portsmouth Harbour, IoW, Southampton Water, Solent	306,400
1989	Portsmouth Harbour, Solent, IOW, Hamble River	637,993
1990	IOW, Portsmouth Harbour	18,832
1991	Portsmouth Harbour, Solent, Gosport	12,192

Year	Source	Mass (dry tonnes)
1992	Portsmouth Harbour, Gosport	36,596
1993	Portsmouth Harbour, Gosport	501,376
1997	Southampton Water/Isle of Wight/Portsmouth Harbour	5,478,246
2007	Southampton Water/Isle of Wight/Portsmouth Harbour	18,362
2008	-	0
2009	Southampton Water/Isle of Wight/Portsmouth Harbour	3,952
2010	Southampton Water/Isle of Wight/Portsmouth Harbour	52,412
2011	Southampton Water/Portsmouth Harbour	158,249
2012	Southampton Water/Isle of Wight/Portsmouth Harbour/Langstone Harbour/Medina	15,836
2013	Medina/Southampton Water/Portsmouth	157,598
2014	Medina/Southampton Water/Portsmouth	2,737,438
2015	Medina/Poole/Southampton Water/Portsmouth/Yare	11,356
2017	-	0
2019	Not specified	38,316

CEFAS (2021) undertook hydrodynamic and sediment modelling to assess the fate of sediments disposed of at the Nab Tower disposal site (WI060) over 30 days, assuming a high rate of disposal (200,000 m^3 total). Their modelling results showed that coarse sand (>500 µm) would remain within the disposal site. Fine sand fractions were initially deposited, but resuspended during peak spring tides, remaining in depressions within the site, or slightly to the east of it. Very fine sand was initially deposited to the southwest and northeast, being carried in this direction by tides, but tended to become resuspended by tidal currents and eventually left the model domain (CEFAS, 2021). Silt and cohesive sediment was rapidly resuspended (within a few minutes of disposal) and spread through the model domain, with suspended concentrations predicted to be low away from the initial release.

The CEFAS (2021) report did not focus on the potential for long term build-up of suspended sediment concentrations of fine sediment in the area associated with the complex residual currents. No plots of the suspended plumes were presented and the model focused mainly on bed deposition at the end of each of the modelled scenarios.

Disposal of material from capital dredging is an input of new sediment into the coastal system. CEFAS 2021 suggests that sediment deposition is likely to be local to the Nab Tower disposal site but fine sediment would disperse away from the site. Guillou et al (2015) and Menesguen & Gohin (2006) both use a combination of satellite derived SPM and numerical modelling techniques to demonstrate that tidal residual circulation patterns largely explain spatial patterns of SPM in the English Channel. In particular, high concentrations of SPM tend to occur to the east and south of the Isle of Wight due to a recirculation of the generally eastward residual that exists further offshore in the Channel.

It is feasible that disposal of dredged material could potentially build up over time in the area around Nab Tower, particularly during periods of low waves. When wind and associated waves increase, and depending on the currents, the higher concentrations could feasibly be transported towards the Sussex coast kelp areas. However further modelling studies would be required to examine this possibility in detail.

5.1.8 Construction in the coastal environment

Construction in the marine environment can include marina development, laying of cables and pipelines on the seabed, and wind farm construction amongst other developments. There is the potential for marine construction to increase turbidity due to bed disturbance during construction and possibly due to changes in flow and wave patterns once the construction is in place.

Rampion Offshore Wind Farm (OWF) is located off the Sussex coast (Figure 5.11). Construction began on Rampion 1 in September 2015 and was completed September 2017. Rampion 2 is currently at consultation stage. There was potential for sediment suspension from dredging to provide stable areas for foundations, trenching of the cables and drilling for the turbine foundations. Drilling would only have been used where impact piling was not possible due to sea bed conditions. Resuspension caused by impact piling was considered to be minimal.

