AGGREGATE DREDGING AND THE MARINE ENVIRONMENT:

an overview of recent research and current industry practice



Edited by
Richard C. Newell and Tania A. Woodcock

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and current industry practice

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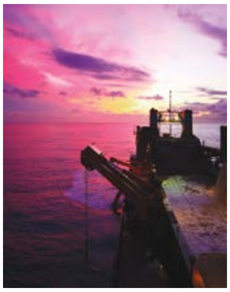
Foreword



The marine Aggregate Levy Sustainability Fund ("marine ALSF") programme represents one of the most substantial investments in UK marine research that has taken place this decade. The research that was commissioned focussed on improving the way that the marine aggregate industry is planned, assessed and managed.

Strategic oversight of the programme, which ran from April 2002 until March 2011, was delivered through a multi-disciplinary steering group, chaired by Defra, which included representatives from Government departments, agencies, advisors, the marine aggregate industry and The Crown Estate. Although a wide range of interests were represented on the steering group, a common goal for the programme was to deliver practical outcomes that improve understanding and knowledge of the environmental implications of marine aggregate extraction in order to ensure such practices are sustainable. In turn, the expectation was that outcomes should increase certainty and provide greater confidence to regulators, advisors and industry alike.

This overview report demonstrates that the marine ALSF programme has delivered significant improvements to our understanding across a wide range of environmental disciplines. Some of these outputs have resulted in immediate changes in the way that the marine aggregate industry is assessed and managed, while others will result in longer term benefits.

There have also been wider benefits, including improved interaction between industry, regulators and scientists, an increased awareness and understanding of the marine aggregate industry, and the continual development of capacity and capability within the marine science community.

Finally, many of the research outputs generated through the marine ALSF programme and described in this report have the potential to provide significant added value to the wider marine science that underpins the planning and management of many activities within the UK marine area.

We believe that a large part of the success of the marine ALSF programme can be attributed to the successful interaction, cooperation and partnership between a range of Government departments and agencies along with industry and other stakeholders. This in turn reflects the truly multi-disciplinary nature of the issues that have to be managed in the marine environment. We also acknowledge the input of the programme's delivery partners and project contractors.

Marine Environment Protection Fund Steering Group Members
British Marine Aggregate Producers Association (BMAPA)
Centre for Environment, Fisheries and Aquaculture Science
Department for Environment, Food and Rural Affairs
English Heritage
Joint Nature Conservation Committee
Marine Management Organisation
Natural England
The Crown Estate
June 2013

Preface

The coastal waters that surround the British Isles support a wide range of economic assets from fish and shellfish to mineral resources such as petrochemicals and aggregates, as well as providing sites for offshore renewable energy, cable routes, shipping and many other activities. It is now widely recognised that these wide range of demands that we place on our surroundings need to be managed in a more integrated fashion, so that the environment is protected for the benefit of future generations. This more sustainable and holistic view of our environmental responsibilities has developed in recent years partly as a result of an improved understanding of the complexity of interactions between the physical and biological environment, and the activities of man.

The economic value of 'goods' that are provided by the marine environment can be quantified with conventional models to provide an estimate of their contribution to the economic needs of society. It is becoming increasingly recognised, however, that our coastal environment is also of importance in supplying less-tangible 'services' that play a central role in ecosystem function, as well as in other activities that make an important contribution to the well-being of society as a whole. The economic value of these is much harder to quantify, as is the economic value of resources of cultural importance such as those of historic and archaeological significance, and species or communities that contribute to the biodiversity of our seas. Understanding the nature and distribution of these resources is central for effective management and protection of assets that may not, in the past, have been recognised as having an important function with economic implications for our environment and well-being.

Our understanding of the nature and distribution of these resources of economic and conservation significance on the seabed surrounding our coasts has been greatly enhanced in recent years through funds made available from the Marine Environment Protection Fund (MEPF). In 2002 the UK Government imposed a levy on all primary aggregate sales, including marine aggregates, to better reflect the environmental costs of winning these materials. As this was an environmental levy, a proportion of the revenue generated was used between 2002 and 2011 to provide a source of funding for research aimed at minimising the effects of aggregate production. This fund, delivered through the Department for Environment, Food and Rural Affairs (Defra) was known as the Aggregate Levy Sustainability Fund (ALSF). A small component of the ALSF relating to the Historic Environment was administered through English Heritage and further funds were disbursed through the Marine Environment Protection Fund (MEPF) administered by the Centre for Environment, Fisheries and Aquaculture Science (Cefas). Reports of all projects funded through the MEPF can be accessed at the following website: **www.cefas.defra.gov.uk** and those for archaeology through the Archaeology Data Service (**www.ads.ahds.ac.uk**). A search engine that assists in identifying relevant projects can be accessed at **www.marinealsf-navigator.org.uk**.

The purpose of this book is to give an overview of the characteristics of the coastal environment in areas where marine aggregate dredging takes place, or is likely to occur in the future. We then highlight how the results of major investment in research carried out in the UK over the past decade, particularly through the Aggregate Levy Sustainability Fund (ALSF), have assisted in our understanding of the nature and scale of impacts of dredging on the marine environment, and how this information has been used to improve the sustainable management of this key resource for the UK economy.

R.C. Newell and T.A. Woodcock – June 2013

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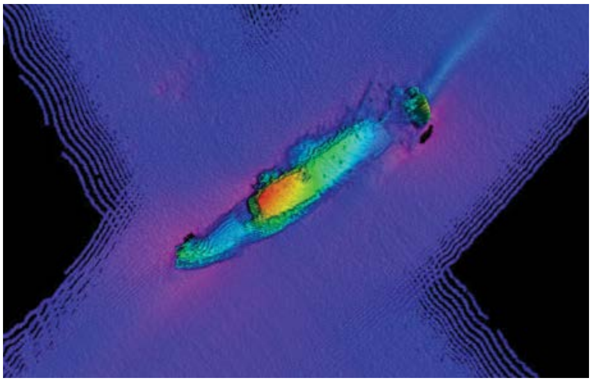

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1 INTRODUCTION

By R.C.Newell, Richard Newell Associates

Fig 1.1 Aerial view of the Olympic Stadium during development. Courtesy of London 2012, © ODA 2008.

Aggregate Supply and Demand

Aggregates consisting of sand, gravel and crushed rock, from both land-won and marine sources play an important part in the UK economy. The construction industry alone requires large quantities of aggregates mainly for use in land reclamation and as a raw material in the manufacture of concrete. Aggregate fill accounts for 60-80% of the concrete by volume, the strength and properties of the material that is used largely determining the load-bearing qualities and durability of the concrete. They are also used extensively in land reclamation for major infrastructure projects and for beach replenishment and other coastal protection schemes. The total demand for aggregates in the UK is estimated to be over 200 million tonnes (Mt) per year (based on 2010 figures), depending in part on the strength of the economy.

Aggregates are supplied from three main sources:
- Recycled and secondary materials
- Land-won aggregates – from quarries
- Marine sand and gravel

Recycled and secondary materials

Recycled materials from demolition waste and waste products from other industrial processes (termed secondary aggregates) are an important source of aggregate supply, representing nearly 25% of total aggregate demand in the UK – the highest proportion of use in Europe.

Government policy actively encourages the use of such products through its hierarchy of mineral supply. This is reinforced by such products being exempt from the Aggregate Levy, an environmental tax imposed in 2002 as a means of reflecting the costs of extraction.

Concrete from demolition can be readily recycled, while secondary aggregates such as china clay and slate waste can be used for a range of construction purposes, such as fill for reclamation of infrastructure projects, but are not generally suitable for premium concrete purposes. Recycled materials are in any case, of insufficient quantity to entirely meet the demand for construction aggregates with levels of supply currently near their maximum. Primary aggregate resources in the form of crushed rock, sand and gravel from land-based quarries and marine sources therefore remain of central importance to the construction industry, and are likely to remain so in the future.

Primary resources – Land-won aggregates

The majority of the primary aggregate supplies necessary to support the UK economy are derived from land-based quarries. Crushed rock is used to supply coarser aggregates – predominantly produced in the north and west of the country, while quarried sands and gravels in the south and east of the country are also extensively used as a source of building materials. Together, land-based aggregates supply 150Mt of primary aggregates per year (2010 figures) which represents roughly 70% of the total market demand in the UK. The access to suitable resources close to centres of population is, however, becoming increasingly constrained by environmental and planning issues such as disturbance to communities in the vicinity of quarries, alternative land use, and the restrictions of transport by road and rail. Environmentally acceptable sites on land close to centres of high demand are therefore becoming increasingly difficult to find and permitted reserves of sand and gravel in areas such as the south-east of England are declining.

Primary resources – Marine aggregates

The UK also has extensive offshore resources of marine sands and gravels, many of which are located in the south and east of England, relatively close to centres of high demand. In this case supplies can be delivered directly to wharves in coastal urban areas and the processed material can be supplied to customers without the need for lengthy road or rail transport. While the landings for construction aggregate only represent around 5% of total UK aggregate production, they still represent over 20% of the total market demand for sand and gravel in England and Wales, a third of all the construction aggregates used in London and the South East of England and nearly 50% of the sand and gravel used in Wales.

Marine aggregates provide an important source of high quality material which is used mainly for concrete. Around 80% of all marine aggregate in England and Wales is used for concrete, which is the premium product of the sand and gravel industry.

The importance of being able to land aggregate cargoes close to the site of use should not be under-estimated. As an example, over 325,000 tonnes (Te) of sand have been used in the production of 380,000 cubic metres of concrete for the Olympic site in east London. Marine sands to supply this site were dredged from the southern North Sea and English Channel and discharged relatively close to the Olympic site at Dagenham Wharf on the Thames where initial processing took place. An average of 5 trains per week then transported the processed material to the Olympic site for use by the concrete plants. This is estimated to have saved over 12,000 lorry movements by road in East London for this project alone (Selby, 2011).

Marine aggregates are also used extensively for beach replenishment ('recharge') and other coastal protection schemes that are required to combat rising sea levels. In this case large volumes of aggregates that match the characteristics of the local beach material can be pumped directly from the dredging vessels to the shore with minimum disturbance to coastal communities.

In beach replenishment (often referred to as 'beach nourishment') schemes, sand and gravel dredged from licensed areas is used to replace beach sediments lost by the combined effects of wave and tide action. This helps to protect the beaches by absorbing incoming wave energy before it meets the shore. Large quantities of material are involved. As part of the Lincolnshire coast protection scheme for example, as much as 19Mt of sand has been placed on beaches between Mablethorpe and Skegness since 1994.

Similar beach replenishment schemes are widely used elsewhere around our coastline and there is no doubt that an increased investment in beach recharge, and other coastal protection schemes will be required to meet the challenges of increased storminess and the global rise in sea levels that are predicted for the future.

Fig 1.2 Pumping material onshore, © Westminster Dredging Company Limited.

Fig 1.3 Coastal defence works underway, © Westminster Dredging Company Limited.

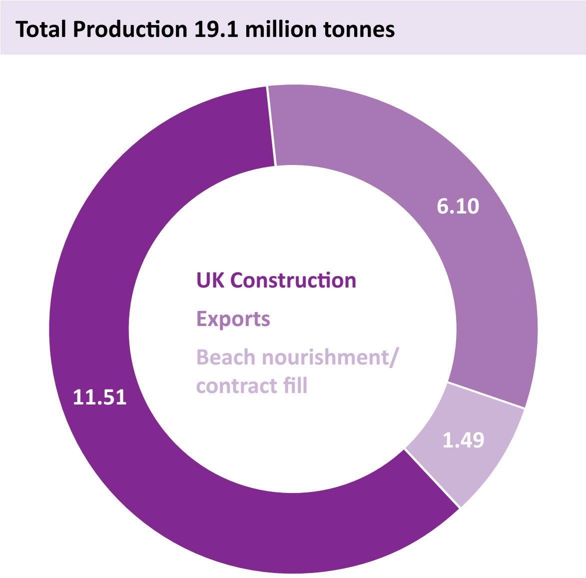


Fig 1.4 Landings of marine aggregates/Mt by principal market, 2011. Source: The Crown Estate.

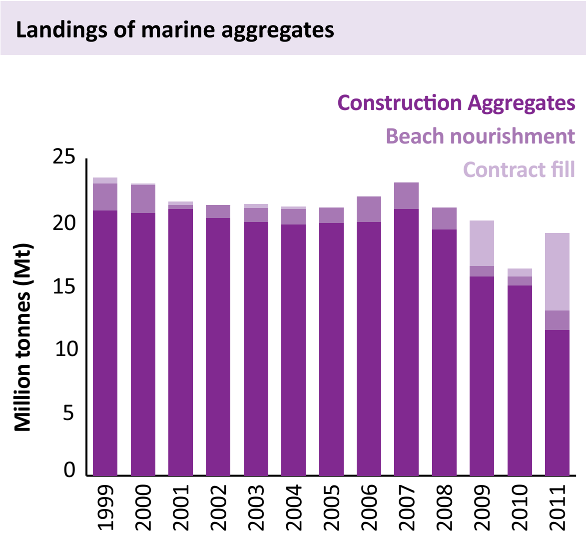


Fig 1.5 Landings of marine aggregates and their principle use in the UK from 1999 to 2011. Original Source: BMAPA.

There are strong regional differences in the contribution that marine sands and gravels make to the total aggregate supply. This largely reflects the local availability of sand and gravel resources, and the construction requirements of large centres of population. Marine sands and gravels account for as much as 38% of the requirement in areas of high demand in the south-east of England and this increases to 80% of the demand in London where sand and gravel can be more easily brought to wharves located near the heart of the city. Marine aggregates meet 46% in the north-east but only 22% in the north-west, mainly due to an abundant supply from land-based resources in north-west England. In contrast, because of a shortage in the availability of natural sand resources in Wales, more than 80% of sand is sourced from marine resources in the Bristol Channel.

There are also larger-scale geographical variations in the availability of coarse aggregates required for the construction industry. Marine deposits off the coast of mainland Europe are dominated by fine to medium sand used for fill and recharge, with a scarcity of gravel and coarse sands of the grade and quality that is required for concrete. The Netherlands and Belgium in particular are heavily dependent on imports of coarse aggregates for construction purposes, and source these mainly from Germany and France, along with crushed rock from Scandinavia. The diverse range and large reserves of marine aggregates located around our coasts allows export of sands and gravels to mainland Europe to be used as construction aggregates, mainly to meet demands from the Netherlands and Belgium. Current exports to mainland Europe account for about 6Mt per year (2011) which is about 57% of that used in the domestic market.

A breakdown of the total marine aggregate landings including exports for 2011 is shown in Figure 1.4. Use for construction purposes amounted to 11.51Mt, that for beach replenishment and contract fill was 1.494Mt and that exported amounted to 6.1Mt. This gives a total production for 2011 of 19.1Mt. It represents a reduction of about 11% from values achieved before the recession, but production is expected to recover in the coming years to a pre-recession average of about 22Mt per year.

A histogram showing the landings of marine aggregates and their principal market use in the UK over the period

1999 to 2011 is shown in Figure 1.5. From this it can be seen that landings for UK construction purposes, beach nourishment and contract fill declined from a maximum of 20-22Mt in 2006/7 to approximately 16Mt in 2010 following the 2008 and current recession. Production has since increased to 19.1Mt (based on data from BMAPA).

The demand for marine aggregates has been supplemented in recent years with the development of major infrastructure projects such as the new airport at Ronaldsway on the Isle of Man, the port extension at Felixstowe and new gravity-based foundations for offshore wind farms. Foundations of this type have already been used at the Thornton Bank wind farm, 30km off the coast of Belgium. The foundations for each of the 60 turbines that have been installed required 1000m^3 of concrete and a further 2000m^3 of sand for ballast. It seems likely that this sector will show a significant expansion as offshore wind farms move into deeper waters.

Origins and Location of Marine Aggregate Resources

The distribution of marine sands and gravels that can be used by the aggregate industry is not random. Most are 'relict' or fossil deposits that have been generated as a result of ancient glacial and fluvial processes and subsequent changes in sea level relative to land. Glacial episodes occurred during the Quaternary period from about 26 million years before present (BP) to about 11,000 years BP. The last Glacial Maximum occurred about 26,000 years ago, during which time much of north-west Europe was covered in ice.

During the warmer interglacial periods, fast-flowing streams carried melt-water from the edge of the ice sheet and from snow and permafrost melt, and formed distinct valleys within which large quantities of eroded material comprising boulders, stones, gravels and fines were deposited. These infilled palaeo-channels, along with other glacial features such as lateral and terminal moraines, cliffs and ancient beaches and spits were then gradually submerged as the climate became warmer and sea levels rose. Today many of these post-glacial deposits lie in water depths of 30-50m in the coastal waters surrounding the British Isles.

Other seabed features have been identified that are not directly related to outwash from the glacial cover. A large palaeo-channel system associated with major gravel deposits is located in the central English Channel extending eastwards towards the Dover Strait. Recent work suggests that this palaeo-valley system may reflect a catastrophic breaching of the Strait of Dover when a glacial lake in the southern North Sea is thought to have burst through the narrow land bridge between the British Isles and mainland Europe.

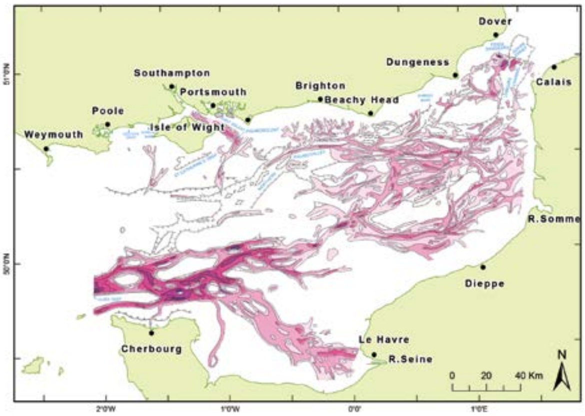
The distribution of potential aggregate resources is therefore directly related to the geographic distribution of ancient geological processes, rather than at random on the seabed. These submerged relict deposits occur in general at the seaward end of major river systems that drain the present-day landscape. Thus deposits on the east and south coast of England are to be found in the Isle of Wight (Palaeo-Solent) region, off the south coast in the Palaeo-Arun region, off the outer Thames and the Wash and Humber. Additional major resources also occur in the eastern English Channel along the course of the palaeo-valley associated with the breach of the Dover Strait, and in the palaeo-valleys originating in the Seine and Somme.

The complex array of palaeo-valleys in the Eastern English Channel is shown in Figure 1.6.

The availability of suitable resources for commercial aggregate dredging is not only controlled by the distribution of ancient palaeo-valleys and other relict features but also by the extent to which subsequent marine processes have affected the deposits of gravel.

Tidal current speeds around the British Isles are generally around 1.2-1.5m/s. Gravels (> 4mm diameter) are essentially immobile at these current speeds and at the water depths at which dredging takes place. The tidal currents are, however, of sufficient velocity to mobilise sand-sized particles which can then form large sand waves that overlay the coarse gravels that are required by the aggregate industry.

Sand banks that are formed by more recent geological processes also form an important potential source of sand over and above the coarse materials that are relict deposits. Sand banks of this type are exploited commercially for aggregates in the Bristol Channel and elsewhere.



Sediment thickness – metres

0-10 20-30 50-60
10-20 30-40 70-90

Fig 1.6 Channel systems and palaeo-valleys in the central and eastern English Channel, © NERC. Courtesy of Dr Ceri James. From Hamblin et al. (1992).

The accessibility of dredging vessels to these resources of coarse sands and gravels also depends on the water depth. At present, most aggregate dredgers are confined to water depths of less than 60m because of constraints imposed by the length of the pipe through which material is pumped aboard the dredging vessel. There are also economic constraints on the commercial viability of dredging sands and gravels that are distant from the centres of market demand. Marine aggregates are a relatively low-value commodity compared with oil, for example. It has been estimated that fuel consumption during transit accounts for as much as 65-75% of the total fuel used during the dredging cycle (see Chapter 9), hence passage time to and from the port to the dredge site and return is an important component of costs. Active marine aggregate dredging sites therefore tend to be developed mainly in areas where a dredger can leave port, dredge a cargo and offload to shore within a 24-36 hour cycle, with many operating on a 12 hour cycle.

The most important resources areas are located in the following main regions around the coast of England and Wales:

- The Humber-Wash area
- The East Coast (Great Yarmouth-Southwold)
- The Outer Thames Estuary
- The South Coast including the Eastern English Channel
- The Bristol Channel
- The North West (mainly Liverpool Bay-Irish Sea)

The distribution of the main marine aggregate resources that are currently being dredged around the UK is shown in Figure 1.7. There are about 70 licences for marine aggregate extraction within these main aggregate resource areas in the waters around England and Wales. They amount to a total of 1274km^2 of seabed of which 114km^2 (around 9%) is dredged in a typical year (based on 2011 figures from The Crown Estate). Within these dredged sites approximately 90% of dredging effort occurs in a small area of only 38km^2 of seabed, or 3% of the area of seabed that is licensed for aggregate extraction.

An obvious question is why such a large area is retained under licence, when only 105km^2 is required to meet the market demand for marine aggregates. The answer is that the much larger area that is retained under licence partly represents the need for operating companies to maintain 'capital reserves' of aggregates on the seabed for future use. Many licence areas have sufficient resources to allow them to be worked for many decades (30 years plus), with the extent and location of dredging operations changing over time as local deposits become exhausted or as market requirements change.

The resource surveying and environmental assessments that are required as part of the Consent and Licence processes can take anything between 3 and 10 years to complete. Coupled with the significant long-term investment required in vessels and wharf infrastructure (a single aggregate dredger can cost £40m and is expected to have a working life of 25 years), this means that reserves sufficient to meet projected demand for at least 20 years ahead are required for effective planning and management of the strategic assets that are required for the long-term operation of the industry.

A second reason for retention of a range of licence areas is that operators require access to a range of resources to allow them to flexibly react to changes in customer requirements together with wider market demands. Coastal defences, for example, may require resources that range from coarse cobbles and gravels to sands. These can only be obtained by retaining a variety of licences, each of which can be used to meet specific market demands.

In other cases it is uneconomic to transport aggregate cargoes long distances from a licence site to meet market demand. The solution is to retain a number of licence areas, each geographically located to meet local market demand and of a sufficient variety of deposit types to meet customer requirements without incurring major transport and environmental costs.

Finally, the demand for, and supply of marine aggregate resources for all the uses described in this section takes place in a hugely competitive market place. In each of the regions where marine aggregate production occurs, licences are operated by a number of competing operators – all of which need the capacity to respond to changes in the demand for marine aggregate materials in order to compete in the market place. In turn, this ensures that the market place is able to receive the most cost-effective solution to marine aggregate demand – whether this is for construction aggregate, beach nourishment or contract fill.

How Marine Aggregates are Dredged

The marine aggregate industry operates a fleet of about 28 dredgers each of which is fitted with a powerful suction pump capable of removing material and transferring it to a cargo hold in the vessel. The capacity of the dredgers is generally between 1,200 and 8,500 Te with a 5,000 Te capacity being typical. All dredgers are fitted with an electronic monitoring system (EMS) that records the position of the vessel while dredging operations are underway to ensure that activity only takes place within licence areas.

On arrival at the Licence site, a suction pipe of 0.7-1m diameter and up to 85m in length is lowered to the seabed. The end of the pipe is fitted with a drag-head that rests on the seabed and through which sand and gravel, along with

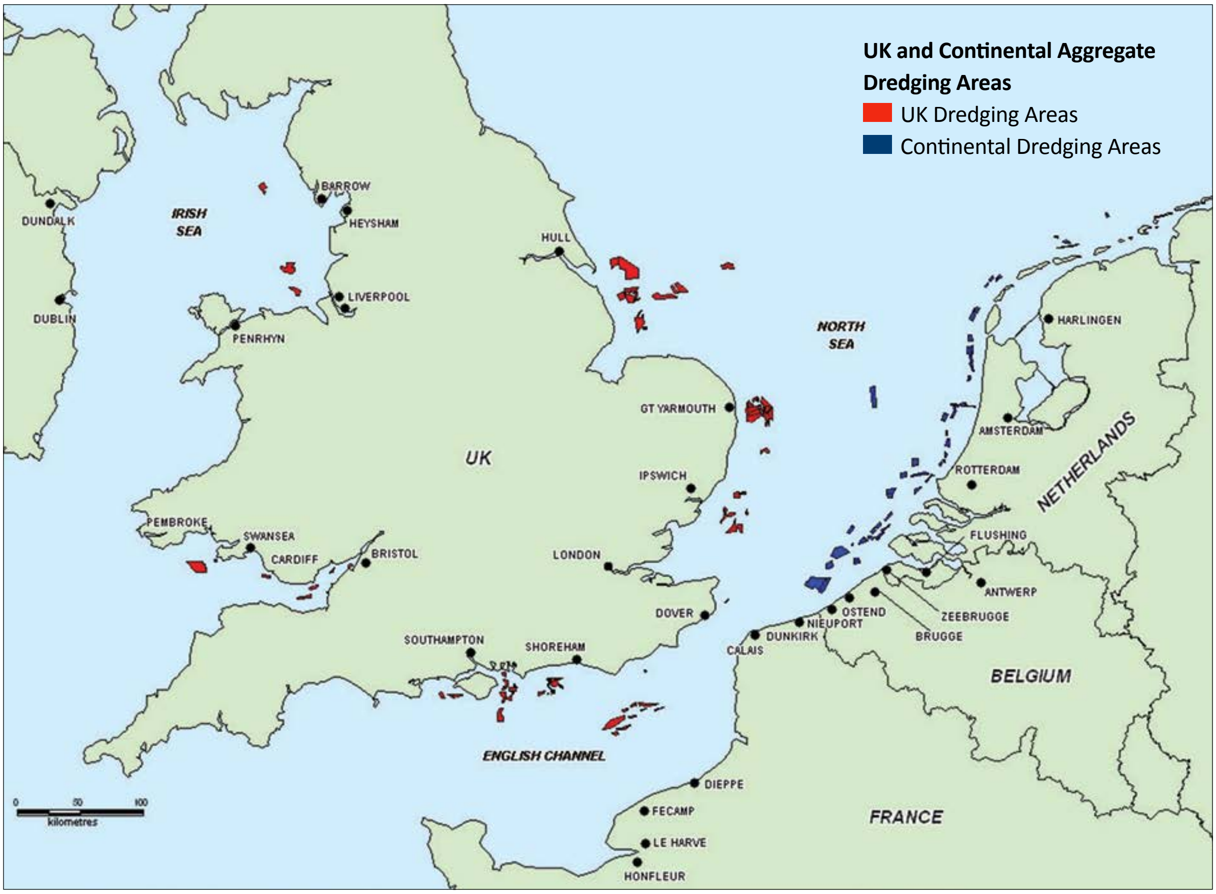


Fig 1.7 Map of the coastline showing the location of aggregate licence areas in the UK and adjacent coast of continental Europe. Courtesy of BMAPA.

Fig 1.8 Dredged material being transferred into the hold of the vessel. Sourced from BMAPA.

seawater is drawn up by a centrifugal pump into the cargo hold. The coarser aggregates settle to the floor of the cargo hold and excess water and some suspended fine-grained material is discharged through overflow spillways located near the top of the cargo hold ('hopper'). As a general rule, deposits that have high silt content are unsuitable for the construction industry so coarse-grained deposits with low silt content are targeted for aggregate dredging. Significant losses of silt through the spillways are therefore very unusual.

In some areas, the deposits are suitable for use in beach replenishment and for the construction industry without significant on-board processing. In this case, the aggregates can be loaded and transported to the wharf as an 'all-in' cargo which is often blended with other sorted materials at the wharf to produce the end product that is required to meet customer demands.

In other areas, however, the proportion of gravel in the seabed deposits can be too low for the all-in material to be commercially viable – concreting aggregate requires sand and gravel in a 50:50 mix. Where this occurs, a process termed 'screening' can be used to increase the gravel content of the sand and gravel retained onboard the dredger while loading. This works by passing the dredged sediment and water mix over a series of screens located in towers on the dredger. A proportion of the water and finer

Fig 1.9 Photograph of the Arco Humber dredger showing reject chutes and overspill, © MES Ltd.

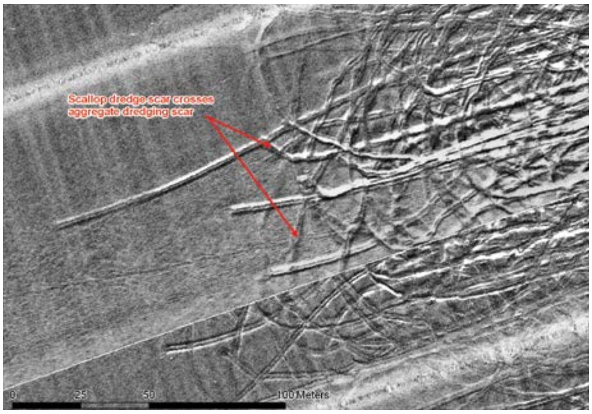


Fig 1.10 Side-scan sonar image showing aggregate dredge trails and scallop dredge scars on the seabed. From Vanstaen et al., (2010).

sediment passes through the screens and is returned overboard, while the coarser sediment and water mix flows into the vessel's hold.

The material being returned to the seabed via reject chutes and the loss of water through the overspills can be seen in this picture of a typical dredger operating in the southern North Sea (see Figure 1.9).

The quantities of material that are returned to the seabed through the screening chutes can be significant. It has been estimated that in order to obtain a 5,000 Te cargo of aggregate with a gravel: sand ratio of 60:40 from a typical North Sea deposit with a relatively low gravel content, it is necessary for the operating vessel to dredge about 12,000 Te of material and to return as much as 7,000 Te of excess sand to the seabed.

The type of dredging that is used also varies according to the depth and distribution of the deposits that are to be dredged. Where the deposits are thick and spatially constrained (up to 10m thick), the dredger can anchor and remove aggregates to a considerable depth below the seabed. Static suction dredging ('Anchor Dredging') of this sort is occasionally used in UK waters. However, over time this form of dredging can result in local dredge depressions of 10m or more in depth and can result in long-term impacts on seabed topography.

Trailer suction dredging is a much commoner form of aggregate dredging and is suitable for deposits that occur in extensive sheets on the seabed. In this case the drag-head is towed slowly across the seabed and along the axis of the tidal current at a speed of about 1.5 knots.

Trailer suction dredging is usually carried along the axis of the tidal streams because it is not possible to dredge at slow speeds across tidal currents that themselves may reach 3 knots on the Spring tides.

In contrast to static suction dredging, trailer suction dredging results in a series of shallow furrows on the seabed that are 2-3m in width and up to 0.5m depth. The dredge furrows can be relatively persistent features of the seabed deposits, depending on the local current regime and mobility of the sediments in a licence area.

This side-scan image (Figure 1.10) of the seabed shows the network of dredge trails from aggregate dredging. It also clearly shows the parallel trails from the heavy bottom gear used by scallop dredgers that deploy dredges on each side of the vessel. Repeated trailer dredging can result in a lowering of the seabed across a wider area (see Chapter 5), although generally the effects on bathymetry are small.

Landing and Processing

Aggregate dredgers are designed to self-discharge the cargo at the wharf. Generally this is achieved by systems such as scraper buckets (Figure 1.11) or bucket wheels (Figure 1.12) that can transfer material onto conveyor belts to deliver the material ashore at rates of as much as 2,000 Te per hour.

Once ashore, the ballast as dredged cargo is screened to separate coarse and medium sand from gravels, and to separate the gravels into the size ranges of 4-10mm, 10-20mm and 20-40mm in line with European product standards. Larger, oversized material is generally reprocessed through a crushing plant to produce smaller particles before being screened again. The screening process involves the dredged aggregate being washed and passed over a series of vibrating sieves that separate the material into sand and specific sizes of gravel which is stockpiled.

The main steps in the processing of aggregates at the wharf are shown in Figure 1.13.

This brief review of the nature and distribution of marine aggregates, their significance in meeting the requirements of the construction industry, and the process of aggregate dredging underlines the importance of the sector to the UK economy. At the same time, it is widely recognised that there are potential conflicts in seabed use with other

Fig 1.11 Dredger unloading its cargo of marine aggregates close to the centre of London using scraper buckets. Courtesy of Mark Russell of BMAPA.

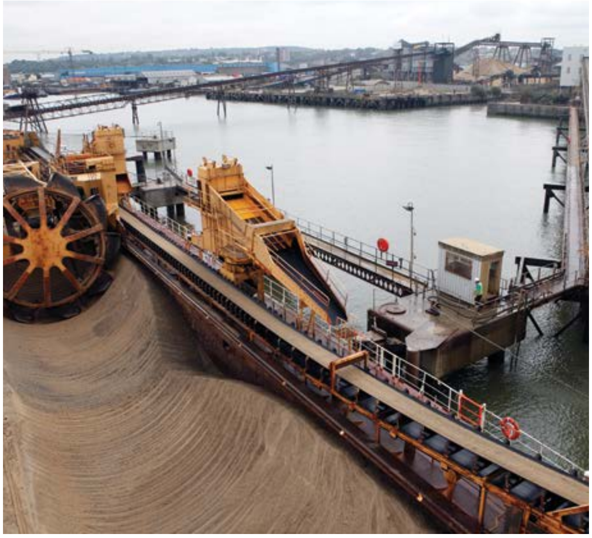


Fig 1.12 Dredger unloading its cargo of marine aggregates at an aggregate wharf using a bucket wheel. Courtesy of Mark Russell of BMAPA.

sectors that also have an important part to play in the well-being of society, as well as potential impacts on resources of conservation and cultural significance.

The purpose of this book is to provide an easily accessible summary of recent research on the impacts of aggregate dredging on the physical environment (coastal processes) and biological resources in the waters that surround our coasts.

Much of this has been supported through funds made available by the Aggregate Levy Sustainability Fund (ALSF) between 2002 and 2010, although where appropriate, we have included the results of work supported from other sources, including the aggregate industry. It includes work which has enhanced our understanding and ability to protect resources of biological, historic and archaeological significance, as well as advances in appropriate mitigation and monitoring of aggregate dredging that have been developed in recent years.

We recognise that much of the work reported in the original research reports is not easily accessible to the non-specialist, and for this reason we have synthesised the results specifically to make the information available in a less technical format. This has necessarily resulted in some loss of detail, and a lack of detailed references which are normally used to support reports in the scientific literature. We encourage the reader to refer to the original research reports for further detail should this be required. ■

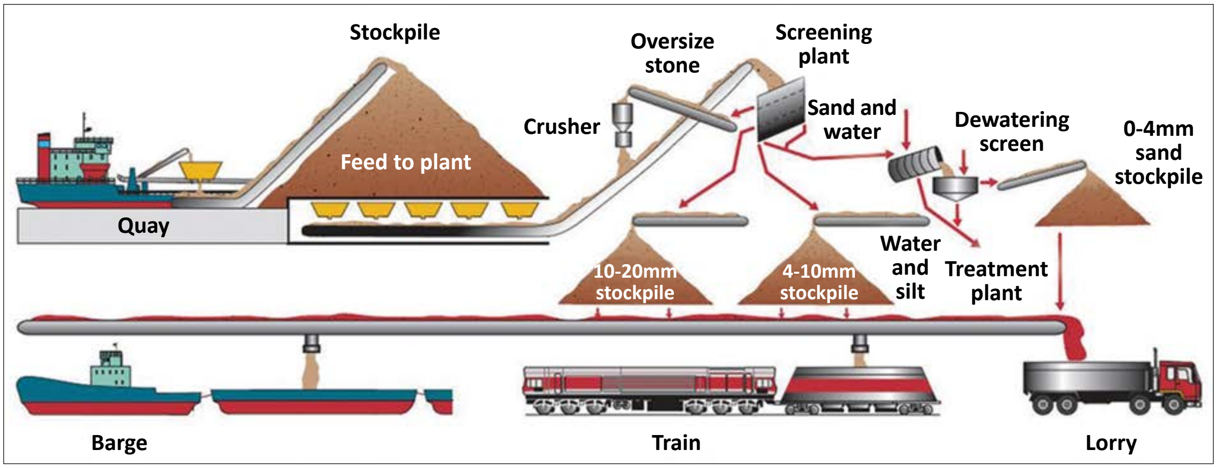


Fig 1.13 Processing of marine aggregates upon arrival ashore. From Highley et al., (2007).

2 HABITATS AND COMMUNITIES THAT CHARACTERISE AGGREGATE DREDGING SITES

By R.C.Newell, Richard Newell Associates

Introduction

The coastal waters that surround the British Isles are under increasing pressure from a wide variety of often conflicting activities. These include commercial fishing, offshore wind-farms, oil and gas installations, spoils disposal and aggregate dredging, as well as capital dredging for ports and harbours. The improved protection of the marine environment that is required to meet these challenges has been approached in recent years through the designation of several types of Marine Protected Areas (MPAs). These include Marine Nature Reserves (MNRs) designated for selected sites under the Wildlife and Countryside Act (1981), Special areas of Conservation (SACs) required under the European Habitats Directive, and Special Protection Areas (SPAs) required under the European Wild Birds Directive. Together the SACs and SPAs form a network of 'Natura 2000' sites that are intended to provide protection for wildlife resources over a relatively wide area around our coasts.

From 2013 onwards new MPAs known as Marine Conservation Zones (MCZs) will be designated across UK waters. The purpose of MCZs will be to protect rare, threatened or representative habitats and species under the Marine and Coastal Access Act (2009). The designation of MCZs will, in combination with existing MPAs, facilitate the creation of a coherent network of MPAs which will conserve our natural marine heritage.

The designation and management of these Marine Protected Areas on the seabed is largely dependent on identification of the nature and distribution of resources of conservation significance, and on an understanding of the interactions between the physical environment, and biological resources that support the marine food web.

Surveys that are required to define the geology, archaeology, historical assets and biological resources are both time-consuming and costly. They require dedicated survey vessels that are capable of deploying multiple arrays of instruments, together with specialist staff. They are, moreover, heavily dependent on suitable weather conditions to acquire data of the quality that can be properly interpreted.

Despite the complexity and costs that are incurred in seabed mapping projects, there has been a considerable investment in recent years in mapping the seabed around our coasts. This partly reflects a significant improvement in the range and quality of geophysical survey equipment, as well as enhanced software that provides improved interpretation of the data. These developments in geophysical survey methods, and in particular multibeam sonar, have revolutionised our ability to map significant areas of seabed, and to interpret the relationship between physical habitats and the biological communities that they support.

This has in the past been achieved by a combination of experienced visual interpretation of remote sensing data and 'ground-truthing' by seabed sampling using traditional grabs, trawls and other methods. More recently, however, there have been advances in our ability to automate the interpretation of geophysical data and to correlate the nature of the seabed with key biological features. The use of novel software to assist in the interpretation of geophysical data is still in its infancy but is likely to be used increasingly to improve the real-time interpretation of survey data aboard survey vessels at sea. Some of these geological and biological mapping techniques have been reviewed in a special issue of Continental Shelf Research (Heap and Harris, 2011; see also Schumann *et al.*, 2010).

Studies of the physical nature of the seabed and associated biological community composition have been an integral component of a number of major habitat mapping surveys carried out in UK waters in recent years. These include the Mapping European Seabed Habitats (MESH) programme (**www.searchmesh.net**), the Irish Sea Pilot and Habitat Mapping for Conservation and management of the southern Irish Sea (HABMAP) project and the UKSeaMap. More recently, combined geophysical and biological surveys have also been carried out under the Marine Aggregate Levy Sustainability Fund (MALSF) programme to define the habitats and other seabed resources in a series of Regional Environmental Characterisation (REC) surveys in the Outer Bristol Channel, Eastern English Channel, off the South Coast, the Outer Thames Estuary, East Coast and Outer Humber regions (**www.cefas.defra.gov.uk/alsf/projects/rec-projects.aspx**).

A chart showing the main areas in the eastern English Channel and southern North Sea that have been surveyed in some detail under the Regional Environmental Characterisation programme is shown in Figure 2.1.

Despite the increased investment in offshore marine habitat mapping that has occurred in recent years, there remain many areas of seabed around the British Isles where

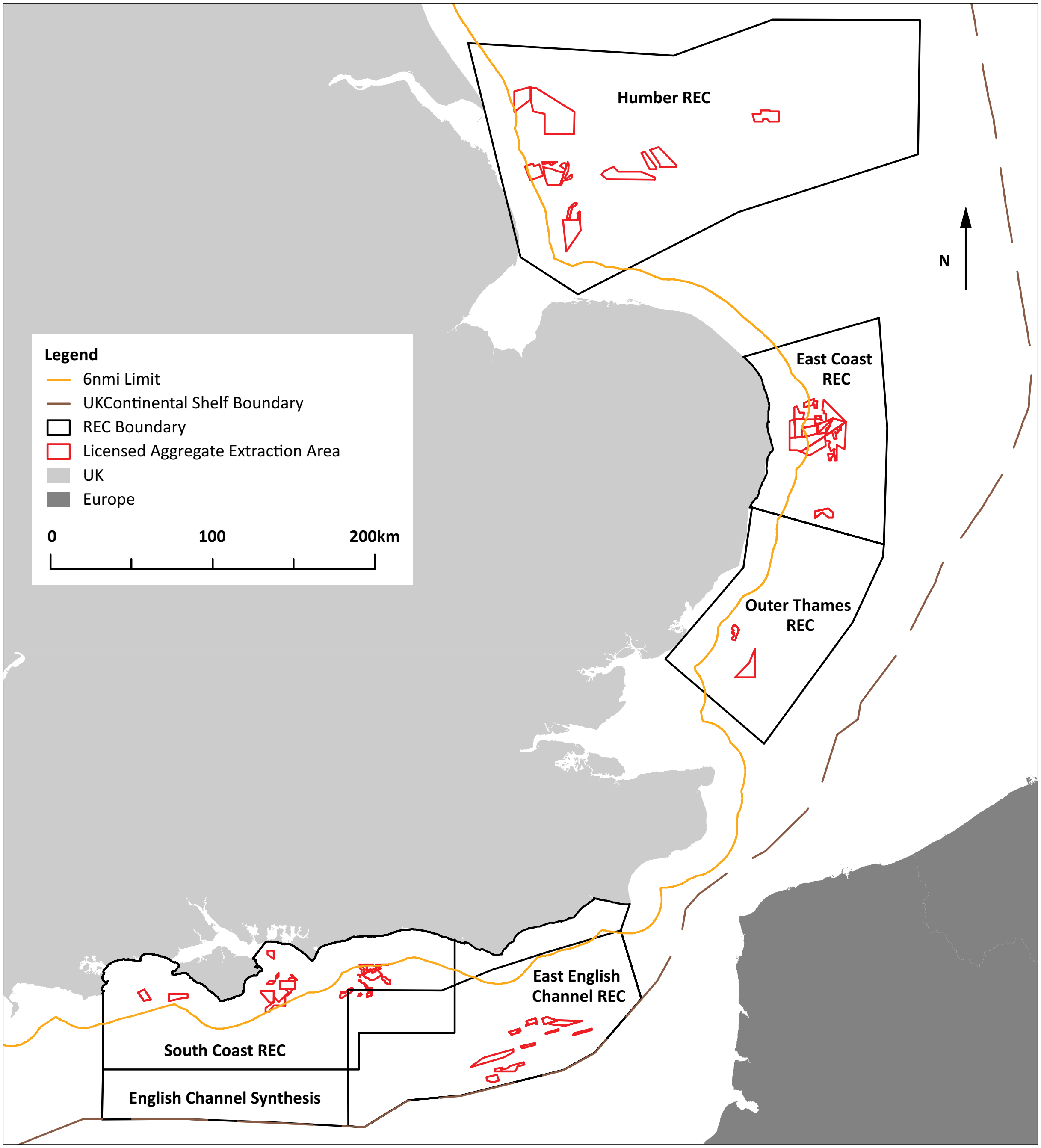


Fig 2.1 Chart of the southern North Sea and eastern English Channel showing the boundaries of the Regional Environmental Characterisation (REC) surveys in relation to the principle aggregate dredging sites under licence. Based on data from The Crown Estate.

we have little detailed knowledge of the nature and distribution of resources of conservation significance including archaeological and historical assets, geological features and biological resources.

Nevertheless as a result of the Regional Environmental Characterisation (REC) surveys carried out in the Outer Thames estuary, off the south coast of England, in the eastern English Channel and in the southern North Sea off the east coast and outer Humber, we now have a much better understanding of seabed assets that occur in areas that are licensed for aggregate extraction, or may be so in the future. A further series of industry-led Regional Environmental Assessment (REA) surveys have also recently been completed. These provide more detailed information for sites where aggregate dredging takes place. Such REA surveys include the Outer Thames Estuary (ERM Ltd., 2010), the Anglian region (EMU Ltd., 2012), the South Coast (EMU Ltd., 2012) and the Humber and Outer Wash region (ERM Ltd., 2012)

The Physical Environment

Habitat Designation and Conservation

The EU Habitats Directive recognises the importance of some features of the seabed both for their intrinsic geological significance, and for their ability to support specific biological communities of conservation significance.