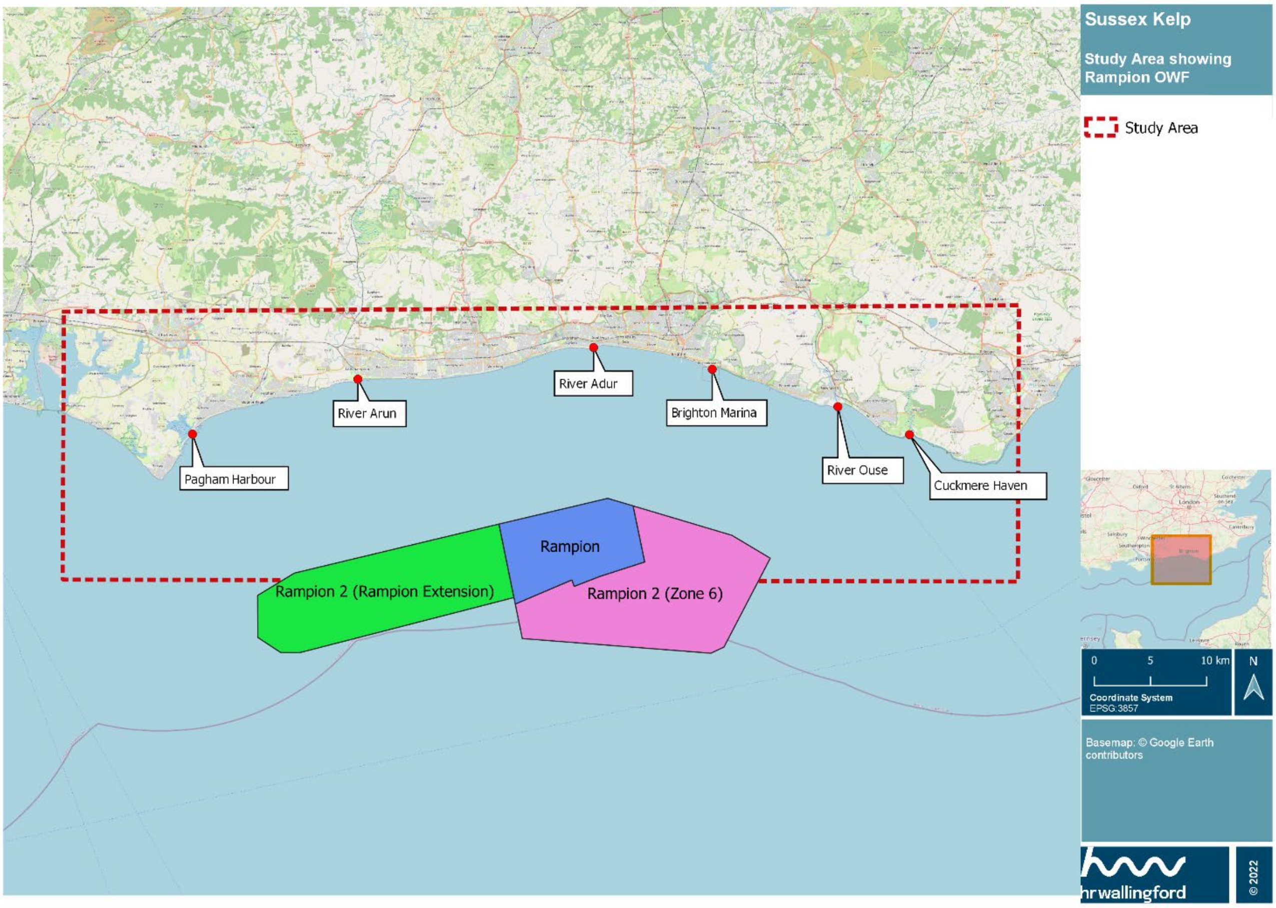

Figure 5.11: Location of the Rampion offshore windfarm site and proposed locations for Rampion 2

Source: The Crown Estate, 2022

ABPmer (2012) estimated that for each 6.5 m diameter monopile installed entirely by drilling, 1,824 m^3 of sediment spoil would be produced. Scaled up to include all of the 116 turbines this gives a potential maximum volume of 211,584 m^3. For context, the average annual input from chalk cliff erosion is 170,000 m^3, so the maximum potential input from drilling was of a similar order. Information on the actual proportion of piles that required drilling for installation has not been found, however impact piling would have been used unless this was impossible. For a single pile installed by drilling, ABPmer (2012) found that peak suspended sediment concentrations would occur at slack water, towards the end of drilling, with depth averaged concentrations reaching up to 200 mg/l. Their modelling suggested that concentrations could be increased by 5 mg/l up to 15 km from the drilling location in an east-north east direction. ABPmer (2012) considered that compared to the natural variability in suspended sediment concentrations, that sediment released by drilling would be of minor significance.

Dredging for pile foundations would be small and would largely remain at the disposal site, with the exception of the finest fractions which would disperse at low concentrations. Dredging to provide stable footings was therefore not considered to be a significant sediment source (Wood Group UK Ltd (Rampion 2 PIER assessment)).

For cable trench activities, trenching through chalk was considered likely to break into large clasts which would deposit close to the trench. Jetting may also have been required to remove unconsolidated surficial sediments. ABPmer (2012) numerical modelling suggested that concentrations of up to 200 mg/l may occur in very shallow water (<5 m) during cable laying. In deeper water, peak concentrations were predicted to be less than 100 mg/l. Over 90 hours following the completion of cable trenching activities, the sediment dispersed with depth averaged concentrations of 5-10 mg/l predicted up to 5 km away. Compared to natural variations in suspended sediment this is small and occurred over a relatively short timescale.

Sediment release from the construction of Rampion is likely to have been less than predicted in this modelling, as conservative assumptions were used (ABPmer, 2012). Unfortunately, no publicly available monitoring data of sediment plumes during construction has been found.

Post construction benthic surveys (Ocean Ecology, 2020a) found no significant changes to sediment composition pre- and post-construction within the Rampion site. They concluded that small changes in sediment were most likely to be a result of natural variation in sediment movements.

CEFAS (2016) used satellite derived SPM data to statistically test the theory that wind farms can increase the SPM in the local region. Two windfarms were tested (Walney and Greater Gabbard) but no significant effect was detected. The authors indicated that higher spatial and temporal resolution satellite imagery would be required to perform such an assessment conclusively.

5.1.9 Trawling

Whilst trawling is not a source of new sediment to the coastal system, it can cause disturbance to the seabed and resuspension of sediment. De Madron et al (2005) measured the concentration of the sediment plume associated with trawls using different fishing gear. For a muddy seabed, plumes of sediment with concentrations averaging 50 mg/l were observed to exist for several hundred metres from the trawling. They observed that the majority of sediment settles in the first hour after trawling, but a small proportion (up to 10%) remained in suspension for several hours. It is possible that sediments disturbed by trawling can subsequently be more readily resuspended by natural hydrodynamic processes, and therefore there may be a longer lasting indirect impact on turbidity.

The footprint of sediment impacts relating to trawling will depend on the trawling gear used (determining the degree of interaction with the bed), the sediment type, and the hydrodynamic conditions. It is therefore difficult to generalise the impacts of trawling to the Sussex coast.

The Sussex nearshore trawling byelaw prevents trawling within the nearshore zone shown in Figure 5.12. Trawling adjacent to the exclusion zone may produce sediment plumes that cause an impact within the byelaw area.