They include unique features such as seamounts and those associated with geological activity such as hydrothermal vents and other forms of seepage which support food webs that operate independently of photosynthesis by plants. Other habitats of conservation significance are more common in the coastal waters that surround the British Isles, and are likely to be encountered in areas that are under licence for aggregate dredging either now or in the future.

Habitats that are specifically identified for conservation in Annex 1 of the EU Habitats Directive and which commonly occur near to areas that are licensed for aggregate dredging include ‘reefs’ and also ‘sandbanks that are slightly covered by seawater all the time’.

Reefs

Reefs arise from the sea floor as hard compact structures that are topographically distinct from the surrounding seabed. They can be either of ‘geogenic’ origin or ‘biogenic’ origin. Geogenic reefs can be formed of rocks (‘Bedrock reefs’), but also include stony reefs formed from cobbles and boulders greater than 64mm diameter. The nature of geogenic reefs and their susceptibility to disturbance has been recently reviewed by Houghton *et al.* (2011).

Biogenic reefs are structures that are formed as concretions by living or dead animals and plants such as mussels, serpulid worms that have calcareous tubes, other polychaetes such as the Ross worm, *Sabellaria spinulosa*, which cement sand grains into tubes, and calcareous algal concretions such as ‘Maerl’ beds. The importance of both geogenic and biogenic reef structures is mainly a result of the increase in habitat complexity which they provide, generally allowing for a greater species diversity and population density than would otherwise occur on a relatively uniform seabed habitat.

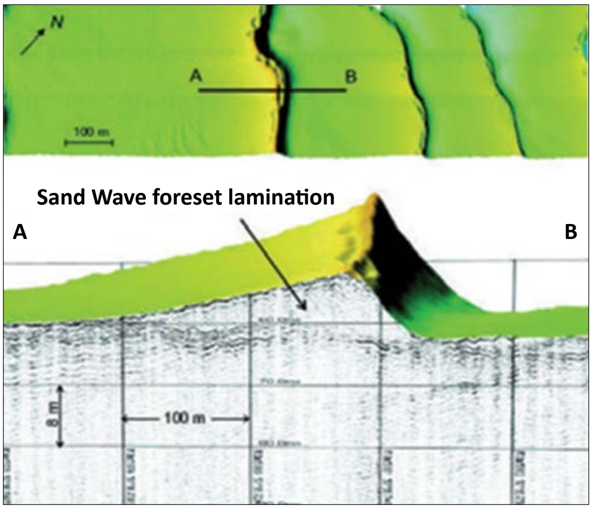


Fig 2.2 A multibeam and sub bottom profile of sand ripples in the Greater Bassurelle Sands in the eastern English Channel. From James et al. (2011), © British Geological Survey.

Sandbanks that are slightly covered all the time

Sandbanks can be either inactive ‘relict’ structures that have been submerged by rising sea levels after the last glacial maximum, or ‘active’ deposits that reflect the local tidal currents and wave regime. Relict structures include gravel beds, sediment waves and some of the large sand banks that occur around our coasts. Important areas of mixed sand and gravel such as the Norfolk Banks, for example, are thought to have originated during the rise in sea level that occurred in the mid-Holocene, about 7,800 years ago. These structures often comprise coarse sands and gravels that have been formed into sediment waves under the strong tidal currents that occurred when sea levels were lower. Other important relict sand banks include the Greater Bassurelle Sands in the Eastern English Channel (Figure 2.2).

In contrast, most active bedforms comprise sand, because current speeds are generally too weak to transport gravel except close to the shore. Active bedforms include large sand waves, smaller sand waves (sometimes referred to as ‘megaripples’), sand ribbons and sand patches.

As far as conservation designations are concerned, 'sandbanks' can consist of sandy sediments, but larger grain sizes including boulders and cobbles, or smaller grain sizes including mud, may also be present on a 'sandbank'. Where the substratum of a relict sandbank is relatively stable because of the presence of gravel and cobbles, they can provide habitats of considerable complexity and they support biological communities that are richer in species than active bedforms of mobile sands.

The Biological Environment – Marine Biotopes and Coastal Food Webs

Introduction

It is widely acknowledged that the nature and distribution of benthic biological communities and individual species is linked to a variety of physical and chemical features of the environment. The most important physical feature is the substrate type, which itself is often linked to sheer-bed stress from tidal currents and waves. But many other physical factors, including water depth (which influences the extent of disturbance of seabed deposits by waves), latitude, light penetration and water temperature as well as other factors including salinity and oxygen, play a part in determining the type of communities and component species that occur on the seabed.

Our understanding of the factors that control community composition is further complicated by the fact that many marine animals modify their environment in such a way that additional components of the community are able to colonise a habitat which might otherwise be unsuitable. The animals and plants that are dependent on the physical nature of the habitat can be regarded as the 'primary' components of the community, whilst those which occur because of their dependence on other members of the community are regarded as 'secondary' components.

A good example of this hierarchy of interdependence between the components of a community can be seen in the biogenic 'reefs' formed by mussels and *Sabellaria* spp. (see Chapter 3). As a result of the habitat complexity that is produced by this interaction between the physical and biological components of the environment, the biodiversity of communities that inhabit complex habitats such as biogenic reefs, or habitats that comprise mixed sands and gravels, is commonly found to be higher than at sites that have a more uniform substrate type (see Figure 2.14).

Habitat Classification

The sum of the physical features of a particular environment is commonly referred to as a 'habitat' whilst the complex environment that includes the animals and plants in a particular habitat is generally referred to as a 'biotope'. In many cases, however, the two terms are used interchangeably. A good deal of effort in recent years has been devoted to Habitat (or Biotope) mapping in the coastal waters surrounding the British Isles, as a necessary precursor to management of the seabed for conservation purposes, in relation to infrastructure projects and for other activities including aggregate dredging.

Essentially two approaches have been used to develop a classification of marine habitats (biotopes). These are a 'Top Down' and a 'Bottom Up' approach to marine habitat classification.

Top-Down Habitat Classification

The 'top-down' approach is a method of habitat classification that has been widely used in the UK and mainland Europe. In the UK the method forms the basis of the Marine Nature Conservation Review (MNCR) habitats classification scheme for Britain and Ireland (Connor *et al.*, 2004). In mainland Europe a comparable scheme forms the basis of the European Union Nature Information System (EUNIS) (European Environment Agency, 2004). Both schemes are used to assign biotope classes based on an assessment of the available information on the substrate type and other environmental factors, as well as the component species. The MNCR scheme takes biological components into consideration at an early stage in the hierarchical classification, whereas the EUNIS scheme classifies initial levels strictly in terms of physical environmental features before taking into account the species composition of the faunal communities.

Both systems have been widely used for marine habitat mapping in European coastal waters. They have, however, some inherent difficulties because they carry the assumption that individual species and community types can be correlated closely with sediment type and a small number of environmental variables such as water depth and current speed.

Whilst it is widely recognised that there is an association between community composition and deposit type, the boundaries between one community type and another are often very blurred. In soft sediments in particular, the number of environmental variables that affect the community composition is so complex that a simple association with sediment type and selected environmental variables is rarely possible. This means, in effect, that many species occur over a wide range of substrate types which can only rarely be used to define clear boundaries for a particular biotope. This is particularly the case in deposits that show a gradual change from one type to another. The fact that different substrate types may support overlapping community biological communities means that a good deal of 'expert judgement' needs to be used to match a particular sample to the constraints of the hierarchy imposed by both the MNCR and EUNIS habitat classification schemes.

The 'Bottom-up' Approach

An alternative is to use a 'bottom-up' approach to habitat classification. This is also a hierarchical system but in this case the biotic community composition is first identified and this is then correlated with substrate type and other environmental variables to arrive at a biotope designation. This system has the advantage that the element of subjective interpretation is removed and community composition can be objectively identified and linked with key environmental variables using statistical methods. The main difference between the two methods is thus that the top-down approach attempts to define boundaries between environmental zones based on geology, sediment type, salinity, depth and other environmental factors. The 'bottom-up' approach relies on establishing the relationship between biological community composition and environmental factors, and then using these to define habitats (biotopes).

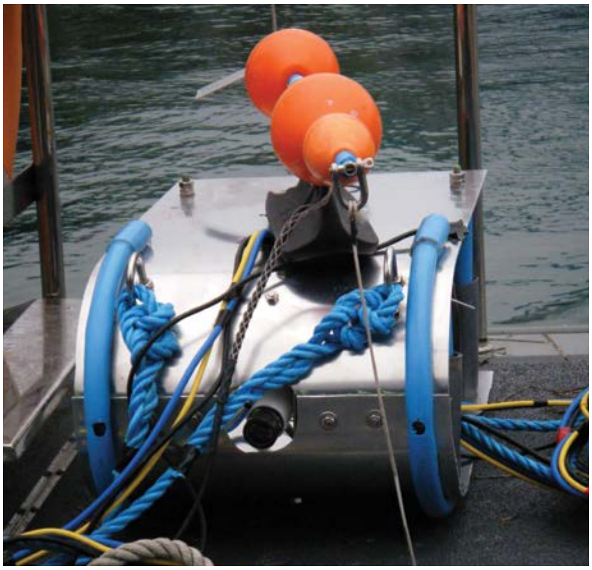


Fig 2.4 Sledge system for deploying underwater video of the seabed, © Envision Mapping Limited.

Fig 2.3 Seabed imaging camera system that uses a freshwater lens to reduce interference from suspended solids in the water column. From MES Ltd.

Whilst the 'top-down' approach has been widely used to define and manage seabed resources of conservation significance, there is an increasing recognition of the need to incorporate some elements of the 'bottom-up' approach into marine habitat classification (James *et al.*, 2010; Hooper *et al.*, 2011; Limpenny *et al.*, 2011). A widely-used technique using a 'bottom-up' approach is to identify biological communities by multivariate statistical methods, and then to link these communities to a combination of environmental variables using a convenient software package such as PRIMER (Clarke and Gorley, 2006). Other methods include multilogistic regression (MLC). This technique is widely-used in remote sensing and mapping applications. It uses the samples to derive statistical signatures that can then be applied to all the pixels in a data layer and allows one to calculate the probability of occurrence of particular biological communities with substrate type and other environmental variables recorded by geophysical methods.

Techniques based on information theory can also be used to calculate the probability of an assemblage occurring whilst making the least assumptions about environmental variables. One such model is Maximum Entropy (MaxEnt) which can be used to establish the relationship between environmental variables and a particular biological assemblage (see Phillips *et al.*, 2004).

Other methods of classification use a non-statistical approach to biotope classification. These include ArtMap (Adaptive Resonance Theory) which uses a neural network system to identify patterns in very complex data (Carpentier *et al.*, 1991a, b). A second model that uses supervised neural networks is Classification Tree Analysis (CTA). This approach develops a 'decision tree' that determines which environmental variables best separate the biological assemblages.

These and other methods have been recently reviewed by Limpenny *et al.* (2011; see also Heap and Harris, 2011).

As part of this process of more objective identification of marine habitats, Hooper *et al.* (2011) have recently developed an improved biotope classification for seabed sand and gravel habitats based on the MNCR system, but incorporating a biotope decision support tool that uses significant elements of the 'bottom-up' approach. This classification, known as 'BioScribe' may assist in more appropriate mapping of offshore sand and gravel habitats and lead to more informed management and regulation of marine aggregate licence areas (see www.Jncc.defra.gov.uk/page-5776).

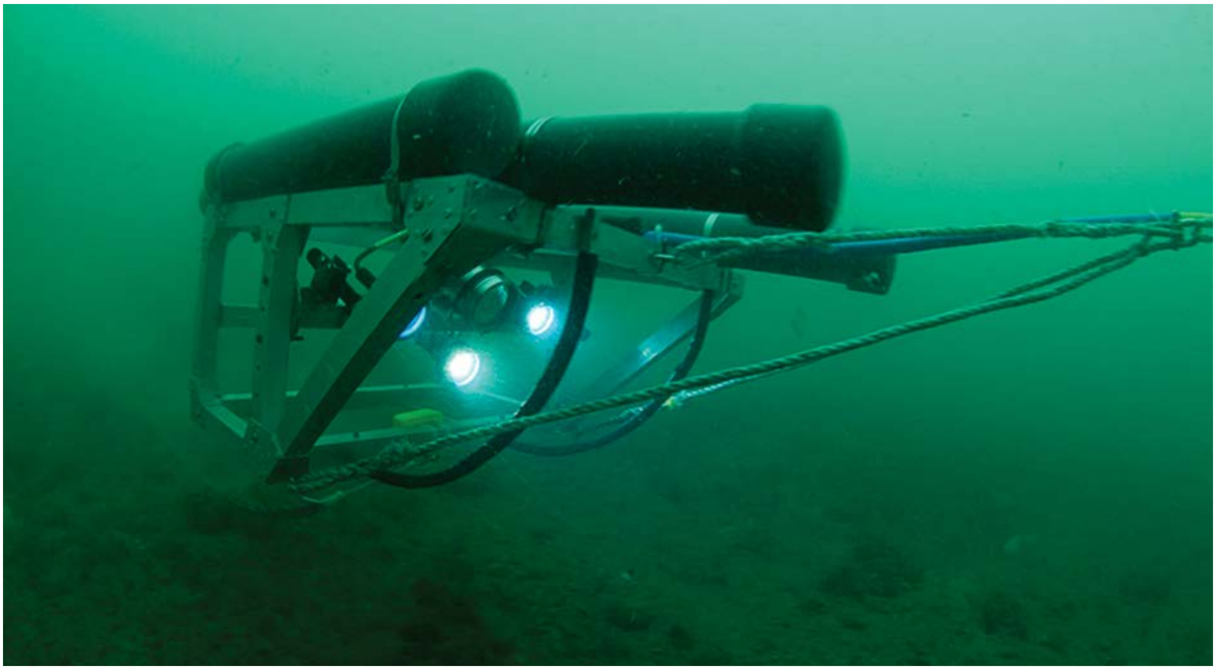


Fig 2.5 Underwater image of a new 'flying array' towed camera system that minimises contact with the seabed. From Sheehan et al. (2010). Courtesy of Prof Martin Attrill.

Sampling Methods

The equipment that is required to sample biological resources on the seabed largely reflects the type of substrates that occur in a particular part of the seabed as well as whether it is the mobile epifauna or the burrowing infauna, or both that need to be sampled. The methods available for sampling and subsequent analysis of benthic samples have been recently reviewed by Ware and Kenny (2011).

Seabed Imagery

Where the seabed comprises boulders or bare rock, estimates of the variety and abundance of sessile epifauna can be made with a drop camera. This takes digital still images of the surface of the seabed via a frame that is generally 0.1m^2 to allow a quantitative evaluation of the fauna in terms of the percentage cover by the component species. Whilst this system has been widely used in surveys of rocky substrata, it is generally suitable only for sites where the water clarity is good and where the tidal current speed is favourable. At other sites where there are high concentrations of flocculent matter or fine sediments in suspension a 'water lens' system has been increasingly used in recent years. Essentially this system has a transparent container of fresh water between the camera lens and the seabed, so that there is minimal seawater with suspended solids intervening between the camera lens and the seabed deposits.

Seabed imagery can also be used to study wider areas of seabed. Where the seabed is relatively flat, a video camera can be mounted on a sledge that is towed slowly behind the survey vessel to take a series of images of the seabed either continuously or at intervals of about 1 minute. This allows direct visual assessment of the substrate and epifauna and can be used to supplement or 'ground-truth' information obtained by geophysical methods. In some cases these can be combined with side-scan sonar imagery to provide a more complete picture of the physical features of the seabed that are associated with a particular biotope (see Foster-Smith *et al.*, 2010).

More recently, Sheehan *et al.* (2010) have developed a high-definition video camera system equipped with LED lights and laser scale markers which is mounted on a 'flying array' system that maintains its height above the seabed by a small length of chain that is trailed below the frame on which the camera is mounted.

The unit has a buoyancy chamber which is compensated for by the length of chain. When the camera system moves up in the water column, the chain loses contact with the seabed and increases the weight sufficiently to draw the unit down. This system is particularly useful when working over rough ground that is unsuitable for a towed sledge, and has the advantage that disturbance of the seabed is confined to the contact between the chain and the seabed. It is, however, heavily dependent on clarity of the water and is less suitable than systems using a 'water lens' when there are significant quantities of suspended matter in the water.

Fig 2.6 Scientific Beam trawl used for sampling epibenthic fauna. Courtesy of MES Ltd.

Fig 2.7 Standard 0.1m^2 Day grab used for sampling soft sediments. Courtesy of Dr John Coppock.

Beam Trawls

Beam trawls are widely used in the fishing industry to capture bottom-dwelling fish such as Dover sole (*Solea solea*) which can bury below the surface of the substrate. Smaller versions are also used in scientific surveys to collect mobile epifauna including small fish. A scientific beam trawl comprises a net with a 3mm mesh that is held open at the mouth by a 2m bar from which the trawl is towed. The lower part of the net is protected from damage by a chain mat, and there is often a coarse chain mesh across the mouth of the net and rock hopper discs to prevent large boulders from entering the trawl and damaging the mesh (see Jennings *et al.*, 1999). The trawl is towed for known distances and time to standardise the catch, which can then be quantified in terms of the numbers of animals captured per standard trawl length or area of the seabed that was sampled (see Curtis and Coggan, 2006).

Beam trawls are the main method of identifying and quantifying the mobile epifauna. They do, however, suffer from several drawbacks that need to be recognised when the data are being analysed at a later stage, and particularly when they are being used for a wider understanding of ecosystem function.

- Beam trawls are generally unsuited to areas where the seabed is very uneven, especially when there are large boulders or intermittent reefs present in the survey site.
- The trawl can only be towed at a slow speed of about 1.5 knots or it 'swims' up off the seabed. The slow trawl speed means that many of the larger mobile species such as fish can avoid capture by the trawl.
- Because of the relatively small size of the trawl aperture, mobile organisms such as fish can often avoid capture.
- The data are (at best) only semi-quantitative and cannot be compared directly with the more quantitative information available from grab samples of the benthic infauna.

This means, in effect, that information on very mobile organisms such as fish should be obtained by deployment of much larger and faster trawl systems, rather than on the data from small scientific beam trawls. It is also important to recognise that estimates of the number and biomass of epifauna per m^2 of seabed surface, based on trawl samples are less rigorous than data from quantitative grab sampling and the data do not include animals of less than 3mm size. Despite these inherent limitations on the data obtained from the use of scientific beam trawls, they remain the only practically useful method of identifying and quantifying the mobile epibenthos and remain a central survey tool for the marine ecologist.

Seabed Grabs

Seabed dredges and grabs are widely used to sample deposits of sand and gravel. Many types have been used in the past to sample seabed deposits and the associated biota. These include the naturalist's dredge and anchor dredges which were used to provide a non-quantitative sample of seabed deposits. The subsequent need for quantitative sampling led to the widespread use of jawed systems including Van Veen, Smith-McIntyre and Day grabs which provide a sample from a known area of seabed so that the numbers of organisms per m^2 of seabed can be quantified (for review, see Ware and Kenny, 2011).

The main difficulty with systems that use opposing jaws to retain the deposits is that small stones can jam the jaws partially open and this leads to large losses of sample whilst the grab is brought to the surface and landed aboard the survey vessel. This led to the development of the Hamon grab which is now widely used in benthic survey work.

The Hamon grab takes a sample from 0.1m^2 of seabed by means of a steel scoop which is closed against a plate by the tension of the wire that suspends the grab. It suffers from a disadvantage that the seabed sample is inverted during collection, so that if a profile of the sediment is required, a standard Day grab may be preferred.

One of the difficulties with using a Hamon grab in the rough sea conditions that often occur offshore is that the grab can touch the seabed and trigger the closing mechanism and subsequently be lifted up off the seabed by the survey ship on a wave before taking a seabed sediment sample. A second difficulty is that the fauna needs to be extracted quantitatively from the entire sediment sample in order to estimate the biodiversity and numbers of organisms in the sample. At the same time it is generally necessary to take a sufficient volume of sub-sample to analyse the particle size composition of the deposits from which the animals were extracted. Where the sample required for particle size analysis comprises a significant proportion of the total sample in the grab, this depletes that required for extraction of the infauna and makes exact estimates of the biodiversity and biomass per unit of seabed problematic.

Some recent developments of the Hamon grab have addressed these difficulties and have also resulted in improvements in the data obtained during deployment of the grab. These include an ability to take an underwater stills or video recording of the deposits that are being sampled by attaching a camera to the frame of the grab.

Other developments include an improved system for extraction of the fauna and for collecting sediment samples simultaneously to allow correlation of the community composition with features of the habitat in which they live. One such development is the Costerus grab (see Coppock, 2011). This system deploys two linked grab scoops that are operated by an air pressure system from a standard SCUBA tank, rather than by the wire suspending a Hamon grab. This means that triggering the grab is independent of the wire deploying the grab and that the equipment can be operated without being jerked up from the seabed during rough conditions.

The dual bucket system can be adjusted to take a variety of depths of sample and provides material for particle size analysis from one 0.1m^2 scoop and for extraction of the fauna independently from the adjacent 0.1m^2 scoop sample. This avoids depleting the material required for quantitative extraction of the infauna, whilst at the same time supplying a large sample for particle size analysis. Sea trials of this recently-developed equipment show that the compressed

Fig 2.8 Mini-Hamon grab which is widely used to obtain seabed samples from mixed sands and gravels. Courtesy of EMU Ltd.

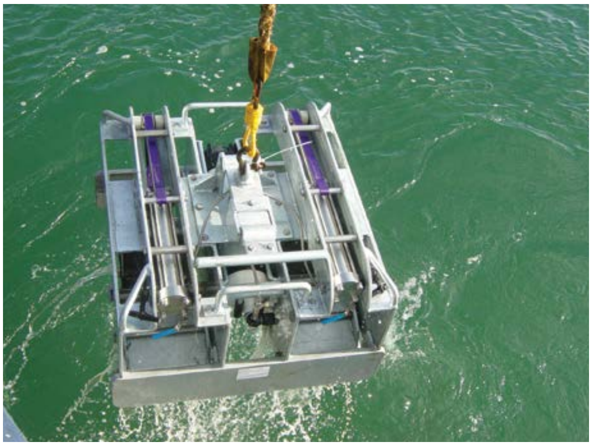


Fig 2.9 Twin Costerus grab developed to obtain two 0.1m² samples from the seabed simultaneously. Courtesy of Dr John Coppock.

Fig 2.10 Laboratory analysis of the fauna. Courtesy of MES Ltd.

Fig 2.11 A red alga, Callophyllis flabellulata and calcareous algae on a seabed reef, © James Watanabe.

air system can be used to obtain 7-15 seabed samples before being recharged from a larger cylinder aboard the survey vessel. The increased weight of the equipment means, however, that it cannot easily be deployed aboard very small survey vessels of the type that are commonly used for Hamon grab surveys in near-shore waters.

Material from the grab sample, whichever type is used, is then transferred to an appropriate mesh sieve, depending on the nature and objectives of the study for which the samples were collected. For many surveys associated with sands and gravels a mesh size of 0.5mm mesh is used, although in some instances a 1mm mesh is more appropriate. The sample is then carefully eluted to remove excess deposits before being transferred into neutral formalin for preservation and later analysis in the laboratory.

Laboratory analysis itself is a time-consuming and specialist job. It requires the separation and counting of all individuals in the sample, as well as identification to species level and analysis of the biomass of component groups. Such analyses are, however, central to our understanding of the nature and variety of communities that live on the seabed, and their relation to the physical environment in which they live.

The Significance of Substrate Type

Seabed deposits represent a relatively wide range of particle sizes, from stones with a diameter of several centimetres down to sands of 1mm. In some cases, deposits are relatively well-sorted but in most instances comprise a mixture of particle sizes that allow a wide range of organisms to survive. There are two features of the environment that largely control the type of biotope that inhabits the seabed. These are the depth of water and the stability of the substrate. The depth of water controls whether plants can survive and grow. The stability of the deposits controls whether surface-dwelling animals and plants can attach and survive.

Plant life is dependent on sufficient sun-light to allow photosynthesis. Hence it is restricted to either shallow areas of seabed of generally less than 20m depth or to the surface waters of the sea as minute planktonic plants such as diatoms.

The leaf-like 'thalli' of larger algae (macrophytes) that are attached to the seabed have different pigments that are adapted to assist efficient use of the light required for photosynthesis at different depths in the sea. The algae along the shore and in very shallow waters are green, much like plants on land. These form the group known as Chlorophyceae, whereas those in shallow waters, such as the fucoid wracks (*Fucus* spp) and oar weeds (*Laminaria* spp) are brown. This brown colour results from the presence of a pigment called fucoxanthin which masks the green chlorophyll responsible for photosynthesis. At depths of a few metres down to about 20m the algae that are attached to stable rocks, cobbles and stones are red in colour, such as those in Figure 2.11. These are members of the Rhodophyceae which have phycobiliproteins that give the plant a red colour.

Below this depth, there is generally insufficient light to allow photosynthesis by even red algae. The biotopes over much of the seabed that surrounds our coasts are thus devoid of larger attached algae, even if the deposits are sufficiently stable to allow attachment. Few of the deposits that are dredged for aggregates therefore have any attached macrophytes because of the lack of light available for photosynthesis at 30-50m depth, and because the deposits are generally too unstable to allow the attachment of algae.

A second factor that controls community composition is the stability of the substratum. Where the seabed comprises larger boulders and cobbles, the seabed deposits are sufficiently stable to allow attachment of a wide range of invertebrate species. These organisms are known as 'Epifauna'.

They can be either sessile – that is, attached to the stones and boulders that comprise the seabed – or they can be mobile, in which case they can crawl or swim over the surface of the deposits.

Sessile epifauna include barnacles, encrusting bryozoans, anemones, ascidians (sea squirts) and branching hydroids. The mobile epifauna include organisms such as crabs, prawns, brittlestars and fish, many of which are interdependent with the sessile epifauna that are attached to the boulders and stones.

Where the deposits are less stable, such as in areas of seabed covered with mobile sands, the sessile epifauna is generally absent. In this case many components of the fauna live in tubes or burrows or seek temporary shelter in the deposits from which they make excursions to the surface to feed. Thus whilst the surface of sands and mud may seem barren compared with the profusion of life on the surface of rocks and boulders, there is in fact an abundant biodiversity of animals that live beneath the surface of the seabed, or amongst the stones and shells that comprise the deposit. These burrowing organisms are known as the 'infauna' to distinguish them from the surface-dwelling 'epifauna'.

Typical members of the infauna include tube-dwelling peacock worms (*Sabella* spp) that filter food from the water column through a crown of feathery tentacles, but are able to retreat into a tube to escape from predation, as well as deposit-feeding polychaete worms and small crustaceans.

Fig 2.12 Photo of a dense epifaunal community on a reef in the Menai Strait, North Wales, © Paul Naylor, www.marinephoto.co.uk.

Fig 2.13 Benthic infauna – the Peacock worm, Sabella pavonina, emerging from its tube in the deposits on the sea floor, © Sue Daly.

Biomass and substrate complexity

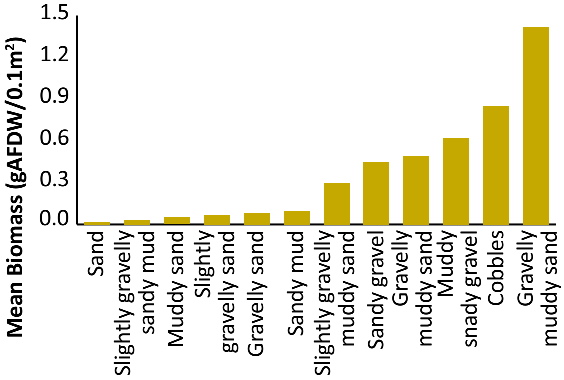


Fig 2.14 Histogram showing the increase in biomass of benthic infauna in complex substrates in the Outer Thames estuary REC. Redrawn from Emu Ltd. (2009).

Community composition

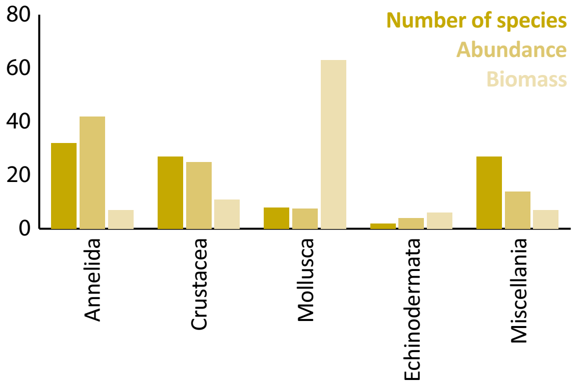


Fig 2.15 Histogram showing the number of species, abundance and biomass of the principal faunal groups recorded from grab sample surveys in the South Coast REC area. From James et al. (2010).

Principal Species – South Coast REC Area

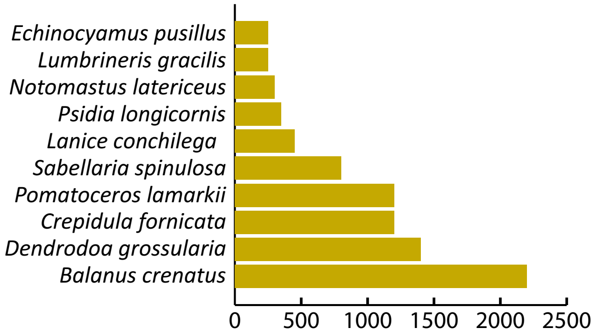


Fig 2.16 Bar chart showing the numbers of the principal ten species recorded from grab samples taken in the South Coast REC area. From James et al. (2010).

Communities in Gravels and Sands

Stones and Gravels off the South Coast of the UK

It is well-known that deposits with a relatively uniform grain size have been found to support a lower species richness, population density and biomass of fauna than more complex deposit types such as sandy gravel, cobbles and gravelly mud. The relationship between the particle size composition of the deposits and the biomass of benthic infauna in the outer Thames REC area is shown, for example in Figure 2.14.

There are other general features of the benthic communities that inhabit sand and gravel deposits in areas that are likely to be licensed for aggregate extraction. These include the predominance of polychaete worms and small crustaceans in mobile sands, and the increased abundance of surface dwelling sessile and mobile epifauna on more stable coarser deposits.

Figure 2.15 shows the principal groups of animals (phyla) that occur in mixed deposits in the English Channel off the south coast of England. This shows that annelid worms and crustaceans were the most important components in terms of species variety and they also dominated the communities in terms of abundance (number of individuals). But the biomass was dominated by molluscs which comprise relatively large organisms. The deposits are thus characterised by large numbers and a great biodiversity of small polychaete worms and crustaceans compared with smaller numbers of larger molluscs such as shellfish.

The analytical techniques that are used to identify marine biotopes also allow identification of the key species that contribute to the biological community that characterises a particular deposit as well as their similarity to other communities that might share some species in common (see Clarke and Gorley, 2004).

Because the deposits in the Regional Environmental Characterisation (REC) area off the south coast of England were predominantly coarse, the epifauna were abundant on the cobbles and stones that were present on the seabed.

Figure 2.16 shows that the most abundant species in this particular sea area was the common subtidal barnacle *Balanus crenatus* which settles on stones and shells after a planktonic phase known as a nauplius. This then metamorphoses into a bivalve cyprid larva that can select a suitable substratum by detecting the physical and chemical characteristics of a suitable substratum, including the presence of adults of the same species.

The second most abundant species was the colonial sea squirt (an ascidian) *Dendrodoa grossularia*, which is also common on coarse stable gravel deposits in the southern North Sea and elsewhere around our coasts.

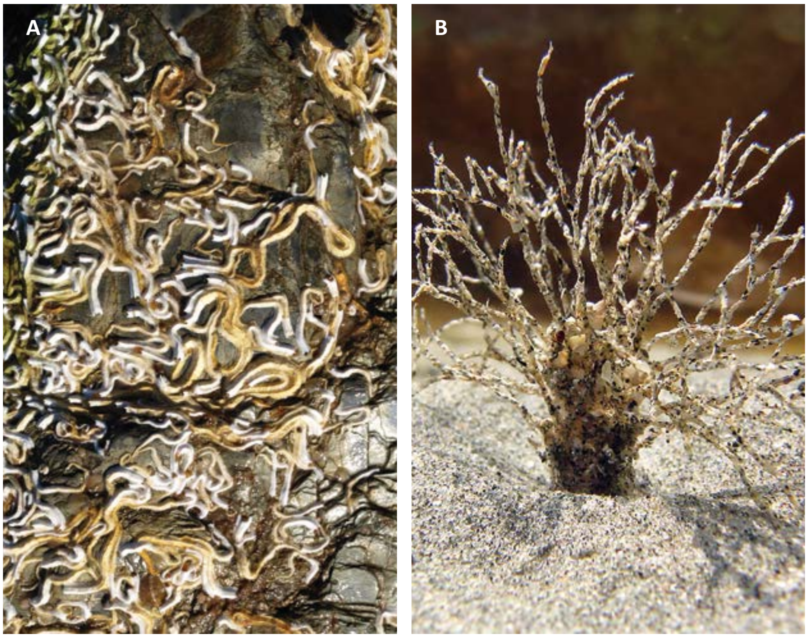


Fig 2.17 A colony of the sea squirt, Dendrodoa grossularia. Courtesy of MES Ltd.
Fig 2.18 Photographs of a A rock colonised by Keel worm, Pomatoceros lamarckii, © David Fenwick, and B a sand mason, Lanice conchilega, tube in the seabed, © Richard Lord.

Fig 2.19 A blenny from mixed aggregate deposits typical of those likely to be dredged for sand and gravel. Photo by Ray Drabble of ABPmer.

The third most abundant species was the American slipper limpet, *Crepidula fornicata*, followed by the serpulid worm, *Pomatoceros lamarckii*, which lives in calcareous tubes attached to rocks, stones and shells and the ross worm, *Sabellaria spinulosa*, which forms sandy tubes attached to stones and shells on the seabed.

Other important components of the biotope include the sand mason, *Lanice conchilega*, the pea crab, *Pisidia longicornis*, burrowing worms such as *Notomastus* sp. and *Lumbrinereis* sp., and the tiny green sea urchin, *Echinocyamus pusillus*.

Similar analyses can be carried out for the surface-dwelling epifauna captured with a 2m beam trawl. Figure 2.20 shows the 10 species that characterised the epifauna in the south coast REC survey area. The commonest was the American slipper limpet, *Crepidula fornicata*. This species is a gastropod snail that is an immigrant species which is now widely established in UK waters. It has an efficient filtering system that allows it to compete with oysters and other bivalves for food suspended in the water column. Other characterising species included brittle stars, prawns, sea urchins, starfish and fish.

The epifauna captured with the beam trawl includes more mobile and larger species than recorded with the grab samples, but both have a high proportion of surface-dwelling epifauna. This reflects the large numbers of epifauna that are able to attach and survive on the coarse stable substrates of stones and gravel that predominate in the South Coast Regional Environmental Characterisation (REC) survey area.

Epifauna – South Coast REC

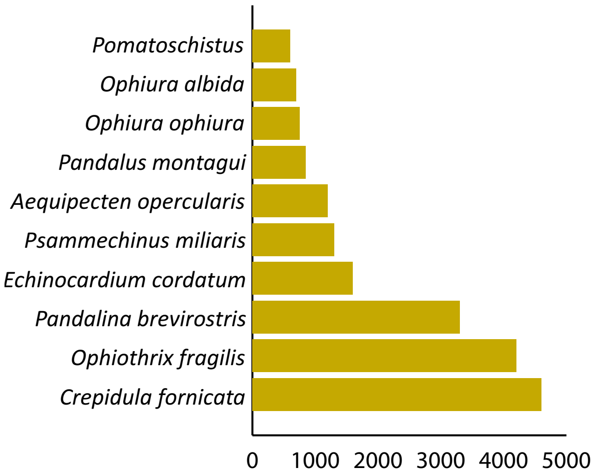


Fig 2.20 Bar chart showing the numbers of the ten most abundant species recorded in a series of 2m beam trawls in the South Coast REC survey area. From James et al. (2010).

Infauna – East Coast REC

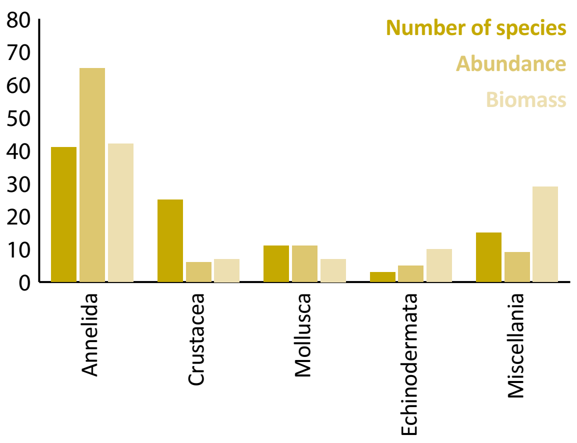


Fig 2.21 Histogram showing the number of species, abundance and biomass of the principal faunal groups recorded from grab sample surveys in the East Coast REC area. From Limpenny et al. (2011).

Mixed Sands and Gravels of the Southern North Sea

Similar analyses of the mixed sands and gravels have been carried out at many sites in the southern North Sea including the East Coast Regional Environmental Characterisation study in 2010 (Limpenny *et al.*, 2011). In this case the community is clearly one that is predominantly characteristic of mixed sands rather than the stable substratum provided by stones and boulders.

Figure 2.21 shows that in common with the gravel deposits in the English Channel off the south coast of England, the community is dominated in terms of biodiversity by polychaete worms (Annelida). In this case they are sufficiently abundant to also dominate the population density and biomass of invertebrates recorded in the survey area. This corresponds with the increased presence of sands compared with epifauna that dominate the stones and boulders of the English Channel REC survey area.

Figure 2.23 shows that the polychaete worm, *Sabellaria spinulosa*, was the most abundant species present, followed by juvenile mussels (Mytilidae), sea anemones and other species including brittle stars. Two potential reef-forming species (Ross worm and mussels) are therefore characteristic of mixed sands and gravels in the southern North Sea along with a wide range of other species that reflect the complexity of the habitat available in mixed deposits.

Similar techniques can be applied to the data for the mobile epibenthic organisms captured by beam trawls (see Figure 2.6).

In this case, however, the epibenthic community is dominated by brittlestars (*Ophiura* spp and *Ophiothrix fragilis*), crustaceans such as the brown shrimp, *Crangon crangon* and pink shrimp, *Pandalus montagui*, sea urchins (*Psammechinus miliaris*), starfish and crabs.

These communities are ones that characterise the types of deposits that are most commonly encountered in areas of the seabed that are licensed for aggregate extraction. Some communities have, however, been identified as 'rare' or threatened on parts of the seabed in European waters, and for this reason have been given additional statutory protection under the EC Habitats Directive. These require specific identification and protection and mitigation in the Environmental Impact Assessment (EIA) that forms part of the licence application procedure. Ones that can potentially be encountered in the coastal waters that surround the British Isles are reviewed in Chapter 3. ■

Fig 2.22 Typical invertebrates from sand and gravel deposits. A – A chain-forming mollusc, the American slipper limpet, Crepidula fornicata. Courtesy of Angela de Burgh – MES Ltd. B – The Ross worm, Sabellaria spinulosa, extracted from its sandy tube, © MES Ltd. C – A dense community of the brittlestar, Ophiothrix fragilis in the English Channel. Courtesy of Dr Nigel Thomas – EMU Ltd. D – The brittlestar, Ophiura albida, Courtesy of MES Ltd. E – Sabellaria spinulosa community with the common starfish, Asterias rubens and juvenile brown crabs, Cancer pagurus. Courtesy of MES Ltd. F – The velvet swimming crab, Necora puber, © Sue Daly.

Infauna – East Coast REC

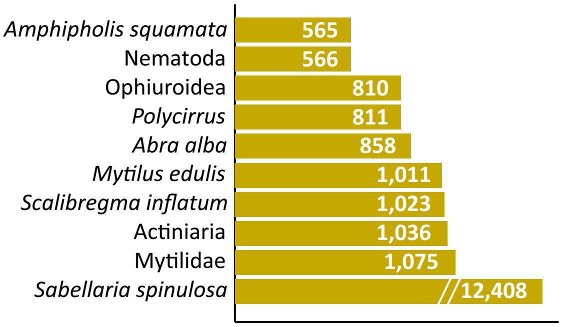


Fig 2.23 Bar chart showing the numbers of the principal ten species recorded from grab samples taken in the East Coast REC area. From Limpenny et al. (2011).

Epifauna – East Coast REC

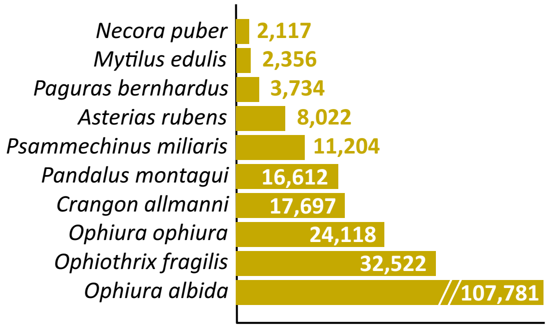


Fig 2.24 Bar chart showing the numbers of the ten most abundant species recorded in a series of 2m beam trawls in the East Coast REC survey area. From Limpenny et al. (2011).

3 SPECIES AND BIOTOPES OF CONSERVATION SIGNIFICANCE AT AGGREGATE DREDGING SITES

By R.C.Newell, Richard Newell Associates

Protected Habitats and Communities

Communities and habitats that have statutory protection under the EU Habitats Directive and are likely to occur in the vicinity of aggregate dredge sites include:

- Sandbanks that are covered by the sea at all stages of the tide
- Geogenic reefs
- Biogenic reefs

Sandbank Communities

The Joint Nature Conservation Committee (JNCC) has issued a summary of the habitat definition that is relevant to sandbank features of conservation significance. They regard an Annex 1 sandbank as an area of sand that is surrounded by deeper water and where the top of the sandbank is covered by less than 20m of water.

In many cases they are relict bedforms comprising relatively coarse material that is not mobilised by the prevailing tidal currents and waves. These stable gravel and sandy gravel deposits can support communities that are rich in both species diversity and population density, because mixed deposits provide a more complex habitat than relatively uniform sandy deposits that occur in active bedforms.

The significance of the communities that inhabit active bedforms of mobile sands should, however, not be underestimated. The animals that live in this habitat type are mainly burrowing crustaceans, polychaete worms and bivalves (known collectively as 'infauna'), or active species that seek temporary refuge in the deposits whilst also making foraging excursions into the water column to feed. Sandbanks located in shallow water often support not only dense populations of shrimps, prawns and other crustaceans, as well as polychaete worms and bivalves, but also a food web of fish and birds that prey on the sandbank community.

Although these communities are generally less diverse than those that characterise the complex habitats provided by rock and cobble reefs, they often support high population densities of invertebrates and represent important feeding and nursery grounds for fish species of commercial importance (see Schuckel *et al.*, 2010; Garcia *et al.*, 2011).

Geogenic Reef Communities

Geogenic reef habitats provide an important holding ground for sessile algae in shallow water. They can provide a holding ground for dense forests of brown algae including kelp which in turn support a rich food web of invertebrates and fish as well as birds and mammals. In deeper waters, red algae dominate reef structures and these are replaced by sessile sponges, hydroids and ascidians in deeper waters where there is insufficient light to support photosynthesis by algae.

Differences also exist between the communities that characterise surfaces and crevices of rocky reef structures, and between hard rocks and softer material such as chalk and hard clays. Hard rocky reefs are characterised by surface-dwelling animals such as barnacles, serpulid worms, sponges, hydroids and ascidians, many of which are dependent on filtering suspended plankton from the overlying seawater for food. Softer rocks support a dense 'epifauna' of animals that are attached to the surface of the rocks, or seek shelter amongst the surface-dwelling community, but also support boring species such as the sponge *Cliona celata*, and bivalves like the piddocks (*Pholas dactylus* and *Barnea parva*)and the false piddock (*Petricola pholadiformis*).

Biogenic Reef Communities

Biogenic reef communities that may occur in the vicinity of marine aggregate dredge sites mainly comprise:

- Mussel beds (*Mytilus* spp and *Modiolus* sp)
- Ross worm reefs (*Sabellaria spinulosa*)
- *Serpula* spp. beds
- Maerl beds

Mussel Beds

Mussel beds are made up of either the horse mussel (*Modiolus modiolus*) or the edible blue mussel (*Mytilus edulis*). Horse mussels are mainly sub-tidal whilst the blue mussel occurs both on the shore and in shallow waters. Both types can form extensive biogenic reefs in which the mussels are attached to one another and to the substratum by byssus threads secreted by the foot. Silt and processed material filtered by the mussel and rejected as either faeces or 'pseudofaeces' may then accumulate between the shells

Fig 3.1 A typical horse mussel (Modiolus modiolus) bed community showing the accumulation of silt and attached epifauna. From Hendrick et al. (2011), © T. Wilding.

Fig 3.2 A small clump of the Ross worm, Sabellaria spinulosa, © Dr Vicki Hendrick.