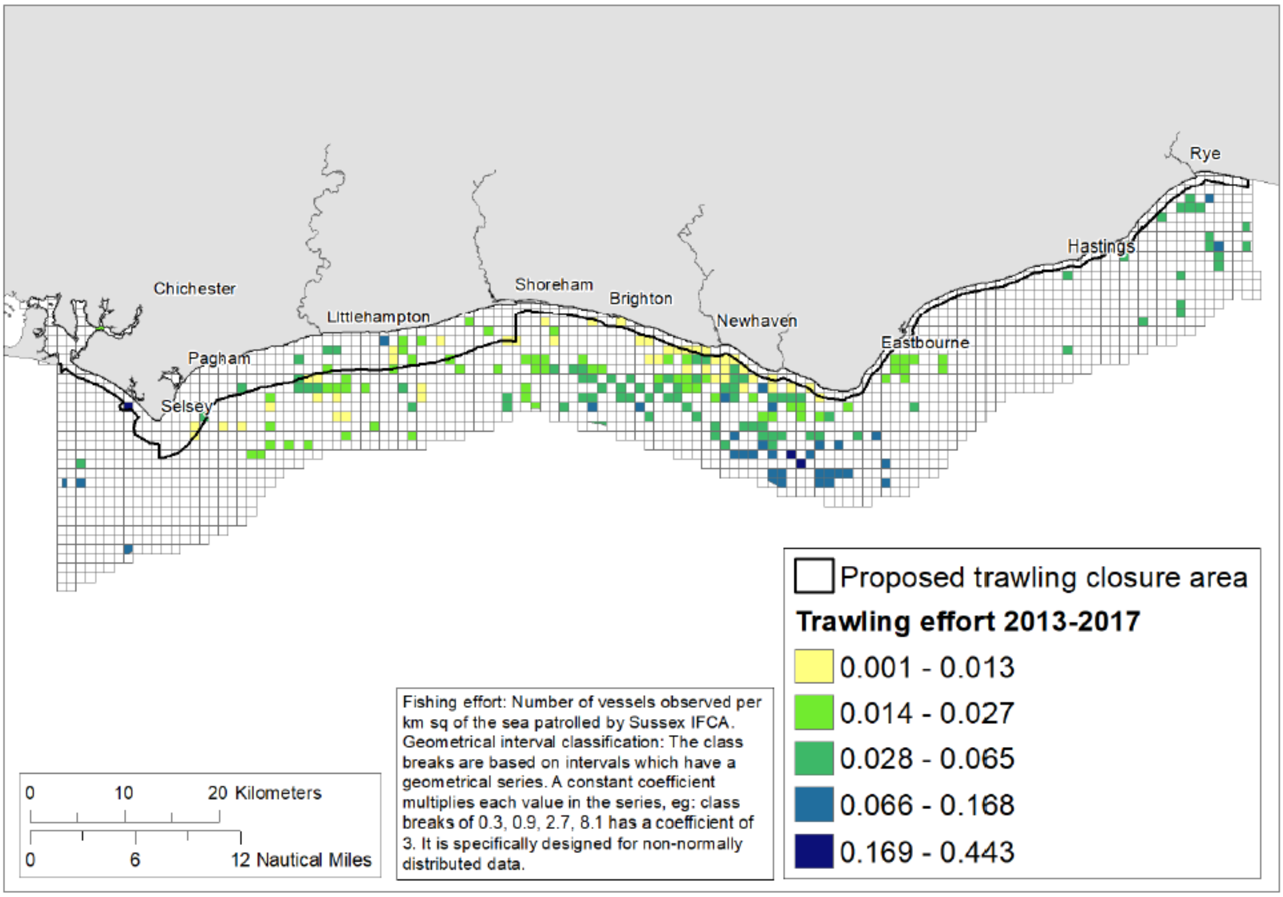

Figure 5.12: Trawling fishing effort between 2013 and 2017, showing the nearshore closure zone

Source: Sussex IFCA, 2020

5.2 Sources of sediment from the land

5.2.1 Rivers

This section considers sources of sediment arising from fluvial (river) and pluvial (rainfall run-off) sources. Table 5.2 below summarises estimated suspended sediment sources from Sussex rivers.

Table 5.2: Estimated fluvial (river) suspended sediment discharges to the sea

River	Estimated river suspended sediment discharges to the sea
Pagham Harbour	Negligible (River Lavant was diverted to Chichester during Roman times)
River Arun	Potentially up to 9-12,000 tonnes/yr, but actual is considered to be less (3, 2, 4)
River Adur	Potentially up to 20-26,000 tonnes/yr but actual is considered to be less (3, 2) Estimate of actual: 2,800 m^3/yr (1), 2,682 tonnes/yr (2)
River Ouse (Newhaven)	3,700 m^3/yr (1), 2,682 tonnes/yr (2) Note also the STONE project (EA, University of Sussex)
Cuckmere	800 m^3/yr (1), 1,320 tonnes/yr (3, 2).

Sources: (1) Gifford Associated Consultants (1997) (2) Rendel Geotechnics and the University of Portsmouth (1996) (3) Scopac (2012). (4) Halcrow (2004)

Separately and in addition to the above figures, riverine sediment inputs were investigated as part of a study by Valegrakis et al (1999), described earlier in Section 5.1.1 as part of the overall sediment budget of the Eastern English Channel (Figure 5.1). The work, which included both English and French rivers, concluded that the English catchments flowing into the Eastern English Channel provide relatively low quantities of sediment, at approximately 45,000 tonnes/year on average (based on estimates by Herrington et al., 1995).

Most of the sediment transported by rivers into the sea will likely occur during higher winter river discharge flows. Overall, the sum of river sediment sources to the study area is estimated to be 8,000 to 9,000 tonnes/ year, and very low in comparison with marine sediment sources. This is lower than the 45,000 tonnes/year reported by Velegrakis et al (1999) because it includes a smaller area. The long term trend over recent centuries will have been of a decrease to its present value, due to reclamation and a corresponding reduction in the estuaries' tidal volumes (SCOPAC, 2012).

It should be noted that the figures above are estimates of river suspended sediment loads, and do not include consideration of the (largely from marine sources) sedimentation into the river/estuary mouths. This is considered in Section 5.1.6. All of the above estimates could be considerably improved through monitoring (SCOPAC, 2012).

A further 580,000-1,000,000 tonnes/year are estimated to be input from rivers along the French coast of the English Channel, contributing to the wider English Channel sediment budget, but are not likely to have impacts at the local level of the Sussex coastline.

5.2.2 Pluvial (from rainfall) sediment sources

A further land-based source of sediments is from direct run-off after rainfall events. This sediment finds its way to the sea via smaller watercourses or simply by running directly off the land after a period of rainfall. Much of the West Sussex coastline is urban and therefore local soil erosion is likely to be minimal. Data relating to this potential source of sediment are sparse, but local monitoring (Boardman, 2003) has clearly demonstrated the correlation between rainfall and estimated soil loss (erosion) from a monitored area in the South Downs. Much of the sediment released by soil erosion will enter rivers in upstream areas of the catchment, rather than directly at the coast, and therefore contributes to the fluvial sediment load, much of which is trapped further upstream.

Table 5.3: Soil loss on eroding fields in the monitored area of the eastern South Downs 1982 -1991 (Boardman, 2003)

Year	Median soil loss (m^3 ha^{-1})	Total soil loss (m^3)	Number of sites
82-83	1.7	1,816	68
83-84	0.6	27	7
84-85	1.1	182	25
85-86	0.7	541	49
86-87	0.7	211	34
87-88	5.0	13,529	97
88-89	0.5	2	1
89-90	1.4	940	51
90-91	2.3	1,527	43
91-92	1.2	112	14

Overall, sources of suspended sediment from rivers and direct rainfall run-off represent a small contribution to the zone of existing and potential Sussex kelp beds, when compared against the much larger marine sources. Climate change, however, with the projected increases to future rainfall, would suggest that this small contribution could increase in the future.

5.2.3 Aeolian transport

CEFAS (2016) considered the influence of aeolian dust (from the Sahara) and volcanic ash but these were estimated as providing negligible input of sediment to UK waters.

6 Sediment sinks

Potential sinks for fine sediment include the estuaries and harbours found along the Sussex coastline. Whilst the harbours and marinas are temporary sinks (sediment build up is removed through regular maintenance dredging), in areas such as Pagham Harbour and some places in the Arun and Adur estuaries, sediment will also be trapped by saltmarshes.

6.1 Saltmarshes

Sediment dynamics around saltmarshes are complex, with vertical accretion of the marsh surface controlled by an interaction of waves, water levels and sediment supply and vegetation dynamics. With rising sea levels, additional depth above the saltmarsh surface is likely to promote accretion of fine sediments and therefore saltmarshes may act as a sediment sink.

In the past, saltmarshes on the south coast have acted as both sediment sinks and sources for sediment.

Spartina anglica, a vigorous hybrid of saltmarsh cordgrass, spread rapidly in the late 19th and early 20th centuries, colonising areas that were previously mud flat (Raybould et al., 2000). In the 1950s, *Spartina anglica* began to die back, reducing its ability to trap sediment and allowing saltmarshes to erode.

6.1.1 Medmerry

The Medmerry realignment site has the potential for up to 184 ha of intertidal habitat (Channel Coastal Observatory, 2018), including saltmarsh. In the long-term this will become a sink for sediment, however in the years following the breach there has been erosion of the flooded farmland as new channels have formed.

6.1.2 Pagham Harbour

Pagham Harbour contains approximately 105 ha of saltmarsh. This decreased by 18% between 1947 and 1965 and has slowly increased since 1965 (Cope et al, 2008). Assuming the surface of the saltmarsh was able to accrete to keep pace with sea-level rise, this could be a sink for around 4,000 m^3 of sediment per year. Assuming a sediment density of 500 kg/m^3 to 1000 kg/m^3 this would give a mass of 2,000 to 4000 tonnes/year.

6.1.3 Rivers Arun, Adur, Ouse and Cuckmere

Small amounts of fringing saltmarsh are visible on aerial photographs of the Arun and Adur (Google Earth, 2021). These are estimated to cover 0.7 ha and 5.2 ha respectively, and therefore represent a rather small sink for fine sediment. The Cuckmere has approximately 4.7 ha of fringing saltmarsh. Relict channels can be seen in the surrounding fields, providing evidence of large scale historical reclamation.

There is a possibility of a small realignment on the east bank of the Adur (Environment Agency, 2010). There have been ongoing discussions about restoring the meander in the Cuckmere, which may restore some of the formerly reclaimed intertidal areas.

6.1.4 Saltmarsh in the eastern Solent

Historical saltmarsh areas in the Solent have been reviewed by Cope et al (2008). In most areas there have been significant declines in saltmarsh area between 1945 and 1980, partly driven by land reclamations. Between 1990 and 2000 saltmarsh areas in the eastern Solent appear to have been approximately stable (Figure 6.1).