Fig 3.3 A A rock covered by the honeycomb worm,Sabellaria alveolata, and B a close-up of honeycomb worm tubes. Courtesy of Dr A J Davies.

to form a matrix. The whole mussel bed community thus comprises mussels, silt and a complex biotope with sessile organisms such as barnacles and hydroids attached to the shells of the mussels. A typical Horse mussel bed community showing the accumulation of pseudofaeces and the presence of sessile epifauna of barnacles and hydroids is shown in Figure 3.1

Mussels have a planktonic larval phase called a veliger which feeds in the plankton. Prior to settlement, the veliger is able to test the substratum for suitability before settling onto hard substrata of rocks, stones and shells. Initial settlement is therefore dependent (amongst other factors) on the presence of rocks or stones that are stable objects on the seabed. The mussels can therefore be regarded as 'primary' components of the community in the sense that their presence is dictated by the physical nature of the habitat.

The activities of the mussels then alter the habitat in such a way that 'secondary' components of the community can appear. The presence of organic-rich mud deposits amongst the mussels, as a result of the accumulation of pseudofaeces, allows deposit-feeding polychaete worms such as *Amphitrite johnstoni* as well as the large ragworm, *Nereis virens*, to colonise the mussel reef. Mussels also play host to the tiny pea crab, *Pinnotheres pisum*, which lives within the mantle cavity and scavenges material filtered by the mussel. Other parasitic animals such as the copepod, *Mytilicola*, inhabit the gut of the mussel, whilst barnacles and hydroids comprise an epifauna that colonises the outer shell.

All of these 'secondary' components of the community are dependent on the presence of mussels, rather than on the physical properties of the habitat that are directly required for mussel attachment.

Finally there are 'tertiary' components to the community. These components are reliant on the secondary components in the hierarchy of species that make up the mussel bed community. In the case of blue mussel beds in the south-east of England, there is often a commensal scale worm polychaete (*Gattyana* sp.) that lives in the burrow of *A. johnstoni* and is therefore dependent on the secondary component rather than either the mussels or the physical features of the habitat that control the primary colonising organisms.

The main threat that can result in a loss of this complex mussel bed community is damage from heavy bottom gear used by fishing vessels. Scallop dredging has, for example, resulted in the almost complete destruction of horse mussel beds in Strangford Lough. Similar losses of other biogenic reef communities such as ross worm (*Sabellaria spinulosa*) have been recorded in the Wadden Sea following the use of heavy bottom gear for capture of pink shrimp. Mussel bed communities are, however, generally well-adapted to survive moderate short-term increases in suspended solids and sporadic burial, such as might occur close to dredging sites where screened material is returned to the seabed during the dredging process. The susceptibility of mussels and other key components of the fauna to suspended solids and burial are reviewed in Chapter 6.

Ross Worm (Sabellaria spinulosa) Reefs

The Ross worm (*S. spinulosa*) is a widespread and abundant species that lives on the seabed in coastal waters around the British Isles. It commonly occurs in small groups of tubes that form clumps on solid substrata such as rocks and stones, but can form crust-like communities on the seabed.

It can also form larger reef-like structures, particularly on the steep sides of seabed features in some areas such as The Wash and in the 'Silver Pit' off the outer Humber estuary. There has been some debate as to what comprises a 'reef', but generally reef-like features comprise many thousands of sand tubes, built up over several to many years and comprising a mixture of old unoccupied tubes

Fig 3.4 Common components of Sabellaria reef communities. The porcelain crab, Pisidia longicornis, and the pink shrimp, Pandalus montagui. Courtesy of MES Ltd.

and those with living worms inside. For reasons that are currently unknown, *Sabellaria* communities can be relatively ephemeral and may undergo a cycle of accretion and decay over a period of 5-7 years.

These communities are regarded as of conservation significance because they support a larger species diversity and/or biomass and population density of associated species, which in turn may form an attractive feeding area for fish of both non-commercial and economic significance (see Griffin *et al.*, 2012). For this reason, *Sabellaria* communities are generally well-known to fishermen. Partly because of their importance in enhancing biodiversity, and also because they are prone to damage by heavy bottom gear used by beam trawlers, *Sabellaria* reefs are protected as 'biogenic reefs' under the EU Habitats Directive (Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora). They are also listed as a threatened and/or declining habitat under the OSPAR Convention and are listed under the UK Biodiversity Action Plan (1994).

A related species (*Sabellaria alveolata*) known as the 'Honeycomb worm', forms dense reefs of sand tubes on rocks and boulders on the mid-lower shore, particularly in the west and south-west of the British Isles.

Occasionally Ross worm can be seen intertidally on the lower shore on low Spring tide in The Wash and in the German Wadden Sea, but it is easily distinguished from the Honeycomb worm. The Honeycomb worm forms tight closely-packed reef structures, whereas the Ross worm forms loosely-packed colonies of parallel tubes that are more prone to damage than their more robust intertidal counterparts which are adapted to survive the high energy wave conditions on the shore.

The biology of Ross worm communities has recently been studied off the east coast of England by Pearce *et al.* (2011) using data acquired during a Regional Environmental Survey of the east Coast. The results of this work, and that of others working on *Sabellaria* reefs off the Wash, challenge some of the attributes that have in the past been considered to underline the conservation significance of Ross reefs. These studies suggest that although the *Sabellaria* reef habitat supports a high biodiversity of fauna, the apparent enhancement compared with surrounding deposits is mainly a reflection of the nature of the deposits against which the reef community is compared. Thus a reef that is surrounded by mobile sands with impoverished species diversity may have many times the biodiversity of the surrounding deposits. If, on the other hand, a reef is surrounded by mixed deposits of gravel and sand which provide greater habitat complexity,

***Sabellaria spinulosa* species richness**

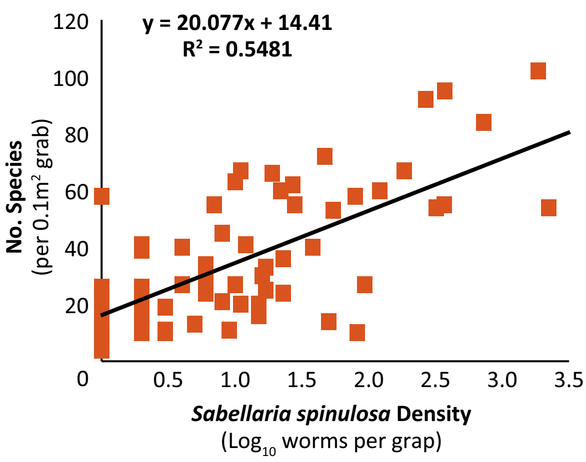


Fig 3.5 Regression line showing the correlation between the number of benthic species and the density of living Sabellaria spinulosa recorded per 0.1m² mini Hamon grab sample taken from Sabellaria spinulosa reefs in the southern North sea. From Pearce et al. (2011).

then there is no significant difference in biodiversity between a *Sabellaria* reef and the surrounding sandy gravel habitat (Pearce *et al.*, 2011).

It should be pointed out that the study by Pearce *et al.,* (2011) shows that major differences in community composition exist between *Sabellaria spinulosa* reefs and the surrounding deposits notwithstanding the high biodiversity that may occur in each habitat type. What does appear to be of significance is the ability of Ross reefs to support high population densities of some species that occur in only relatively low numbers in the surrounding deposits. These locally enhanced populations of crustaceans such as the porcelain crab, *Pisidia longicornis* and the pink shrimp, *Pandalus montagui*, along with the *Sabellaria* worms themselves, in turn form an important food resource for commercially significant fish including Dover sole (*Solea solea*), plaice (*Pleuronectes platessa*), dab (*Limanda limanda*) and many other fish that are important in the food web leading to birds and mammals.

Sabellaria reefs can persist for some time, even though the worms themselves have disappeared. It has previously been assumed that 'relict' reefs of this type may retain their significance in providing a complex habitat with high biodiversity and population density. The study by Pearce *et al* (2011) shows, however, that there is a strong correlation between the biodiversity (number of species recorded) and the proportion of living *Sabellaria* worms in the reef. In other words, reefs comprising mainly empty *Sabellaria* tubes do not support the same biodiversity as their living counterparts. Figure 3.5 shows that reefs with mainly dead *Sabellaria* supported about 15 species per 0.1m^2 grab sample whereas reefs with large numbers of living worms were capable of supporting a biodiversity of as much as 80 species per grab sample.

The work also suggests that the enhanced number of invertebrates that characterise *Sabellaria* reefs is fairly consistent, irrespective of the size of the reef. Thus small clumps of reef or the crusts of *Sabellaria* that occur in many parts of the southern North Sea can have just as an important role in supporting marine food webs as the larger mature reefs – a feature that is well-known to the fishermen who recognise the importance of areas of Ross worm when targeting their fishing effort.

It should be noted that the use of heavy bottom gear used in trawling and dredging for oysters and mussels may have a significant effect on Ross worm communities.

The loss of large *Sabellaria* reefs in the Wadden Sea, for example, has been linked in the past to trawling for shrimp, and similar damage has been reported for the Thames and Morecambe Bay in the 1950s. *Sabellaria* is, however, broadly tolerant of increases in suspended solids

Fig 3.6 Serpulid worm showing feeding tentacles and the modified tentacle that forms a plug (operculum), © Hugh Brown, National Facility for Scientific Diving, Scottish Marine Institute.

mobilised by aggregate dredging (see Chapter 6) and shows rapid recolonisation and growth at sites adjacent to active dredge zones (ADZs) in aggregate licence areas on the Hastings Shingle Bank (see Pearce *et al.*, 2007). The main threat to this species thus appears to be the direct removal or disturbance of the reef structure under the footprint of dredging or fishing gear, rather than indirect impacts of fishing or dredging activities nearby (see also Holt *et al*, 1998).

Serpula Reefs

Biogenic reef communities with a complex array of interdependent organisms are sometimes formed by the serpulid tube worm *Serpula vermicularis*. Serpulid worms are filter-feeding animals that capture suspended food from the water column by means of an array of tentacles and can withdraw into a calcareous tube which is then closed by a plug-like calcareous operculum.

There are many genera of serpulid worms in UK waters and they can form relatively dense incrustations on shells and rocky surfaces, as well as on a variety of different algae. Some have specific habitat preferences, including the type of algae that are preferred for settlement. The planktonic larva also has an ability to detect the presence of other members of the same species and this is also used as part of site selection during settlement. Only the relatively large species *Serpula vermicularis* forms reef-like colonies, and even then is perhaps more commonly represented by isolated or small groups of individuals attached to shells, mooring buoys and clean rocky surfaces, especially those colonised by encrusting bryozoan colonies on the lower shore and in shallow waters down to about 15m water depth.

It has been reported at depths of as much as 200m but the only recorded reef structures in the UK are in very sheltered waters of Loch Creran and Loch Sween in Scotland. *Serpula* reefs have also been recorded in Ardbear Lough, Salt Lake, Cliffden and Killary Harbour Co Galway, Ireland. The species is, however widely-distributed and relatively common in the coastal waters that surround the British Isles especially off the coast of north-east England.

Serpula reefs are associated with a wide range of invertebrates. These include encrusting sponges, and

Fig 3.7 A Serpulid reef found in Loch Creran, Scotland, © Hugh Brown, National Facility for Scientific Diving, Scottish Marine Institute.

ascidians such as *Ascidiella aspersa*, *Ascidia mentula*, *Diplosoma listerianum* and *Dendrodoa grossularia*. *Molluscs* such as queen scallop, *Aequipecten opercularis*, brittlestars, *Ophiothrix fragilis*, and the sea urchin, *Psammechinus miliaris*, are also typical members of the *Serpula* reef community which also includes squat lobsters, *Galathea squamifera*, and velvet swimming crabs, *Necora puber*.

Typical fish species recorded from *Serpula* reefs include corkwing wrasse (*Crenilabrus melops*), ballan wrasse (*Labrus bergylta*), cod (*Gadus morhua*), butterfish (*Pholis gunnellus*) and sand gobies (*Pomatoschistus* spp.). None of these species appear to feed on the *Serpulid* worms themselves, but are dependent on the associated invertebrate community that characterises the reef biotope.Serpulid reefs are considered to be sensitive to physical damage from heavy bottom gear used for scallop dredging and probably also from local sources of organic enrichment from alginate extraction in sea lochs. Although isolated or small clumps of tubes are likely to be recorded from areas of cobbles and stones that may be targeted for aggregate extraction, there are no records of any *S. vermicularis* reefs in, or near any of the sites that are currently under licence for aggregate extraction, or are likely to be licensed in the future.

Maerl Beds

The nature and occurrence of maerl biotopes has been reviewed in some detail by Birkett *et al.* (1998). The term 'maerl' is used to describe aggregations of unattached calcareous red algae that may include a significant proportion of dead material. The principal coralline algae that contribute to maerl formation in UK waters are *Lithothamnion coralloides*, *Lithothamnion glaciale*, *Phymatolithon calcareum*, and *Lithophyllum incrustans*, although at least six other species have been recorded from maerl deposits in other areas. *Phymatolithon calcareum* is the most widely-distributed and abundant maerl species in the UK whilst *L. coralloides* is replaced in Scottish waters by *L. glaciale*. The two principal UK species (*P.calcareum* and *L.coralloides*) are included in Annex V of the EC Habitats Directive and are also included in the UK Biodiversity Action Plan list.

Maerl is formed when these crust-forming species undergo fragmentation and produce free-living fragments that grow very slowly and reproduce by further fragmentation to form flat beds and sometimes large banks. They can be formed in association with a wide range of sediment types from fine mud to coarse sand and gravels as long as these occur in sites with relatively low suspended solids and strong currents. Maerl appears to thrive in conditions where the seabed is naturally disturbed by strong currents and waves, such that the maerl thalli are frequently moved around (Hinojosa-Arango *et al.*, 2009). Like all seaweeds, maerl requires sunlight to grow and is generally found at depths of up to 20m although some records show that it can occur down to 40m.

Some of the most extensive maerl beds in Europe are located in Norway, along the coasts of Brittany and in the west of the British Isles, particularly in Scotland and Ireland, as well as in the south-west of England on the St Mawes Bank in the Fal and in the Helford estuary. They are, however, absent from most of the North Sea, the Baltic, the Irish Sea and eastern English Channel.

Maerl beds comprise a habitat of considerable complexity and biodiversity compared with more uniform seabed features of sand and mud, but do not usually support a richer biodiversity than mixed substrates with a wide range of sediments (see Birkett *et al.*, 1998). Few of the animal species recorded from maerl beds are confined to these biotopes, but several species of algae are generally confined to maerl (eg., *Gelidiella calcicola*, *Cladophora rhodolithicola* and *Cruoria cruoriaeformis*), and hence some are protected as 2007 UK Biological Action Plan (BAP) Priority Species. Dead maerl beds also support diverse communities although, as in the case of *Sabellaria* reefs described above, they are less rich than those of live maerl beds. Thus whilst the individual species that comprise the maerl community are not generally unique to maerl itself, the community as a whole contributes to a biotope that is of conservation significance in terms of its biodiversity compared with more uniform deposits that occur on the seabed.

The growth rate of some maerl species has been estimated to be less than 1mm per year so the rates of regeneration are exceptionally slow compared with other algal species (see Blake and Maggs, 2003). Hence the maerl itself, as well as the complex community that develops within maerl beds is regarded as unusually susceptible to long-term damage and has a high conservation status in UK waters.

Maerl deposits are extensively dredged in Brittany (see Grall and Hall-Spencer, 2003) and have been dredged on a limited scale in the Fal estuary, although this ceased in 2004. It is mainly used in crushed powder form as a soil conditioner on acidic ground and for other purposes including road fill, as an animal food additive, for filtration of acidic water and in the pharmaceutical industry. The biotope is susceptible to damage from heavy bottom gear used in scallop dredging, from suction dredging for bivalves and from sedimentation from capital dredging works (Blake *et al.*, 2007). Although maerl is very susceptible to burial by fine-grained or anoxic sediments, it appears to be more tolerant of some other environmental pressures such as extremes of temperature, salinity and heavy metal pollution than had previously been supposed (Wilson *et al.*, 2004).

Maerl beds do not occur in any of the areas that are currently licensed in the UK for aggregate extraction and would, in any case be subject to rigorous protection under the Environmental Impact Assessment and statutory Consent processes that are required to obtain a licence for aggregate dredging.

This overview of the nature and distribution of seabed biotopes suggests that some species and communities of conservation significance are susceptible to damage by direct removal of the seabed during dredging, and by disturbance from the use of heavy bottom gear used in dredges and trawls. There are also examples of 'secondary' impacts caused by the mobilisation of sediment and subsequent deposition in areas of seabed outside the immediate footprint of impact. The nature and scale of impacts of aggregate dredging and the tolerance of seabed communities to disturbance, is reviewed in Chapter 6. ■

Fig 3.8 Crustose calcareous algae and branching maerl from deposits in Iceland. Courtesy of Prof Juliet Brodie.

Fig 3.9 A branching maerl fragment from Iceland. Courtesy of Prof Juliet Brodie.

4 MARINE ARCHAEOLOGY

By A. Firth, Fjordr Limited

Introduction

Archaeology is the study, conservation and public dissemination of humanity's past through its material remains. Archaeologists investigate objects and sites, their environmental context and broader setting in order to generate insights about people and society in the distant – and not so distant – past. They seek to share these human stories with today's public, to inform, engage and entertain so that now and in the future we remain mindful of the lives of our predecessors. Archaeologists also seek to conserve important material remains from the past so that they continue to have a physical presence in our environment, and can be appreciated, explored and understood by future generations. We all have a tremendous responsibility, over our few decades, to avoid needless damage to elements of our environment that have accrued over centuries and millennia; nor should we ignore or compromise the stories that the historic environment tells, or may yet tell.

For centuries, people have been aware that old objects and structures can be found under the sea, and from time to time have devised means to recover or explore them. In the 19th century (C19th), Charles Lyell noted in his Principles of Geology (1832) that:

"It is probable that a greater number of monuments of the skill and industry of man will in the course of the ages be collected together in the bed of the ocean, than will exist at any one time on the surface of the Continents." (Quoted in Muckelroy, 1978, 11).

However, scientifically-based archaeology directed at objects and structures under the sea has only become widespread since the 1960s, prompted by the availability of the aqualung but now encompassing a much broader range of methods. 'Marine Archaeology' now encompasses the methodologies, types of site, management frameworks and scope of enquiry that are most relevant to marine aggregate dredging.

Diving is the methodology most often associated with marine archaeology, but it forms a relatively low proportion of most archaeological investigations prompted by marine aggregate dredging for reasons that are discussed below. As well as diving, desk-based study, geophysical survey and geotechnical investigation have come to play a very important role, with important innovations also occurring in various forms of sampling of the surface of the seabed.

The range of objects and sites that may be investigated is also very wide, including shipwrecks and other maritime remains arising from ships, boats and seafaring. Prehistoric remains – dating to periods when sea-level was much lower and much of the UK Continental Shelf was exposed and inhabitable as dry land – are increasingly being recognized as an important component of marine archaeology. From the more recent past, aircraft remains – dating predominantly to WWII – have also become a particular cause for archaeological concern. Although other forms of archaeological material may come to light, it is these three – maritime, prehistory and aircraft – that are most often addressed day-to-day in the marine aggregates industry, and have been used to structure the substance of this chapter.

History of Investigations

As noted above, marine archaeology is a source of fascination, but it is also an issue of environmental concern. The history of archaeological investigations relating to the marine aggregates industry – starting in the mid-1990s – has been driven by this environmental concern, and particularly by the regulatory framework through which dredging is licensed. Far-reaching environmental regulations affecting all major developments, both on land and at sea, were introduced as a consequence of the Environmental Assessment Directive, 1987, reflecting a wider, global trend to carrying out Environmental Impact Assessment (EIA). From the start, the Directive specifically included 'archaeological heritage' equally amongst the elements of the environment that had to be considered. This in turn was consistent with international law as set out in the European Convention on the Protection of the Archaeological Heritage as revised in 1992 (known as the Valletta Convention), which included specific obligations on dealing with the archaeological heritage affected by major development schemes.

Although archaeology was rapidly becoming a significant feature of EIA for land-based development in the UK, application to developments in the marine sphere was patchier. Applications for licences by marine aggregate companies became subject to EIA through the Government View procedure, and although they addressed archaeology in the early-mid 1990s it was typically as a very short section saying how many charted wrecks were in the area, and how many were subject to statutory protection.

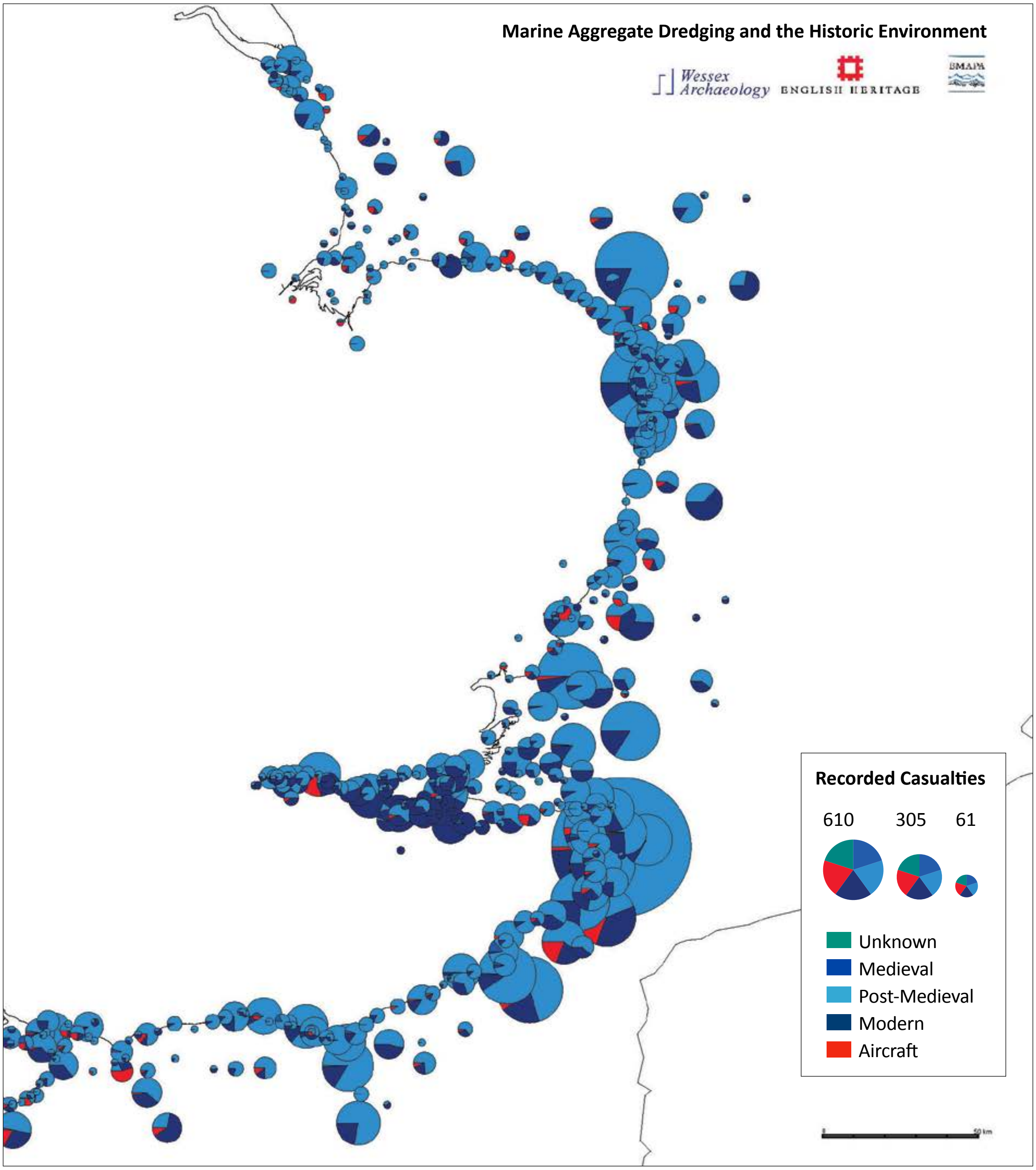


Fig 4.1 Map summarising records of shipping losses on the East Coast, drawn from the National Record of the Historic Environment (NRHE) in the course of a pre-ALSF project for BMAPA and English Heritage. Courtesy of Wessex Archaeology.

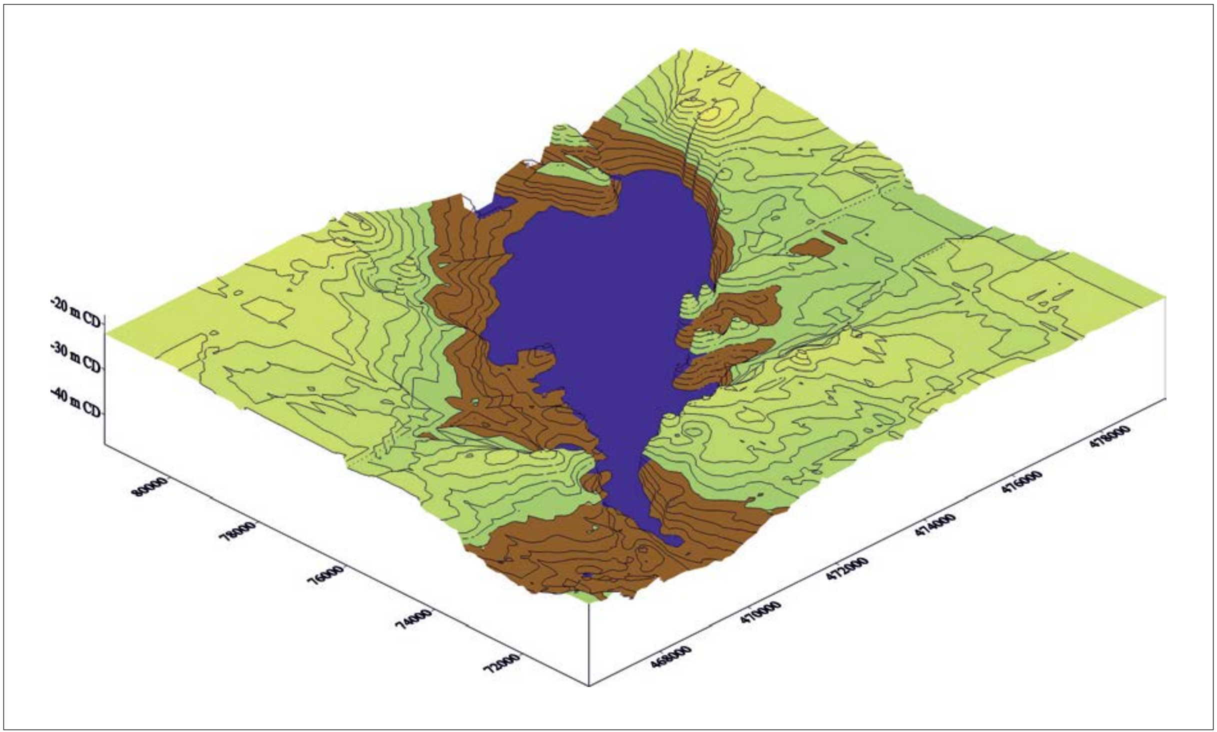


Fig 4.2 Visualisation of the dry, intertidal and sub-tidal landscape of the palaeo-Solent in Area 451 off the Isle of Wight, from the 1998 EIA. Courtesy of Wessex Archaeology.

Concerns over the adequacy of EIAs with respect to the archaeological heritage started to be raised by archaeologists working in local authorities, who were being consulted in the course of the Government View procedure. As a consequence, aggregate companies started to commission more detailed technical reports on marine archaeology from specialist archaeological contractors. Simultaneously, the marine aggregate industry as a whole started to take a very proactive role towards archaeology at a more strategic level, alongside other key environmental concerns, in order to better understand the potential for impacts to improve the evidence-base for decision-making, and provide guidance for the industry (Russell and Firth 2007; BMAPA and English Heritage 2003). More detailed consideration of archaeology also became a feature of regional environmental studies, specifically those in the Bristol Channel and Eastern English Channel.

In the mid-late 1990s, this improved provision for archaeology was predominantly desk-based. There was a very low level of knowledge of what archaeological material might actually be present within an aggregate licence area, reflected in short sections listing charted wreck sites and designated wrecks. Although the archaeological resource that was 'known' was very slight, it was recognised that the as yet unknown resource – or 'archaeological potential' – might be much more numerous, and much more important. The low level of knowledge was a reflection of the source data and how it had been acquired, so technical reports sought to better capture this potential using additional sources available to desk-based research. These included lists of ships known to have been lost in the region whose remains had not yet been found (i.e. documented losses or 'casualties'), details of unidentified features on the seabed – identified only as bathymetric anomalies or fishing snags – which might prove to be archaeological in origin, historic charts and sailing directions that referred to navigational hazards, and the general history of seafaring in the region, nationally and internationally, to indicate overall patterns of historical activity and the types of site that might be encountered.

The effort to better represent potential for maritime archaeological sites was accompanied by simultaneous attempts to address prehistory, for which there was no known direct evidence within aggregate licence areas but which was of particular concern to local authority archaeologists. The potential for prehistoric sites was addressed by extrapolation from archaeological information from adjacent coastlines and river catchments; and by combining current seabed bathymetry with information on sea-level change to gauge the presence, age and character of possible now-submerged landforms.

Both for maritime archaeology and prehistory, these desk-based estimations of potential had to be tempered in some way by field-based data. In these early stages, this meant desk-based review of field data acquired by the aggregate companies and their surveyors.

Specifically, desk-based assessment would include a review of the core logs obtained by vibrocores obtained predominantly for testing the thickness of aggregate resources. Desk-based assessment also started to include a review of geophysical data from the seabed – especially sidescan data that was made available on paper rolls. In addition to this relatively raw field data, archaeologists also had access to the interpretations carried out by the aggregate companies for their own purposes – such as bathymetric contours, contours of resource thickness, charts showing seabed features, and the accompanying interpretive reports.

Although such data was field-based, archaeologists' access was fundamentally desk-based, as users of the results rather than having any role in acquisition, processing or interpretation. Furthermore, the archaeologists engaged in reviewing such data, whilst specialised in marine archaeology, did not necessarily have additional specialisms in geophysical or geo-archaeological interpretation as would become increasingly the case in later years

It is worth noting that the expertise amongst aggregate company staff – especially with respect to quaternary seabed geology and its implications for archaeological potential – made a significant contribution to the early desk-based assessments. Technical discussions between archaeologists and aggregate company staff about how the seabed formed and how aggregate dredging processes operated were important in establishing a collaborative approach between industry and archaeologists to establishing key questions and seeking to resolve them (Bellamy 1995; 1998).

Although good progress was made through this early phase of desk-based assessment, very high levels of uncertainty remained in terms of what might be present and how it might be affected by dredging. Approaches to mitigation were correspondingly cautious, comprised mainly of the use of relatively small defined zones around features that were known or suspected to be of archaeological interest in which dredging would not take place – known as exclusion zones – which followed the approach then being taken to avoid impacts to sensitive ecological habitats such as *Sabellaria* reefs. Exclusion zones were accompanied by protocols for reporting any archaeological finds to act as a 'safety net' for archaeological material that had not been identified in desk-based work. Approaches based on protocols, where industry staff would report anything they found, were chosen instead of the traditional land-based approach of a 'watching brief' because such watching briefs – whether they took place on-board the dredger or onshore at the processing wharves – were likely to be hazardous, ineffective, and unreasonably costly.

Experience started to show, quite quickly, that exclusion zones could be overly precautionary and operationally constraining. Whilst exclusion zones around known wrecks made sense to everybody because of the need to avoid damage to dredging equipment as well as to avoid damaging the wrecks themselves, the case was less certain for placing exclusion zones around ambiguous seabed features – net snags or geophysical anomalies – that might prove to be archaeologically important but might equally prove to be modern debris, boulders or rock outcrops. Although each exclusion zone might be small relative to the aggregate licence area, a series of exclusion zones in the same area could sterilize a wider area by making dredging impracticable. Nonetheless, the costs of investigating the seabed feature – to establish its true character and potentially remove the need for an exclusion zone – might be costly and complex.

Equally, reporting protocols – the other main form of mitigation – were problematic insofar as they had to be set up to accompany each licence, causing bureaucratic duplication and potential for inconsistency, and because of the very complex relationship between dredgers, licence areas and wharves. If one protocol applied to dredging in one area, and a second protocol to dredging in another, and yet there was no protocol for discoveries in a third area because it operated under an older licence, it would be difficult for staff to know what they should do in the event of a discovery. Such complication would not encourage any party to have confidence in the effectiveness of the mitigation.

In the early years of the new millennium, therefore, there was very great uncertainty about the baseline archaeological resource that might be affected by dredging and what those effects might be, and already some concern about the principle mitigation methods that were available. More positively, archaeologists and aggregate companies were already working closely together, establishing and codifying best practice and taking initial steps to address some of the uncertainties that had been identified. These uncertainties needed to be addressed at wider scale than a single aggregate licence, and needed also to be based more firmly on actual field-based evidence. Both the wider scope and the need for evidence from costly fieldwork placed a limit on what might be reasonably achieved in the course of a single EIA. However, it also meant that when additional resources became available through the Aggregate Levy Sustainability Fund (ALSF), archaeologists already had some very clear ideas about projects that could directly improve the sustainability of aggregate dredging.

Significance of the Aggregate Levy Sustainability Fund (ALSF)

As a consequence of the ALSF, the period 2002-2011 saw very rapid advances in the capability of archaeologists to address the questions raised by aggregate dredging (Newell and Garner, 2007; Newell and Measures, 2008; Flatman and Doeser, 2010). Anything less would have been disappointing, given the high level of spending on archaeological projects through the ALSF (Flatman *et al.*, 2008; Miller *et al.*, 2008; Richards, 2008) The ALSF is largely responsible for the 'current state of knowledge' and its technical impact is set out below, but it is also worth noting some of the broader impacts attributable to the ALSF. Equally, not every important development in the period 2002-2011 was a direct consequence of the ALSF, so it is worth touching on some of these also.

Aside from the enormous leap forward in technical understanding afforded by the ALSF, which is discussed below, the ALSF had some secondary but very important impacts. Probably greatest amongst these was the increase in expertise available to industry, which had several facets.

The scale of support and the generally longer term of projects provided both greater demand and certainty for existing providers of archaeological services, and attracted additional providers to the aggregates sector especially amongst universities.

Demand and certainty enabled investment in recruiting and training, effectively creating a new generation of professional marine archaeologists. Furthermore, the ALSF enabled increased specialisation amongst archaeologists, creating niches for specialist geophysicists and geo-archaeologists in particular. In addition, demand and certainty enabled investment in specialist equipment for underwater tracking and geophysical interpretation, for example, so that such facilities could be brought in-house and become fully-integrated with archaeological methodologies. Taken as a whole, this meant that the marine aggregates industry was being served by a bigger, more diverse, specialized and well-equipped range of archaeologists. It is difficult to imagine how such an increase in expertise could have been achieved had the period 2002-2011 comprised solely of individual licence applications.

Another major advance brought about by the ALSF – incidentally in its earlier years but more instrumentally in Round 3 – was much closer integration between archaeology and the other marine and environmental sciences engaged in the assessment of marine aggregate licensing. As indicated above, archaeological assessment was being increasingly informed by seabed data that was originally acquired for geological or ecological purposes. Archaeologists were already starting to re-use other scientists' data – geophysical data such as bathymetry, sidescan, magnetometer and sub-bottom surveys; and geotechnical data such as samples from vibrocores – but the scale and technical sophistication of such re-use was substantially augmented over the course of the ALSF. The cross-disciplinary approach adopted by the Marine ALSF programme in particular, which required archaeologists to mix, present and publish alongside the other sciences, undoubtedly increased mutual awareness and allowed connections to be made.

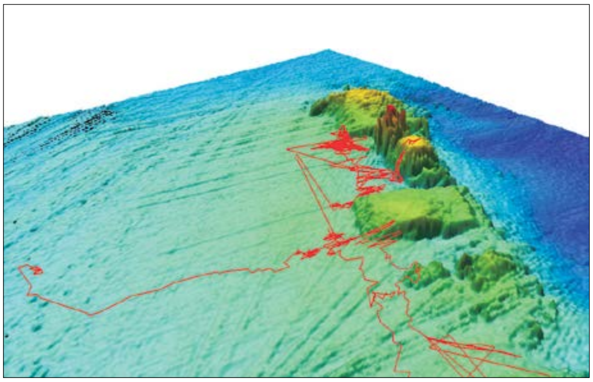


Fig 4.3 Diver track superimposed on a multibeam image of the wreck thought to be the 19th century steamship, Concha (WA 5004) – survey methods made possible by advances in position fixing and sonar technology. Courtesy of Wessex Archaeology.

The consequences are best illustrated, perhaps, by the Regional Environmental Characterisation Surveys (RECs). By Round 3, archaeologists were integral members of the project consortia, playing a key role in decisions about survey planning, acting as on-board monitors of survey quality, and making major contributions to the overall interpretative reports. This represented a significant step forward in maximizing the environmental value of marine surveys, teaching practical lessons that could be applied subsequently to regional and licence-specific surveys.

Obviously, individual licence applications continued to be progressed in the course of the ALSF, and the Marine Aggregate Regional Environmental Assessment (MAREA) programme increased in scope. These assessments benefited directly from the ALSF projects underway in terms of methodologies, baseline understanding, appreciation of impacts and approaches to mitigation, easing the assessment process and reducing uncertainty both for aggregate companies and the regulators. Greater capacity and capability helped prevent supply-side issues from emerging.

Several other factors contributed to a generally improving situation during the period of the ALSF. Broadly coinciding with the introduction of the ALSF, English Heritage – the Government's advisor on the historic environment in England – finally received a formal, statutory mandate to address archaeology beyond low water, introducing specialist staff, administrative processes and funding that would support aggregate licensing. Although there are relatively few explicit references to the historic environment in the Marine and Coastal Access Act 2009 – which evolved over the same period – the overall framework of spatial planning and integrated licensing provided a new infrastructure within which marine archaeology would be comprehensively and consistently considered.

Other forms of development, such as ports and particularly offshore wind farms, were encountering archaeology in the EIA process in the same way as aggregates. Although they had their own specific concerns, these forms of development were able to benefit from experience in the aggregates sector, but also contributed to overarching methods and understandings from which aggregates could draw.

As well as these longer-term trends interwoven with the ALSF, there were also some more abrupt influences arising from the historic environment, notably some quite surprising discoveries that significantly changed the scope of archaeological concerns. Two sets of discoveries were particularly important, at opposite ends of the temporal scale. First, from the recent past, a large amount of structural material from a crashed German aircraft was discovered during dredging in Area 430, together with human remains. Second, from the distant past, numerous flint artefacts were discovered as a result of dredging in Area 240. Both discoveries presented issues in assessing potential and importance, in site location methods, and in achieving reasonable mitigation. These issues are elaborated below; it is sufficient at this point just to emphasise how limitations on knowledge and understanding can be quickly exposed by new discoveries.

The final point to consider, before looking at each of the main receptors in turn, is expressly concerned with archaeological discoveries, and is intertwined with the ALSF and the other trends discussed above, as well as cutting across all the types of receptors.

It has also been the most visible expression of the growing relationship between aggregates and marine archaeology, and typifies the collaborative approach that has been so important; namely the Marine Aggregate Industry Protocol for Reporting Finds of Archaeological Interest (MAI Protocol, BMAPA and English Heritage 2005: see also Chapter 9).

Reference has already been made to the use of licence-specific protocols as a means of mitigating impacts, noting the potential for duplication and confusion that could arise from multiple protocols. Recognising this, the aggregate industry – with BMAPA – took the initiative in proposing a single industry-wide protocol. This started to take shape in the early 2000s, going through numerous phases of consultation before being launched in August 2005. The success of the MAI Protocol has clearly exceeded expectations, is demonstrably effective, and has gone on to influence the introduction of industry-wide protocols for offshore renewables and fishing.

Prehistoric Sites

Importance and Sensitivity

Prehistoric sites within marine aggregate licence areas were formed when sea level was very much lower than today. As we are currently experiencing a period of historically-high sea-level, and sea-level has been lower for much of human history, then the potential for prehistoric sites under the sea encompasses vast swathes of time. Although this has long been recognised, it has become a focus for a great deal of research in recent years, not least because of the coincidence between aggregate dredging and the potential for prehistoric sites (see Coles, 1998; Wenban-Smith, 2002; Flemming, 2004; Bicket, 2011; Firth, 2011; Benjamin, *et al.*, 2011).

In general terms, prehistoric sites will have formed in two different ways. Firstly, when sea level was lower – coinciding with generally cooler periods when water was locked up in ice sheets – harsh erosion caused by thawing ice would have caused human artefacts laid down on higher ground to be washed down the river valleys and deposited amongst other sand and gravel. This is the sand and gravel now targeted by the aggregate industry offshore, so there is scope whilst dredging to recover these displaced artefacts. Because they are displaced and have probably been moved and tumbled over quite large distances, the information they can reveal about the lives of the people who created them is relatively limited. This material is referred to as being in secondary context, because it has been moved from the primary context in which it was originally deposited by people.

Although archaeological material from secondary contexts has been degraded by major geological processes, it can still be very important to understanding the distant past. Artefacts from secondary contexts form the most numerous source of information about our earliest predecessors.

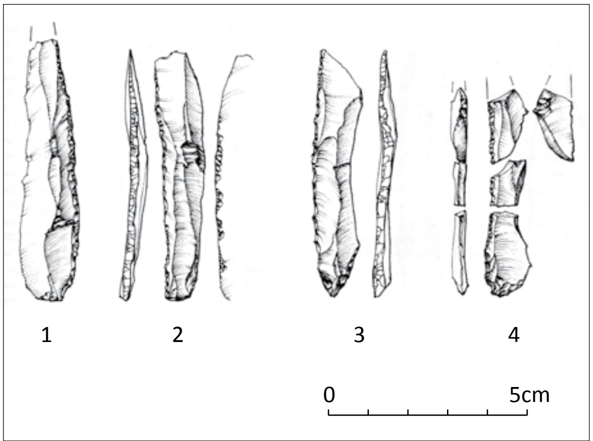


Fig 4.4. Late Upper Palaeolithic backed blades from Hengistbury Head. © Christine Wilson Barton, 1992.

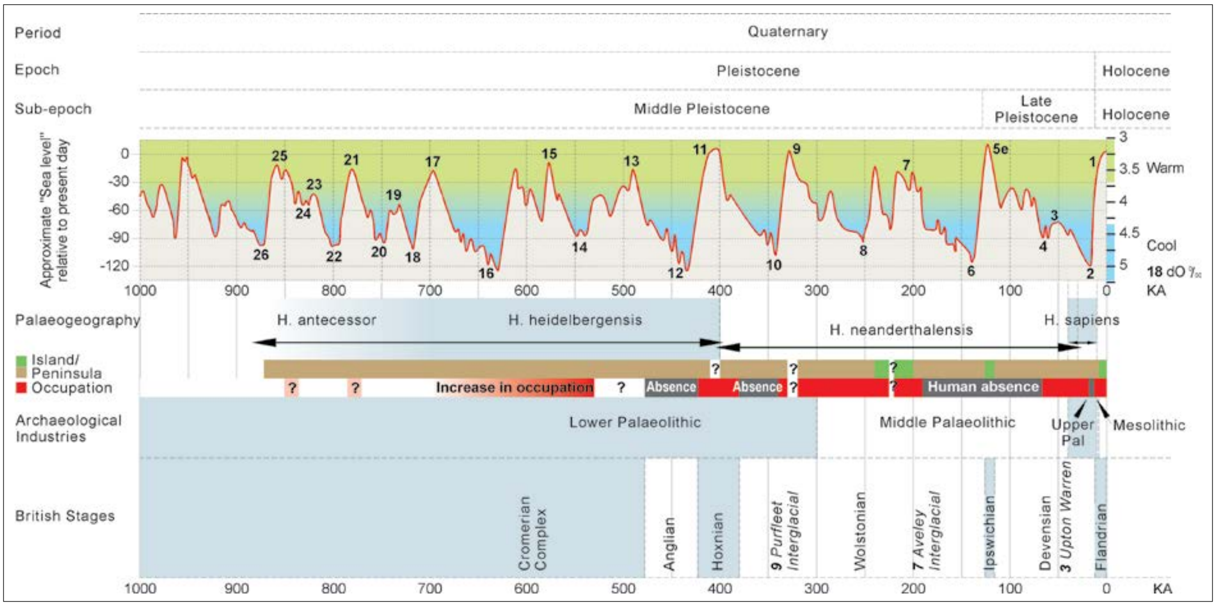


Fig 4.5 The sea level curve over the last 1 million years showing the major glacial and inter-glacial stages and evidence of human inhabitation. Courtesy of Wessex Archaeology.

Secondly, when sea level was lower, people were able to live, gather food, hunt and carry out a wide range of activities on what is now the seabed. Although the sea-level had been lowered by cold climatic conditions, for large periods of time the environment was in fact quite temperate and would have provided a wide range of resources. Artefacts deposited at these times may not have moved far as a result of subsequent geological processes; in fact they may have been covered and preserved by soils and alluvium that also contains microscopic remains of plants, insects, pollen and other indicators of prevailing environmental conditions. As well as flint artefacts, it is possible that organic artefacts – made from wood, fibres, leather and so on – may also have been preserved. Being so little-disturbed and accompanied by organic remains and palaeo-environmental indicators, such material could shed tremendous light on our predecessors' lives. The possible presence of prehistoric material in such primary contexts is a particular concern for archaeologists.

Until relatively recently, it was presumed that prehistoric material in primary contexts was only likely to have survived the latest phase of global warming and sea-level rise. That is to say, it could date only to the re-occupation of North West Europe following the last glacial maximum about 13,000 years ago, in periods known as the Late Upper Palaeolithic and the Mesolithic. The possibility that material in primary context could have survived repeated glacial cycles and marine transgressions was thought to be very remote. It was thought that the earlier periods – Lower, Middle and Early Upper Palaeolithic – could only be represented by material in secondary context.

This understanding has been fundamentally changed by the discoveries in Area 240 in the Southern North Sea off the coast of East Anglia, which have demonstrated that primary context material – little-moved from its original place of deposition and accompanied by palaeo-environmental information – has survived from about 200,000 years ago (see Tizzard, *et al.*, in Benjamin, *et al.*, 2011). If material in primary contexts offshore could survive at least one major glacial period, then perhaps it could survive many such episodes. The consequence is, therefore, that the potential for material in primary context is now considered to encompass much of human prehistory.

Prehistoric material on the seabed within marine aggregate areas is potentially very important – at a European and international scale as well as a UK scale. Sites – especially primary context sites – are relatively rare globally, even on land (Stringer 2006). Such sites from underwater, as well as having the advantages of enhanced palaeo-environmental and organic survival, tell us about areas we know very little about.

The wide, flat plains that are now covered by water may have been the real focus of early human activity in the vicinity of Britain, with what we know from today's land being peripheral. For vast amounts of human time, encompassing major migrations, changes in human species, and responses to environmental change, it is possible that there is more to be discovered from the seabed than from the land.

Prehistoric archaeological material in primary context is very sensitive to dredging activity because it comprises small artefacts and even smaller palaeo-environmental indicators whose greatest potential to inform arises from the precise relation between artefacts and their surroundings. Although flint artefacts are quite robust themselves, and seem to be able to pass through dredgers and processing plant almost unscathed, dredging will destroy the relationship between the artefacts and their surroundings. Prehistoric material in secondary context is less sensitive in this respect, because its relationship to its surroundings was changed many thousands of years ago. Nonetheless, understanding secondary context material certainly benefits from understanding the geological matrix with which it was associated, so again it is preferable for it to be investigated before dredging takes place. Furthermore, artefacts that are dredged are very likely to be lost within the overall volume of aggregate unless specific mitigation measures are put in place.

Assessment

With the emphasis, as ever, on identifying possible sites before dredging takes place, archaeological assessment in the course of EIA plays an essential role.

As indicated above, assessment is generally desk-based but draws upon detailed re-examination of already-acquired geophysical and geotechnical data by specialised archaeological staff.

Desk-based assessment has been strengthened by a series of strategic projects at national and regional levels that provide a much better basis for gauging the potential presence of prehistoric material. BMAPA and the Royal Commission on the Historical Monuments of England (RCHME) commissioned a preliminary overview of the potential for Palaeolithic and Mesolithic material on the seafloor (Wenban-Smith 2002) and a detailed consideration of the matter was prepared in the early stages of the ALSF by the University of Southampton (Westley *et al.*, 2004).

At a regional level, desk-based assessments can now draw upon studies that include specific archaeological investigations, which provide firm evidence of the presence of buried and submerged landscape features, of their age and their environment. Examples include the work carried out by Imperial College, London on the Palaeo-Arun, and by Wessex Archaeology on the Arun, East English Channel, Great Yarmouth, and Humber regions. In Round 3 of the ALSF, Wessex Archaeology also carried out very detailed work in Area 240, and the University of Southampton in the Outer Thames. These projects had a very limited geographic scope, but by acquiring and studying new samples they provide a key evidential underpinning to interpretations of adjacent areas Details of these projects are set out in project reports that are summarised by Bicket (2011).

Seabed prehistory figured heavily in the Regional Environmental Characterisation Surveys of the South Coast, Outer Thames, East Anglia and Humber. Whilst comparable surveys in the Eastern English Channel and Bristol Channel were not accompanied by archaeological work at the time, further work was subsequently carried out in both regions, and in the Irish Sea. Archaeological interpretation of the South Coast and Eastern English Channel regions was also integrated and extended as part of a synthesis study of the central and eastern English Channel. Detailed results are set out in the project reports for the REC surveys and the related regional projects (EMU and University of Southampton, 2009; Fitch and Gaffney, 2011; James, *et al.*, 2010; James, *et al.*, 2011; Limpenny, *et al.*, 2011; Tappin, *et al.*, 2011; Wessex Archaeology, 2011).

The REC surveys and other regional investigations were principally concerned, from an archaeological perspective, with re-using geophysical, geotechnical and sample data being acquired for geological and ecological purposes. The exceptions were the East Anglia and Humber RECs where archaeological objectives were fully integrated into the survey acquisition programmes, so data and samples were acquired expressly for archaeological purposes alongside geological and ecological sampling. Even where the regional investigations did not include acquisition of specifically archaeological data, other more site-specific investigations – as discussed above – provided direct evidence from the seafloor.

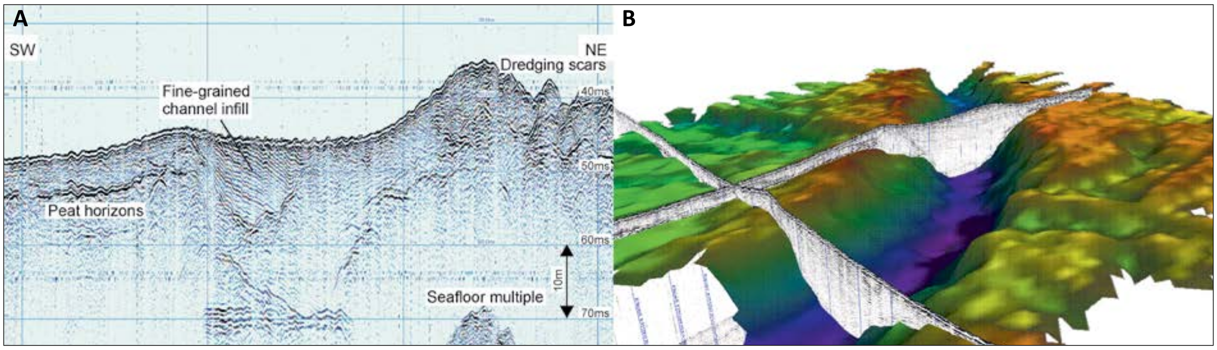


Fig 4.6 Sub-bottom profiling image (left) developed into a palaeo-landscape surface reconstruction of the palaeo-Arun (right). Courtesy of Wessex Archaeology.

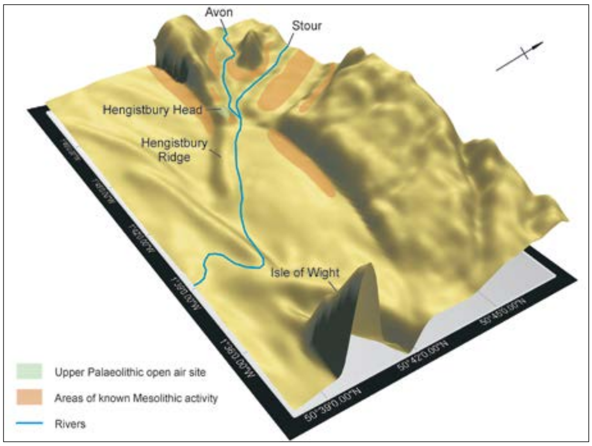


Fig 4.7 Upper Palaeolithic and Mesolithic palaeo-landscape reconstruction of the Solent and Isle of Wight region based on integration of geophysical data for the South Coast Regional Environmental Characterisation (REC). Courtesy of Wessex Archaeology.

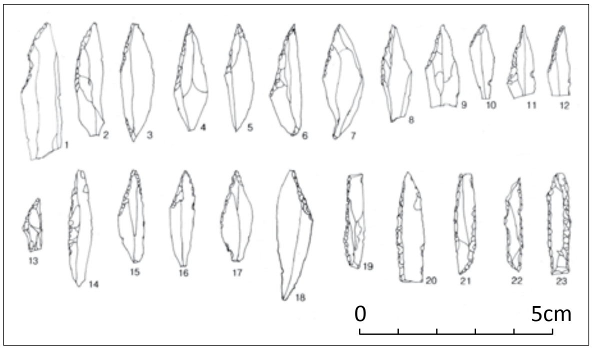


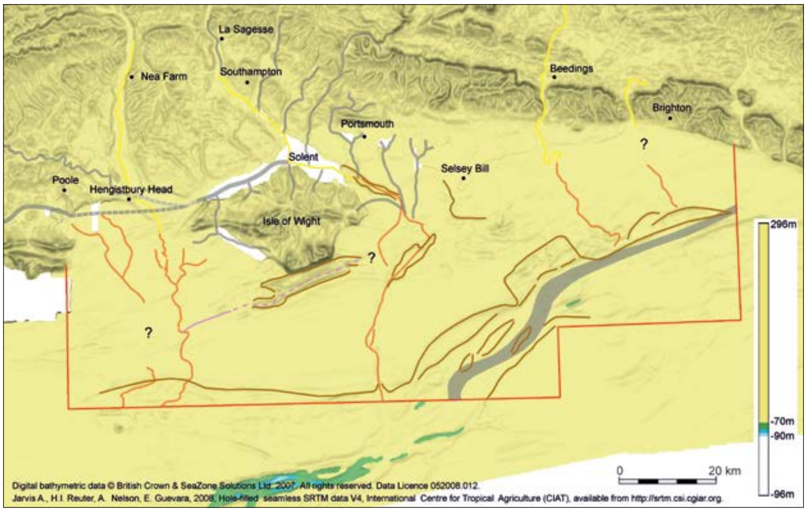
Fig 4.8 Mesolithic microliths from Rock Common (Harding, 2000). Courtesy of Wessex Archaeology.

The overall result has been that, for most aggregate regions, there is a regional-scale characterisation of the potential for prehistoric archaeological material based on archaeological interpretation of data acquired primarily for geological and ecological purposes, supplemented in most regions by specific archaeologically-directed survey and sampling. Where suitable samples have been obtained, they have been subject to archaeological assessment, scientific dating and analysis, providing a firm basis for interpretation.

It will be recalled that an early concern of the initial desk-based assessments accompanying EIAs was to use archaeological knowledge of adjacent coastlines and catchments to better understand the potential for prehistoric material offshore. Projects such as Artefacts from the Sea sought to maximise the usefulness to EIA of archaeological data from adjacent land by re-examining records of coastal finds from two pilot areas – the Humber to the Tees, and the Solent – including recording and photographing the private collection of prehistoric artefacts maintained by fisherman Michael White.

This array of work means that although assessment is desk-based, it can draw upon very much more detailed evidence that pertains directly to archaeological concerns in the specific licence areas under consideration, often at a range of scales. This range of scales is important because not only does it mean that an individual licence area can be fitted against the most relevant data, but it also provides a wider context for discussing relative potential and importance.

As noted above, desk-based assessment also draws upon geophysical and geotechnical interpretation. As previously, these are data predominantly acquired for geological and ecological purposes rather than for archaeology. Acquisition of data for solely archaeological purposes is rare. The



South Coast REC Study Area
Channel margins
Rivers/channels: Bridgland 2001
Rivers/channels: Bridgland 2001 (Early Pleistocene)
Rivers/channels: Bridgland 2001 (date unknown)
Rivers/channels: South Coast REC from bathymetry/Lidar data
Rivers/channels: BGS interpretation
Rivers/channels: Hamblin *et al* 1992
Rivers/channels: Hamblin *et al* 1992 (date unknown)
? Rivers/channels: Unknown

Fig 4.9 Reconstruction of the Upper Palaeolithic landscape (12,000 BP). Sea levels were about 80m below those at present and the English Channel was largely dry except for a well-established Channel River and tributaries. Courtesy of Wessex Archaeology.

advance that has occurred in recent years is that the quality of data is very much improved, and it can be interpreted by specialist archaeological geophysicists/geo-archaeologists. The improvement in data quality is largely a product of technical improvements, including in position-fixing, with the result that data are acquired digitally and can be re-examined in detail, rather than on the basis of a paper trace. It is now commonplace for such data to be examined by archaeologists specialising in this field using industry-standard software. Furthermore, the experience of several organisations in examining very large, high-resolution datasets in the course of various ALSF projects means both that interpretation methodologies are much better established, and specialists are better versed in the specific geophysical and geological context of the regions they are examining.

Evaluation

The principal improvements to evaluation methodologies have largely been manifested through the better provision for desk-based assessment, insofar as the methodological advances have resulted in better data being acquired and reported in the context of site-specific and regional studies. Further, and as noted above, there has not been much call to carry out specific archaeological fieldwork by way of evaluation, because the data acquired for other purposes is suitable for specialised re-use by archaeologists.

Nonetheless, methodological development and experience of data acquisition, processing and interpretation in the course of ALSF projects does mean that, should the need arise, archaeologists are very much more capable of deploying geophysical and geotechnical methods to identify and characterise submerged prehistoric sites than was previously the case. Further to this generality, specific work has been carried out on the selection and application of different sub-bottom sources to the investigation of submerged and buried horizons of prehistoric interest. Work has also been carried out on the particular difficulties of carrying out investigations in near-shore areas, to help correlate sequences known on land with sequences found offshore. Turning to geotechnical investigations, scientific dating using Optically-Stimulated Luminescence (OSL) has been successfully incorporated into vibrocore-based surveys, and combined with other scientific dating and palaeo-environmental analyses.

Desk-based assessment and evaluation based on geophysical and geotechnical methods have a key weakness with respect to submerged prehistoric material, in that they are not especially capable of producing direct evidence of archaeological material such as artefacts. Geophysical and geotechnical methods have a central role in identifying, mapping, dating and gauging the palaeo-environmental context within which artefacts may be found, including producing indirect evidence of human occupation such as charcoal fragments. However, geophysical methods are not yet capable of directly imaging artefacts, especially (as in early prehistory) where the culture is not characterised by the building of structural features.

Whilst it is certainly conceivable that high resolution sub-bottom survey or sidescan of an outcropping land surface might reveal structural material of Mesolithic date, this has yet to occur in UK waters. Equally, and except by rare good fortune, vibrocores and boreholes (typically only 10cm in diameter) are generally unlikely to recover individual artefacts. There is a clear lacuna, therefore, in bridging the gap between indicating surfaces and deposits that have clear potential to include prehistoric material of very high importance; and demonstrating whether such material is actually present.

Investigations to address this lacuna were carried out in the course of the ALSF, focussing on adapting seabed sampling methods used by geologists and ecologists for use by archaeologists. In principle, seabed grabs and trawls could recover samples of seabed including any artefacts present at the sample point, and video and stills cameras could be used to obtain images on which artefacts might be visible. Seabed sampling using a 0.1m^2 Hamon grab (which takes a sample of up to 10 litres of seabed deposits) was carried out in the course of the Seabed Prehistory projects in the Arun, Eastern English Channel, off Great Yarmouth and the Humber. The results from the Arun were

Fig 4.10 Analysis of a sediment vibrocore sample from the Humber REC. Courtesy of the University of Birmingham.

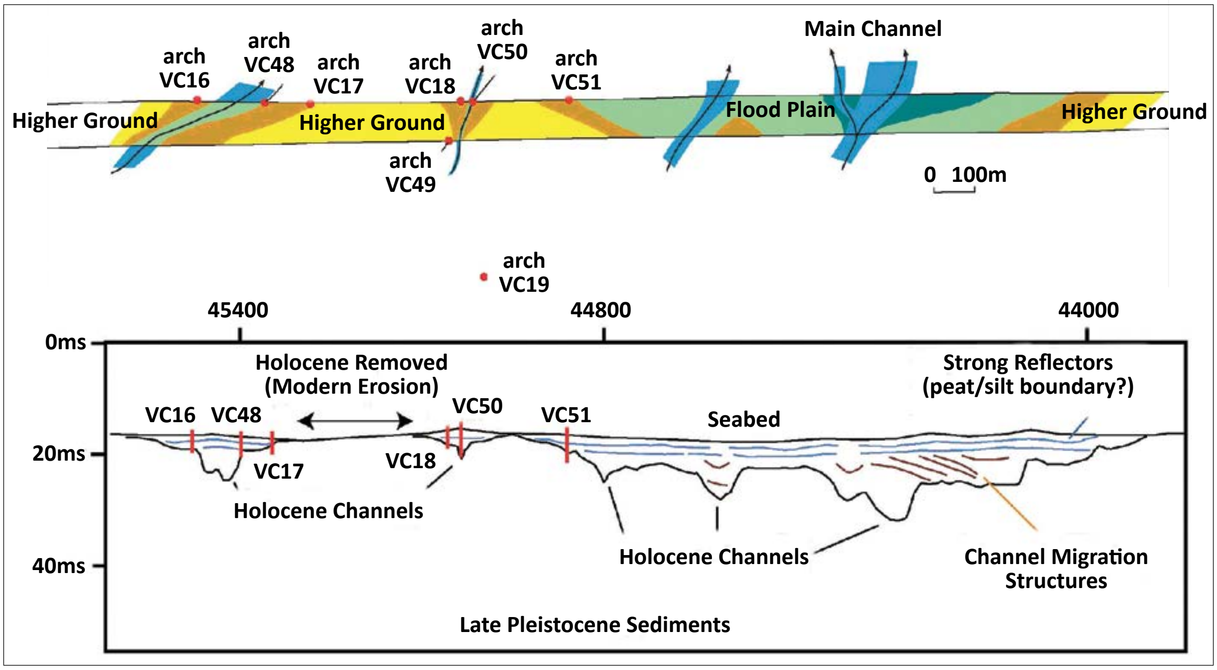


Fig 4.11 Geophysical, geotechnical and landscape interpretation from the Humber REC (2011). Courtesy of the University of Birmingham.

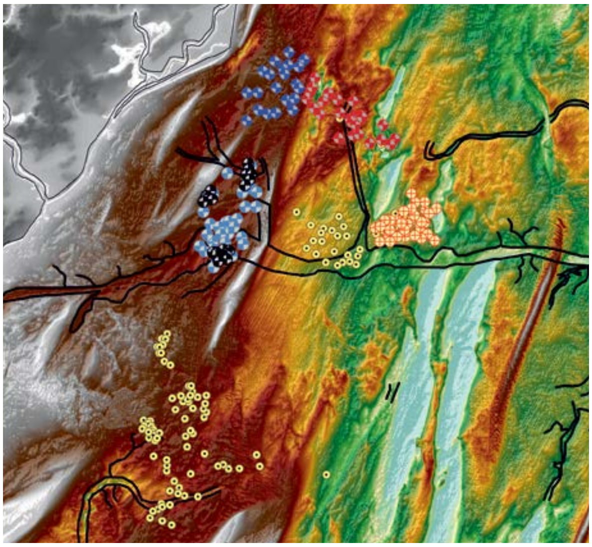


Fig 4.12 Locations of cores examined in the course of palaeo-landscape interpretation of the Thames. © Prof. Justin Dix, University of Southampton.

Fig 4.13 Palaeolithic hand axe from Area 240 in the southern North Sea off the coast of East Anglia. Courtesy of Wessex Archaeology.

most promising and resulted in 15 flints considered to be 'highly probable' to be of human origin. Grab sampling off the Arun also recovered charcoal that was thought to be direct evidence of burning by humans. Nonetheless, seabed grab sampling off the Arun (or in the other locations) did not produce incontrovertible evidence in the form of recognised tool types. Discussion turned to the need to obtain bigger volume samples, and when dredging in Area 240 recovered artefacts, this was the approach adopted. A clamshell grab being carried out primarily for geological purposes as part of the East Coast REC was targeted on the location where artefacts had been recovered from Area 240, and recovered a worked flint (a broken secondary flake). Subsequently, a programme of clamshell grab sampling was

Fig 4.14 Visualisation of the palaeo-Arun based on integration of palaeo-environmental analysis, archaeological material and interpretation of geophysical survey data. Courtesy of Wessex Archaeology.

carried out in the vicinity, accompanied by the use of scientific trawls, video sled and drop camera. The clamshell sampling was most successful, producing four flints 'most likely' to be of human origin. This piece of work established that clam shell sampling could be used as an effective evaluation method for prehistoric sites in aggregate areas.

Although clam shell sampling had been successful, it still had not produced finished tools. Even with the increased capacity of the grab, there was a stark contrast between the volume obtained by sampling (about 16.7 tonnes) and the volume obtained by dredging when the artefacts had been found (about 2,500 tonnes per hour). Attention turned, therefore, to obtaining an even bigger volume by 'test dredging' through an innovative project undertaken by Hanson Aggregate Marine Limited. In a first for the UK, archaeologists were deployed on the dredging vessel to carry out a 'walkover' of the top of the load of aggregate that had been dredged, which had been constrained to a limited area by the dredging method. Archaeologists also inspected the aggregate when it was being processed at the wharf. Both on-board and at the wharf, the archaeologists recovered worked flint, including finished artefacts, that was entirely consistent with the material recovered originally. Test dredging accompanied by archaeological inspection is, therefore, the most recent evaluation method to be added to the range of techniques available.

Direct inspection of the seabed using archaeological divers or remotely operated vehicles (ROVs) has yet to be trialled as an evaluation method for prehistoric sites implicated by aggregate dredging in the UK. Aggregate areas are distant from the shore, exposed, relatively deep and often subject to major tidal currents. Moreover, underwater visibility can be poor, and in cases like Area 240 the horizons of most interest are sometimes covered by mobile sand. In these circumstances, diving is likely to be both costly and speculative; for it to be effective, the presence of archaeological material would already have to be confirmed within a known, localised area. Diving has certainly been productive on other submerged prehistoric sites in the UK and around the World, and if the circumstances are right it may yet prove to be important for UK aggregates.

Mitigation

The presence of prehistoric archaeological material has only been confirmed in one instance to date, within Area 240. The principle means of mitigation has been avoidance; Hanson Aggregate Marine Ltd established an archaeological exclusion zone immediately they were informed of the artefacts that had been found. In several other instances, exclusion zones have been introduced in the course of the EIA process to avoid areas where there is potential for prehistoric material to be present, but usually this is because the potential relates to the presence of fine-grained material that would in any case contaminate the aggregate load if dredged.

The other main form of mitigation is the Marine Aggregate Industry Protocol, which has seen the reporting of numerous examples of material of prehistoric interest, including peat, wood fragments, fossil animal bones and worked flint. Except in the case of Area 240, such discoveries have not pointed directly to the presence of localized material *in situ*, but the gradual accrual of evidence is certainly helping to provide much better contextual evidence of the presence and character of prehistoric material in aggregate areas generally.

Looking ahead, other forms of mitigation can be anticipated. Offsetting in particular is likely to be a productive strategy, whereby physical impacts are balanced by improvements in knowledge and understanding gained by analysis and dating. These improvements feed back into better assessment and evaluation, as well as providing a tangible improvement to the overall corpus that is available to researchers. Offsetting is especially valuable given the current low level of baseline knowledge, where the evidence-base is insufficient to reasonably preclude dredging whilst the knowledge gained in the course of mitigation will add to the future baseline. Offsetting also accords with curators' emphasis on conserving the significance of important archaeological material, rather than just protecting the physical remains.

Offsetting may take several forms, ranging from the acquisition of seabed samples or core material for analysis and dating, through periodic monitoring of dredging by archaeologists on board or at wharves, through to detailed investigation of a site prior to its destruction by dredging. Although not yet called upon, there is certainly scope to provide satisfactory mitigation for prehistoric material in aggregate areas through offsetting.

A final point to make about mitigation for prehistoric material is the scope for enhanced appreciation and awareness by the public. This might not be regarded as mitigation, but it is certainly a very positive aspect of the aggregate dredging industry's relation to prehistoric archaeology. Early prehistory is a source of fascination for the public, with stories often being picked up by the news media. Prehistoric remains from under the sea seem to have a special attraction to the public and knowledge and discoveries arising from the aggregate industry have already played an important role in extending peoples' awareness of these lost landscapes.

Prehistory has featured in a series of outreach activities connected to marine aggregates, either through the ALSF or other initiatives, and it is to be hoped that this important contribution to society continues.

Shipwrecks

Importance and Sensitivity

Shipwrecks present the most immediately engaging facet of marine archaeology, with every one holding a story to deduce. Shipwrecks can range widely in age, type, original function, circumstances of loss and current form, hence also their importance and sensitivity can vary also (Muckelroy 1978; Catsambis *et al.* 2011). This range is exemplified by the extensive investigations carried out with the support of the ALSF, summarised by Hamel (2011). The most commonly encountered shipwrecks in aggregate licence areas date to the later C19th and C20th and have major components such as frames and boilers – if not the hulls and superstructure – made from iron or steel. Very many are merchant ships, casualties of the First and Second World Wars.

The reason that these wrecks are most commonly encountered is because they are numerous – the war years

Fig 4.15 Bringing Archaeology to the Public and in particular to children in the 'Explore the Seafloor' project supported through the Aggregate Levy Sustainability Fund (ALSF). Courtesy of Wessex Archaeology.

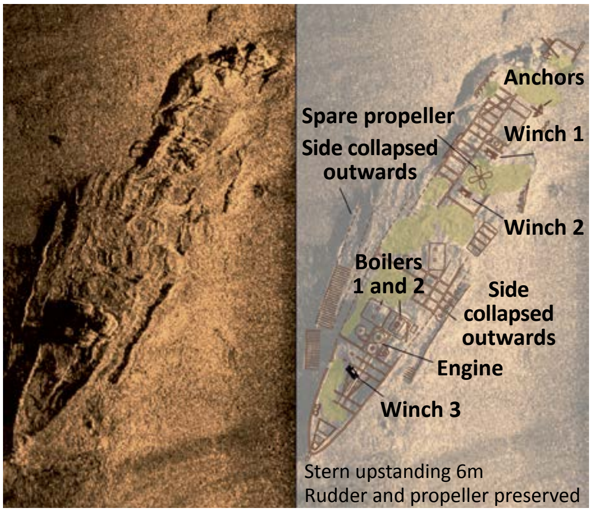


Fig 4.16 Sidescan sonar image and site plan based on ROV and diver surveys of the wreck of the Talis (WA 5009), a 19th century Swedish steamship that sank in 1906. Courtesy of Wessex Archaeology.

are relatively short but very large numbers of ships were sunk around the UK by military action or wartime accident – and because they are relatively easily found. With such substantial ferrous components, wrecks from recent centuries often remain prominent on the seabed and produce large magnetic anomalies. There is already a good record of their presence from decades of hydrographic surveying. Previously unknown metal wrecks also show up readily in the course of geophysical survey work in advance of aggregate dredging. Moreover, there are often good documentary records relating to the original vessels and their loss.

This is not to say that these later wrecks are all fully known. In many cases, the presence of a wreck may be known but its identity – which may have a major bearing on its importance – is not. Such wrecks may also be less prominent because structural remains have been heavily disrupted by the original wrecking process or by subsequent damage, by clearance for navigation, for example. Even substantial metal wrecks may be covered by mud or buried by mobile sediment such as sand waves. Also, the wrecks of recent centuries are not always big and metal; smaller wooden boats and ships remained an important component of maritime traffic through the first half of the C20th, including fishing boats and local vernacular forms. Wrecks of such ships are much less well-known and are less visible to the main methods of hydrographic and geophysical survey.

In particular, wooden ships will usually collapse and degrade down to the level of the seabed, unless they have become buried. In either case, wooden ships generally have only low relief at the seabed and generate ephemeral anomalies. Notwithstanding, wooden remains below the surface can be very substantial and long-surviving where they have reached a degree of equilibrium with their environments, as demonstrated by various well-known centuries-old wrecks in UK waters. Discoveries elsewhere around the world, and from bits of the sea that have been reclaimed around Britain, demonstrate the potential for substantial wrecks of very much older boats and ships to survive in the seas around the UK, stretching back even into prehistory.

The wrecks of boats and ships are not only important for their structural remains. The contents – equipment, cargo or personal possessions – can all provide insights into past societies. Such contents can be spread widely around a wreck as part of the 'debris field', and in some instances it may be the contents that survive – or are most visible – rather than the vessel structure. In the case of some sites in UK waters it seems that only the contents actually made it to the seabed, perhaps as a result of the vessel capsizing and discharging its load.

On the other hand, a vast amount of ship-borne material has made its way to the seabed without the vessel necessarily being wrecked, as all sorts of items have been lost, thrown, deployed or fired overboard. Amongst these items, some may be of intrinsic interest despite being isolated from their original context. Moreover, it can be difficult to tell whether an item on the seabed is an isolated find, or the first sign of a debris field linked to a more substantial wreck. Distinguishing between isolated finds and more coherent sites has become an important concern because modern geophysical survey and interpretation is capable of identifying ever smaller anomalies on the seabed, and because of the amount of ship-related finds being made through the Marine Aggregate Industry Protocol.

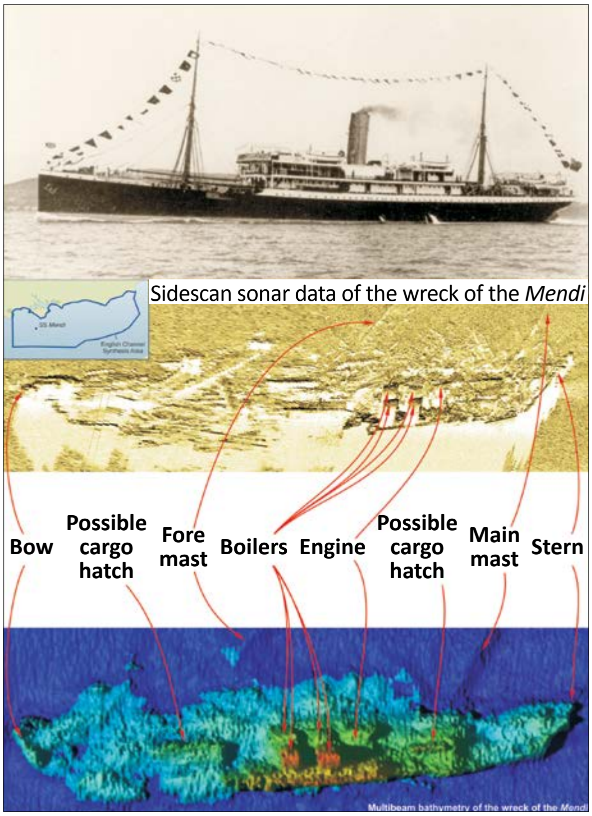


Fig 4.17 Photograph of the World War 1 British troopship SS Mendi lost after a collision with the steamer Darro in February 1917 with the loss of 646 lives. © South African Navy, courtesy of Wessex Archaeology). Lower images show sidescan sonar and multibeam bathymetry of the wreck 11 nautical miles off St Catherines Point, Isle of Wight.

The wrecks of boats and ships are important for many reasons, providing insights to major events or trends in maritime activity, commerce, politics, society, technology and the day-to-day lives of individuals on land as well as at sea. The importance of a wreck might relate to its building and equipping, its life as a vessel in use, or its

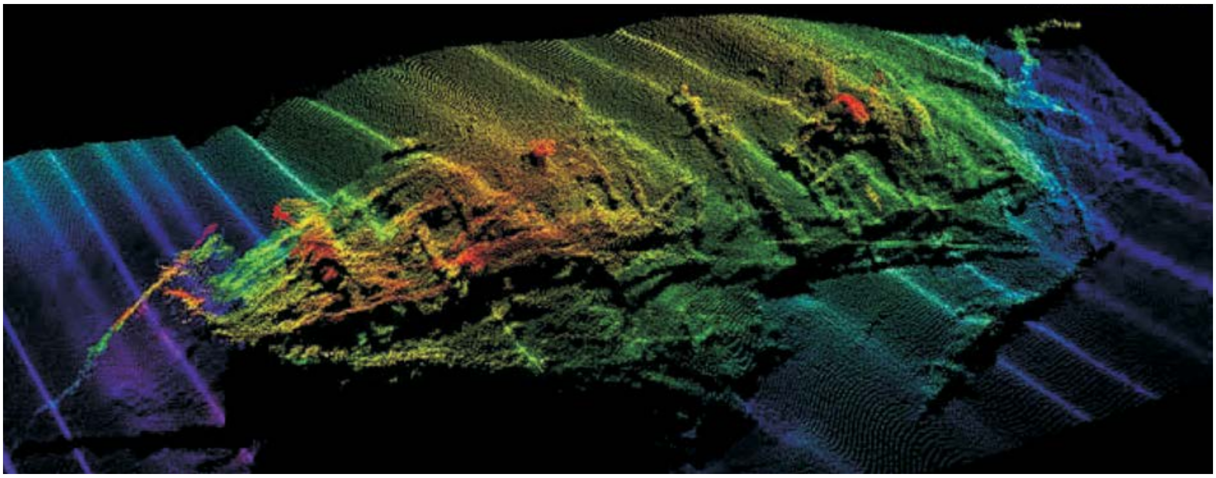


Fig 4.18 Wreck of a wooden ship on the Goodwin Sands exposed by movement of the sands. This caused the collapse of the bowsprit between April and September 2005 and illustrates the fragility of wrecks to sediment movement. (From Bates et al., 2007). © University of St Andrews.

loss – or any combination of these factors. Wrecks can also be important on account of their survival. The quantity and quality of surviving material may present innumerable possibilities for investigation and knowledge, or the particular way in which a wreck has degraded may provide important insights that will aid future wreck management.

It was noted above that many of the wrecks encountered in aggregate areas are of late C19th or C20th date. Typically these have been considered to be largely unimportant archaeologically, on account of being so numerous or having been built, used and sunk within (almost) living memory. Attitudes to these more recent wrecks are changing, however, for a number of reasons. The period from about 1850 to 1950 saw absolutely revolutionary changes in almost every aspect of seafaring, so wrecks from this period help chronicle the rapid pace of change. The period also encompassed the two World Wars, when the destruction of both military and merchant shipping (as opposed to its capture) was a strategy adopted by all sides, aided by the new technologies of torpedo, submarine, mine and aircraft.

As has been recognized of wartime sites on land, wrecked ships are monuments of those cataclysmic events that are important for what they can tell beyond words, pictures and documents, as physical reminders of our recent past, and as memorials to the many thousands of peoples whose lives were lost. Moreover, being made of iron and steel – and often already subject to massive damage – wrecks of the C19th and C20th are perhaps more fragile than the wooden wrecks of previous centuries; in our own era we may be particularly privileged to experience them in their current state.

With such wide variety in the wrecks of boats and ships, it is unsurprising that their sensitivity to aggregate dredging varies widely also. But it is worth noting that aggregate dredging is also sensitive to shipwrecks: the draghead and pipe is sensitive to debris and collision, and the load may become contaminated by the former contents of the wreck such as coal. It is in the clear interest of aggregate companies, therefore, to identify the presence and precise location of any wrecks, including the debris around them, and to seek to avoid them.

Greater difficulty arises from less prominent, wooden wrecks, which are both difficult to identify in advance and more susceptible to impacts from dragheads. That said, the substantial structural timbers of a wooden wreck may be resistant to impact and could jeopardise dredging equipment, so again there is a mutual interest in locating even ephemeral sites before dredging commences.

If the draghead passes sufficiently close, small finds and wreck debris will undoubtedly be disturbed and probably lost from their original context – to be found caught in the draghead, within the load or on the electromagnets used at the wharf to remove ordnance. Dredging may uncover material that was previously buried and stable, exposing it to renewed physical, chemical and biological degradation. Dredging might also undermine wreck material either directly or as a consequence of a general lowering of seabed level by dredging. One particular concern has been that wrecks within exclusion zones could be subject to longer term destabilization if dredging around the zone causes the remaining ‘plinth’ around the wreck to slump, which is a question that has been subject to specific research.

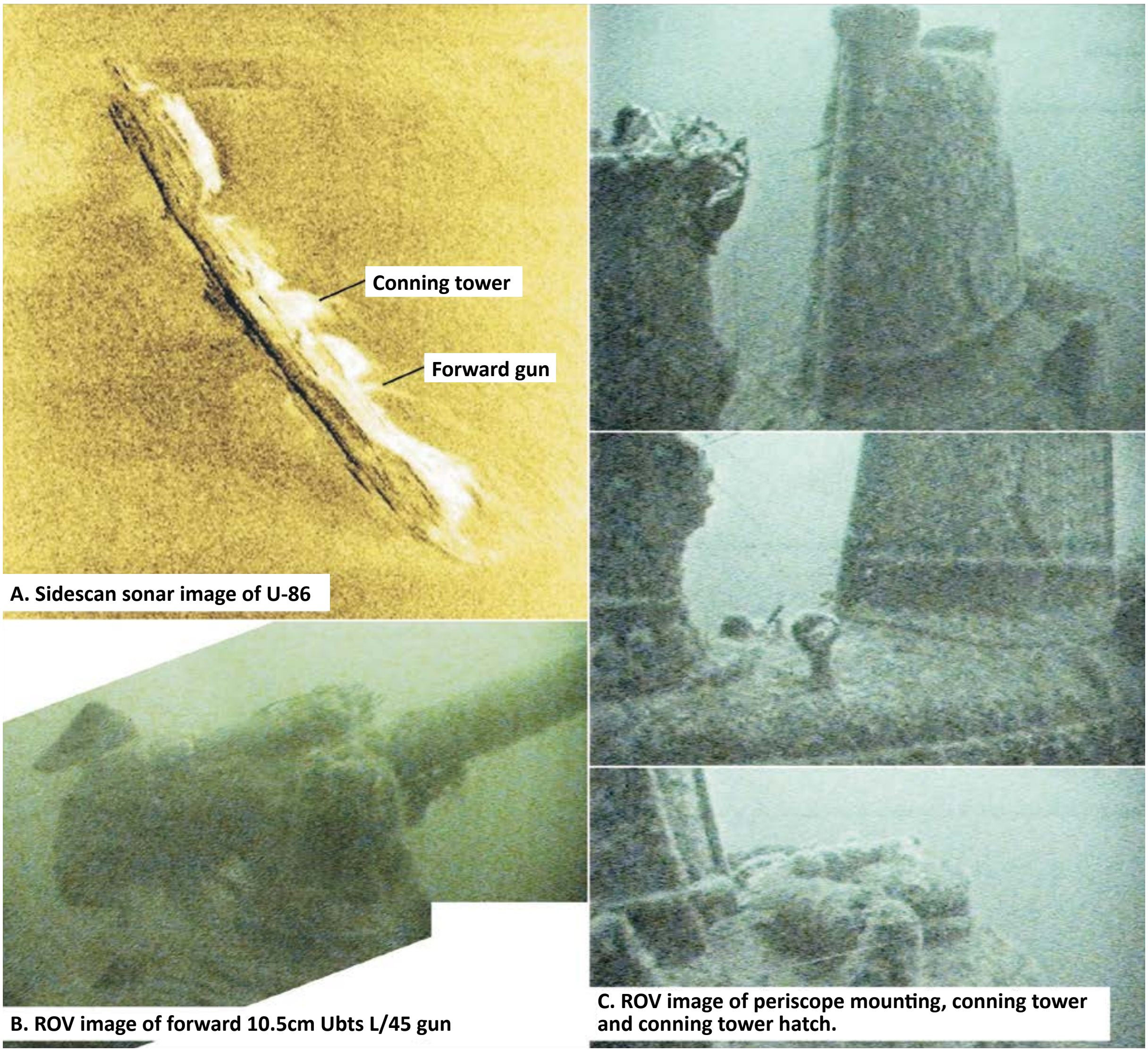


Fig 4.19 Sidescan sonar and ROV images of a German attack U-boat dating to WWI (WA 1003). Thought to be the U-86 which sunk at least 33 allied ships and was responsible for sinking the British hospital ship Llandovery Castle, and the subsequent murder of the surviving crew members in the water. Courtesy of Wessex Archaeology.

Assessment

Desk-based studies and geophysical investigation are the two main methods for assessing wrecks as part of the EIA process. Desk-based sources can be broadly divided into two: information about wrecks whose presence is known, and information about wrecks that might be present but are currently unidentified.

The two main sources of information about known wrecks – and also about features on the seabed that might prove to be wrecks, are the Wreck Index of the UK Hydrographic Office and the National Monument Records (NMRs) maintained by the heritage agencies (e.g. the National Record of the Historic Environment (NRHE) for England and NMRW for Wales). Information is sometimes available through local authority Historic Environment Records (HERs). Secondary sources including recreational diving publications, can also provide useful information.

The NMRs and UKHO contain information about known wrecks that have already been identified by name – and thereby age, type, function and so on – but also about wrecks that are known to be present but which are as yet unidentified. In some cases it is possible to use other sources of information about known (but as yet unlocated) losses in an area to help resolve such known unidentified wrecks.

There are extensive records of ships known to have been lost in an area, but whose remains have yet to be found.

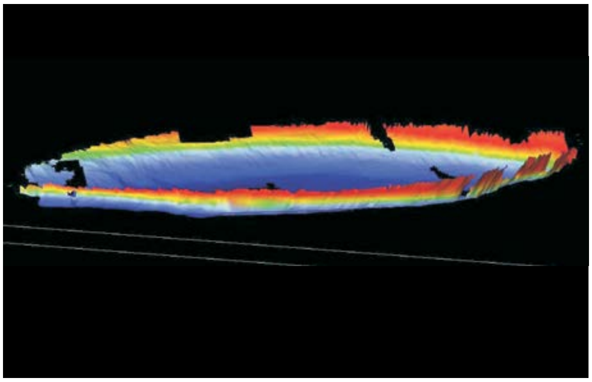


Fig 4.20 Reconstruction of the hull of the Grace Dieu, based on a high-resolution 3D sonar system developed with the support of the ALSF. © Prof. Justin Dix, University of Southampton.

These records of wrecks known only as documented losses – often referred to as 'casualties' – can be accessed through the NMRs but often originated as entries in Lloyds List or other contemporary sources of information about ships that had been lost. A more general sense of the likelihood of ships having been lost in a particular place can be obtained from an understanding of the main hazards to shipping, as shown on historic charts and described in sailing instructions.

Information on the overall pattern of shipping activity in a region can be gained from more generalised accounts of maritime activity set out in published sources. All these sources of information are based to a large extent on the availability of accessible documents, so they favour the periods after around 1750. Although there is certainly a wealth of earlier documentary evidence going back into the Medieval period, such sources are not readily accessible in the course of assessment unless they have already been made available through separate research. To gauge the potential for earlier losses, reference is made to the relatively few known early wrecks in UK waters and around the World, and to indirect evidence such as iconography or discoveries on land that imply maritime activity.

Another line of enquiry in gauging potential is to consider the propensity of different types of marine environment to preserve the remains of ships and boats. As noted above, fantastic levels of preservation over centuries and even millennia are known from some places, where the vessel came to rest in a suitable environment. Equally, wrecks occurring in other areas may have little in the way of surviving remains. Consequently, some projects have sought to map out different environments as a guide to where wrecks are more or less likely to survive in good condition. However, the processes that wrecks undergo are complex and may vary even within a site, so apparently unpromising environments can still produce surprises.

The actual pattern of archaeological material, substantially augmented by reports made through the Marine Aggregate Industry Protocol, is providing an important empirical underpinning to understanding the potential presence of maritime remains within aggregate dredging zones.

There are some key contrasts between prehistory and shipwrecks when considering the impact of aggregate dredging. Although individual prehistoric flint or stone artefacts are relatively robust and have been successfully recovered at the end of the dredging process, the relation of the artefacts to their context – and to any organic or palaeo-environmental material – is very sensitive to dredging. Given the current state of knowledge, all instances of prehistoric material actually being present – especially in primary context – are likely to be very important. Shipwrecks, on the other hand, are more diverse. Undoubtedly, the first pass of a draghead on an as-yet unknown wreck that has a light wooden structure and is hitherto little disturbed is likely to have a high magnitude of impact, as indeed will the action of the draghead on isolated items in the debris field. Even if they suffer themselves, wrecks with heavier wooden structure or constructed of metal are likely to have a notable impact on the draghead. If previously unknown, then the dredger will want to avoid a second pass that might jeopardise its equipment, and if the wreck is already known the dredger will prefer to avoid the site altogether.

The magnitude of physical impacts from dredging is therefore more varied, and not necessarily 'high'. Similarly, whilst shipwrecks dating earlier than about 1850 will almost certainly prove to be important, the importance of the more numerous wrecks from around 1850 to the present will be more equivocal. Specific research has been carried out to provide a clearer guide to the importance of shipwrecks, especially from later decades.

Evaluation

With the emphasis on avoidance, the need for further evaluation of shipwrecks has only been required rarely. Examples include where the character of an anomaly is uncertain and an exclusion zone would be difficult operationally and when a hitherto unknown site has come to light.