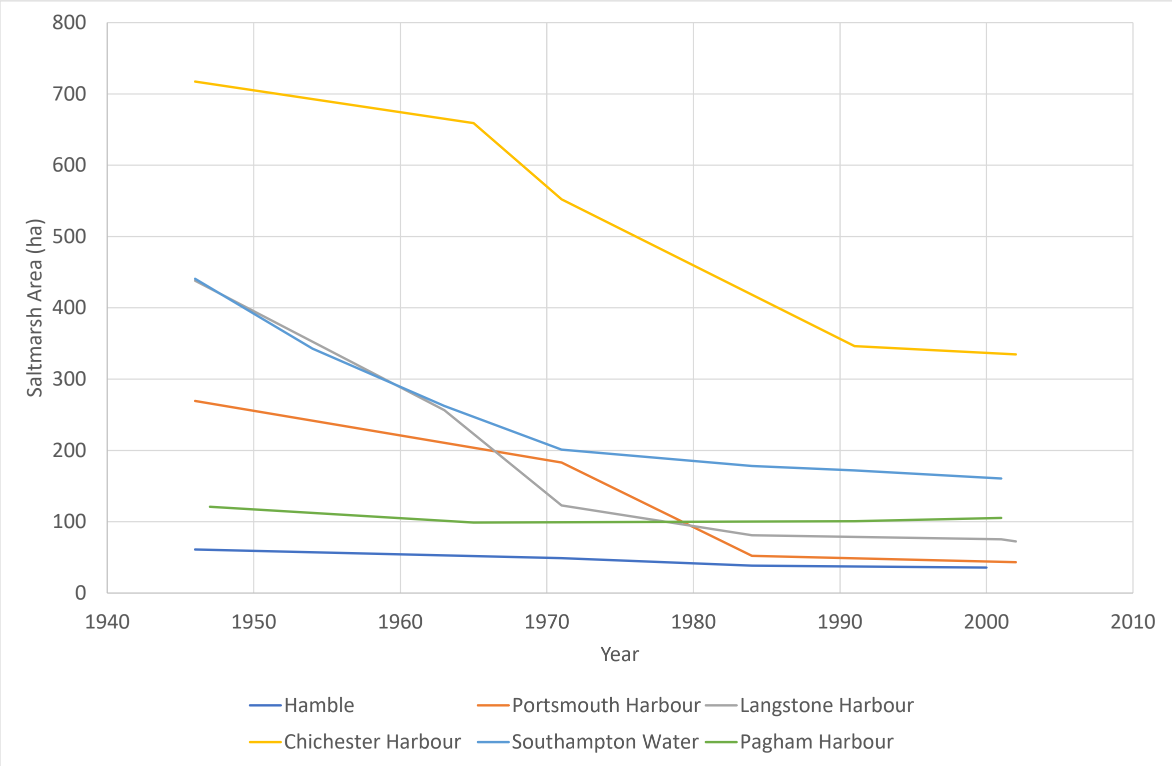

Figure 6.1: Changes in saltmarsh area in the eastern Solent

Source: From data in Cope et al, 2008

In 2002 the total area of saltmarsh in the eastern Solent was 752 ha (including Pagham Harbour already mentioned). In the scenario that the marshes accrete to keep pace with sea-level rise (~4 mm/year), east Solent saltmarshes are a potential sink for 30,000 m^3 of fine sediment a year (up to 30,000 tonnes/year). As sea-level rise accelerates, it is less likely that marshes are able to accumulate enough sediment to follow sea-level rise. Further, the decline in area of saltmarsh described above suggests that the actual amount of accretion could be lower and there could even become a net export of fine sediment. Further investigations of more recent changes in saltmarsh coverage would help to understand the current situation and future trend, however relative to other sediment sources and sinks the annual volumes of sediment involved are quite low.

6.2 Marinas and harbours

The marinas and harbours at Shoreham, Brighton, Newhaven and Eastbourne are effective traps for fine sediment, providing calmer waters needed for fine sediment to settle out of suspension and accumulate compared to the open coast. These locations can be considered temporary sinks as the accumulated sediment is regularly removed through maintenance dredging. Disposal, locally, in the near shore zone means this sediment is essentially recycled and remains available in the coastal system.

6.3 Suspended sediment flux through the English Channel

Local sediment sources and sinks within and adjacent to the study area are set against a background of the large scale eastward sediment flux thorough the English Channel. Lafite et al (2000) concluded that the average flux through the Dover Straits is in the order of 20 M tonnes/year but varies significantly through the spring neap cycle and seasonally (range 2 to 70 M tonnes/year).

7 Suspended sediment budget summary

7.1 Sources

Within study area

- Erosion of chalk cliffs and platform contributes around 187,000 m^3/years (317,900 tonnes/year) of new sediment (mainly fine chalk) to the coastal waters.
- Coastal erosion between Chichester Harbour and Brighton Marina is largely of beach material, coarse sand, shingle and pebbles. Shoreface erosion is estimated to yield between 3,400 and 12,000 tonnes/year of fine sediment.
- Where the shingle barrier has eroded exposing the underlying consolidated mud (e.g. at Medmerry) muds can also be eroded and therefore increase the nearshore turbidity. This is estimated to be 8,500 tonnes/year from the shoreface although within the site is thought to be a net sink.
- Beach renourishment schemes contribute mostly coarse grain beach sediment to beaches, but may contribute up to 4,700 m^3/year (up to 6,000 tonnes/year) of fine sediment.
- Fluvial sediment input within the study area is estimated to average 8,000 to 9,000 tonnes/year.
- Pluvial sediment input (run-off directly from adjacent land) may increase with increasing rainfall, however much of the soil erosion caused by rainfall will enter rivers further up the catchment and therefore contribute to the fluvial sediment inputs.

Adjacent to study area

- Offshore aggregate dredging may cause a release of 40,000 to 50,000 tonnes/year of fine sediment to the wider sediment budget but this is likely to have negligible impacts at the kelp beds.
- Maintenance dredging, averaging 360,000 tonnes/year, from around the Solent is disposed of at Nab Tower.
- Capital dredging, largely disposed of offshore at Nab Tower, contributes up to 370,000 tonnes/year of sediment, although this varies from nothing to 5.7 M tonnes (in 1997). Only a proportion of this disposal will be fine sediment (details of the material types are not available). The nature of the material dredged through capital dredging differs from maintenance dredging, with the material likely to be coarser grained and/or more consolidated and hence less erodible and more likely to fall straight to the bed and remain there. The actual amount of suspended sediment introduced is likely to be considerably smaller than the total disposal.

7.2 Sediment recycling

Within study area

- Maintenance dredging of the harbours and marinas located along the Sussex coast moves around 225,000 dry tonnes/year of recently deposited fine sediment from the temporary sinks to the nearshore disposal sites.

- Beach sediment is also recycled in a number of places, but is unlikely to contribute significantly to the suspended sediment budget.

7.3 Sinks

Within study area

- Pagham Harbour is a potential sediment sink and could trap up to 4,000 tonnes/year in the saltmarshes.

Adjacent to study area

- Over the east Solent, saltmarsh provides a potential sediment sink of up to 30,000 tonnes/year.

7.4 Suspended sediment flux

Wider environment

There is a large west to east suspended sediment flux of fine material through the English Channel. This varies with spring-neap cycles, and seasonally, but is in the order of 20 M tonnes/year. The eastward flux between the Isle of Wight (UK) and Cotentin peninsula (France) and through the Dover Straits is thought to be approximately in balance.