The main evaluation methods for maritime archaeology are further geophysical survey, and archaeological inspection by diver or ROV. Whilst geophysics used to be capable of indicating the presence and position of a wreck but revealed relatively little detail of the feature itself, the tools now available are capable of very high resolution such that a great deal of data can be obtained remotely that would otherwise have involved some fairly laborious diving.

Notwithstanding, there is usually a trade-off between the detail that can be resolved by geophysical surveys and the time or area that can be covered: high resolution is more

Fig 4.21 Divers preparing to enter the water to survey a wreck in the eastern Solent. © Hampshire and Wight Trust for Maritime Archaeology.

time-consuming both in survey time and in processing/interpretation. Consequently, it is often sensible to 'phase' or 'nest' surveys, so that big areas can be covered relatively quickly, with the option to return to carry out higher-resolution surveys of features if warranted. In this sense, regional or area surveys, covering wide areas usually as a regular pattern of long uniform lines and cross-lines, can be contrasted with site-based or intra-site surveys, where instrument settings and much shorter lines are optimised according to the specific form of the target.

Traditionally, sidescan sonar and magnetometer have been the principal geophysical instruments for investigating shipwrecks. These tools have improved significantly in recent years, together with position-fixing and processing capabilities, so that they are capable of resolving individual details within a wreck site. Multibeam echosounders have become a very important addition to the toolkit, providing a high density of 3D data that is capable of amazing visualisations and – perhaps more importantly – real-world dimensions that significantly reduce the need for diver-based surveying. Another important addition has been higher resolution sub-bottom profiling using various techniques, that are starting to enable 3D mapping of the entire wreck prism, including its buried extents, in a relatively accessible and cost-effective manner.

Despite the many advances and advantages of geophysical survey, there is no substitute for direct examination of wreck material on the seabed by archaeologists. Improvements in image quality from digital still and video cameras have certainly made it easier to 'see' wreck sites from the surface – at least where the visibility permits – but either a diver or ROV is required in order to place the camera in positions where it will best inform the viewer. ROVs are capable of carrying out detailed intrusive investigations at great depths, but to do so requires a large ROV and a large support vessel, both of which are very expensive. Smaller, survey-class ROVs can be a cost effective option, especially in deeper water or on extensive wreck sites that would require a diver to cover a lot of ground. Survey-class ROVs are, however, principally used as mounts for cameras and other sensors; they do not generally have the capacity to manipulate things on the seabed, or to recover samples and artefacts. For these, divers remain the best option.

Divers also have advantages in poorer visibility and with complex structures, because unlike a ROV they have a direct three-dimensional awareness of their immediate surroundings. They can also manipulate things on the seabed, pick up possible artefacts, make judgements about them, and quickly discard or recover them as appropriate. Other judgements about the form, age, condition, potential etc. of a wreck site are also better made by a diving archaeologist on the seabed than by a remote observer looking at a screen.

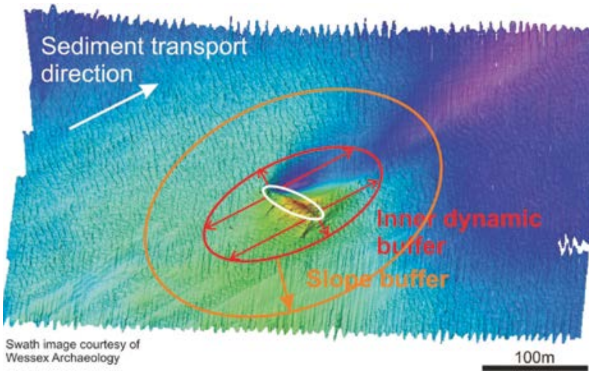


Fig 4.22 Model for designing exclusion zones in dynamic environments, based on a wreck site off the south coast of England (from Dix et al., 2007). © Prof. Justin Dix, University of Southampton.

Of course, the best approach to evaluation is usually to combine all the available tools – geophysics, ROVs and divers – to make the best of their respective strengths and weaknesses. The scope to combine and integrate the results of different forms of investigation has been another area of advancement in recent years. Much improved position-fixing has been key; as well as better positioning of geophysical datasets, methodological advances have meant that acoustic positioning underwater of ROVs and divers has become a realistic expectation for many wreck investigations. Marine aggregate dredging has provided the stimulus and – through the ALSF – the funding that has enabled shipwreck evaluation methodologies to undergo a very significant step-change in capability.

Mitigation

For reasons outlined above, avoidance is the clearly preferred method for mitigating potential impacts from dredging on known shipwrecks. Avoidance is typically achieved through the use of exclusion zones within which dredging is not allowed to take place. Exclusion zones encompass both the known wreck material itself and an area beyond, to provide protection for any debris field or buried items, to prevent undermining of the wreck by the effects of dredging, and to provide a margin for navigation that will avert accidental impacts. The main innovation in the use of exclusion zones – other than the quality of baseline data available – has been in their form. Whereas exclusion zones used to be defined typically by a radius around a single position more or less centred on the wreck, it is more usual for them now to be drawn as a polygon buffering the actual extents of the wreck. This means that the extremities of a wreck receive the same protection as the central portion, but without precluding access to substantial areas of seabed that can be safely dredged.

Fig 4.23 Late C19th and C20th wrecks serve as 'artificial reefs' to provide habitat, as here in the engine of the Concha (sunk 1906) (see Fig 4.3). Courtesy of Wessex Archaeology.

Another improvement has been to start better understanding the relationship between wrecks and their environments, especially with respect to concerns about whether dredging will affect the plinth of undredged material upon which a wreck stands and could thereby undermine it.

Other work has considered whether archaeological exclusion zones might have benefits for ecologically-important resources, because the dredged seabed within the zone provides a degree of sanctuary or because the wreck acts like an artificial reef to increase diversity and abundance. Exclusion zones have the advantage that they can be monitored remotely, by comparing dredger trackplots to the exclusion zones, or by repeat survey using multibeam to identify changes in seabed level.

The other principal mechanism for mitigating impacts on shipwrecks, especially any hitherto unknown wrecks, is the Marine Aggregate Industry Protocol (see Chapter 9). A broad range of ship-related material has been reported through the Protocol, and a number of instances where discoveries have indicated the presence of substantial wreck sites have been investigated.

Air Crash Sites

Importance and Sensitivity

Air crash sites have only recently come to prominence as a concern for aggregate dredging. Higher resolution geophysical surveys have been able to pick out these relatively ephemeral sites in some cases, whilst aircraft fragments have been an unexpectedly common source of reports through the Marine Aggregate Industry Protocol, including reports that have indicated relatively coherent crash remains (Hamel, 2011; Wessex Archaeology, 2008).

In principle, air crash sites at sea could date right back to the earliest experimental flights from the UK. Some of the earliest pre-WWI flights were over the Thames estuary from the Royal Aero Club aerodrome on the Isle of Sheppey and the Royal Navy seaplane base on the Isle of Grain. Seaplane activity was extensive during WWI itself, which also saw raids from across the North Sea by Zeppelins and early strategic bombers. In the interwar period, civil and commercial flying added to military traffic – and casualties – over the sea. Nonetheless, it is the intense military activity over UK waters during WWII that is the overwhelming source of most air crash material, though post-war crash sites are also present.

It might be reasonably presupposed that aircraft remains dating from before WWII are unlikely to occur or be found often. The much lower volume of air traffic, even if flying was hazardous, would have resulted in far fewer crashes into the sea. The craft themselves were also less substantial, more likely to disintegrate on impact and to decay, presenting (at best) highly ephemeral traces on the seabed, and little that might

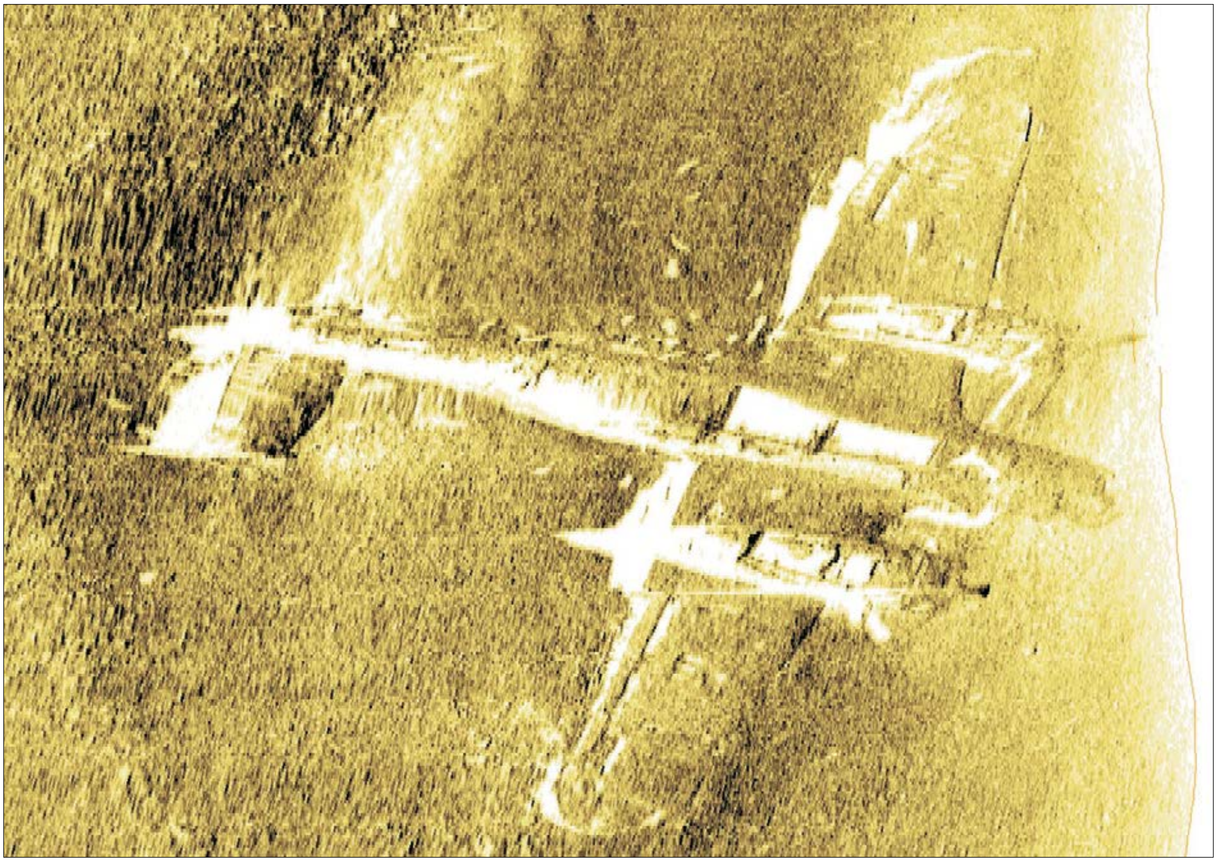


Fig 4.24 Sidescan sonar image of a near intact and very rare German Dornier aircraft on the seabed off the south east coast of England. Courtesy of Wessex Archaeology.

survive to be noticed through the Marine Aggregate Industry Protocol. Even so, the possibility that pre-WWI remains might be encountered in aggregate dredging areas cannot be entirely discounted; any such discovery is likely to be very important.

The aircraft typical of WWII were increasingly robust and there are numerous examples of sites surviving on the UK seabed in relatively coherent condition. This increased robustness is only relative, however; aircraft are of generally light construction and are typically going very fast when they encounter the water (if indeed, they have not already disintegrated above it). Retaining coherence to the seabed requires a range of circumstances to combine, as does subsequent seabed survival of corrosion and disintegration as a result of various natural and human factors. Consequently, many aircraft crash sites may comprise only isolated or fragmentary remains.

As with WWII shipwrecks, aircraft crash sites from the same conflict are not necessarily straightforward in terms of their importance. Whilst there has been a fair amount of public interest in aircraft remains on land – especially through aircraft recovery groups – their archaeological importance has only come to the fore relatively recently (English Heritage 2002), and the same is true also for crash sites at sea. Despite aircraft being mass produced, and there being many vintage aircraft in preservation in museums or even still flying, there are some types of which there are no remaining examples, or perhaps just a collection of parts survives. Consequently, even fragmentary remains may be rare survivals. This is especially true if considering the many marks and variants of some aircraft, especially as some versions will have been modified from their earlier condition. Of those that survived many will simply have been scrapped at the end of their careers. Examples in preservation will have undergone often extensive restoration and maintenance.

Aircraft that survive from crashes, even if in fragments, present a direct connection with the events of their original use and loss that is more distant in the case of examples in preservation; and this is true even where there might be extensive documentary records or detailed design drawings. It is worth recalling that archaeology is concerned with the people that are entwined with these machines, not just the remains of the machines themselves: aircraft crash sites are important to the extent that they embody – and are monuments to – the enormity of the cataclysmic events

Fig 4. 25 Magazine from a MG15 machine gun recovered from an aircraft wreck on the seabed at Area 430 in the southern North Sea. Dates on the ammunition suggest that the aircraft was lost in 1940 during the Battle of Britain. © Tarmac.

Fig 4.26 Marine aggregate staff examining artefacts, including aircraft fragments, as part of a BMAPA Awareness Programme workshop. Courtesy of Wessex Archaeology.

and changes in which societies were embroiled in 1939-45. As well as commemorating those who were killed or injured, all of those who participated in the last total war were affected by enormous changes in technology, communication, organisation and production of which aircraft were focal points, and by aerial campaigns with enduring repercussions for the generations that have followed.

Individual fragments of aircraft can survive the dredging process and many examples have been reported through the Marine Aggregate Industry Protocol (see Chapter 9). However, more coherent remains are highly sensitive to dredging. Even a single pass by a draghead is likely to cause major damage to a light, corroded airframe and its contents. It should also be borne in mind that human remains and personal effects may be closely associated with the airframe, and will be similarly sensitive to even a single pass. Of all the different types of archaeological material, military air crash sites are in fact the only type to be automatically subject to legal protection, through the Protection of Military Remains Act 1986.

Assessment

In terms of assessment, aircraft crash sites share characteristics with both prehistoric and shipwreck material. Like more recent shipwrecks, there is information available on both known crash sites – in the UKHO and NMRs – and on aircraft that are known to have been lost but whose crash site is not yet known. But like prehistoric sites, aircraft crash sites are generally difficult to 'see' using geophysics as they tend to be low-lying and not to have large masses of ferrous material that are readily detected by magnetometer. Notwithstanding, some aircraft crash sites produce remarkable geophysical traces, with their apparent coherence belying their corroded condition.

The desk-based information that is available for aircraft is very extensive. As well as previously-known crash sites, there is a range of sources for aircraft that have been lost – including detailed accounts of the loss of many individual aircraft. This means that if an aircraft can be identified, then there is a good chance that a rich documentary narrative can be accessed. The principal difficulty, however, is that existing records are not easily accessed geographically, from the point of view of knowing whether an individual aggregate licence area might contain air crash sites. This is hardly surprising as having left the aerodrome, the character of aircraft is to be absent for hours whilst they range over hundreds of miles, largely out of sight and subject to a wide range of hazards, including all manner of accidents as well as the active efforts of the enemy to down them. Information on aircraft losses can, therefore, be vague about where the loss might have occurred. Many aircraft simply did not return.

Even if the point of loss can be localised, the position of the crash site will be difficult to determine at scales relevant to an individual licence area. Impact with the sea, any time afloat before sinking, the movement of relatively light structures through tidal water columns, seabed processes and impacts from fishing or other activities will all have an effect on the eventual position and form of an aircraft wreck that is unlikely to be determined from documentary records. There are some sources which help, however, such as the records of rescue boats and aircraft dispatched to pick up survivors, though these may also be imprecise about location due to the limitations of contemporary position-fixing.

As with shipping, reference may be made back to more generalised patterns of aviation to indicate the potential for crash sites to be present. Certainly, the southern North Sea and English Channel witnessed intense air traffic, both

Allied and Axis, at different stages of the war. In other sea areas the air traffic may have been more diffuse, but losses occurred widely around the UK in connection with convoys, anti-submarine patrols, air-dropping of mines, training exercises and other such operations.

Evaluation

Where a suspected air crash site has been localised, then additional high-resolution geophysical survey is an appropriate form of evaluation that has been employed by marine aggregate companies in at least one instance. Sidescan sonar remains the tool of choice for identifying debris and structural remains; if the relief is sufficient then a multibeam echosounder can be used to map out extents. Magnetometer survey at a sufficiently narrow line-spacing may reveal the presence of ferrous components, including ordnance, but it should be recalled that the majority of aircraft parts are non-ferrous. Unfortunately, as aircraft present such ephemeral sites, even high-resolution survey may produce only ambiguous results – though 'negative evidence' demonstrating the absence of a localised and coherent site may be sufficient to inform the choice of mitigation.

Processing and interpretation are as important as the survey itself, because although an instrument may record a trace relating to a feature on the seabed, it does not necessarily follow that the trace will be recognisable. Data processing – even the process of turning raw sidescan into a geo-referenced mosaic – can disguise ephemeral features,

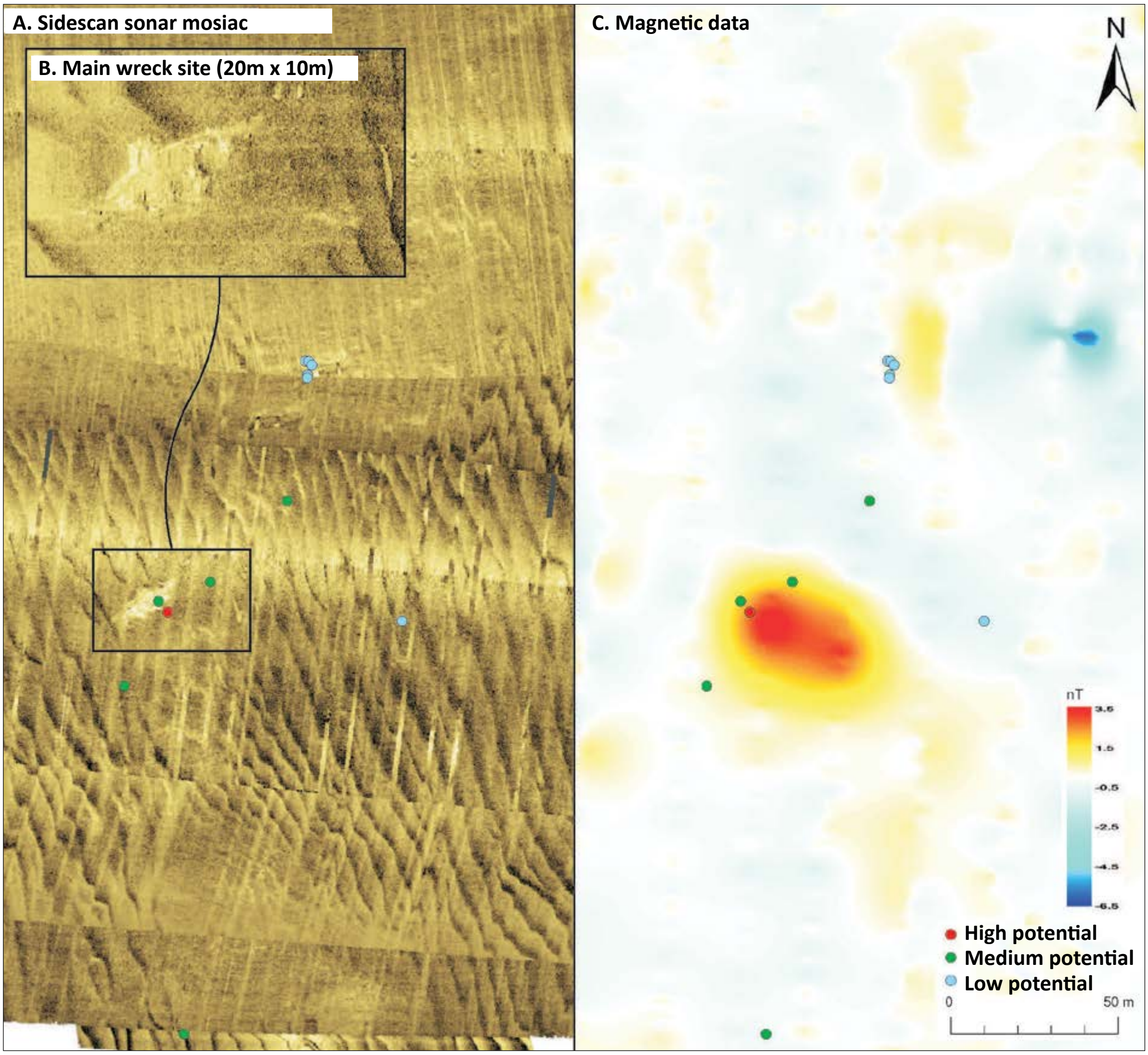


Fig 4.27 Sidescan and magnetometer data showing the crash site of a B-24 Liberator off the Isle of Wight. Sunk 1897. Courtesy of Wessex Archaeology.

and in any case a manual judgement is required to distinguish archaeologically-notable features from the wide variety of returns from natural or otherwise irrelevant features of the seabed. Although the point applies in respect of other forms of marine archaeological material, seeking to identify hitherto unknown aircraft crash sites from geophysical surveys underlines the need for archaeologists to have access to original data and to processing capability, and to employ specialist staff with experience of interpreting aircraft crash sites.

Direct observation by divers or ROV is another key means of evaluating air crash sites; many of the points made above with respect to evaluating shipwrecks are relevant to aircraft also.

Given their generally limited spatial extent the accuracy of position-fixing may be especially important, though such smaller sites, accompanied by generally very high levels of pre-existing documentation (such as plans, models and photographs), may be relatively quick to evaluate.

Mitigation

As above, avoidance is the preferred approach to mitigation – not least because disturbance will be subject to additional statutory licensing requirements by virtue of the Protection of Military Remains Act 1986. Bearing in mind the points about geophysical survey of aircraft sites, the difficulty lies in establishing position and extents with sufficient confidence to achieve an Exclusion Zone that protects the remains without preventing dredging across a wide area.

There are cases of aircraft being removed from the seabed in their entirety, which might be regarded as a possible means of mitigation. But even allowing for relatively small size and some remaining structural strength, aircraft recovery in UK waters is logistically and operationally difficult and therefore costly. Upon recovery, long-term and – again – costly measures will need to be put in place quickly to arrest corrosion.

Recovery efforts have, therefore, generally been driven by research or public education objectives, with the input of large amounts of additional funding. Recovery of whole aircraft is unlikely to be a cost-effective form of mitigation for marine aggregates.

Where the remains are relatively fragmentary, of limited importance or no human remains are present, then it is possible that a mix of recording, research and selective recovery might be a satisfactory means of enabling aggregate dredging to take place. This option has been employed in the UK in cases of navigational dredging for ports. It is worth noting that the UK position with respect to air crash sites covered by the Protection of Military Remains Act (PMRA) is that no licence will be allowed if there are human remains present, the intention being that such remains be left in peace where they lie.

Discussion and Future Directions

Provision for archaeology implicated by marine aggregate dredging has gone through a remarkable transformation since the mid-1990s. From being a negligible concern, a comprehensive framework of knowledge, understanding and methodologies has been developed, resulting in high levels of engagement throughout the industry and with the wider public. Undoubtedly the support of the ALSF played a major role in this transformation, but marine aggregates has benefitted from – and contributed in a very significant way towards – changing regard for marine archaeology across a range of marine sectors.

There are commonalities between the main types of archaeological material affected by aggregate dredging – prehistory, shipwrecks and air crash sites – but important distinctions also. A great deal of progress has been made across the board, especially in the technological capabilities that can be deployed, and in the very positive industry-wide response to initiatives such as the Marine Aggregate Industry Protocol. The generalised framework set out here – considering importance and sensitivity, and the current state of the art in assessment, evaluation and mitigation – has highlighted both strengths and weaknesses. These weaknesses are the prompt to consider what future directions might be taken.

- *Importance:* In EIA, understanding the importance of any particular receptor is essential in trying to establish whether an impact is significant. This concern with importance is reinforced by planning policy both on land and at sea, in that harm or loss of importance is to be avoided or must be offset by advancing the understanding of importance and

Fig 4.28 Image of an engine from a B-24 Liberator obtained using a ROV (see Fig 4.27). Courtesy of Wessex Archaeology.

making the evidence publicly accessible. Establishing the importance of prehistoric, shipwreck and air crash material at sea is still problematic even though major improvements have been made. Further work to understand national and regional context – based on the actual presence of material rather than just its potential to be present – should be coupled with more incisive elaboration of the importance of specific assets as benchmarks for future casework.

- *Magnitude of impact:* The need to focus on 'actual' rather than 'potential' is a concern for gauging the magnitude of impacts from aggregate dredging, as well as the importance of assets. Reference was made above to research to improve the evidence-base for the design of exclusion zones, which certainly warrants further elaboration coupled to empirical results on the effectiveness of previously-established exclusion zones. Evidence from existing licence areas could usefully be reviewed to temper assumptions made in the EIA process about impacts on the main classes of archaeological feature. As noted above, some features – the airframes of air crash sites and prehistoric material in primary context – are likely to be highly sensitive to dredging, but other types of archaeological material may be more resistant or tolerant to some impacts.
- *Best use of available data:* This is an area in which again, major strides have been made, but the momentum provided by the ALSF in particular needs to be maintained. Noting the point above about the relationship between importance and national and regional context, the overarching baseline of knowledge about the marine historic environment needs to be fostered. The regional and site-specific data generated by RECs, REAs and licence-based investigations should continue to be built-upon and integrated, and measures taken to look sideways in order to profit from, and contribute to, the knowledge being gained from other sectors such as offshore renewables. As noted above, investment in data infrastructure should focus on historic environment themes that are of direct relevance to the assessment of aggregate dredging, especially on the types of material that are actually present (or very likely to be present) in specific licensing zones.
- *Mitigation methods other than avoidance:* Avoiding historic assets is a commendable approach to mitigation, endorsed – for the most important sites – by national planning policies. However, exclusion zones can impede dredging operations beyond their immediate footprint, especially if they are numerous or clustered. Consequently, opting to establish exclusion zones rather than investigate a feature or anomaly whose archaeological character or importance is uncertain may prove to be a false economy. Moreover, avoiding investigation robs the opportunity to test geophysical interpretation with direct observation, necessitating continuing caution in the future interpretation of geophysical data. Where a degree of archaeological interest is proved, again there may be scope to conserve the feature's importance by recording, removal and advancing its understanding rather than instituting an Exclusion Zone. The technical capability already exists; all that might be required is greater robustness in acknowledging that sites of lesser importance can be mitigated by selective recording, removal and dissemination.
- *Evaluation methods for prehistoric archaeological material:* Echoing points above, prehistoric material on the seabed is a key concern because its presence, distribution, character and importance is poorly understood. Innovative adoption of seabed sampling techniques and test dredging are very promising, but will need to be applied in a variety of contexts and targeting different types of material. It is notable that the greatest success so far has been in systematically recovering older (Palaeolithic) forms of prehistoric material. Little progress has been made recently in developing methods for more recent (Late Upper Palaeolithic/Mesolithic) material, which are likely to be much more widely distributed.
- *Maintaining the effectiveness of the Protocol:* The Marine Aggregate Industry Protocol has been a fantastic success as a demonstrable means of offering mitigation for chance discoveries, and as a conduit for awareness and engagement across the whole industry and beyond. The success of the Protocol stems only in part from the core arrangements set out in its documentation; prompt, effective and positive responses to discoveries depend upon the maintenance of the Implementation Service that makes sure that archaeological advice is always on hand. That the Protocol remains an active part of day-to-day business on wharves and dredgers depends on a programme of visits by archaeologists to industry staff to introduce new participants to the Protocol and to pass on advice about how best to record, photograph and handle discoveries, and to a regular Newsletter that highlights and acknowledges new discoveries and good practice. The Implementation Service and Awareness Programme are generously supported by BMAPA, English Heritage and The Crown Estate; it is important that this support is maintained.
- *Maximising the value of archaeological information:* As the chapter has made clear, aggregate dredging has made a massive contribution over the last 10-15 years to knowledge and understanding of the marine historic environment. Industry, regulators and archaeologists have all benefitted. But as stated at the outset, public dissemination of archaeology is as fundamental as the conservation of sites and research of new ideas. It is important that archaeological results arising from aggregate dredging are shared with the widest audience, to engage and excite people not only in how earlier societies have used the sea, but in how we should best use the sea sustainably today, and in future. ■

5 IMPACTS ON THE PHYSICAL ENVIRONMENT

By N. J. Cooper and D. S. Brew, Royal HaskoningDHV

Introduction

The physical marine environment is naturally dynamic, with changes to it driven by daily and seasonal fluctuations in tidal and meteorological conditions and by longer term trends that are associated with global climate change. Within this context, there are various anthropogenic pressures and interventions, such as the construction of coastal defences or port structures, the development of offshore wind farms and arrays of wave and tidal devices, the installation of sub-sea cables and pipelines, and the exploitation of natural resources, which could potentially directly or indirectly affect the physical attributes of the seabed and shorelines.

As one of many possible pressures on the marine environment, marine aggregate extraction could, potentially, exert an influence on three principal receptors: (i) the seabed and its sediments; (ii) the sediments suspended within the water column; and (iii) the coastline. This influence could arise through direct physical change associated with the extraction process itself (covering both dredging and screening of sediments) or through indirect consequences of the extraction, causing changes to the wave, tide and sediment regimes operating across and beyond the dredged area.

The main direct impacts caused by marine aggregate extraction are due to disturbance of the seabed, arising from the passage of the drag head over the seabed and changes in bathymetry directly resulting from removal of deposits. These direct impacts have been judged to be the most serious with respect to the physical aspects of marine aggregate extraction (Newell *et al.*, 1998; Desprez, 2000).

Indirect impacts on the physical environment can potentially result from: (i) changes in wave transformation processes due to the altered seabed bathymetry; (ii) reduced shelter afforded to adjacent shorelines by dredged banks and bars; (iii) drawdown of sediment from the shoreface or seabed to infill dredged areas; (iv) changes in tidal currents; (v) alteration of regional sediment transport pathways and the supply of sediment to adjacent sandbanks or beaches; and (vi) formation and dispersal of a sediment plume in the water column, and subsequent deposition of the entrained sediment particles.

In addition, impacts can potentially occur from the combined physical impacts associated with a number of dredge sites within an area, depending on the extent and sequencing of extraction operations. Physical impacts from marine aggregate extraction can also arise cumulatively with other seabed activities, such as offshore wind turbine construction, cable or pipeline laying, or fish trawling.

The extraction of marine aggregate will cause some changes to the hydrodynamic and sedimentary process regimes, but these changes in themselves are not necessarily considered to be impacts. Rather, they are changes, or effects, which may result in impacts to other receptors, such as coastal habitats, marine ecology and the historic or archaeological environments. For example, changes in the transport and deposition of sediment may impact upon the character of marine habitats and their associated species. Similarly, changes in hydrodynamic processes may alter the erosion and deposition patterns around shipwrecks or at the shoreline. Impacts on the historic and archaeological environments and on the biological environment are considered in Chapters 4 and 6 respectively, while the effects to the physical environment per se are discussed further in this chapter.

Regulation and Industry Good Practice

Recent History

The United Kingdom has developed and applied a world-leading role in the assessment of potential changes to waves, currents and sediment transport from marine aggregate dredging. This process was initially facilitated through a non-statutory Government View procedure introduced in 1968, which became statutory in 1998 through updated interim measures that introduced the formal requirement for assessment of impacts on seabed and coastal processes (although such studies had been undertaken previously on many sites). Around this time, the Construction Industry Research and Information Association (CIRIA) published two reports to assist the industry in undertaking appropriate studies:

- CIRIA C505: Regional seabed sediment studies and assessment of marine aggregate dredging (Brampton and Evans, 1998); and
- CIRIA C547: Scoping the assessment of sediment plumes from dredging (John *et al.*, 2000).

Subsequently, regulation of marine aggregate dredging, including its effects on the physical environment, has been established to supersede the Government View procedure in the form of the Environmental Impact Assessment and Natural Habitats (Extraction of Minerals by Marine Dredging) (England and Northern Ireland) Regulations 2006 and the Environmental Impact Assessment and Natural Habitats (Extraction of Minerals by Marine Dredging) (Wales) Regulations 2007. Policy and procedural guidance on transposing these regulations into practice in England has been incorporated within Marine Minerals Guidance Note 1 (CLG, 2002) and Marine Minerals Guidance 2 (MFA, 2008).

Commercial rights to extraction of aggregates from the seabed are granted within licensed areas by The Crown Estate. Licensed sites within the UK are located along parts of the seabed off England and Wales. Regulation of marine aggregate extraction is now undertaken by the Marine Management Organisation (MMO) in England or the Marine Consents Unit (MCU) of the Welsh Government in Wales. The process of applying to the MMO or MCU for permission to dredge for marine aggregates usually involves preparation of an Environmental Impact Assessment (EIA) which includes:

- Characterisation of the baseline physical environment, often using various survey and sampling techniques or drawing from existing studies and surveys;
- Impact assessments, usually involving a Coastal Impact Study (CIS) and covering both direct and indirect effects from the proposed dredging activities, when considered both alone and cumulatively or in-combination with other marine activities; and
- Mitigation of impacts through licence conditions and pre- and post-dredging monitoring to ensure that conditions have been met.

Running alongside individual licence applications with accompanying EIAs, the marine aggregate dredging industry encourages the development of industry-wide research and dissemination of good practice. These aspects are further discussed in turn.

Baseline Characterisation

Prior to prospecting for aggregate extraction sites and then assessing the potential impacts on the physical environment of dredging at the potential sites, it is important to have an accurate understanding of the physical and sedimentary processes operating across the seabed (and if appropriate the adjacent shorelines). This understanding is needed to characterise the physical environment and to assess the interactions that exist between the physical, biological and archaeological environments. The types of physical environment parameters that need to be covered by a baseline characterisation exercise are shown in Table 5.1 and taken from:

- Marine Aggregate Extraction: Approaching Good Practice in Environmental Impact Assessment (ODPM, 2005).

Survey and Sampling Techniques

A range of survey techniques and sampling methods are available to capture information to characterise the baseline physical environment.

Table 5.1 Summary of baseline data requirements for the physical environment (ODPM, 2005)

Geology	Description of the seabed sediments, the mineral resource and underlying geology, in terms of:
	Type and nature of sediment/ bedrock
	Depth
	Particle size
	Lithology
	Origin
	Composition
	Thickness
Geomorphology	Bathymetry
	Bedforms and notable seabed features
	Characteristics of seabed sediments
	Seabed mobility
	Sediment transport pathways and rates
	Suspended sediment concentrations
	Coastal morphology and change
Hydrodynamics	Tidal regime (tide strength and direction)
	Wave conditions
	Residual water movement

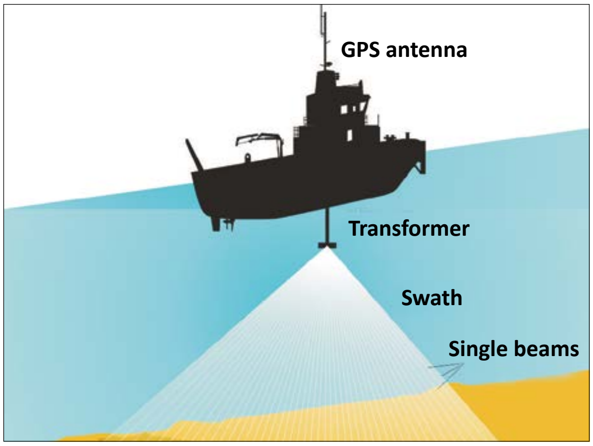


Fig 5.1 Diagram showing the multibeam sending out a swath of acoustic signals towards the seabed, © Wessex Archaeology.

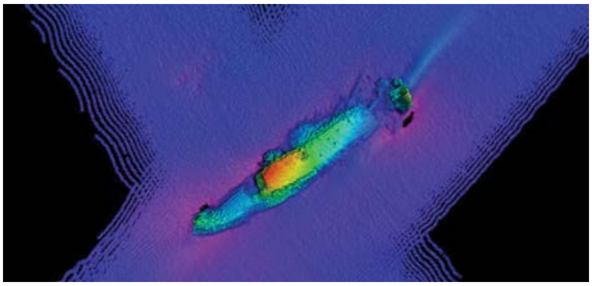


Fig 5.2 Multibeam bathymetric image of a submarine wreck on the seabed. Courtesy of Cefas.

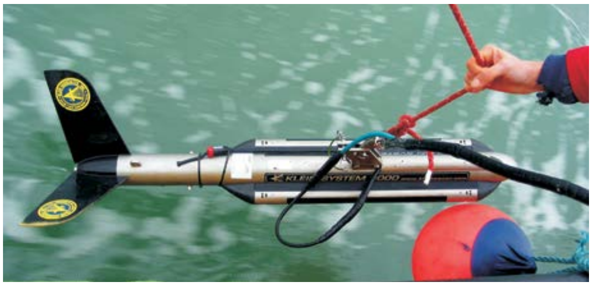


Fig 5.3 Side-scan sonar equipment.

Geophysical Surveys

The nature and distribution of seabed features is widely captured using a combination of several pieces of equipment including, most commonly, multibeam echo-sounders (MBES), side-scan sonar, and boomer sub-bottom profilers. These technologies are widely used and referred to in technical reports. It is also important to note that careful interpretation of data from these sources by an oceanographer or geomorphologist can assist in understanding sediment transport mechanisms as inferred, for example, through asymmetry of bed forms or differentiation between contemporary and relict deposits.

Multibeam echo sounder (MBES)

This instrument is normally fixed to the hull of the survey vessel. It sends a swath of acoustic signals (sound) that fan out towards the seabed and are reflected back to be recorded on the ship (Figure 5.1). The time taken for the sound to return from the seabed to the ship can be converted to water depth. The width of the swath is normally about 4 times the water depth and the data can be processed to produce three-dimensional images showing the seabed in considerable detail.

Multibeam imagery has been widely used along with side-scan sonar to identify wrecks on the seabed and changes in bathymetry associated with dredging (Figure 5.2).

Side-scan sonar

This instrument (Figure 5.3) is towed at depth behind the survey vessel. It provides a record of the sound reflecting back off seabed features such as rocks, wrecks and sand waves based on the intensity and strength of an acoustic signal that is reflected back from the seabed. There is also a weaker diffuse signal called 'acoustic backscatter' that is produced by interaction of the sound with the surface texture of the seabed. Rough textured deposits such as rocks, boulders and gravel produce a darker tone on the acoustic record than sands and muddy deposits. This feature can be used to provide information on the grain size of seabed deposits (see Collier and McGonigle, 2011).

Side-scan sonar can be used to define a zone of 100-200m width behind the survey vessel, depending partly on the height above the seabed that the 'fish' is towed. The survey vessel therefore needs to make a number of sweeps across the seabed with an accurate differential Global Positioning System (dGPS) to provide details of the seabed morphology and texture at known positions. Clearly it is not possible to provide 100% overlap for very large areas of seabed, so in general large-scale surveys depend on relatively widely-spaced geophysical survey lines with a good deal of interpolation for areas of seabed between the survey lines. In other sites, such as the relatively smaller marine aggregate licence areas, the survey lines can be arranged to give 100% coverage and detailed information over the entire site for geology, bathymetry and seabed assets of conservation significance. A typical side-scan sonar trace showing sand ripples and a wreck on the seabed is shown in Figure 5.4.

Boomer sub-bottom profiler

This instrument (Figure 5.5) is used to identify geological structures as much as 20-100m below the surface of the seabed, by recording images of the geological layers. The boomer is towed on a raft at the surface of the sea and produces sound waves that are partially reflected or refracted by differences in the rocks or sediments below the seabed (Figure 5.6). These are then recorded by a hydrophone that is towed just beneath the sea surface behind the survey ship. A

CHIRP system can also be deployed to provide higher resolution imagery of the sub-bottom structure and greater penetration.

Boomer sub-bottom profilers have been widely used to identify potential oil-bearing structures, gravel deposits and sites of potential archaeological significance. An example of the images produced by this equipment can be seen in Figure 5.7.

Physical Sampling and Optical Methods

Physical sampling techniques and optical methods, (described in Chapter 3) are used alongside the acoustic technologies described above to further improve our understanding of baseline environmental conditions. Samples obtained by grabs, coring and beam trawling are often collected to analyse the biological resources, but the physical properties of the seabed sediments can also be used to ground-truth the data from the acoustic surveys. Data captured by optical methods such as underwater video and still photography (discussed in Chapter 2) can be used in a similar way.

Oceanographic Surveys

The baseline description of oceanographic conditions in the dredging area can be based on direct measurements. Oceanographic surveys (sometimes called metocean surveys when combined with meteorological measurements) are the main means of directly collecting observations/data on currents, tidal elevation, suspended sediment, turbidity, waves, sediment dynamics and the horizontal and/or vertical structure of the seawater. Guidelines for the conduct of benthic studies at aggregate dredging sites (DTLR, 2002) provides detailed information on a range of techniques to monitor these parameters.

Worthy of particular note is the Acoustic Doppler Current Profiler (ADCP) (Figure 5.8). This is a device which emits an acoustic signal from a series of transducers and measures the Doppler Shift in a series of depth strata (bins) thus giving a profile of currents vertically through the water column (Rees and Boyd, 2002). One of the particular reasons why ADCP is a widely used instrument is that the acoustic backscatter intensity (ABSI) information from the bins can also provide additional valuable information on the suspended sediment profile through the water column. In order to achieve this, the ABSI data needs to be calibrated against field measurements of suspended sediment concentrations in order to get quantitative results, although it can be difficult to obtain sufficient data across a range of oceanographic conditions in order to undertake such calibration robustly.

ADCPs can either be mounted on the seabed and directed vertically upwards or mounted on a vessel and be directed downwards. Typically a deployment will be for at least a spring-neap tidal cycle, but ideally a deployment should be sufficiently long to also capture the effect that a range of wave and surge events (characterised by separate wave and tidal level measurements) have on currents and suspended sediment concentrations.

In a MALSF-funded project, Black *et al*. (2006) identified that there was limited reported field data specifically on either sediment entrainment thresholds or sediment transport rates pre- and post-dredging activities. To assist in filling this gap, a new benthic flume technology was developed to directly measure these parameters and was tested at an aggregate extraction site offshore from Great

Fig 5.4 Side-scan sonar image showing ripple marks in the sand and a seabed wreck. Courtesy of Cefas.

Fig 5.5 Boomer sub-bottom profiling equipment. Courtesy of Wessex Archaeology.

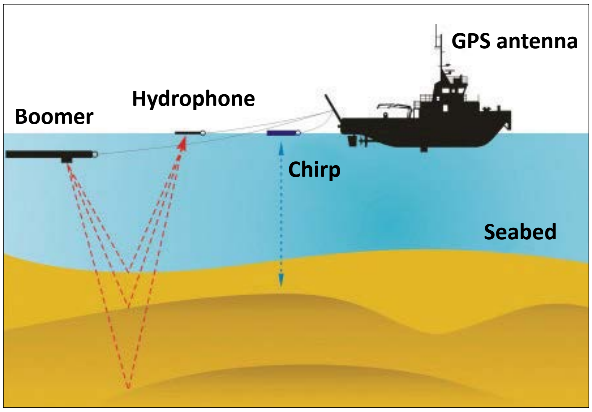


Fig 5.6 Diagram showing the deployment of the boomer and systems to record sound waves, © Wessex Archaeology.

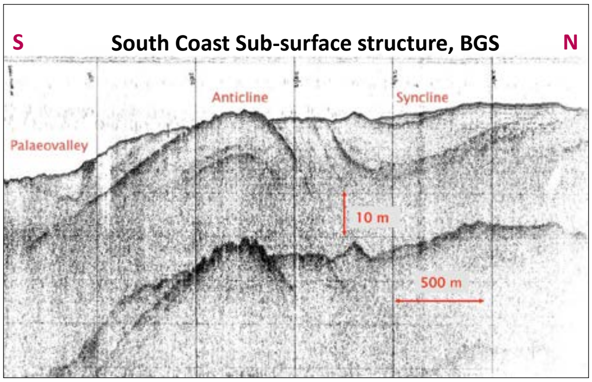


Fig 5.7 Section of the seabed showing the sub-bottom geology in the English Channel off the south coast of England. Courtesy of British Geological Survey.

Fig 5.8 Acoustic Doppler Current Profiler (ADCP), © MES Ltd.

Yarmouth. In this device, water is pumped or driven onto the seabed by bed-mounted flumes until erosion occurs, and optical back-scatter (OBS) instrumentation is then used to measure the time-evolution of suspended sediment under an imposed flow speed, enabling relationships between the forcing stresses acting on the seabed and the physical properties of the sediments to be established, and assessments made of sediment mobilisation, transport and deposition.

Impact Assessment

Adverse changes to the coastline and seabed arising from marine aggregate dredging would be unacceptable in all but exceptional circumstances. Hence, in order to determine if an adverse impact is likely, an Environmental Impact Assessment (EIA) is usually undertaken for marine aggregate dredging applications. A key component of the EIA process involves the comprehensive assessment of any potential physical effects on coastlines within a Coastal Impact Study (CIS).