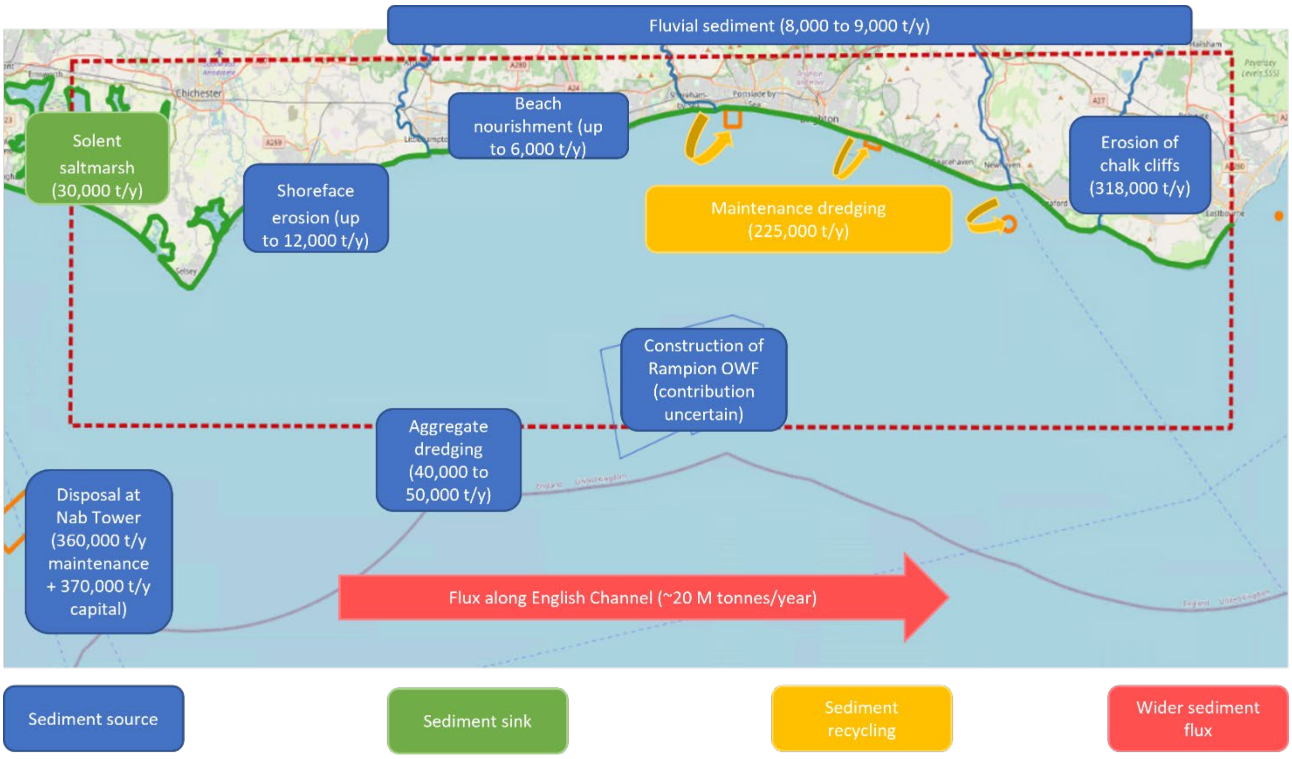

Figure 7.1: Summary fine sediment budget for the West Sussex coastline

7.5 Historical trends

In general, it has not been possible to identify historical trends in suspended sediment concentrations.

- The nearshore maintenance dredging records do show a slight increasing trend over the last decades, however this is influenced by increases in dredging at Shoreham since 2005 and the opening of Sovereign Harbour (Eastbourne) in 2000. Dredge disposal at the other sites shows no trend, so it is not clear that the increase in dredging at Shoreham represents an increase in suspended sediment. Much of the Shoreham dredging is of sandy material.

- The satellite monitoring data (CEFAS, 2016) shows no overall trend in annual suspended sediment concentration, but does report a significant increase when looking only at the spring months. A longer dataset would help to confirm or dismiss this apparent trend.
- The release of sediment from coastal erosion may have decreased over the last centuries as the coastal defences have progressively increased.
- The evidence is insufficient to identify any long term trends in suspended sediment concentration.

8 Future outlook for sediments along the Sussex coastline

8.1 Climate change allowances

UKCP18 is the latest generation of national climate projections for the United Kingdom and provides users with the most recent scientific evidence on projected climate changes (Lowe et al, 2018; Fung, et al 2018). Of particular interest for existing and potential future kelp beds are the projected future changes to:

- Sea water temperature
- Sea water acidification
- Rainfall (typical and extreme)
- Sea level (typical and extreme)
- Waves (typical and extreme).

In terms of potential changes to suspended sediments it is the projected changes to mean sea level, rainfall, and waves that is of most interest. Table 8.1 shows projected changes to sea level, precipitation, and wave heights from UKCP18.

Table 8.1: UKCP18 Climate Change Projections

	Location, date	Low emissions scenario	High emissions scenario
Sea Level	London, 2100	0.29m - 0.70m*	0.53 – 1.15m*
Rainfall/ precipitation	Central England, 2070s	41% drier to 9% wetter summers 3% drier to 22% wetter winters	57% drier to 3% wetter summers 2% drier to 33% wetter winters
Significant wave height	England	21st century projections of average wave height suggest changes of the order 10-20% and a general tendency towards lower wave heights. Changes in extreme waves are also of order 10-20%, but there is no agreement in the sign of change among the model projections.	

**UKCP18 cannot rule out additional changes in storm surges*

The main driving force leading to a projected increase in sediment supply is the projected accelerated sea level rise leading to more potential sources of sediment in the nearshore / coastal area. Sea level rise brings the sea further inland and enables larger waves to impinge on the shoreline, potentially increasing erosion of undefended cliffs. Much of the Sussex coastline is defended which somewhat mitigates (for some time into the future) this effect, and the results of accelerated sea level rise will be more complex. Estuaries will continue to infill with fine sediments at a rate dependent on supply, and managed realignment sites should also attract more sediment deposition. For the existing / potential kelp beds, the water will become deeper.

The small river sediment contributions will likely increase due to increased winter peak river flows but overall the contribution will remain small compared with marine inputs.