A CIS is a scientifically robust assessment that uses validated techniques and/or models and the latest data and understanding. It provides an assessment of potential impacts across both the 'near field' (i.e. within site) and 'far field' (i.e. across the wider seabed and adjacent coastlines) in a transparent and auditable manner. The procedures to be followed adopt a 'cautious view' that overestimates dredging volumes, assumes instantaneous lowering of the seabed due to dredging, and makes no allowance for partial infilling of furrows. In addition, a modern CIS involves consideration of not only the potential impacts arising from a specific site application, but also the cumulative impacts arising from all adjacent marine aggregate dredging sites and the in-combination impacts with other activities on neighbouring seabed areas.

Following this impact assessment procedure, there has been no evidence through pre- and post-dredging monitoring to date of any consented dredging activities adversely affecting the coast, indicating that the CIS approach is both suitable and rigorous.

Mitigation and Monitoring

Assessment of potential impacts through a CIS prior to the licensing process is the primary form of mitigation of the potential changes to the physical environment arising from marine aggregate extraction. Should unacceptable changes be identified in the CIS, they are reduced to acceptable levels or removed entirely by modifications to the proposed dredging activities. These proposed amendments are then re-assessed with respect to changes to the physical environment until the mitigation criteria are met. If the changes cannot be mitigated to levels that are acceptable to the regulators then a license may not be pursued.

As part of the strict regulatory procedures adopted to ensure that aggregate extraction does not adversely affect the marine environment, all licences granted are subject to a finite operational lifecycle, typically 15 years. After this time, dredging companies must apply for a renewal of the licence and undertake a further EIA and CIS to inform the decision-making process.

The majority of marine aggregate licences granted are subject to monitoring conditions. One example can, on occasion, apply to the measurement of suspended sediment concentrations in the water column during dredging activities.

This has resulted in a suite of potential mitigation measures being identified which can be used to minimise the increase in suspended sediment concentrations and reduce the area affected by sediment plumes. These measures are summarised in Tables 5.2 and 5.3 and described in detail in:

- Aggregate Extraction – Approaching Good Practice in EIA (ODPM, 2005).

Following the dredging activity, it is important to ensure that the seabed sediment remains similar to its pre-dredging condition. A mitigation condition therefore generally requires a layer of sediment at least 0.5m thick to be left over the underlying strata. This mitigation measure also has benefits in terms of reducing the impact on the biological environment. In addition, surveys of the seabed and any adjacent sedimentary features, both pre- and post-extraction of aggregates, may be required as part of the dredging licence conditions. Over time, these monitoring studies have provided much useful data, which has increased confidence in our understanding of dredging impacts and in the validity of predictive methods used during the application process (Tillin *et al*., 2011).

In the past there has sometimes also been the requirement for monitoring of shorelines associated with some licence conditions, even when a CIS has identified no significant impact on the adjacent shore from the dredging.

Government and Industry Initiatives

In 2002, the Government imposed a levy on all primary aggregates production, including marine aggregate, to reflect the environmental costs of winning these materials. A proportion of the revenue that was generated was used to provide a source of funding for research aimed at minimising the effects of aggregate production. This fund, delivered through Defra, is known as the Aggregate Levy Sustainability Fund (ALSF). A vast quantity of high quality science has been produced during the lifetime of the marine aspect of this programme, called the Marine Aggregate Levy Sustainability Fund (MALSF).

The MALSF has commissioned comprehensive interdisciplinary marine surveys that help characterise the marine environment, and targeted research and development (R&D) that has addressed specific information gaps, such as better understanding of the pressures and impacts from marine aggregate extraction, or testing new survey technologies and assessment methodologies.

Regional Environmental Characterisation (REC)

A key aspect of the MALSF-funded activities over the past decade has been the publication of a series of multidisciplinary marine Regional Environmental Characterisation (REC) studies encompassing the geology, biology and archaeology of extensive areas of seabed in regions of known importance for marine aggregate extraction. The RECs provide a background context for assessments of pressures from long-standing historic and potential new extraction activities in these seabed regions of the Outer Thames Estuary, South Coast, East Coast, and the Humber. In addition, similar habitat mapping studies (although not called RECs) were also produced at earlier dates for the Irish Sea, Outer Bristol Channel and Eastern English Channel, meaning that all areas of the UK with licensed marine aggregate extraction activity are now covered by these studies.

The principal objectives of each REC were set by the MALSF, and hence the studies were focused on the needs of the aggregate industry. In essence, the studies involved: characterisation of rock, sediments and biological communities, mapping of biotopes and areas of potential conservation interest, characterisation and mapping wrecks and objects on the seabed and the potential of the area to contain submerged sites of prehistoric occupation.

A final assessment was made to identify any gaps in data, analysis, understanding and interpretation prior to and remaining after completion of the study.

The results, interpretations and conclusions were published as REC reports. Appendices of data and analysed and interpreted results were also provided on DVD-ROM, accompanied by an ArcMap GIS and associated databases (in some cases integrated with data from other relevant studies) and ArcExplorer software.

In all areas notable advances have been made in characterisation of the geology, biology and archaeology of the regional seabed. For most areas significantly enhanced datasets are now readily available through bespoke multi-disciplinary marine data acquisition programmes. The geomorphology of some of the areas covered by the RECs is diverse and complex (e.g. East Coast). The REC studies have improved understanding of sediment transport processes in these areas, including better definition of the complex circulations around sand banks. All of the studies benefited from the integration of scientific skills from a range of disciplines.

It should be recognised that despite involving comprehensive multidisciplinary surveys, the RECs captured only a single snapshot in time, and further work will be required at sites of interest to aggregate extraction companies in order to capture the temporal variability and stability of key features. Furthermore, in the South Coast REC, there was a significant shortfall in geophysical survey coverage across the study area due to adverse weather conditions.

Notwithstanding these aspects, the RECs have provided valuable characterisation and datasets for the regional seabed areas of the South Coast, the Outer Thames Estuary and the East Coast, respectively. The RECs have been extensively used to support assessments of the cumulative and in combination effects of extraction as part of a voluntary programme by the industry to produce Marine Aggregate Regional Environmental Assessments (MAREAs), as discussed later.

Table 5.2 Mitigation measures to reduce the increase in suspended sediment in the water column
Appropriate operation of dredging equipment
Sediment re-suspension can be reduced by optimising trailing velocity of the dredger, the position of the suction mouth and pump discharge.
Reduction of intake water
Smaller volumes of water taken up through the suction head means there is a more dense aggregate load, and this reduces the need for overflowing. Dilution doors located at the dredge head are used to control the volume of water taken onboard the dredger. A certain amount of water is always necessary to ensure the efficiency of the pumping of the aggregate mixture into the hopper, therefore the scope for reducing water intake is limited and is highly dependent on the sediment being dredged.
Reduction of air in overflow mixture
Air can readily be taken out of the overflow mixture onboard by the installation of a well-designed overflow system. This allows the overflow mixture to descend more quickly to the seabed, rather than be suspended at the surface because of the presence of air.
Minimisation of screening and overflow, where feasible
This will reduce the magnitude of the sediment plume.
Avoidance of dredging areas with finer grain sizes
Dredge appropriate targets within the dredging licensed areas, and plan to avoid fine grain sizes.

Table 5.3 Mitigation measures to reduce the area affected by the increase in suspended sediment
Dredge parallel to peak tidal currents
This measure is often included in the dredging conditions, but is also practised by the aggregates industry voluntarily, for operational reasons. This method can be used to reduce the area covered by the sediment plume, but is dependent on the geometry and orientation of the aggregate resource.
Minimisation of the area dredged
By minimising the area within the licensed site that is dredged, other areas within the licensed site will not be affected by suspended sediment. Minimised areas are often then worked to exhaustion.
Use of specialised equipment, where feasible
New technologies such as the anti-turbidity valve and the Green Pipe can be used to minimise plume dispersal. The anti-turbidity valve is effective in reducing turbidity by reducing air entrainment in the overflow process, and has been widely adopted by European and US dredging industries. However, this valve would only really be effective in very fine sands and silts, and not for commercially exploited aggregate resources. The Green Pipe is the name often given to an approach of re-circulating overflow water to the drag head. The aim of this is to eliminate the dredging plume from the upper part of the water column. However, this system has high capital and operational costs that cannot be justified by the UK dredging industry for simply reducing suspended sediment in the upper water column.
Use of water jets to reduce overflow
Water jets can be located on the drag head to help break up compacted sediments when dredging hard ground. These drag-head jets can use water recycled from the hopper overflow water rather than clean seawater, thus slightly reducing the overflow.

Historical Records and Resources

Other work funded through The Crown Estate demonstrates that historic resources, such as maps, charts, photographs and art, comprising landscape paintings, watercolour drawings and prints, can prove to be valuable tools alongside other techniques in assisting understanding of the complex issues of coastal change, particularly at the shoreline and in the context of climate change and sea-level rise. Such historical resources can provide a useful benchmark for assessing the locations, nature, scale and pace of coastal change over the last two centuries, particularly with respect to:

- Understanding of geology, geomorphology and coastal evolution;
- Comparing beach levels;
- Comparing coastal change as a result of coastal erosion;

Of particular relevance has been the use of these historic resources to demonstrate that coastal erosion has been occurring for many centuries and hence is a long-standing issue in areas where public perception has been that marine aggregate dredging has triggered such processes (see McInnes and Stubbings, 2010, 2011).

Science Monograph Series

A series of six science monographs was commissioned that collectively provide a comprehensive review of aspects of the marine aggregate dredging industry in the UK. Of particular relevance to the physical environment are Monograph 1 (Tillin *et al*., 2011) and Monograph 2 (Hill *et al*., 2011). Monograph 1 was commissioned to review current understanding of the main direct and indirect impacts (including physical effects) of aggregate dredging on the marine environment and other marine users. Monograph 2 considers the physical (and biological) recovery of the seabed resources following marine aggregate extraction.

MALSF Navigator

The MALSF Navigator is a web-based repository that collates and disseminates the knowledge generated by the MALSF. It marks a significant step-change in the accessibility of key outputs from the MALSF programme to the broadest possible audience and must be considered as a significant asset produced by the MALSF programme.

MALSF Research Projects

A large number of research projects have been funded by the MALSF. Key findings from many of these were synthesised during a conference held in 2006. The resulting proceedings provide a concise review of research mainly funded through the MALSF between 2004 and 2007:

- Marine aggregate extraction: helping to determine good practice (Newell and Garner, 2007).

Other Research Projects or Studies

Other research and information sources are available from the UK marine aggregate dredging industry, most notably through the British Marine Aggregate Producers Association (BMAPA) and the Mineral Industry Research Organisation (MIRO). In addition, notable studies of regional seabed processes and the impacts of marine aggregate dredging have also been undertaken in the Bristol Channel (Posford Duvivier and ABP Research and Consultancy, 2000) and the Southern North Sea (ABP Research, 1996; HR Wallingford *et al*., 2002), whilst numerous papers have been published in the scientific or professional literature (e.g. Bradbury, 2003; Phillips, 2008). Relevant information is also available from Marine Aggregate Regional Environmental Assessments (MAREAs) covering several seabed regions and Coastal Impact Studies (CIS) pertaining to many applications for new licences or licence extensions. These are discussed further within the context of cumulative effects.

Direct Impacts on the Physical Environment

This section discusses the principal potential direct impacts of marine aggregate extraction on the physical environment and, where applicable, highlights where research funded by the MALSF and information available from other sources has advanced knowledge on these issues. The principal direct impact on the physical environment from marine aggregate extraction is associated with the removal of surface layers of sediment from the seabed. This activity alters the physical characteristics of the seabed, including its bathymetry (shape and depth below the water surface) and, if certain particle sizes are preferentially targeted during dredging, the texture of the sediment.

Changes in Bathymetry of the Seabed

The most commonly used method of aggregate extraction in the marine environment is trailer hopper suction dredging (Figure 5.9). This method creates furrows typically 2-3m wide and initially only around 0.5m deep, but which may extend for several kilometres in length (Figure 5.10). Over time, the seabed may be lowered by up to approximately 3m through repeat activities (Kenny and Rees, 1996; Newell *et al*., 1998; Desprez, 2000).

Static (or anchor) dredging (Figure 5.11) may also take place, which tends to create deeper (5-10m) pits in the seabed (Figure 5.12). These pits may coalesce over time to form an irregular bed topography (Tillin *et al*., 2011).

The direct 'footprint' of the physical effect from the dredging activity is confined to dredging lanes or pits within the licensed area. The rate of recovery of the furrows, through subsequent infilling with sediment, is governed by the mobility of seabed sediments within the region and the intensity (frequency and spatial extent of dredging within a seabed area) of the dredging activities. Monitoring studies have shown that in areas of relatively low wave exposure and reduced tidal currents, the depressions may typically be degraded over a period of 3-7 years following cessation of dredging (Cooper *et al*., 2005), whereas this period can be less than one year in areas where sediment is more mobile (Kenny and Rees, 1996; ICES, 2001). At an experimental

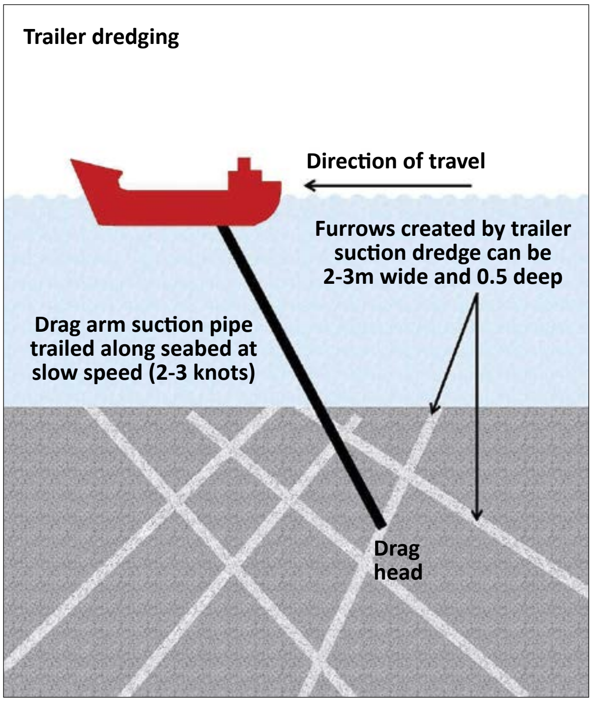


Fig 5.9 Schematic of the process of trailer hopper suction dredging, © MES Ltd.

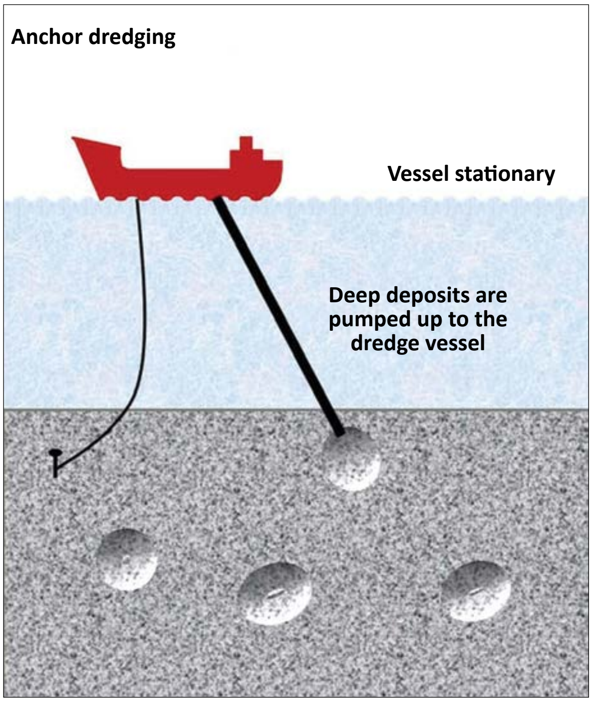


Fig 5.11 Schematic of the process of anchor dredging © MES Ltd.

Fig 5.10 Furrows created on the seabed by trailer hopper suction dredging, © BMAPA.

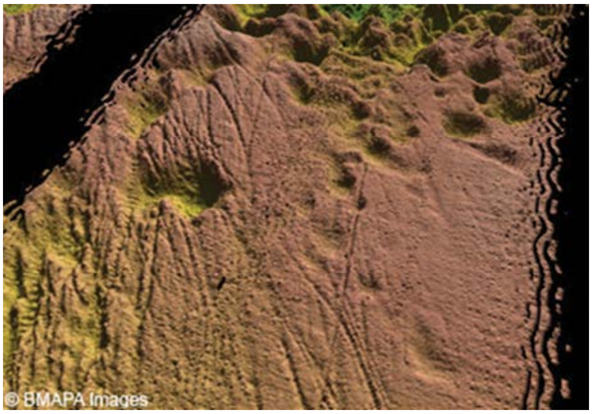


Fig 5.12 Pits created on the seabed by anchor/static dredging, © BMAPA images.

dredge site off the Norfolk coast, dredge tracks in 25m of water were degraded within three years (Kenny and Rees, 1996). In some cases, particularly when relict deposits (sediments that are no longer active under contemporary processes) have been dredged, the resultant lowering of the seabed may be permanent (Tillin *et al*., 2011). Repeat bathymetric surveys, required by regulators for several years offshore from Great Yarmouth, have shown that post dredging of relict deposits in licensed areas the depressions have not become infilled. This evidence has been used to show that the dredging has not interrupted sediment transport.

Hill *et al*. (2011) provided a summary of recovery times from a review of monitoring undertaken by other authors at dredging sites located in a variety of physical environments (Table 5.4).

In addition to directly monitoring the recovery of the seabed following dredging, Rees (2006) reported an alternative assessment approach involving computation fluid dynamics (CFD) model simulations of the changes in flow and sediment re-suspension, transport and deposition within dredge tracks in dredging lanes arising from marine aggregate extraction, with the intention of providing advice on minimising changes to the sediment regime. These tracks, generated by the action of the drag head, have the potential to act as sand sinks.

In the reported study, changes were made to the coding of an existing CFD model, including the addition of pressure-grading forcing and simulation of rough boundaries. A sediment transport module involving re-suspension, transport and deposition was also developed, allowing budgets of material to be computed. The model results were compared with analytical solutions and previous model studies over flat beds and the scenarios modelled included: (i) dredge-track orientation with respect to the principal axis of the tidal ellipse; (ii) dredge-track morphology; and (iii) particle size. It was noted that other scenarios, which were not modelled, could also influence local changes in flow and sediment transport, including: (iv) curved dredge tracks; (v) the sequence of dredge tracks occupation; and (vi) static dredge pits.

As output from the reported study, a robust CFD numerical model was developed that is capable of describing the velocity flows within complex areas of morphology such as found in aggregate extraction areas. These flow fields have been utilised within numerical suspended sediment models to predict re-suspension, transport and deposition of sediment within the model domain. The results clearly indicated a mechanism for retention of sands by dredge tracks, arising from the lower bed shear stresses within the tracks compared to the surrounding higher flat regions. This

Table 5.4 Examples of physical recovery times at a range of marine aggregate extraction sites around the U K after the cessation of dredging

Area	Description of Impact	Energy of Site	Dredging Intensity	Recovery Time	Recovery Description	Refs
North Sea	Dredge tracks 0.3m to 0.5m deep in gravelly substrate	High		8 months	Area exposed to wave action, dredge tracks rapidly disappeared	1
Bristol Channel	Dredge tracks in sandy habitats	High/ Mod		< 1 year estimated	Tracks eroded by strong water movement and probable sediment transport	2
North Norfolk Experi-mental area	Dredge tracks in gravel, increased gravel content		High	3 years	Two years after dredging furrows were eroded and only just visible as features using side-scan sonar. Weathering probably due to increased winter wave action and prevailing tidal currents and infilling from sand transport	3, 4
Offshore Humber Area 408	Tracks in sand and sandy gravel	Weak		> 5 years	Weathered dredge tracks still visible 5 years after dredging ceased and sediment composition not returned to pre-dredge and non-dredge conditions	5
North Norfolk Area 107	Dredge tracks	Mod		> 7 years	Tracks still visible 7 years after cessation of dredging	6
Hastings Shingle Banks Area X	Coarse sandy gravel	Mod	High	> 7 years	Weathered dredge tracks still observed in side-scan sonar 7 years after dredging stopped	7
		Mod	Low	2-3 years estimated	Weathering of dredge tracks occurred after 12 months	
		Low	High	> 8 years	Tracks still visible 8 years after cessation of dredging	
	Large pits resulting from static anchor dredging	Low		Decades	Almost no recovery, features have remained as recognisable features for many years	8
Thames Area 222	Dredge Tracks in very coarse sand	Weak/ Mod		> 9 years	Tracks still visible many years after cessation of high intensity dredging	6

Energy categories refer to the tidal stress: Low = 0-1.8 Nm-2, Moderate = 1.8-4.0 Nm-2 and High = >4.0 Nm-2 (tidal stress categories from Foden et al., 2009).

References: 1 Boyd et al., 2004. 2 Newell et al., 1998. 3 Kenny and Rees, 1994. 4 Kenny and Rees, 1996. 5 Cooper et al., 2005. 6 Cooper et al.,2007a. 7 Cooper et al., 2007b. 8 Dickson and Lee, 1973.

mechanism appeared relatively insensitive to track orientation with respect to main tidal axis but was observed to be sensitive to particle grain size, preferentially trapping coarser particles. It was suggested in the study that it is plausible that a similar mechanism will also be observed for particles transported as bedload, as well as the suspended load case considered in the modelling scenarios. The reported study concluded that isolated dredge tracks with a large depth/width ratio (i.e. deep and narrow) are more likely to accumulate sediment than tracks with a smaller depth/width ratio (i.e. shallow and wide).

It is important to note that only a limited number of scenarios were considered due to problems encountered in setting-up and validating the CFD model, and that recommendations were made for further development of the research. Despite this, the findings are of some use to assessments of management and restoration of a local site arising from the direct physical impacts of aggregate extraction. They are also of some use to assessments of potential influences on broader sediment transport pathways through, and indirectly beyond, the aggregate extraction region, an issue that is discussed later in this chapter.

Whilst the changes in topography of the seabed are therefore local in extent, being confined to dredge tracks or pits, and in many cases are non-permanent in duration, there may be associated indirect effects on the wave, tide and sediment regimes.

Changes in Sediment Character of the Seabed

Marine aggregate extraction may also lead to subtle changes in the sediment type that characterises an area of the seabed. For example, the selective removal of gravels can lead to 'fining' of the residual sediments on the seabed, due to a relative increase in the proportion of sands (Cooper *et al*., 2011). Although aggregate extraction may have this immediate effect of making the seabed sediments finer, water currents may remove (winnow) these sediments so that the seabed will become coarser again over time (Tillin *et al*., 2011). The extent to which this occurs depends on the prevailing hydrodynamic regime and the degree of natural mobility of sediment particles or larger-scale bedforms. These changes in seabed sediment character can potentially have implications for resident and re-colonising fauna following dredging activities and are discussed in Chapter 6.

Indirect Impacts on the Physical Environment

This section discusses the principal potential indirect impacts of marine aggregate extraction on the physical environment and, where applicable, highlights where research funded by the MALSF and information available from other sources has advanced knowledge on these issues. Whilst the direct impact of seabed lowering as a result of dredging is localised to within the dredge lanes or pits, and in many cases is non-permanent in duration, changes in bathymetry have the potential to alter the existing wave, tide and sediment regimes and cause indirect impacts that extend beyond the dredged area, potentially extending to the coastline. In addition, sediment plumes formed by the release of material into the water column from a combination of extraction, loading and screening processes will become displaced vertically and laterally, potentially resulting in sediment deposition in areas that are remote from the source.

Changes in Wave Regime

Changes in bathymetry have the potential to alter the wave transformation processes across the affected seabed, with a residual effect potentially extending to adjacent areas of seabed, sand banks or even the shore. In particular, the processes of wave refraction across the seabed may be altered following dredging activities, thereby potentially altering the distribution (or 'focusing') of wave energy in the lee of the dredged area. These factors in turn may alter the processes of shoreline sediment transport, potentially altering patterns of erosion and accretion at the coast. Aggregate extraction undertaken on sand or gravel banks or bars will lower the crest level; wave dissipation across the feature may be reduced, potentially lessening the shelter afforded by the feature to adjacent areas of seabed and coastline.

The extent of any changes to the wave energy distribution is assessed as part of the CIS for each licence application. In the majority of cases, changes in the wave climate of greater than around 2% are restricted to the immediate vicinity of the licensed area (Tillin *et al*., 2011). Changes of ±3% are considered as the resolution of the modelling techniques typically used, as well as being within the likely accuracy of any wave measurements that may be carried out. Similarly, Houghton *et al*. (2011) reported that recent numerical modelling undertaken for the MAREAs has shown that changes in wave conditions are typically small and localised and that the adjacent seabed would not be subject to large increases in wave energy. Published industry guidance states that changes in wave transformation due to aggregate extraction are unlikely to be problematic at the coastline if the activity occurs in water depths of greater than 15m (Brampton and Evans, 1998), although this would usually need to be confirmed on a case-specific basis.

Tillin *et al*. (2011) reported that there have been occasions in the past (for example off the south coast and in the eastern English Channel) where modelling carried out for a CIS has predicted unacceptable changes to the nearshore wave climate. Due to this prediction

Fig 5.13 Waves breaking at the shore, © Royal Haskoning.

it was necessary to revise either the proposed dredging plans or the dredging area before the licence application was approved. Similarly, at Area 472 (Culver sand bank) in the Bristol Channel, proposals to dredge the crest of the sand bank were altered, with dredging moved to the southwest of the main bank.

This change was instigated based on assessments that included modelling of the changes in wave refraction processes and the impact that would be caused by altering the form of the waves approaching the coastline.

Modelling undertaken by the Tyndall Centre for Climate Change Research (2006) concluded that the effects of dredging on wave conditions between Happisburgh and Blakeney in Norfolk were very small and no larger than the margin of error inherent in the modelling process. Given this finding, subsequent modelling of cliff erosion was not strictly justified, but the models were run nonetheless, with only minor fluctuations (both positive and negative) observed, and hence no link was found between seabed lowering in the dredged area and increased cliff recession due to loss of sheltering effects from the banks.

Bradbury *et al*. (2003) evaluated the effect of dredging the Shingles Bank in Christchurch Bay, Dorset, which was used as a source for recharge material at Hurst Spit (Bradbury and Kidd, 1998). This was a rare example of aggregate dredging from a shallow nearshore area and six years of post-scheme data were analysed to assess the impacts of dredging on the physical environment. Shore responses demonstrated that beaches adjacent to the areas of dredging were not affected by dredging activity.

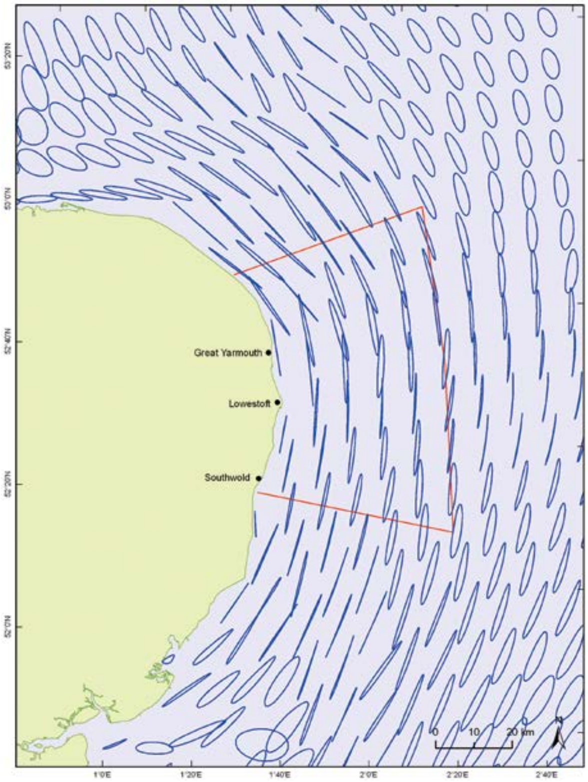
Phillips (2008) noted that there is commonly held public belief, predominantly centred around the Norfolk and South Wales coastlines, that marine aggregate dredging from sandbanks has resulted in severe local beach erosion. Despite his extensive surveys along the Gower and Penarth coastlines, he concluded "*no qualitative or quantitative causal link was found between marine aggregate dredging and beach erosion. However, many qualitative and quantitative relationships were established between water level, wind and waves, and beach erosion*."

Changes in Tidal Regime

Marine aggregate extraction is carried out along dredge lanes that are usually oriented parallel to the tidal currents. Ridges and furrows are formed by the drag head. Typically furrows are 2-3m wide and initially around 0.5m deep, although over time repeat activities may lower the seabed by up to around 3m. This alteration of bathymetry directly caused by removal of the substrate during dredging has the potential to cause changes in tidal current flow locally within the dredge lanes (as modelled using CFD techniques by Rees, 2006) and potentially across a wider area of seabed in the lee of the dredged area. However, as the majority of dredging is carried out in deeper water, the relative increase in seabed depth is very small. Numerical modelling studies have demonstrated that whilst flow speeds increase through the dredged area, with a corresponding reduction in flows along both sides, it is generally accepted that changes to tidal currents are confined to within an area less than twice the size of the dredged area (Brampton and Evans, 1998; HR Wallingford, 2002). Published industry guidance states that measurable changes in flow regimes due to aggregate extraction are unlikely to be problematic at the coastline if the activity occurs in water depths of greater than 10m (Brampton and Evans, 1998), although this would usually need to be confirmed on a case-specific basis.

It remains theoretically possible that changes in flow regime could occur within an area of seabed that in turn affects the stability of morphological or archaeological features within the affected zone. For this reason, CIS may recommend the closest that a dredging operation can be to adjacent sandbanks or EIA may recommend exclusion zones around interest features. Exclusion zones around archaeological features have been considered in a MALSF-funded study by Dix *et al*. (2007). As tidal currents pass around and over a shipwreck on the seabed, the flow is modified locally causing characteristic patterns of erosion and accretion. Dredging too close to the wreck could affect the flow regime and alter the established sedimentary pattern, potentially exposing or covering the wreck or its associated artefacts.

Based on results from field and laboratory tests and literature reviews, Dix *et al*. (2007) recommended that exclusion zones should be designed as elliptical environmental buffers, aligned along the tidal axis. This is because the majority of ambient sediment transport in offshore dredging areas occurs along an axis parallel or sub-parallel to the tidal flow as is shown in Figure 5.14. The ‘upstream’ separation prevents undermining of naturally stable sediment slopes leading up to the wreck whilst the ‘downstream’ separation encompasses regions likely to contain artefacts transported from the immediate wreck site. Having defined this environmental buffer, an additional ellipse is then added at a fixed offset around that buffer to define the resulting exclusion zone. The new exclusion zones take the form of tidally-aligned ellipsoids which may prove operationally more convenient than the previous circular zones and should minimise the area of aggregate resource lost.



East Coast REC Study Area
Tidal Ellipses

Fig 5.14 Tidal ellipses along the East Anglian coast, © Cefas.

Research into the potential effects of dredging in shallower water than considered above was undertaken in the late 1990s (Brampton and Evans 1998). This work simulated tidal current changes in response to intense dredging on the Dolphin Bank system in Poole and Christchurch Bays and demonstrated that even in extreme situations, the changes in current speed close to the shoreline were negligible.

Changes in Sediment Regime

Dredging of the seabed potentially could lead to interruption of local and regional sediment transport pathways as furrows become infilled or as flow regimes become altered. Changes to regional sediment transport pathways or circulations could potentially translate into changes to adjacent sandbanks or areas of coastline. In the

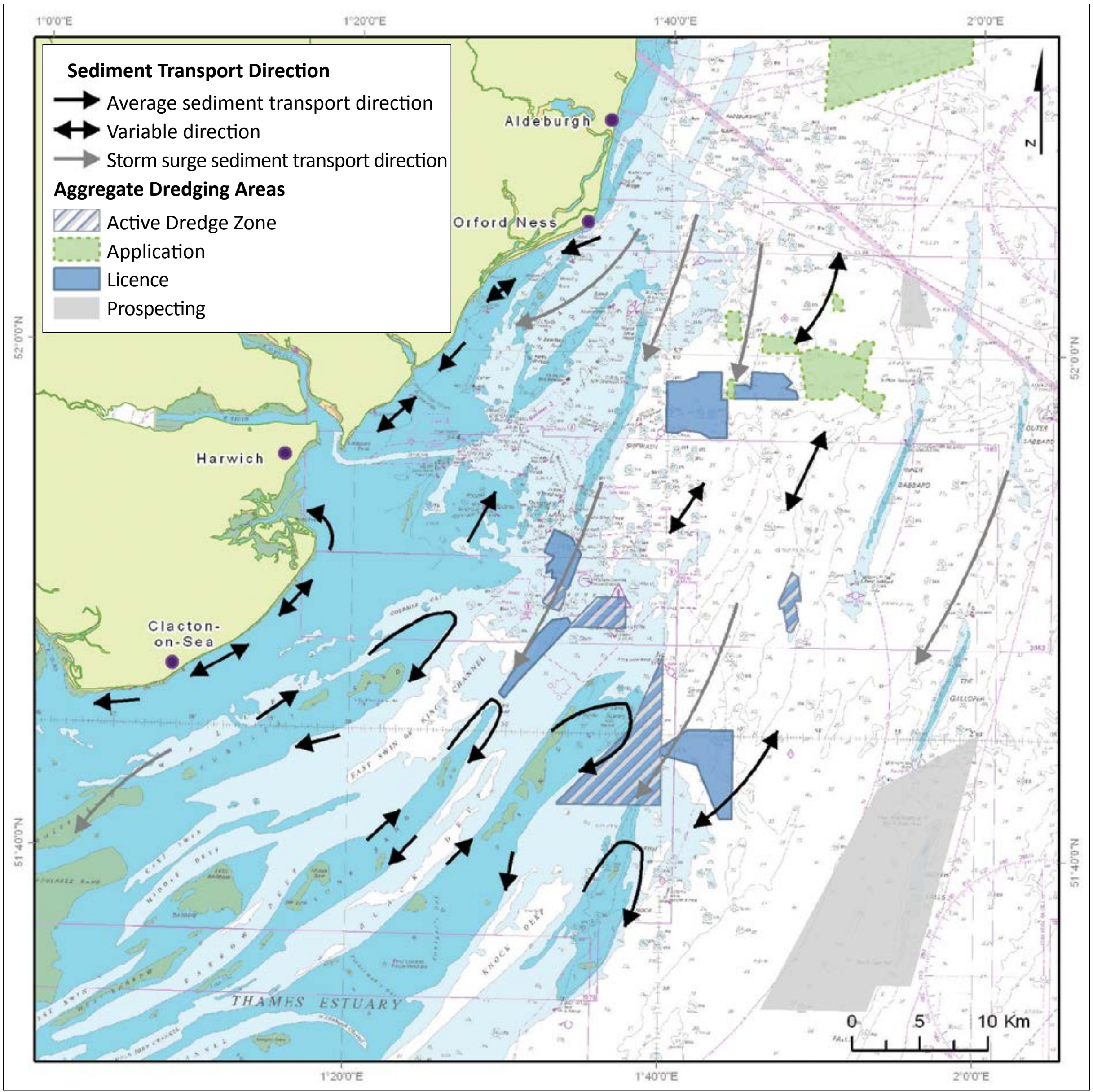


Fig 5.15 Generalised regional sediment transport patterns as determined by the Southern North Sea Sediment Transport Study Phase II (2002).

UK, dredging is typically carried out in water depths greater than 20m, and sometimes into relict deposits located within infilled palaeovalleys. As such, the sediments that are extracted are unlikely to be mobile except under extreme wave and tidal conditions (HR Wallingford, 2002). Therefore, it is unlikely that dredging will directly remove sediment that would have ultimately supplied adjacent beaches.

Tillin *et al*. (2011) reported that when determining the extent to which dredging might impact sediment transport pathways or circulations, it is important to consider the natural variability of the seabed. For example, mobile bedforms are generally used as an indicator of sediment transport rate and direction. Even where there is little or no evidence of sediment transport, the seabed is seldom flat and in some areas natural depressions exist that are far larger than those created by dredging. Hence, if these natural features do not interrupt the supply of sediment to adjacent coasts, it is unlikely that dredging would have any measurable impact upon this process.

Notwithstanding this, considerable research has been undertaken over recent decades, much of it funded by the

MALSF, to investigate and characterise sediment transport processes across large areas of seabed. This research includes regional sediment transport studies (e.g. Kenyon and Stride, 1970; HR Wallingford *et al*., 2002) and more recent multi-disciplinary Regional Environmental Characterisation (REC) studies in the Outer Thames Estuary (EMU Ltd., 2009) the South Coast (James *et al*., 2010), the Central and Eastern English Channel (James *et al*., 2011), the Humber (Tappin *et al*., 2011) and the East Coast (Limpenny *et al*., 2011). This information provides a comprehensive baseline understanding of regional sediment transport regimes against which the potential impacts of marine aggregate extraction activities can be compared to assess their scale of influence on the broader sediment regime.

The net sediment transport pathways in the vicinity of aggregate dredging licence areas in the southern section of the North Sea are shown in Figure 5.15 from which it will be noted that these generally run parallel to the coastline. Sediment accretion at one site on the coast is therefore sourced from erosion at other points along the coastline within this region, with no significant contribution from offshore sediments.

The Southern North Sea Sediment Transport Study (HR Wallingford *et al*., 2002) concluded that aggregate dredging off the East Coast is too far offshore to be of significance to coastal (nearshore and shoreline) processes and cites sediment transport evidence to demonstrate the high degree of confidence in this judgement. This landmark study was undertaken independently of the dredging industry-funded assessments and was led by the coastal local authorities along the east coast of England. More recently Cooper *et al*. (2008) investigated dredging in the East Coast region, where a link between aggregate extraction and beach erosion has often been claimed by some members of the public. The work identified that the relict and largely immobile sediments in the dredging areas did not contribute to sustaining the inshore bank system, which in turn affords protection against waves to the shore, and therefore aggregate dredging was not accountable for any potential deficit in sediment supply to those banks.

Beach Drawdown

There is the potential that if marine aggregate dredging is carried out too close to shore, that sediment could be drawn down the beach to infill the dredged area. This infamously occurred at Hallsands in Devon at the turn of the 20th Century when aggregate dredging very close to shore caused beach levels to drop and the village was destroyed during a severe storm (Melia, 2002). However, present-day aggregate dredging is regulated and is only allowed to occur sufficiently far offshore to extend beyond the active limit of the beach. Nonetheless, beach drawdown remains an issue that is often perceived to be related to dredging activities and is therefore discussed below.

To determine the timescales and processes associated with coastal erosion, it is important to understand the dynamic nature of the coastal and marine environments. This can be achieved through interpretation of historic data such as maps, charts, photographs, and works of art (e.g. McInnes and Stubbings, 2010a; 2010b) alongside baseline geological and geomorphological descriptions (e.g. Defra, 2002) and contemporary records of shoreline change (e.g. Cooper *et al*., 2009; Bradbury, 2009). It is also important to understand the natural process inter-relationships between the beach and the nearshore seabed. Beach drawdown is a natural phenomenon, which occurs during storms as the beach profile flattens when beach sediment is transported seawards (temporarily, but often relatively rapidly) from the upper foreshore to the lower foreshore and then potentially beyond into the nearshore. During calmer weather, sediment is progressively returned to the beach from the nearshore. The seaward limit of this initial seaward-directed and subsequent landward-directed sediment movement depends on a number of factors, including the severity of the wave climate, the nature of the beach sediment, and the nearshore seabed morphology, and is described as the ‘closure depth’ of the active beach profile (Hallermeier, 1981).

As part of a CIS, it is critical to determine the position of seasonal sediment movement, since extraction too close to the shore could cause sediment drawn down from adjacent beaches to be trapped in the dredged depressions and thereby lost permanently from the beach. Studies have shown that around much of the UK the ‘closure depth’ is between 7m and 10m water depth (Halcrow, 1991) and dredging in shallower water would not be permitted. Published industry guidance suggests that if dredging is in water depths of greater than 10m, then it will not induce loss of sediment through the process of beach drawdown (Brampton and Evans, 1998), although this will usually need confirming on a case-specific basis.

The drawdown process could also potentially occur if dredging is undertaken close to offshore banks, with sediment being drawn down from the bank to infill the depression. Again, the CIS plays an important role in determining where dredging may be undertaken without inducing drawdown from the bank. The CIS for Area 439 (Inner Dowsing), for example, recommended that no dredging should be carried out within 1km of the crest of the Inner Dowsing Bank (HR Wallingford, 1999). This further demonstrates the rigour that is applied in the UK in assessing applications for dredging licences.

Fig 5.16 Sediment plume created by the release of sediment back into the water column, © MES Ltd.

Sediment Plumes

The dredging process can form plumes of fine sand in the water column (Figure 5.16). These plumes could potentially have direct biological and chemical impacts due to the increase in turbidity of the water column (which can limit transparency in the water) or due to changes in dissolved oxygen concentrations or remobilisation of contaminants (see Chapter 6). Of particular importance is the plume dispersal and the subsequent deposition of the suspended sediment particles from the plume.

Sediment plumes may arise from: (i) the action of the drag head on the seabed causing a physical disturbance; (ii) overflow from the hopper during loading processes (shown in Figure 5.17); and (iii) deliberate on-board screening of recovered sediments (in circumstances where this is required) (also shown in Figure 5.17). Collectively, these processes are likely to result in enhanced suspended sediment concentrations in the water column.

Once sediment is suspended within a plume it will become displaced vertically by gravitational settling and advected laterally by waves and tidal currents before ultimately becoming deposited on the seabed. The distance the plume travels will largely depend on the particle sizes of the sediment and the strength of the tidal currents, and involves both a 'dynamic plume' and 'passive plume' phase (see Whiteside *et al*., 1995). The dynamic plume is influenced by the rapid downward mode of release from the dredger, typically resulting in deposition of the majority of the material within a few hundred metres of the activity. The passive plume involves a smaller proportion of the sediment load that is either stripped from the dynamic plume or re-suspended from the seabed, but can have an influence over a few hundred metres. Where tidal currents are particularly strong, this effect can extend up to 5km from source (Hitchcock and Drucker, 1996).

Fig 5.17 Screened and overflow sediment returned to the water column during dredge screening processes at sea (courtesy of BMAPA).

Measurement of plumes generated by the drag head alone has shown that the volume of sediment lifted into suspension is negligible (John *et al*., 2000), indicating that the principal contributors of sediment to the plume are the processes of overflow and screening. Where screening is not required, the volume of discharged material is considerably smaller, and the effects of a sediment plume may be confined to within the dredge area (Hitchcock and Bell, 2004; Newell *et al*., 2004).

Deposition of sediment on the seabed from a plume could be unwanted if the sediment infills navigation channels or leads to smothering of important seabed habitats or species. However, in most cases the plume concentrations are highly diluted and sediment widely dispersed. Once deposited on the seabed, the sediment could also be transported further by wave-driven bedload transport processes, ultimately reaching areas remote from the initial dredging activity (although in decreasing concentrations as the sediment becomes ever more widely dispersed).

Tillin *et al*. (2011) reported plume modelling, undertaken for multiple licence areas in the Eastern English Channel, that showed the highest suspended sediment concentrations would occur for a short time around high water and remain within the dredger tracks, whilst concentrations in excess of 50mg/l would not extend beyond the licensed area. Plumes containing lower suspended sediment concentrations (e.g. 5-10mg/l) were predicted to extend for 5-10km along the direction of the tidal flows but these were barely distinguishable from background levels (ECA, 2003).

Andrews Survey (2004) and Robinson *et al*. (2005) noted that a depositional ‘footprint’ associated with the dredging plume could be identified on the seabed for approximately 3-4km from the dredging area in a dynamic environment with strong currents re-mobilising sediments from the seabed and where screening was undertaken as part of the dredging process. By comparison, Andrews Survey (2004) reported that no plume depositional ‘footprint’ could be identified in an area where no screening was undertaken. BMAPA has commissioned research into the impact on benthic communities of marine aggregate dredging in Area 408 (Coal Pit). It was found that no accretion surrounding the dredged areas could be discriminated, suggesting that there was no determinable build-up of overspill sediment returned to the marine environment (Coastline Surveys, 2002).

In addition to plumes formed from disturbed sand particles, the disturbance, transport and ultimate re-settling of finer silts and clays can occur, potentially with significant detrimental effect on the biological environment. However, in the case of marine aggregate dredging, these potential effects are generally limited because dredging is only being licensed for areas where the proportion of silts and clays is less than 5% of the total dredged material (Tillin *et al*., 2011).

Cumulative and In-Combination Impacts

In addition to the potential effects on the physical environment associated with dredging in a single licence area, there is potential for impacts to arise cumulatively from the combined physical impacts associated with a number of dredge sites within an area.