In addition to the above, projected increases to seawater temperature will impact on the kelp but that is outside the scope of this report. The small change in sea temperature associated with climate change will have insignificant (less than a few percent) effects on the settling velocity of the suspended material. This is insignificant compared to the seasonal variation from summer to winter.

8.2 Coastal management policies

The coastal management policy for the Sussex coastline is largely “hold the line” in order to protect the urban areas behind the defences (Figure 8.1). Between Elmer and Littlehampton, the policy (all epochs) is managed retreat. East of Newport West Pier breakwater the short to medium term policy is “no active intervention” and the long term policy is managed retreat. The chalk cliffs between Seaford and Beachy Head have a policy of “no active intervention”.

In the future cliff erosion is likely to increase as sea-level rise allows large waves to reach more of the cliff toe. In addition, increased projected winter rainfall and drier summers may lead to increased cliff falls.

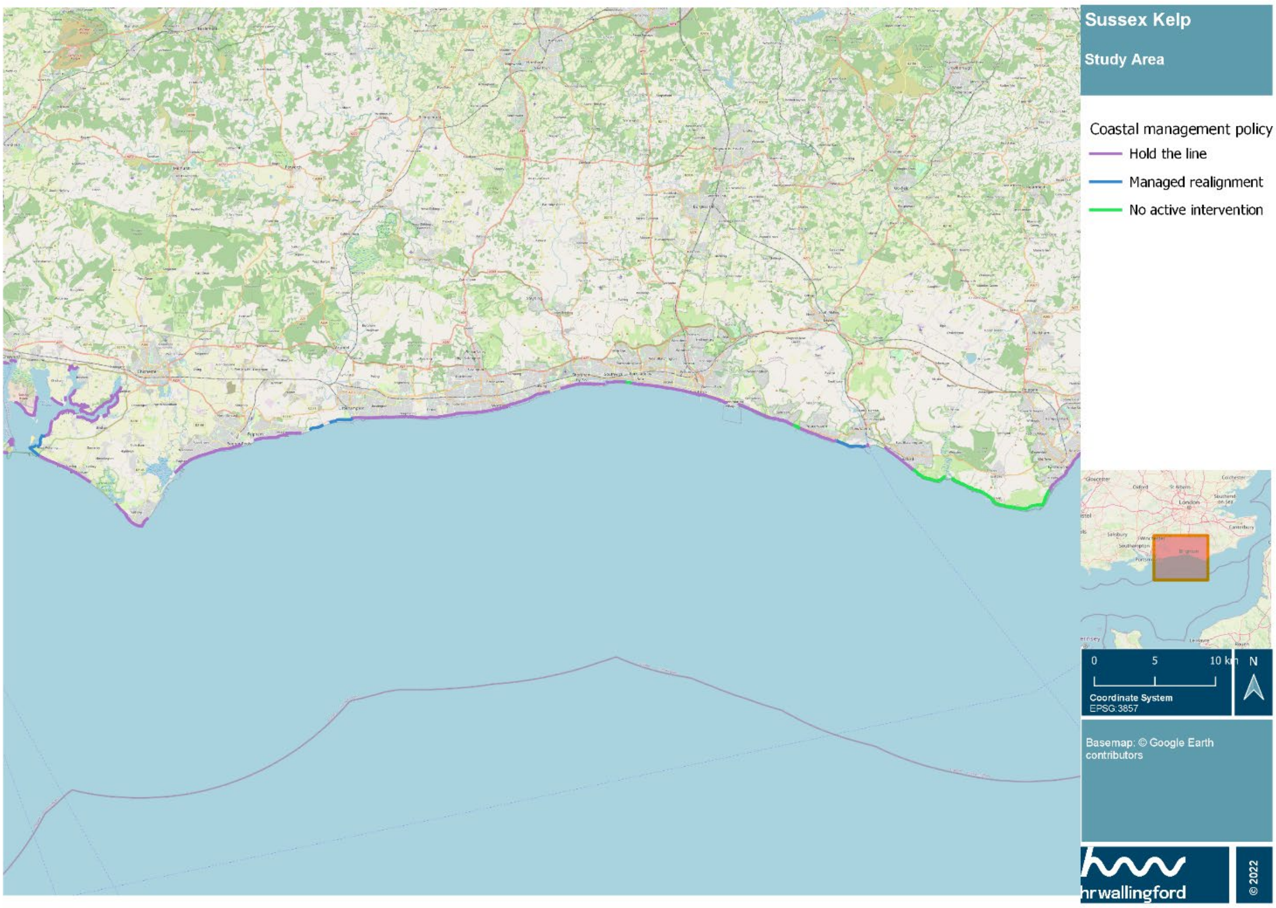

Figure 8.1: Shoreline management policies for the West Sussex coastline (long-term)

Source: NCERM 2022

8.3 Catchment management policies

There are many initiatives designed to decrease pollution of waterways from farming, which would decrease both chemicals and sediment reaching rivers. These include Countryside Stewardship and Catchment Sensitive Farming to encourage changes in land management for the benefit of the environment.

It is not clear to what extent these initiatives will decrease sediments reaching rivers and delivered onwards to the coastal zone.

8.4 Future construction

Future construction has the potential to release sediment from the seabed into the water column. Proposals for Rampion OWF 2 are at consultation stage. The maximum number of turbines for Rampion 2 is 116, so the impacts are likely to be similar to Rampion 1. Increases in suspended sediment relating to windfarm construction are likely to be localised and relatively short lived. The residual current directions for the Rampion 2 sites may be different to that of the Rampion 1 site.

8.5 Future sinks

Saltmarsh may become an increasingly important sink for sediment, assuming sedimentation on the marsh surface keeps pace with sea-level rise. Saltmarshes in Pagham Harbour could be a sink for as much as 1,260,000 m^3 of fine sediment between now and 2125. However, this estimate relies on the saltmarsh area remaining constant and accumulating sufficient sediment to maintain height relative to sea-level. Long-term policies of managed realignment at some sites may create additional areas where fine sediment can become trapped, although the area available is likely to be small.