The proximity of marine aggregate licence areas in the Southern North Sea, for example, is shown in Figure 5.18. The impacts from aggregate extraction may also act in combination with impacts arising from other human activities in the marine environment.

Until recently there has been relatively limited scientific evidence for cumulative, or in combination impacts on the physical environment. These issues are now gaining prominence, particularly due to the requirement for marine spatial planning, which aims to foster a more integrated approach to the assessment and management of marine resources and activities. An example of this more integrated approach to marine planning issues is summarised in a recent publication by the Marine Management Organisation of the East Inshore and East Offshore Marine Plan Areas Evidence and Issues Report 2012 **http://www.marinemanagement.org.uk/marineplanning/issues.htm**.

The development of Marine Aggregate Regional Environmental Assessments (MAREAs) is a major step forward in understanding the cumulative and in combination effects of dredging within regional seabed areas. These documents not only consider cumulative effects but also provide a regional context for subsequently assessing in more detail individual dredging licence applications, where potential for noticeable change has been identified by the MAREA. This should enable subsequent application-specific EIAs (and associated CIS) to become more targeted on quantifying those issues that are most relevant for detailed consideration.

The MAREA programme is a voluntary initiative, endorsed by the British Marine Aggregates Producers Association (BMAPA), The Crown Estate and the Marine Management Organisation. Even though the MAREA process is non-statutory, guidance has been provided by the Regulatory Advisors Group (RAG), members of which include Natural England, CEFAS, the JNCC and English Heritage.

The main objectives of a MAREA are to describe the baseline environmental characteristics within a seabed region that contains several marine aggregate licence/application areas and to evaluate the potential cumulative and in combination effects of all the existing and planned future dredging operations. However as part of the planning and permitting process, EIAs (where necessary

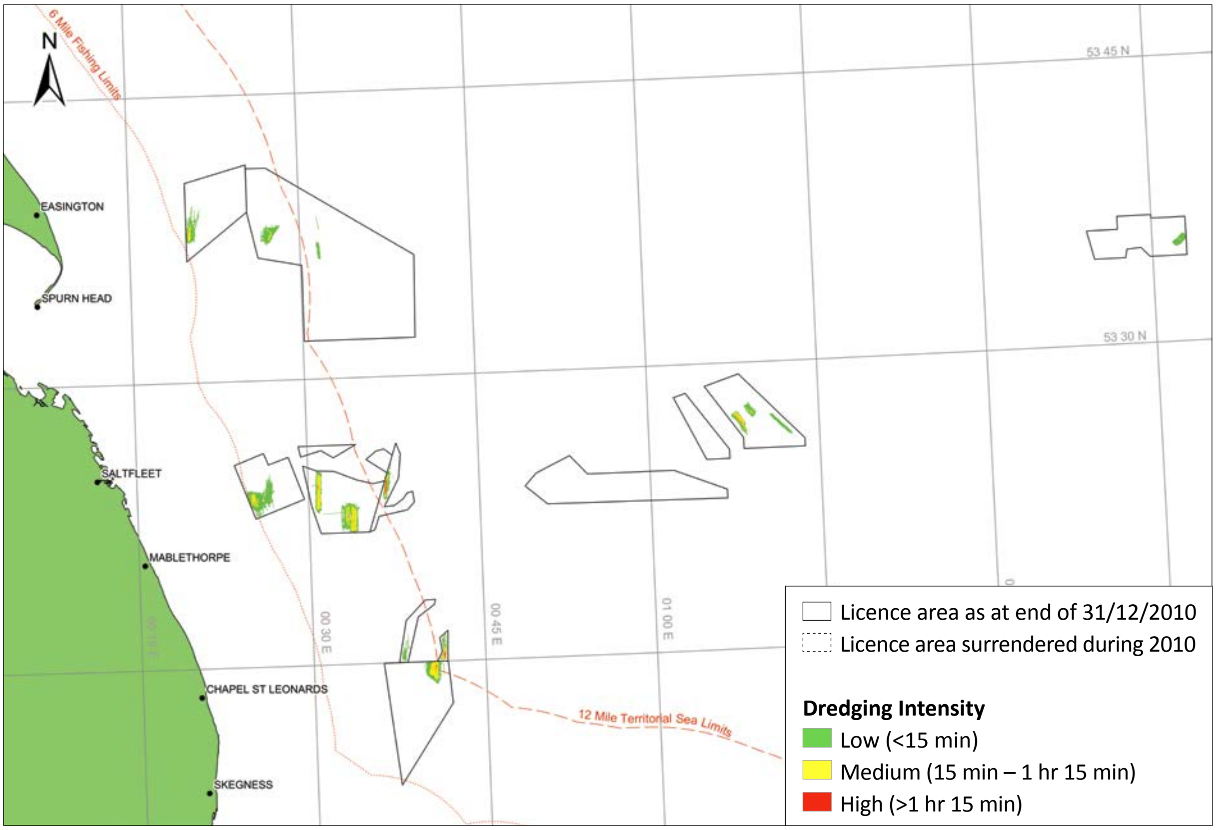


Fig 5.18 Combined dredging activity within a seabed region may lead to cumulative effects, © The Crown Estate.

incorporating Coastal Impact Studies), will still be carried out for individual licence applications. It is anticipated that MAREAs will allow the EIAs to be considered in a regional context and therefore allow a better understanding of the interaction with the surrounding environment and other sea users.

Information from the South Coast and Eastern English Channel MAREAs was incorporated in the MALSF-funded Science Monograph Series No. 1 (Tillin *et al*., 2011) which described the direct and indirect impacts of aggregate dredging. This highlighted the value of the regional perspective that the MAREA provides.

The Outer Thames Estuary MAREA (TEDA, 2010) was supported by an extensive suite of desk-based and numerical modelling studies, incorporating:

- Data review;
- Coastal characterisation;
- Plume modelling study;
- Wave modelling study;
- Tidal flows and sediment transport modelling study.

Brampton (2010) summarised these studies, identifying that the effects of cumulative dredging were deliberately assessed using an overly conservative approach that maximised the predicted spatial extents and magnitudes of possible changes to the physical environment. Despite this approach, measurable effects only occurred within and just outside of the dredging areas themselves. Based on the findings Brampton (2010) suggested that, effects on the physical environment can be predicted to extend no further from the boundary of a dredged area than the maximum dimension of that area. All sites considered in the Outer Thames were located further offshore than their maximum dimension and therefore were not predicted to have any effect on the coastline.

Conclusions

Direct Effects

Changes in seabed topography inevitably occur as a direct consequence of marine aggregate dredging. These impacts are local in extent, being confined to dredge tracks or pits, and in many cases the affected areas may recover due to natural infilling of sediments over timescales of typically between 3 to 7 years, depending on the intensity of dredging (how frequently and over what spatial area the seabed area has been dredged) and the energy of waves and tides at the site. In some cases, where dredging is undertaken in relict deposits or in very low energy environments, the effects may be permanent, but remain local in extent. Subtle changes in the character of the seabed sediments may also occur, which can have an impact on biological resources.

Indirect Effects – Coastal Impact Studies (CIS)

Coastal Impact Studies have been carried out for more than 30 years, during which time the techniques and numerical modelling tools used to predict the effects of dredging have been substantially improved. In addition, the pre- and post-dredge monitoring data collected as part of licence conditions, together with industry-funded research and development, have improved understanding of pressures from marine aggregate dredging and their effects on the physical marine environment. Consequently, we have high confidence in our understanding of the impacts of marine aggregate dredging on the seabed, the sediments suspended within the water column, and the adjacent coastline. These more detailed assessments over recent decades have confirmed the general applicability of advice provided in published industry guidance that often is used to indicatively determine the depths of water within which dredging can be undertaken without affecting the adjacent coastline.

Despite extensive modelling and monitoring, including in some cases monitoring of the beach closest to an aggregate extraction site, there has been no scientific evidence to date that any consented marine aggregate extraction has adversely affected the coastline. Furthermore, there is considerable evidence from modelling, research studies and monitoring that effects on the physical environment are confined to the immediate vicinity of the dredge site. The potential effects of aggregate dredging on the physical environment are tightly regulated so that only localised effects occur and are primarily limited to changes in local bathymetry and water depth within dredged areas. Although concerns may be expressed that aggregate extraction could lead to wider scale effects, the licensing process excludes dredging activities from areas where this could occur, ensuring that wider effects are avoided.

Whilst much research has been undertaken over the past few decades investigating how the pressures from aggregate dredging may affect the physical, biological or heritage attributes of the marine environment, there remains a challenge in developing predictive methods of linking these three aspects, which currently largely relies on expert interpretation. Recently, progress has been made in the development of numerical models that link physical and biological components (e.g. ABPmer, 2007) and this remains an exciting area of activity into the future.

Marine Aggregate Regional Environmental Assessments (MAREAs) consider cumulative effects of marine aggregate dredging within regional seabed areas. Outputs from these studies may provide a useful starting basis for discussions between applicants and regulators regarding proportionate approaches to Coastal Impact Studies in cases where an individual dredging activity is proposed which sits within the worst case envelope previously modelled.

Indirect Effects – Monitoring the Physical Environment

To date, monitoring has also been an important component of the regulatory requirements, often being incorporated within conditions imposed on marine aggregate extraction activities within licensed seabed areas. The purpose of monitoring has been to:

- Ensure that dredging operations are undertaken in accordance with any conditions of the licence (pre- and post-dredge surveys; turbidity of plumes; electronic monitoring system of vessel locations and dredging activities);
- Ensure that there are no adverse effects on adjacent areas, including the coastline; and
- Provide information to enhance knowledge and assist in managing the seabed and coastline.

Over time, the requirements for monitoring have intensified, largely due to either the need to address perceived concerns or because of advancements in surveying technology. There is an undoubted need for monitoring and its use is widely accepted throughout the industry. However, monitoring is a relatively high cost activity and with advances in scientific understanding over the past decade, regulators remain keen to ensure that the type, scale and frequency of monitoring should be proportional to the potential impact that has been identified in the EIA and CIS process and is related to any uncertainties in the decision-making process. This will need to be determined, through discussion with the regulators, on a case-specific basis.

In conclusion, it is worth remembering that the UK marine aggregate industry is tightly regulated in order to minimise the impacts of dredging on environmental resources. Expenditure of over £30m through the marine Aggregate Levy Sustainability Fund (ALSF) alone, as well as investment in individual research initiatives and studies attached to specific licence areas, has resulted in a considerable advancement in our understanding of the pressures and effects of aggregate dredging on the marine environment. ■

6 IMPACTS ON NATURAL MARINE RESOURCES

By R.C. Newell, Richard Newell Associates

Introduction

Near-shore waters support a considerable biodiversity of animals and plants, reflecting the wide range of habitat types that occur on the seabed from shallow water sands and muds through to mixed sands and gravels and rocky reefs. Phytoplankton communities are supported through nutrient-rich runoff from the land, and there is a complex food web of fish, birds and marine mammals supported from both the water column and the animals that live on the seabed.

Traditionally the impacts of aggregate dredging on these natural resources have been monitored and regulated through identification of specific habitat types, or simple indices such as the species diversity, population density and biomass of the component species that comprise a particular biotope. The difficulty with this approach is that most biological communities on the seabed undergo major and often unpredictable variations over time. Even for the relatively stable communities that inhabit sands and gravels, episodic events such as storm surges can affect the stability of the community structure of shallow water biotopes for long periods.

It is difficult to identify the impacts from a point source of disturbance on non steady-state systems of this sort where the natural variability is high. The situation is further complicated as far as seabed resources are concerned by the fact that the activities of the fishing industry are not subject to the same environmental management processes that apply to other sectors. No environmental impact assessment (EIA) or monitoring is required for the fishing industry, and there are few constraints on the location or intensity of fishing effort in a particular part of the seabed. It is thus entirely possible that apparent impacts of dredging and other infrastructure developments reflect a combination of several sources of anthropogenic disturbance including disturbance from heavy fishing gear. Furthermore, areas left to 'recover' after cessation of dredging are likely to be subject to continued disturbance from the fishing industry, making it difficult to determine whether recovery is genuinely slow following long-term alteration of the habitat by aggregate dredging or whether it has been halted or delayed by additional disturbance from fishing gear.

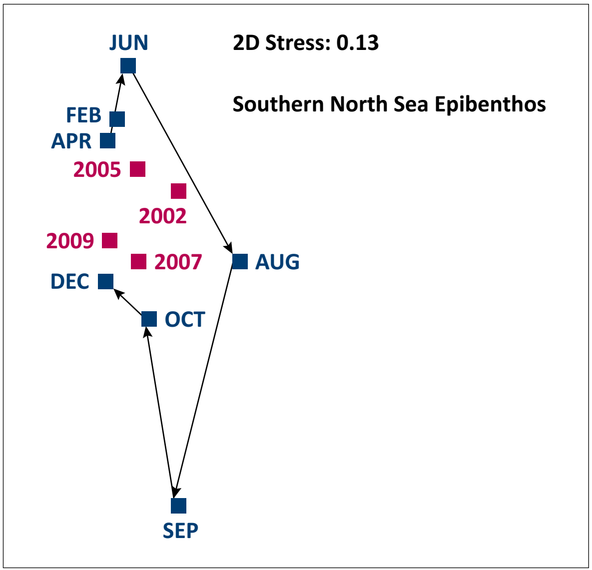


Fig 6.1 A two-dimensional ordination MDS plot showing how a community composition of epibenthic invertebrates and fish varies throughout a year reflecting seasonal changes. (Based on original research data from the Outer Thames Estuary).

Analysis of the effects of aggregate dredging on the marine environment is even more problematic when considering mobile animals that live on the surface of the seabed (epifauna). These animals are subject to major seasonal variations in community composition and population structure, and are moreover also affected by a wide range of environmental variables that may be unrelated to one particular source of disturbance. This is particularly true of coastal communities near to estuaries where many species such as brown shrimp, *Crangon crangon*, crabs, *Liocarcinus spp*, and fish migrate into deeper waters in the winter and back again in the summer. These seasonal changes generally reflect sea temperature, and so are linked to long-term and often irregular seasonal cycles over time.

A schematic diagram for a typical epibenthic community in sand and gravel deposits in the outer Thames estuary is shown in Figure 6.1. This two-dimensional multidimensional scaling (MDS) plot indicates the similarity between communities captured with a small otter trawl on successive years from 2002-2009.

The plot shows that the values for the pooled data in each year from 2002-2009 are close to one another, indicating that overall there is relatively little inter-annual variability in the epibenthic community composition, over this time period. The plot also shows that samples taken in the early part of the year from February to June are similar to one another, but that there are major changes in community composition in August and even greater differences in September before the community reverts in December towards that characteristic of the winter months. This seasonal change in community composition reflects the increase in sea temperature in coastal waters in August and September. This emphasises the importance of taking seasonality and many other sources of variation into account when assessing the impacts of aggregate dredging on mobile epibenthic communities.

Partly because of the variability of epibenthic community composition, and the complex array of factors that affect mobile invertebrates and fish, trawl samples are more often used to define the baseline resources in a particular area rather than to identify the nature and scale of impacts from a particular point source of disturbance such as that from aggregate dredging. Despite these difficulties, epibenthic trawl samples form an important part of the tool kit available to marine scientists to develop an understanding of the impacts of aggregate dredging on the marine environment. They have been used to examine the effects of aggregate dredging on the mobile epifauna (Smith *et al*., 2006) and are included routinely in most characterisation programmes carried out for the aggregates industry (see also Ware and Kenny, 2011). Additionally, before employing towed gear consideration should be given to the scientific value of the data obtained in relation to the risk of damaging potential features of conservation importance (e.g. biogenic reef).

More recently it has been recognised that marine communities play a central role in ecosystem function. This includes carbon capture and energy cycling, enhancement of seabed stability and the provision of habitat complexity through the development of complex species interactions. This has led to the view that management of marine systems requires not only knowledge of how individual organisms and communities may vary over time, but also an understanding of the biological traits that relate organisms to their function in the marine community.

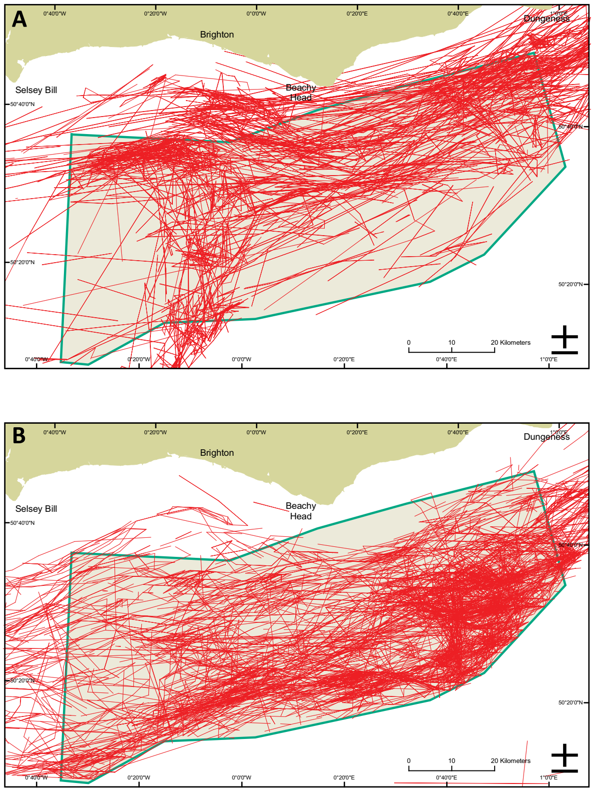
Widely diverse types of animals such as barnacles, polychaete worms and shellfish may, for example, be better linked as a filter feeding group that plays an important part in transferring energy and materials from the water column to the seabed rather than focussing on their taxonomic relationships. Other major trophic groups such as predators, scavengers and deposit-feeders can also be recognised and ascribed a role in ecosystem function.

Biological traits such as mobility, body size, fecundity and type of larval dispersal can be included within the feeding guilds identified above and this can be used to compare communities in disturbed and undisturbed habitats on the seabed (see Bremner *et al*., 2006; Pacheco *et al*., 2010). Not surprisingly, communities that are regularly disturbed by heavy bottom gear from trawling and dredging are characterised by large numbers of small mobile organisms that have recently colonised the deposits. In contrast, undisturbed communities have more long-lived and large-bodied species that have had sufficient time to colonise and grow to a large size.

The significance and scale of persistent impacts of disturbance of the seabed by bottom gear used by fishing vessels should not be under-estimated. Figure 6.2 shows, for example, vessel monitoring data for beam and otter trawling in English waters of the eastern English Channel for the relatively short period between January and July 2005. The tracks of fishing vessels are shown in red and emphasise the widespread pressure on seabed resources that are imposed by the fishing industry.

Figure 6.3 shows the summed VMS data for beam trawlers in part of the eastern English Channel for the period 2002-2005. It can be seen that most of the seabed in the Eastern English Channel survey area is likely to be repeatedly disturbed by beam trawlers over a 3 year period, to which should be added the impacts of otter trawling. This is less than the recovery time reported for many of the biological components that live on the seabed (see Chapter 7). Hence the seabed in intensively-fished areas such as the Eastern English Channel is likely to be held in a permanent state of disturbance by the use of heavy bottom gear used by the fishing industry.

A literature review by Foden *et al*. (2009) identified both aggregate dredging and bottom trawling as having



Vessel Monitoring System

A – Footprint Beam Trawlers January-June 2005

B – Footprint Otter Trawlers January-June 2005

Fig 6.2 Vessel monitoring system (VMS) data for UK waters showing the movement of A) beam and B) otter trawls (shown in red) in the English Channel between January and June 2005. The lack of data for near shore waters off the south coast is due to a lack of VMS data for this area. From Vanstaen et al. (2008).

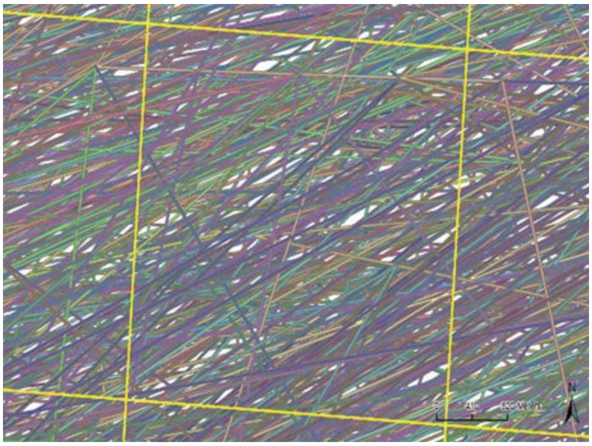


Fig 6.3 Vessel Monitoring System: Beam Trawling Footprint in the Eastern English Channel, January 2002 to June 2005. From Vanstaen et al. (2008).

a significant impact on seabed resources, but pointed out that the footprint of impact of aggregate dredging was less than 1% of that for bottom fishing for the years 2001-2007. Thus whilst we commonly think of the seabed around our coasts as being 'pristine', much like a forest area on land, it is probably closer to the truth to regard significant parts of the seabed in our near-shore waters as more akin to managed farmland. This does not imply that it is unproductive, merely that the communities that inhabit the seabed surrounding the British Isles, and especially in the North Sea and eastern English Channel are probably now held in a quasi-permanent state of disturbance from a combination of natural episodic events such as storms, the effects of trawling and other activities that affect the seabed deposits.

The Nature and Scale of Impacts of Aggregate Dredging

The nature and scale of potential impacts from marine aggregate dredging have been widely recognised (for reviews, see Newell *et al*., 1998; Tillin *et al*., 2011). Essentially they comprise direct or 'primary' impacts under the footprint of the draghead. Then there are indirect or 'secondary' impacts that may occur outside the boundary of the dredge site. These include the impacts of sediment mobilised by the dredging process and transported along the seabed by the prevailing currents, as well as potential impacts of noise and disturbance to organisms that are higher in the food web such as fish, mammals and birds.

Some of the potential impacts of aggregate dredging on physical and living resources on the seabed have recently been reviewed in the British Marine Aggregate Producers Association (BMAPA) Biodiversity Action Plan (BAP) for the UK Marine Aggregate Industry (2011). The impacts of dredging on higher levels in the marine food web are, however, poorly understood. We have very little information, for example, on the significance of the small areas of seabed that are under licence for aggregate extraction as feeding areas for seabirds. A recent review by Cook and Burton (2010) identified a wide range of potential impacts that heavy fishing gear such as scallop dredging might have on seabirds, but were unable to identify any documented studies that relate to aggregate dredging or to specific aggregate dredge sites. The area under licence for aggregate dredging is relatively small compared with the foraging range of seabirds and at this stage it is uncertain whether seabirds are significantly impacted by aggregate dredging. Any such impacts are likely to vary from site to site, depending among other factors on their significance as a foraging area for seabirds.

The impact pathways of dredging on the water column and adjacent seabed are summarised in Figure 6.4. Passage of the draghead results in the removal of seabed deposits and associated benthic organisms within the active dredge zone. If the dredged deposits are transferred as an 'all-in' cargo and do not require the composition of the cargo to be adjusted by screening, then secondary effects on the water column and adjacent seabed deposits are mainly confined to the relatively small sediment plumes generated by the draghead and from overspill from the hoppers.

Discharge during the screening process, however, results in larger sediment plumes and significant deposition of material on the seabed, both in the immediate vicinity of the dredger and as a thinner layer of mobilised sediment over a wider area along the axis of transport by seabed currents. Figure 6.4 shows that material discharged through the screening chutes comprises an active density flow driven to the seabed by the velocity of discharge, and a subsequent passive dispersion and diffusion phase. Both of these processes have potential impacts on seabed resources in the vicinity of aggregate dredge sites.

Direct (Primary) Impacts

The direct effects of dredging on biological resources within licensed aggregate sites depend largely on the intensity of dredging. Reports in the literature range from a suppression of the population density, species diversity and biomass of between 40-90% depending on the intensity of dredging (for review, see Newell *et al*., 1998; Foden *et al*., 2009). This suppression of biological resources on the seabed is, however, not uniform across the whole of a dredge site. Most aggregate dredge sites are only lightly dredged, with some areas remaining undredged and others being intensively dredged within an active dredge zone.

One characteristic of aggregate dredge sites is therefore a high degree of spatial variability of the benthic fauna. This can range from communities that are insignificantly different from those in undredged deposits outside the boundaries of the licence area, to ones directly under the path of recent dredge trails which are essentially devoid of animals. The primary impacts of dredging on the marine fauna are therefore significant, but affect only a small area of seabed under the path of the draghead in active dredge zones.

In almost all instances, aggregate dredging is reported to result in a major suppression of species diversity, population density and biomass of invertebrates that live in seabed deposits that have been dredged. A similar suppression of diversity, abundance and biomass of more mobile epifaunal assemblages has also been reported for a number of dredge sites in the southern North Sea and English Channel by Smith *et al*. (2006). Most studies, however, have been confined to the benthic infauna because these have limited powers of movement and hence can be used to define 'contours' of impact in relation to distance from a dredge site. Many of these studies have used univariate indices of community composition such as the number of species, number of individuals and biomass.

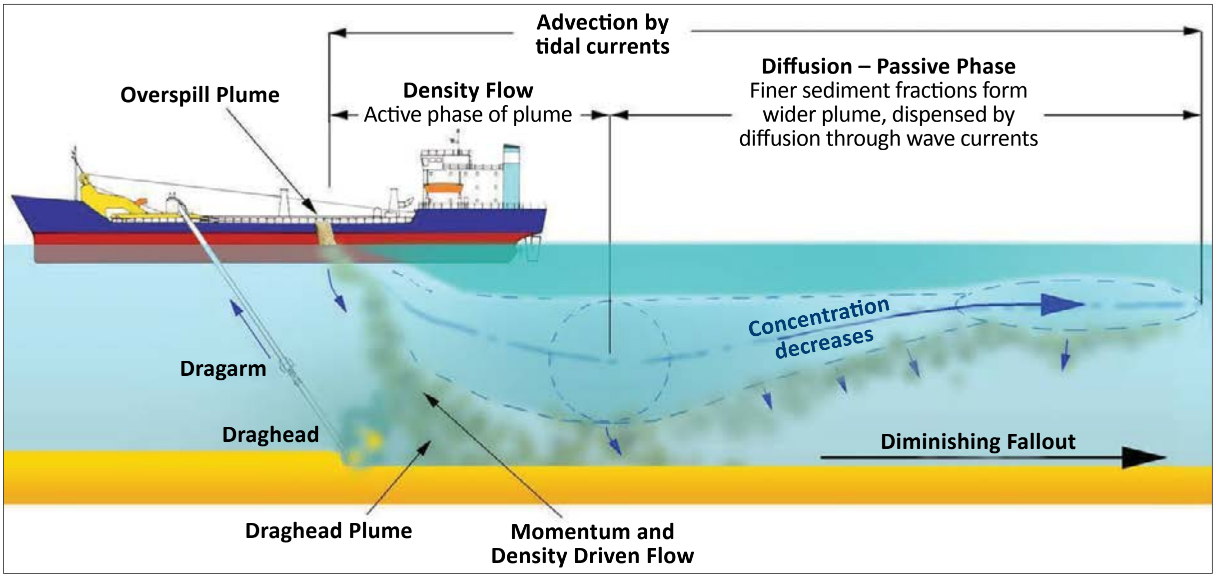


Fig 6.4 Sediment plumes and turbidity as a result of overspill and passage of the draghead along the seafloor during marine aggregate dredging, © ENTEC.

Figures 6.5 and 6.6 show the number of species, the number of individuals, the biomass and the average body size of benthic invertebrates in a series of 0.1m^2 Hamon grab samples taken within and surrounding Licence Area 430 in the southern North Sea in June 2003. The size of the symbols indicates the relative values and these have been superimposed onto the relative backscatter image from the dredger which was loading a screened cargo. The two active dredge zones in the central part of the licence area are clearly characterised by a relatively impoverished species diversity, population density and biomass compared with non-dredged parts in the west of the licence area and in the surrounding deposits. Effects of deposited material along the dispersing plume outside the boundaries of the licence area appear to be small. This probably reflects the tolerance of the resident invertebrates to sedimentation (see Chapter 7).

Newell *et al*. (2004a) estimated that the dredging process itself resulted in a 30-70% reduction in species variety, a 40-95% reduction in the number of individuals and a similar reduction in the biomass of benthic communities in the dredged zones at Area 430. The data also show that the dredged areas were characterised by smaller sized animals than in the surrounding deposits.

This reversion in community composition from the relatively high species diversity, population density and biomass that characterises complex habitats of mixed sands and gravels, to an impoverished one typical of more uniform deposit types is widely reported in the literature. A survey carried out in the eastern English Channel in licence areas 454 and 464 (West Bassurelle), for example, showed that there was an average of 155 species recorded from Hamon grab samples taken in coarse gravel deposits, 63 species in gravelly sand and only 13 species in sandy deposits (cited in Newell *et al*., 2004a).

This sequence is shown in schematic form in Figure 6.7 which shows a two dimensional MDS ordination for the macrofaunal assemblages in the West Bassurelle survey area. Also shown as circles is the relative proportion of gravel-sized particles >4mm diameter at each site. The deposits associated with biological community C (coded green) have a high proportion of gravel, those associated with biological community B (coded dark blue) have relatively less gravel-sized particles, whereas biological community A (coded light blue) are mainly sandy.

The lower part of the diagram shows the species that characterised 75% of the similarity in each of the three main biological communities identified in the different

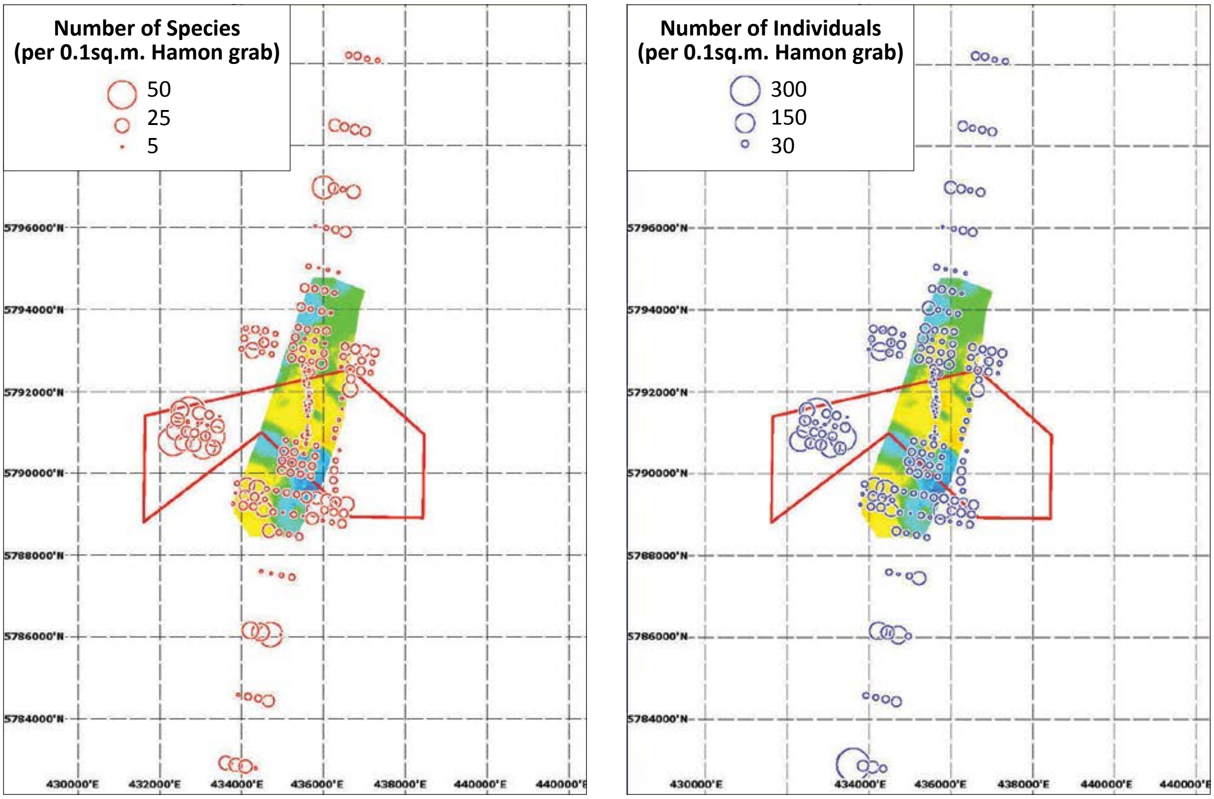


Fig 6.5 Charts of licence area 430 in the southern North Sea showing the number of species and number of individuals of benthic invertebrates sampled with a 0.1m^2 Hamon grab in 2003. From Newell et al. (2004a).

deposit types in the West Bassurelle study area. Clearly the coarse mixed deposits with a high proportion of gravel-sized particles supported a wide variety of characterising species, each of which contributes to a relatively small proportion of the population density of the community as a whole. The gravelly sands support lower species diversity whilst the sands support very few characterising species and were dominated by burrowing worms.

A change in deposit type in actively-dredged areas from mixed gravels and sands to one which is dominated by sand following dredging is therefore likely to have a major impact on biodiversity and community composition within the dredge site – a feature that has been widely reported in recent years (Desprez, 2000; Boyd *et al*., 2003, 2005; Ellis, 2003; Newell *et al*., 2004a; Cooper *et al*., 2007a; Foden *et al*., 2009; Tillin *et al*., 2011).

Indirect (Secondary) Impacts

Secondary impacts are mainly generated by sediment deposition from the dispersing plume, and from the deposition of material mobilised by the dredging process and transported along the axis of the seabed currents. Most coarse material, including sands up to 2-3mm in diameter settles in the immediate vicinity of discharge from the dredger. Hence relatively large quantities of sand (up to 7,000 Te per cargo – see Chapter 1) are deposited within the licence area along the path of the dredger. This material is unconsolidated and can, over time, be transported significant distances outside the boundaries of the licence area, depending on the strength of local seabed currents (for review, see Newell *et al*., 1998).

A second source of deposition is the fine sand that settles from the dispersing plume generated from both the screening process and from overspill. This material can contain significant quantities of organic matter that is released from the sediments and may also comprise fragmented invertebrates that have been damaged as they passed through the screening chutes. This fine material in the dispersing plume generally becomes indistinguishable from background levels of suspended particulate matter at a distance of up to 3km behind the dredger (see Newell *et al*., 1999).

Whilst the sand rejected during screening settles close to the point of discharge, it is relatively unconsolidated, and in some sites may be mobilised as a benthic boundary layer at the sediment-water interface. Figure 6.9 shows an acoustic backscatter image reported by Hitchcock and Bell (2004) for a dispersing plume behind a dredger operating in the central

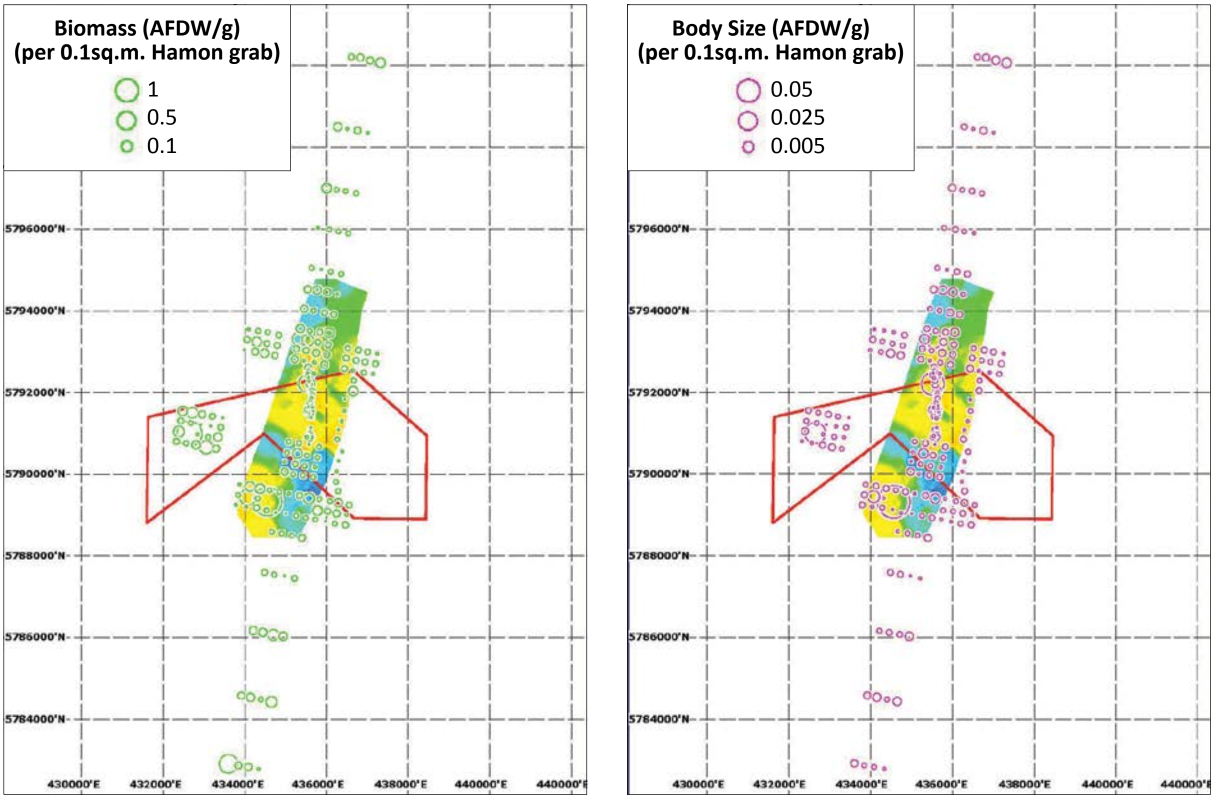


Fig 6.6 Charts of licence area 430 in the southern North Sea showing the biomass and average body size of benthic invertebrates sampled with a 0.1m^2 Hamon grab in 2003. From Newell et al. (2004a).

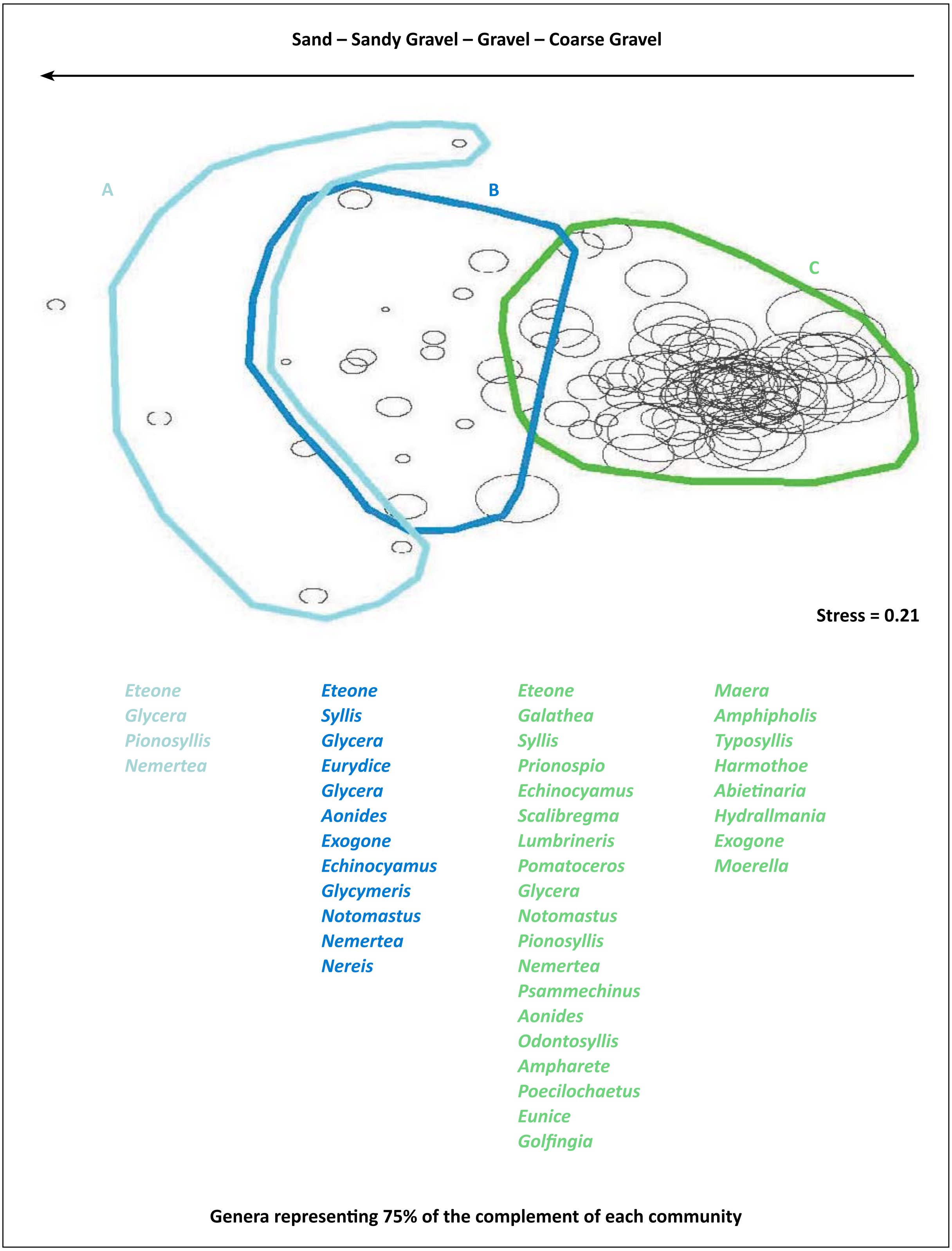


Fig 6.7 A two-dimensional MDS ordination showing the similarity and abundance of invertebrates in samples taken in gravel deposits (green – C), mixed sandy gravels (blue – B) and sands (turquoise – A). The species that account for 75% of the similarity in each of the deposit types are shown in the lower part of the diagram. From Newell et al. (2004a).

Fig 6.8 Sediment released into the sea from overspill. Courtesy of Stephen Robinson.

English Channel at Owers Bank off the south coast of England. The profile shows the initial rapid settlement of coarse material, followed by fine sand-sized particles approximately 300m down-tide of the dredger as well as a more widespread and persistent plume of dispersing organic matter and silt-sized particles in the water column.

The immediate benthic zone up to about 1m above the seabed is often difficult to interpret from Acoustic Doppler Current Profiler (ADCP) data. This is commonly referred to as a 'data corruption zone'. Nevertheless the data from the study at Owers Bank suggests that the deposited material can form a distinct benthic boundary plume of mobilised sediment some 2-4m thick and a few tens of metres wide. Where the cargo is loaded without screening, the benthic boundary plume may extend only a short distance beyond the boundaries of the licence area. But where additional sand is returned to the seabed by the screening process, Hitchcock and Bell (2004) reported that the benthic boundary plume may extend as much as 4.5km down-tide from the site of initial deposition.

Similar results have been reported for dredge sites in the southern North Sea where fine well-sorted sediments have been found up to 3km from the primary dredge site (Newell *et al.*, 2004a). Figure 6.10 shows the track of a dredger and the surface and benthic plumes recorded by acoustic backscatter (ADCP) during discharge of screened material and overspill from a dredger operating on the north-going current in Licence Area 430 in the southern North Sea. The dispersing plume can be seen to extend up to 1km outside the boundary of the licence area to the north, and this is likely to be reflected in a similar dispersion plume to the south when the tidal streams reverse.

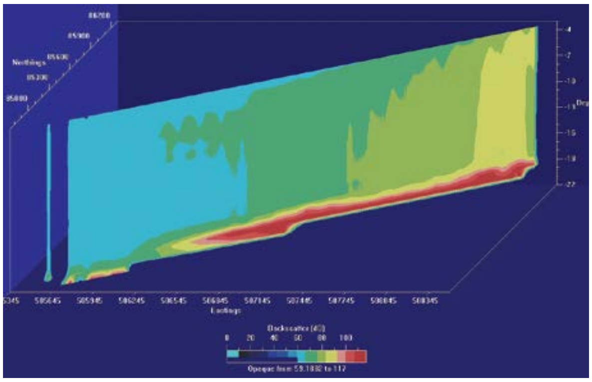


Fig 6.9 Longitudinal section of the sedimentation plume from a dredger loading a screened cargo at Owers Bank in 1995. Based on acoustic backscatter data taken from Hitchcock et al. (2002). The red side of the scale indicates high backscatter levels and the blue side of the scale indicates low backscatter levels. From Hitchcock and Bell, (2004).

Analysis of the sediment composition of the sediments at Area 430 in the southern North Sea also gives some information on the 'footprint' of aggregate dredging and screening on the seabed sediment composition at this site. Seabed transport at Area 430 is in a generally northward direction. Figure 6.11 shows the proportion of well-sorted fine sand along the path of the dispersing plume from the active dredge site.