8.6 Summary

Climate change may impact the Sussex coastline in a number of ways. Sea-level rise will mean that water levels along beaches and cliffs are higher, allowing larger waves to reach further up the beach or cliff. This may increase coastal erosion where the coast is undefended, potentially increasing the sediment supply from coastal erosion. The management policy for much of this stretch of coastline is largely “hold the line” and increased coastal erosion will therefore be limited to the undefended stretches of chalk cliff around Beachy Head.

9 Conclusions and Recommendations

9.1 Conclusions

A review of the sediment regime off the Sussex coast has been undertaken. Particular consideration has been made of the sources and sinks for fine sediment that could affect kelp recovery and growth by contributing to increased turbidity (reducing light levels to the kelp) or contributing to smothering of young plants. Historically kelp may have been present in water depths of up to 10 to 15 m off the Sussex coast. Whilst the tidal regime is broadly similar from one year to the next there can be significant variability in wave conditions and storms over time. Over the long term the observed decline in areal coverage of kelp beds is not considered to be related to changes to either tidal currents or wave action.

Off the west Sussex coast the width of seabed out to depths of 10 to 15 m is greater than that off the east Sussex coast where the seabed is steeper and the 10 m and 20 m seabed contours are closer inshore. The kelp beds off the west Sussex coast were more extensive than those to the east.

Tidal currents influence the dispersion of zoospores when kelp reproduces. The residual (time-averaged) water movements are complex off the Sussex coast with zones of recirculation. A westerly residual runs to the west of Brighton over most of the area of the historic kelp beds. An easterly residual runs to the east of Brighton. These tidal residuals will be complemented by wind induced circulations which will vary over time.

Wave action drives sand and coarser material along the coast by the process of littoral drift. There are also important processes of on and offshore (cross shore) transport of coarse material as a result of wave action. Much of the Sussex Coast is protected by coastal engineering works because there is little input of beach sediment and therefore the natural beach is insufficient to protect the coast.

Wave action also results in the suspension of finer fractions of material (silts, clay and chalk particles) which are then transported by tidal, wind and wave induced currents. Suspended sediment influences the amount of light penetration to the seabed. Finer particles, particularly chalk, have a greater impact on light penetration than coarse particles. There are no long-term time series of direct measurements of suspended sediment concentrations or turbidity available over the kelp beds. Turbidity is expected to vary through the tidal cycle, through the fortnightly spring-neap tidal cycle, in response to storm and rainfall events and seasonally. The sediment budget for the study area off the Sussex coast exists within the wider scale of the sediment budget of the English Channel. The English Channel sediment budget is dominated by a flux of fine sediment moving eastwards. This flux has a magnitude in the region of some 20 M tonnes. The study area represents only a fraction of the cross-section of the English Channel through which this flux passes and as a consequence it is important to consider a more local scale sediment budget for the kelp beds.

In this local scale sediment budget the main source of fine sediment arises from the erosion of the cliffs and nearshore rock platform. On average about 300,000 tonnes of fine sediment is released each year as a result of erosion. The erosion tends to occur as frequent, low volume falls; however large cliff failures can occur. Most of this erosion occurs on the unprotected length of the shoreline close to Beachy Head. Additional sources of fine material are from wash out from beach nourishment projects and from river inputs from the Sussex rivers. These inputs are small in comparison to the cliff erosion but may be of local significance. Whilst there are some offshore sources of fine material from nearby offshore aggregate dredging, or windfarm installation, these sources are also small in comparison to the continuous cliff erosion and, being offshore, are also being generated at locations less likely to directly influence the kelp beds.

The harbours and marinas along the Sussex coast trap and act as sinks for fine sediment (both sand and mud). However, this sediment is largely recycled through licensed maintenance dredging with disposal at local nearshore disposal sites. Local disturbances to the fine sediment regime occur during maintenance dredging campaigns. The mass of fine sediment (sand and mud) recycled through annual maintenance dredging is comparable to the long-term input from erosion of the cliffs.

Other sinks for fine sediment include the saltmarsh and intertidal areas of the harbours, estuaries and managed realignment sites on the Sussex Coast. The likely scale of fine sediment trapping in these areas is small compared to the source.

Further afield the larger scale of offshore disposal of dredged material at the Nab Tower disposal site to the east of the Isle of Wight and the offshore aggregate dredging activity in the English Channel contribute fine material into the wider English Channel sediment budget but are generally too distant and too far offshore (in terms of tidal streams and residual currents) to directly influence the Sussex kelp beds.

With climate change rising sea levels can be expected to result in increased rates of cliff erosion. This can result in elevated nearshore suspended sediment concentrations, increased turbidity and reduced light availability over the kelp beds. There may also be a need for increased amounts of maintenance dredging (sediment recycling) in the Sussex harbours and marinas, with increased local disturbance to the fine sediment regime from disposal activities.

With the data currently available, there is no clear evidence that the observed decline in areal coverage of kelp beds is related to long term changes in the suspended sediment regime off the Sussex Coast.

9.2 Recommendations

An improved understanding of the residual flows over the kelp beds could be achieved using a fully coupled tide, wind and wave numerical model of this part of the English Channel.

Improved understanding of the wider residual flows in the English Channel would enable an assessment of the significance of some of the offshore and more distant sources of fine sediment releases. Areas of flow recirculation may lead to accumulation of fine suspended sediment over time such that the significance of the larger scale offshore activities requires reconsideration.

There are no long-term direct measurements of suspended sediment concentration, turbidity or photo-synthetically available radiation in the water column or at the seabed in the vicinity of the Sussex kelp beds. If suspended sediment concentrations and light availability are considered significant for the health or restoration of the kelp beds then a suitable programme of measurement should be instigated. During such measurements records of wave activity, larger scale cliff falls and harbour/marina sedimentation and dredging should also be obtained.

Further investigations of more recent changes in saltmarsh coverage would help to understand the current situation and future trends and the rates at which fine sediment is being accumulated or eroded from these areas, however relative to other sediment sources and sinks the annual volumes of sediment involved are quite low.

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