This material overlies more poorly sorted sediments to a depth of as much as 10cm within the licence area (Figure 6.12) and up to several centimetres at distances of up to 3km from the dredge site. This surface layer of well-sorted

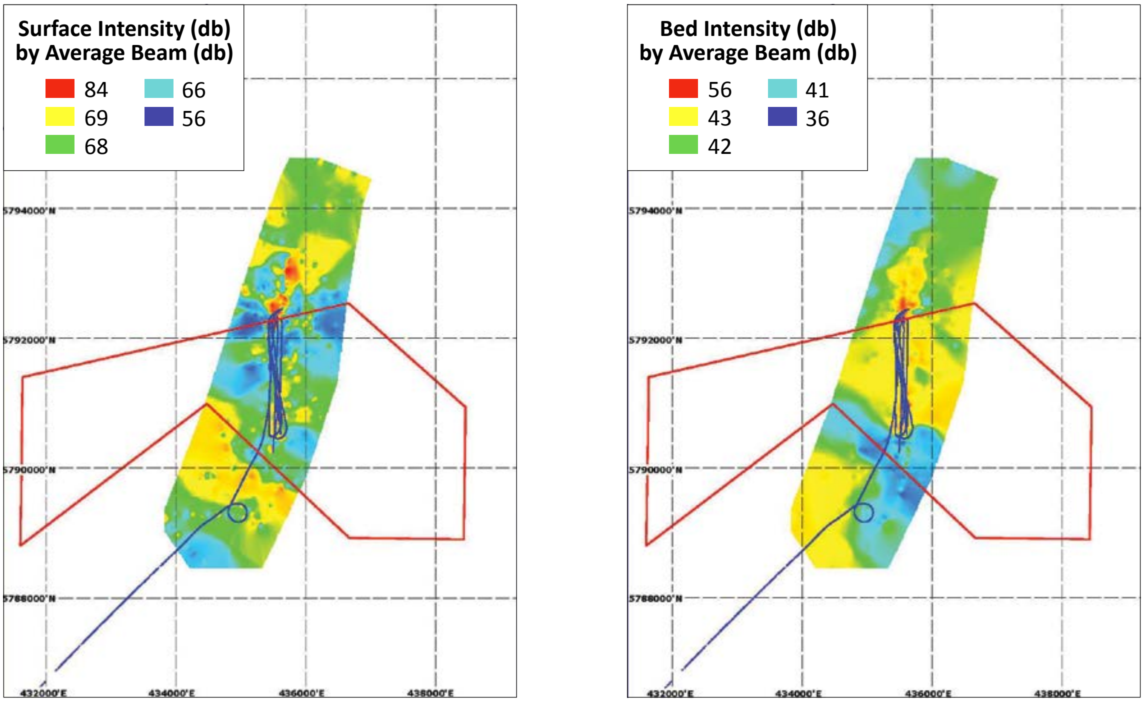


Fig 6.10 Chart of licence area 430 sampled in June 2003 on the north-going current. The track of the dredging vessel is shown together with acoustic backscatter at the surface and near the seabed during discharge of screened material and overspill. From Newell et al. (2004a).

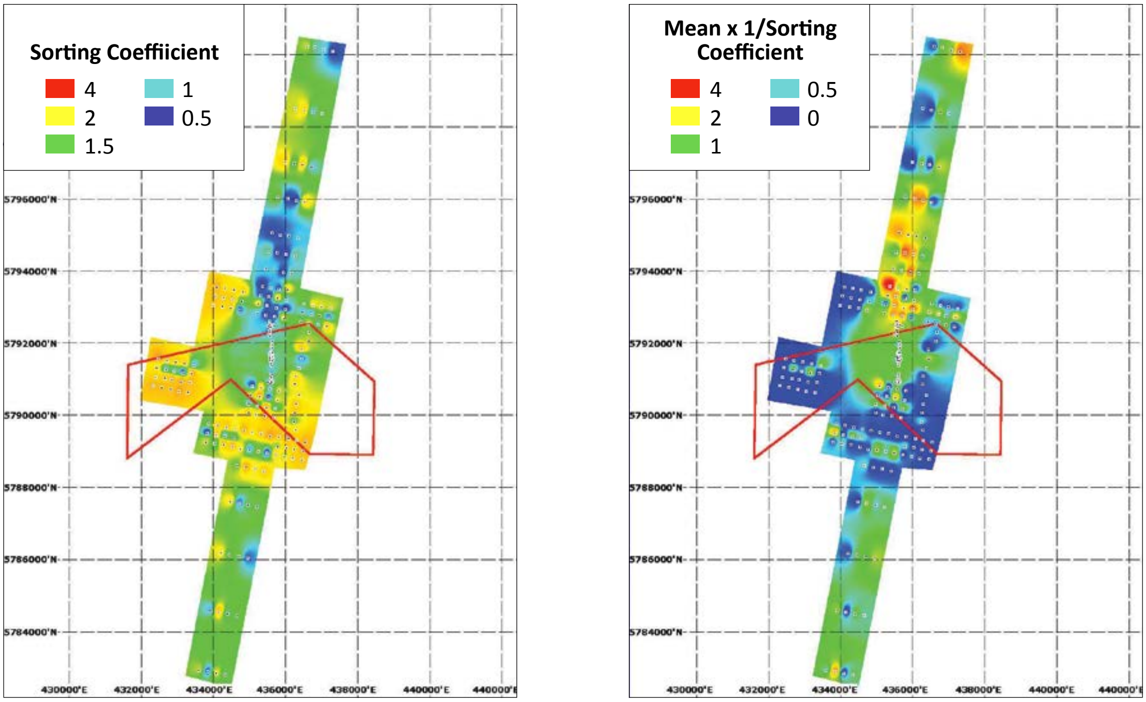


Fig 6.11 Chart of the licence area 430 in the southern North Sea showing the sorting characteristics of the deposits in relation to the boundaries of the licence area. The chart shows the sorting coefficient of the deposits (left) and an index of well-sorted fine sand (right) based on the product of the mean particle diameter and the reciprocal of the sorting coefficient (after Evans, 2002). From Newell et al. (2004a).

fine sand outside the boundaries of the dredge zone is likely to derive from unconsolidated fine sediment that has been deposited from the dispersing plume during screening, and subsequently transported northwards on the prevailing net current drift at the seabed. The significance of impacts of material mobilised by dredging on the physical and biological characteristics of the seabed close to dredge sites depends to a large extent on the natural bedload mobility in the area at which dredging takes place, and the tolerance of the organisms that characterise the benthic community. These are discussed below.

This suggests that seabed transport of sand mobilised by the dredging process may have an impact on sedimentation and raised concentrations of suspended particulate matter some distance outside the boundaries of dredging. There have, however, until recently been few experimental studies on the tolerances of the resident organisms to sedimentation on the scale likely to be experienced by communities outside the boundaries of aggregate dredge sites.

Impacts on Component Species

The process of aggregate dredging and subsequent on-board screening has the capacity to increase the suspended particulate matter load in the water column, and to bury benthic organisms located within, or near licence sites. Until recently, however, very little was known of the impacts of either raised concentrations of suspended particulate matter or sediment deposition on key components of the biological communities that live on the seabed near to aggregate dredge sites.

Last *et al*. (2011) have recently completed a series of experiments to determine the sensitivity of a variety of benthic animals to both raised concentrations of suspended particulate matter and to burial. They constructed a series of paddle vortex re-suspension tanks (as shown in Figure 6.13) that could provide a range of controlled current flows (between 5-20cm.sec-1) and sedimentation rates (between 0.08-0.6g.cm^2.h-1) at suspended particulate matter concentrations of between 0-95mg.l-1. The experimental animals were placed on a mesh holder and could be viewed through a transparent viewing port in the side of each chamber (see Figure 6.13).

Survival and ability to escape from burial by the seabed organisms is of particular importance for assessment of the potential impacts of discharge of screened material from dredgers operating in mixed sands and gravels in the southern North Sea.

The results are of considerable interest because they suggest that many common components of the benthic fauna that are likely to be found near to aggregate dredge sites in the southern North Sea in particular, are more resilient to both elevated concentrations of suspended particulate matter and burial than had been generally supposed. This is not altogether surprising in that the benthic fauna in sandy gravels is adapted to relatively high naturally-occurring levels of sediment transport at the sediment-water interface, and must also be able to survive extreme events such as the re-deposition of sand that is mobilised during storms.

Survival following burial was determined by Last *et al*. (2011) in relation to burial depth, duration of burial and the size fraction of the deposited sediments. The conclusions from this experimental work can be summarised as follows:

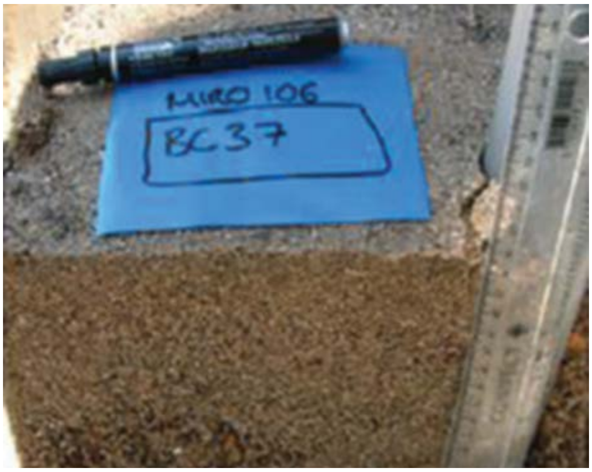


Fig 6.12 A box-core profile showing the structure of the seabed deposits sampled approximately 300m south of an active dredge zone in licence area 430 in the southern North Sea. The sand deposited over the surface of coarser gravel material can be seen. From Newell et al. (2004a).

Fig 6.13 VOrtex Resuspension tanks (VORTS) used by Last et al. (2011) at the Scottish Association of Marine Science (SAMS) to measure the sensitivity of animals to varying levels of suspended sediment and to burial, © Dr Kim, Last of the Scottish Association for Marine Science.

Fig 6.14 A blue mussel, Mytilus edulis, reef. Mussels are capable of tolerating burial for up to 32 days in coarse sand. © Paul Naylor, www.marinephoto.co.uk.

The Blue Mussel (*Mytilus edulis*)

This species is of conservation significance because it can form biogenic reefs that increase habitat complexity and biodiversity compared with deposits of a uniform particle size (see Chapter 3). The experimental work showed that mussels are moderately tolerant of burial and show less than 15% mortality in any of the burial depths. They can survive for up to 32 days burial by coarse sand, although they cannot survive for such a long period when buried by fine sediments. Mussels can also re-emerge from burial by up to 2cm of sediment.

This suggests that mussels are likely to be tolerant of episodic burial at the boundaries of aggregate dredge sites and can probably re-emerge from the relatively thin layer of deposited sediments that occur for up to 3km along the axis of dispersion from dredging operations.

Ross Worm (*Sabellaria spinulosa*)

This worm is also of conservation significance because of its ability to form biogenic reefs (see Chapter 3). This tube-dwelling polychaete worm is capable of survival following burial by fine sand for more than 32 days and has the ability to construct an 'emergence tube' to allow survival whilst the worm migrates to the surface. Many polychaete worms construct a tube through which water can be drawn to allow feeding and oxygen-rich water to pass over the gills. The Ross worm can survive within the deposits by means of this relatively fragile 'emergence tube' and then constructs a more robust tube of sand at the surface where it needs to withstand the turbulence that occurs at the sediment-water interface.

The 'emergence tubes' constructed by *Sabellaria spinulosa* during burial are shown in Figure 6.15. Tube growth was significantly higher under conditions of high suspended particulate matter suggesting that the presence of mobile sands is necessary for successful tube formation. This supports field observations on the survival and recolonisation of *Sabellaria* close to an actively-dredged site on the Hastings Shingle Bank. These showed active recolonisation and growth in deposits immediately adjacent to dredge zones, and rapid recolonisation and growth at sites where dredging had ceased (see Pearce *et al*., 2007).

Both field studies and this experimental work suggest that Ross worm is well-adapted to survive and thrive in conditions of high sediment mobility, and that moderate rates of sedimentation are unlikely to adversely affect survival. It should be pointed out, however, that *Sabellaria spinulosa* is an ephemeral species and reef structures can appear and disappear even in the absence of aggregate dredging.

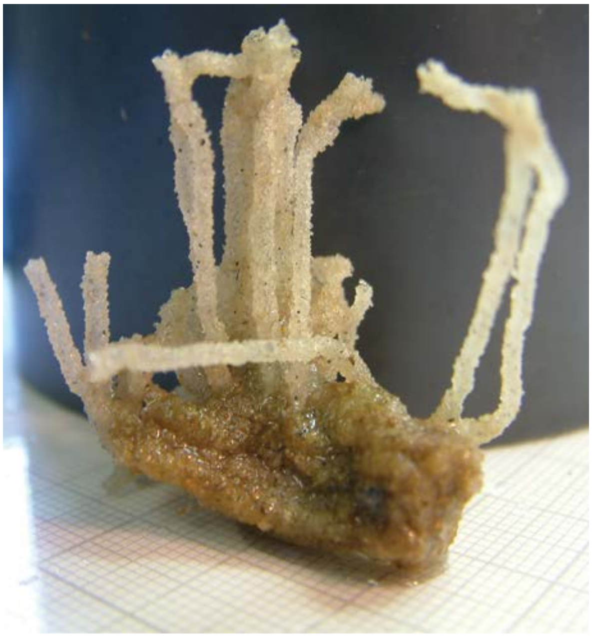


Fig 6.15 Emergence tubes of the Ross worm, Sabellaria spinulosa. Courtesy of Dr Kim Last of the Scottish Association for Marine Science.

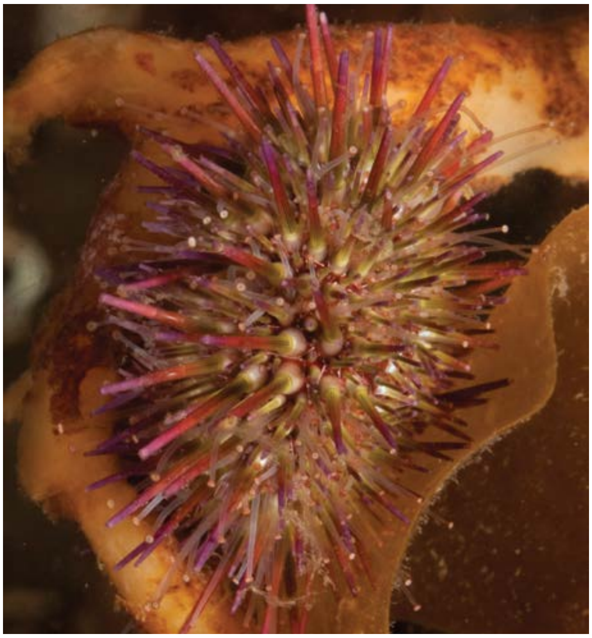


Fig 6.16 The sea urchin, Psammechinus miliaris, © Elaine Azzopardi, National Facility for Scientific Diving, Scottish Marine Institute.

The Green Sea Urchin (*Psammechinus miliaris*)

The Green sea urchin is another common member of the community of mixed sands and gravels and is likely to occur in aggregate dredge sites in the southern North Sea and English Channel licence areas. This sea urchin can tolerate relatively short-term burial of up to 12 days with less than 25% mortality after which mortality increases, especially in fine deposits. Unlike mussels which can tolerate lengthy burial and have relatively limited ability to re-emerge to the surface after burial, the survival of the green sea urchin is primarily due to an ability to re-emerge from depths of as much as 7cm by coarse sand.

These results again suggest that this common component of the fauna of gravels has a survival strategy that allows it to survive and grow in an unstable environment where episodic burial is likely to occur. It is unlikely to be seriously affected by the levels of sediment deposition that occur outside the immediate boundaries of an active dredge site, even one where significant quantities of sand are returned to the seabed during the screening process.

The Brittlestar (*Ophiura ophiura*)

This brittlestar is a very common component of sands and sandy gravels in the coastal waters surrounding the British Isles.

It is highly tolerant of burial events, with less than 10% mortality even after 32 days of burial. Like the green sea urchin, it has a remarkable ability to re-surface after burial from all of the depths and sediment fractions that were tested and is clearly well-adapted to survive in the dynamic conditions that occur at the surface of the seabed.

It is very unlikely that this species would be seriously impacted by the sediment deposition that occurs at the boundary of aggregate dredge sites, even when significant quantities of sand are returned to the seabed following screening.

The Sea Anemone (*Sagartiogeton laceratus*)

Even sea anemones from mixed sand and gravel deposits have a high tolerance of burial. In this case the anemone is very tolerant of short-term burial of up to 16 days, during which there is less than 1% mortality. This low overall mortality is a reflection of the ability of this species to re-emerge after shallow burial of up to 2cm.

An ability to both tolerate burial and to actively re-emerge to the surface is therefore a common survival strategy for those species that are typical components of the communities that occur at sand and gravel sites. In contrast, species that characterise stable rocky and cobble substrates are much less likely have adaptations that allow survival following burial by sand. This is to be expected in organisms that do not experience highly mobile sediments under natural conditions.

Fig 6.17 A brittlestar, Ophiura sp, © Hugh Brown, National Facility for Scientific Diving, Scottish Marine Institute.

Fig 6.18 The sea anemone, Sagartiogeton laceratus, © Elaine Azzopardi, National Facility for Scientific Diving, Scottish Marine Institute.

Fig 6.19 The ascidian (sea squirt) Ciona intestinalis, © Elaine Azzopardi, National Facility for Scientific Diving, Scottish Marine Institute.

There is little detailed experimental evidence on the tolerance of high suspended particulate loads and sediment deposition on animals from coarse substrata. Last *et al*. (2011) have, however, shown that the yellow sea-squirt ascidian, *Ciona intestinalis* (Figure 6.19), which characterises water with low suspended sediment concentrations, is very intolerant of burial events. In this case there was 100% mortality of individuals buried for up to 2 days and there was no ability to re-surface after burial.

It seems likely that the high sensitivity to burial shown by this ascidian will apply to other species that characterise coarse deposits where sediment mobility is low. Experimental studies on free-living coralline algae (maerl), for example, suggest that this species which characterises current swept deposits is very intolerant of sedimentation especially by fine or anoxic sediments (Wilson *et al*., 2004).

The implication from these experimental studies is that sand mobilised from the screening and dredging processes is likely to have a significant effect on rocky reef and cobble assemblages if these happen to occur along the axis of dispersion and settlement. However, the ability of many of the species that characterise mobile sandy deposits to tolerate episodic burial and to regain the surface of the deposits under natural conditions suggests that the relatively thin deposits of sand outside the boundaries of the dredge site are unlikely to have an impact on some of the characteristic components of the resident community of sands and gravels unless the depth of deposition is very high.

Impacts on Community Composition

There have been numerous studies of the impacts of dredging on communities that live on the seabed. Whilst most show site-specific differences from one another, some generalisations and predictions can be made on the potential impacts of aggregate dredging based on our knowledge of the biological traits of the fauna, the nature of the seabed deposits and the type of dredging that takes place. The results of earlier studies that have been carried out on the impacts of dredging and the subsequent recovery of biological resources on the seabed have been reviewed by Newell *et al*. (1998).

A key point that emerges from the recent experimental work reviewed above is that the benthic fauna that occurs at a particular site is generally well-adapted to survive and thrive in the dynamic conditions that occur on the seabed. As we have seen above, the animals that characterise mobile sandy gravels are generally able to regain the surface of the deposits after intermittent burial. Equally animals that live in current-swept coarser deposits are well-adapted to anchor themselves to the substrate, but are much less able to survive deposition events such as might occur as a result of aggregate dredging.

The type of dredging that takes place has an important influence on the impacts associated with aggregate dredging. Removal of 'all-in' cargoes from the seabed with minimal screening is unlikely to result in long-term changes in substrate composition provided that sufficient deposits are left over the underlying geology. However, the return of relatively large quantities of sand to the seabed that is required for efficient use of gravel resources in the southern North Sea and other mixed sandy gravels elsewhere, commonly results in major long-term change in sediment composition. This in turn can have a profound and long-lasting impact on the communities that live on and in the deposits that occur in the vicinity of aggregate dredge sites.

This means that prediction of potential impacts of aggregate dredging on seabed communities needs to take into account the type of dredging that is to take place, as well as the nature and susceptibility of the fauna, together with the likely distribution of seabed sediments that are mobilised by the dredging and screening processes.

Studies carried out at a dredge site off Dieppe, France give some insight into the impacts of dredging both within, and beyond the boundaries of the area dredged. Desprez (2000) monitored the sediment and associated macrofauna at an aggregate site over a 10 year period and reported that the original heterogeneous substrate of gravels and coarse sands was progressively dominated by fine sands and dredge trails. Dredging within the site was associated with a reduction in species richness by up to 80%, and up to 90% for both abundance and biomass. This supports the results of many other studies elsewhere (for reviews, see Newell *et al*., 1998; Foden *et al*., 2009).

At the same time, the structure of the community changed from one of coarse sands with the lancelet *Branchiostoma lanceolatum* as a characterising species to one of fine sands characterised by polychaete worms including *Ophelia borealis*, *Nephtys cirrosa*, *Spiophanes bombyx* and the sessile serpulid worm *Pomatoceros triqueter*. Subsequent work at this site showed that similar effects on the seabed communities associated with sand mobilised by the dredging process extended somewhat outside the boundaries of the dredge site for distances of up to 2km.

The general conclusion from these studies off Dieppe and sands and gravels in other areas such as the West Bassurelle (Newell *et al* 2004a) and the outer Thames estuary (EMU Ltd, 2009) is that mixed deposits with a wide variety of micro-habitats (niches) support a high species diversity and population density compared with sands which are dominated by a few resilient species that are adapted to life in a relatively unstable habitat (see Figures 2.14 and 6.7). Removal of aggregates has an immediate and obvious impact on living communities in the active dredge zones whether these comprise coarse material dominated by long-lived epifauna or the mixed sands and gravels characteristic of the southern North Sea. Although these impacts are severe, they are confined to a relatively small area of seabed in the case of removal of 'all-in' cargoes with minimal screening losses from the dredger.

Alteration of the composition of the seabed deposits has, however, a wider and potentially long-lasting impact on marine biotopes. Removal of coarse material by aggregate dredging and the return of excess sand to the seabed by screening leads to a reduction in biodiversity and impoverishment of population density and biomass of seabed communities over a wider area than the dredge zone itself. This alteration in the composition of seabed deposits occurs mainly in close proximity to the dredge site but can also affect surface sediment composition for distances of up to 3km along the axis of transport of material mobilised during the dredging and screening processes, depending on the strength of sediment flux at the seabed.

Impacts on Fisheries

There is much less information on the effects of aggregate dredging on fisheries, mainly because of the difficulties in linking the abundance and variety of mobile organisms such as fish and shellfish such as crab and lobster to point sources of disturbance including aggregate dredging. For the most part, reported impacts on fisheries are concerned with either exclusion of fishing vessels from active dredge zones, or alteration in the seabed topography which interferes with use of traditional fishing gear.

An overview of potential impacts of aggregate dredging has been given by Carlin and Rogers (2002). They point out that in many cases we do not know the spatial extent of fish populations that may be under threat, their rate of migration between regions, or even the proportion of the reproductive area of a stock that would be considered essential for future stock viability. Hence even if there were to be impacts of dredging on fish spawning grounds, it is unknown at present what the vulnerability is nor what impact this might have on the stocks as a whole.

Faced with a lack of detailed information on the distribution of fish stocks, their susceptibility to loss of food resources represented by the benthos during dredging, and the impacts of sedimentation and other 'secondary' impacts of plume dispersal, Carlin and Rogers (2002) have proposed the application of a formal risk assessment process for fisheries to be included in the Environmental Impact Assessment (EIA) for marine aggregate licence applications. This ensures consistency between EIAs for different regions and ensures that, as far as possible all potential impacts on fisheries are taken into account.

One output from such an approach is the development of geo-referenced charts showing the overlap between areas of known significance for fisheries of different types, and other activities such as shipping, spoils disposal and aggregate dredging. The degree of overlap between these intensively-used zones and individual aggregate licence areas, or other activities can then be used to assess the potential impact of individual site-specific activities on sensitive areas.

This approach has been widely adopted in recent years and forms the basis of a number of major seabed and resource mapping projects such as the Channel Habitat Atlas for Marine Resource Management (Vaz *et al*., 2007; Martin *et al*., 2009). It has recently been used by the Marine Management Organisation to assess the sensitivity of offshore habitats off the east coast of England to multiple activities including disturbance by fisheries, offshore renewables, oil and gas installations and aggregate dredging (see the East Inshore and East Offshore Marine Plan Areas Evidence and Issues Report 2012 which is available at: **http://www.marinemanagement.org.uk/marineplanning/issues.htm**

Use of geo-referenced data allows GIS layers for spawning and nursery grounds to be superimposed over those of known sand and gravel resources as part of the Environmental Impact Assessment. Potential impacts on the eggs and larvae of commercial fish species can then be minimised by avoidance of spawning and nursery areas (a requirement of Government policy).The principal mitigation method is therefore to understand both the distribution of resources that are to be protected, and a detailed understanding of the size and nature of the footprint of any proposed aggregate dredging.

Any potential direct impacts on demersal fish species by the draghead are very difficult to distinguish from the widespread and intensive bottom trawling and shellfish dredging that takes place in many aggregate licence areas. Inspection of Figures 6.2 and 6.3 suggests, however, that the losses of fish by entrainment through a draghead of only 1.5 metres width operated by an aggregate dredger at slow speed in a confined area of seabed are likely to be insignificant compared with the targeted removal by specialised bottom gear used by fishing vessels.

The potential cumulative impacts of depletion of the benthic infauna on higher trophic levels in the marine food web are also difficult to investigate. This is partly due to the fact that fish species generally move and feed over a wide area, and are hence affected by environmental factors well outside any aggregate dredging sites, and partly because fish stocks and the benthic habitat in which they live are overwhelmingly affected by the intensive fishing activity that occurs in European coastal waters.

Effects of Noise

There have until recently been very few detailed studies on the noise levels generated by aggregate dredgers, so it has not been possible to place these into context in comparison with natural background noise levels at aggregate dredge sites, and in relation to other sources of noise from activities such as windfarms, seismic surveys and vessels passing through the licence area. A scoping review by Thomsen *et al*. (2009) provided an overview of the available information on the ability of marine mammals and fish to detect noise in the frequency range generated by dredgers. However the study highlighted the lack of information available for noise emissions from aggregate dredging, and the scarcity of data on the impacts of noise on fish and invertebrates, as well as on many of the mammals and birds that form part of the food web.

Source levels of noise by operating dredgers

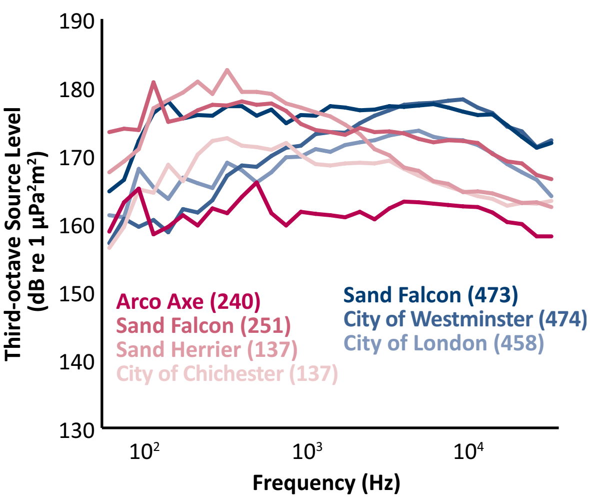


Fig 6.20 Source levels of noise generated by a series of different operating dredgers. The licence areas at which measurements were taken are shown in brackets. From Robinson et al. (2011).

Robinson *et al*. (2011) have subsequently carried out a detailed series of measurements to define the source terms for noise generated by seven typical aggregate dredgers operating in different areas and deposit types in coastal waters of the British Isles. The work involved measurements with a hydrophone at differing distances from dredgers operating in a variety of deposit types from sandy gravels to coarser deposits. Measurements were made at frequencies up to at least 48kHz for most vessels, but up to 100kHz for four of the vessels and occasional data up to a frequency of 200kHz.

The measured source level data for all vessels is shown in Figure 6.20. From this it can be seen that there are some differences between the noise levels generated by the different dredgers operating in different licence areas (shown in brackets). This may partly reflect the particle size composition of the deposits being taken on as cargo in the different licence areas, sandy deposits being associated with less noise than coarse aggregate material. But the results overall showed that the sounds radiated at frequencies less than 500Hz were similar to that of a merchant ship passing at modest speed. In other words, the noise levels attributable to aggregate dredging are probably indistinguishable from background levels in areas of busy shipping lanes in the English Channel and southern North Sea. It should be pointed out, however, that some aggregate licence areas such as those located off the North Norfolk coast are subject to low levels of shipping. In this case the relative impact of noise from aggregate dredging operations is likely to be higher than in licence areas close to busy shipping lanes in the eastern English Channel.

The data are also of interest because they show that the noise levels at frequencies above 1kHz are higher than those reported for merchant shipping vessels. This appears to be due to the impact and abrasion of coarse material passing through the draghead and suction pipe into the hold of the dredging vessel.

Figure 6.21 shows the sound levels recorded at 100m from the trailer suction dredger 'Sand Falcon' compared with background noise in the absence of other shipping. This shows the enhanced noise generated by shipping compared with background noise levels over the full frequency range. The noise levels generated by the dredger in the higher frequency range are similar to one another when the suction pump was off and when it was pumping water only, but levels were higher when seabed aggregates were being drawn by the suction pump through the draghead and up into the hold of the dredger.

This shows that the main element of noise generated by aggregate dredging in the higher frequencies is associated with material being removed from the seabed and passing up through the suction pipe. Higher frequencies in

Noise levels during dredging phases

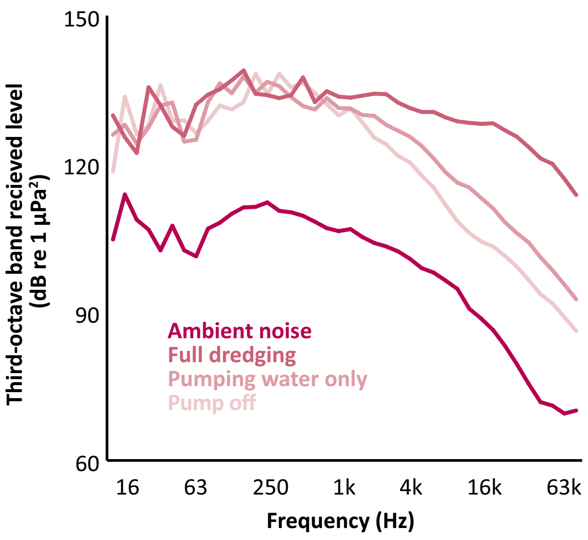


Fig 6.21 Noise levels recorded for the dredger "Sand Falcon" operating in licence area 251. The graph shows source levels recorded when the suction pumps were off, when they were pumping water only, and when aggregates were being pumped into the cargo hold. The background noise levels are also shown. From Robinson et al. (2011).

particular attenuate rapidly with distance, so the extent of potential impacts is likely to be limited to the immediate vicinity of the dredger.

There remain significant gaps in our understanding of the significance of the noise generated by shipping on living resources. Clearly many animals including cetaceans such as whales and dolphins, other marine mammals such as seals, as well as birds and some fish and invertebrates are capable of detecting sound in the frequencies generated by shipping. Some may be able to detect such frequencies at distances of several kilometres from the source, but the levels are far below those that are known to cause damage such as can occur near to high intensity sources such as pile driving.

At this point the general consensus is that whilst the noise generated in busy shipping areas is considerably higher than natural ambient levels, there is no evidence so far of direct impacts on living resources by aggregate dredging. This is not to imply that no such impacts could potentially occur, merely that whilst we now have good data on the source terms for noise generated from aggregate dredgers, there is far less information on the effects of noise by shipping, including that from aggregate dredging operations. ■

7 RECOLONISATION AND RECOVERY

By R.C. Newell, Richard Newell Associates

Introduction

It is widely-recognised, and is clear from Chapter 6, that the impacts of aggregate extraction within the active dredge zone are moderate to severe, depending on the intensity of dredging. It is also well-established that changes to particle size composition outside the immediate boundaries of the licence area are mainly associated with the transport of sediments that have been mobilised by the dredging and screening processes along the axis of transport by the seabed currents. In some cases this can lead to a 'footprint' of deposition of well-sorted fine-grained sand for several kilometres beyond the site of initial deposition.

There is some evidence of an impact on biological community composition outside the boundary of the dredge site, but this appears to be limited to a small distance along the axis of dispersion of material mobilised by dredging. The absence of significant impacts except in the immediate vicinity of the dredge site probably reflects the ability of many components of the community in sandy deposits to survive natural deposition events and to resurface after modest depths of burial by material that is deposited as a surface veneer outside the boundaries of the dredge site (see Chapter 6).

The key focus is therefore not on whether impacts occur within and close to a dredge site, but on the extent to which seabed resources can 'recover' following cessation of aggregate dredging, and if they can recover, how long is this likely to take?

The first point that should be recognised is that despite the very large number of detailed studies that have taken place in recent years, few generalisations can be made that can be applied to a specific aggregate dredging site. This is partly because the inherent variability of benthic populations is very high, both spatially and over time and partly because many other factors interact with one another and over time. These can result in cumulative effects that are difficult to distinguish from one another. Hence it is often difficult to establish the statistical significance between dredged sites and non-dredged reference sites, particularly when the number of samples is commonly too few to provide an accurate indication

of the resources that are actually present (for review, see Appendix 2 in Cooper *et al*., 2011b).

Even if we do have an adequate sampling regime to provide a robust data set to compare with a 'baseline' that varies over time, the recoverability is affected by a complex interaction of many different factors including:

- The intensity of dredging
- The size of the dredged area
- The biological traits of the resident fauna
- Whether the particle size composition of the substrate is changed by dredging
- The strength of the seabed currents
- The time over which the recovery process is allowed to continue

Despite these limitations, some general patterns do emerge from the literature. These have been summarised by Newell *et al*. (1998) and more recently by Foden *et al*. (2009; see also Hill *et al*., 2011). The literature review by Foden *et al*. (2009) showed that physical recovery at aggregate sites where dredging had ceased was generally reported to be dependent on substrate type and the strength of tidal currents, with fastest restoration in fine muds and sandy deposits. Sandy deposits in strong tidal streams had a physical recovery time (T_{Phys}) of 1-3 years and a similar biological recovery time (T_{Bio}). Reported rates for the coarser deposits that are mainly targeted for aggregate extraction were, however, amongst the slowest to recover, with a recovery time for the physical substrate of as much as 20 years and up to 8.7 years for recovery of biological resources.

There is however, wide variation reported in the literature and this is partly due to a lack of agreement as to what constitutes 'recovery' in a system that is subject to major change even in the absence of perturbation by man (see Ellis, 2003). Most studies on the recovery of marine communities regard 'recovery' as the establishment of a community that is similar in species composition, population density and biomass to that present prior to dredging or in a non-impacted reference site (see Kenny and Rees, 1994; Boyd *et al*., 2003; 2005; Cooper *et al*., 2007). However many ecologists would argue that a more appropriate definition might be the return of the community to one that is within the normal spatial and temporal variation recorded prior to dredging or in non-dredged reference sites. Other studies suggest that a restoration of the functionality of the ecosystem, whether this is achieved by a similar, or a different community

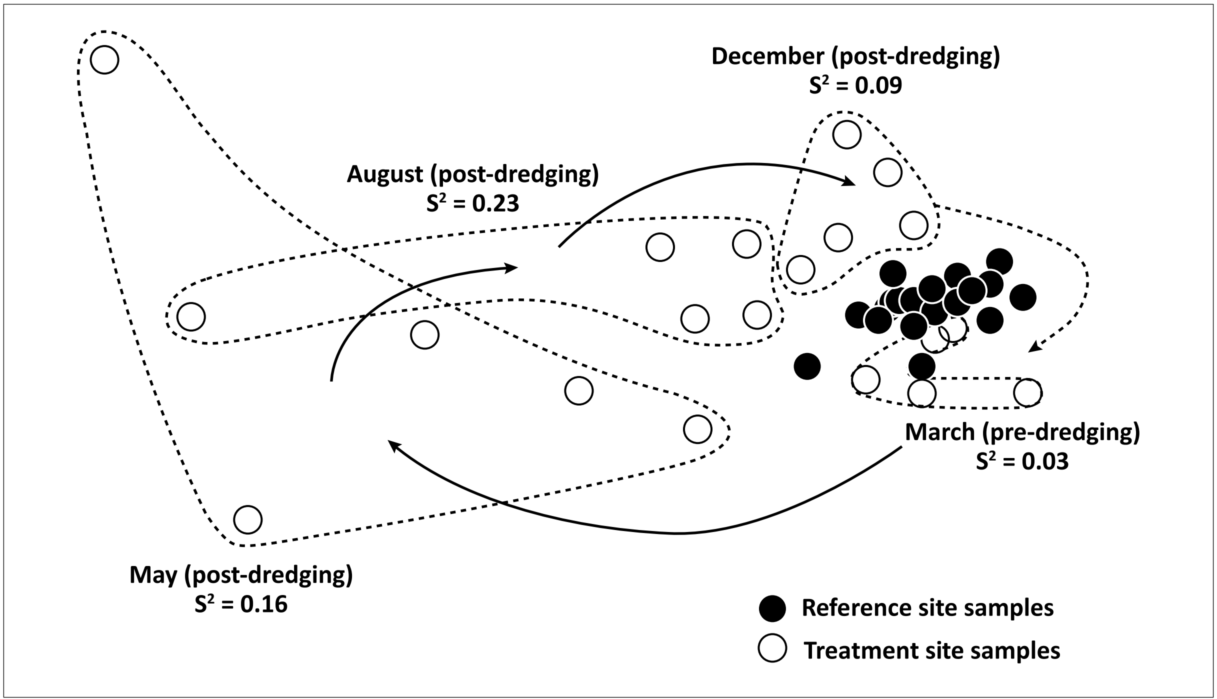


Fig 7.1 Two-dimensional MDS ordination for the benthic macrofauna at an experimental dredge site off the coast of Norfolk. The closeness of the symbols in the plot indicates communities that are similar to one another. Following dredging the symbols were very separated from one another and from the pre-dredge samples. This indicates a major change in community composition following dredging. Over time, recolonisation results in a community that becomes progressively closer (i.e. more similar) to the pre-dredge community. From Kenny and Rees (1994).

composition after cessation of dredging, constitutes a 'recovery' of ecosystem goods and services that is an acceptable end-result of the recovery process (see Cooper *et al*., 2008; 2011; Froján *et al*., 2011).

Despite the wide variability of the data, and the lack of a clear definition of what we regard as recovery, an overview of the literature confirms what has been generally agreed for some years. Namely that recovery of both substrate composition and associated biological resources is relatively fast in high energy environments characterised by sands that are colonised by mobile opportunistic species with a high rate of growth and reproduction. This is in contrast to more stable coarse substrata where the resident fauna is slow-growing and has complex interactions between components of the community that develop over many years (for reviews, see Newell *et al*., 1998; Foden *et al*., 2009).

Recolonisation in Sand and Gravelly Sand Habitats

One of the few detailed studies of the initial stages in the recovery of biological resources on the seabed was carried out at a gravelly sand site in the southern North Sea by Kenny and Rees (1994). A small experimental area of seabed was dredged in April 1992 down to a depth of about 0.3m and resulted in the removal of the surface deposits of about 70% of the trial dredge site. The impacts of dredging and the subsequent recolonisation of the deposits were then compared with a non-dredged reference site over a period of six months between March and December 1992.

As might be anticipated, dredging initially resulted in a marked reduction in the number of species, population density and biomass of the resident species compared with the non-dredged reference site. However the subsequent changes in community composition over time in the dredged site are of considerable interest. Figure 7.1 shows a multi-dimensional scaling (MDS) ordination for the benthic community sampled with a Hamon grab in the deposits in March (prior to dredging), in May (one month after dredging) in August (4 months after dredging) and in December (8 months after dredging). The reference site samples are also shown on the MDS ordination.

Inspection of Figure 7.1 shows that the community in the dredge site in March prior to dredging was very similar to that in the non-dredged reference site. This is shown by the fact that the communities in each case are close to one another on the MDS ordination. However samples taken one month after dredging (in May) were very different from one another and from the pre-dredge community. This indicates a high site-to-site variability reflecting the characteristic impacts under the drag head of the dredge and sites nearby. It also shows a major change n community composition from that which occurred prior to dredging and in the reference site. In August (4 months after dredging) some, but not all of the sites within the dredged area had recolonised to form a community that was similar, but not identical to that prior to dredging and in the non-dredged reference site.

Finally, by December all five sites sampled within the dredge area had recovered to a community that was similar to that in the non-dredged reference site and that prior to dredging.

It is important to point out a full 'recovery' to a community composition that was similar to that in the pre-dredge deposits did not occur for several years at this site. Nevertheless it does show that substantial recovery of community composition can occur in mobile sandy deposits in the Southern North Sea over a period of months. This supports the results of other studies carried out in sandy deposits elsewhere (see Dalfsen *et al*., 2000; Desprez, 2000).

In the case of the experimental dredge site in the southern North Sea, one of the effects of dredging was to remove the overlying sand and expose coarser stones and gravels underneath. Part of the explanation of the different community composition achieved in this site after cessation of dredging was colonisation by species such as the barnacle *Balanus crenatus* and the sea-squirt (ascidian) *Dendrodoa grossularia* on the coarse deposits exposed by removal of the overlying sand. This might not otherwise have occurred if the deposits had remained identical after dredging to that in the pre-dredged site. The effects of dredging on the particle size composition of the residual substrate thus have an important bearing on the nature of the community that develops in a particular dredge site after cessation of dredging.

Alteration in substrate type as a consequence of aggregate dredging becomes very important at sites where the aggregate dredging process involves return of sand to the seabed. The process of aggregate dredging in mixed gravelly sands commonly involves return of significant quantities of sand to the seabed during the screening process and this sand generally falls within a zone of up to 300m from the site of discharge (see Chapter 6). Over time, the deposits in actively dredged zones then become sandy where there is limited sand bedload, due to the removal of the coarser fractions and the return of sand to the seabed (see Desprez, 2000). In other areas such as the Southern North Sea, however, the effects of the return of sand to the seabed during screening can be difficult to differentiate from those of natural seabed transport.

If the seabed currents are strong enough to transport sand away from the dredge site, then there is a mechanism for overlying sand to be 'winnowed' away leaving coarser material on the surface of the seabed again. In this case it is possible over time for the deposits to support a community that is similar to that prior to dredging, although it has to be said that this is likely to take several, or many years. However in sites where the seabed currents are not strong enough to transport the deposited sand from the site of deposition, then essentially the original mixed sandy gravel biotope is likely to be replaced with one characteristic of sandy deposits. This will in turn support a biological community that is different in species composition from that in the original deposits.

Much of the literature reporting lengthy recovery times of several to many years at dredge sites in the southern North Sea and English Channel reflects the change in deposit type that inevitably occurs in a site where the gravel component has been removed and excess sand has been returned to the seabed. The communities that replace those that characterised the deposits prior to dredging are dominated by small and often mobile invertebrates such as polychaete worms, crustaceans and molluscs that have a high intrinsic rate of growth and reproduction. They are well-adapted to rapid recolonisation of deposits following episodic disturbance and tend to have a relatively short life-cycle of 1-5 years.

There is relatively little information on whether these communities have an ecosystem function that is similar to that in the non-dredged deposits, and they may form a quasi-permanent altered community in the small area under the footprint of dredging and deposition within the licence area.

Recolonisation in Coarse Substrata

The benthic fauna that characterises coarse stable substrata such as reefs, cobbles and coarse gravels is quite different from that which occurs in mobile sands (see Chapter 3). In this case the community is characterised by organisms that have complex interactions with one another, and often have very slow intrinsic rates of growth and reproduction. Some of the biological traits of these and other species are summarised in the Genus Trait Handbook (Marine Ecological Surveys Ltd., 2008,) and on the MarLIN Website (**www.marlin.ac.uk**).

Whilst some species such as barnacles can colonise rapidly from a planktonic dispersal phase, others such as some encrusting bryozoans brood their larvae which, once released, settle within a matter of hours in close proximity to the adult colony and recolonize areas only slowly. Others such as sea spiders (*Pycnogonids*) and small crustaceans like Caprellids are highly dependent on other members of the community such as hydroid colonies, so that colonisation does not start until a complex community structure has been achieved. Once colonisation has occurred it may then take several or many years for the animals to grow to a large size. Recolonisation can therefore result in an initial recovery of 'biodiversity' over time but subsequent restoration of biomass always lags behind the initial recruitment phase of the recovery process and may take many years to achieve.

Figure 7.2 shows the growth data for the dog cockle (*Glycymeris glycymeris*) from Newell *et al*. (2004a). This is one of the larger slow-growing members of gravel communities and serves to illustrate the likely time sequence for restoration of the biomass of some of the slowest-growing components of the marine community following initial recolonisation. Species such as this set an upper time limit within which recovery of community composition is likely to occur.

This shows the age based on growth rings and the corresponding shell height for this species. A shell height of 5cm corresponds with about 14 years of age. An age of about 10 years is not unusual for the larger bivalves in marine deposits, although many others, such as Queen Scallop (*Aequipecten*) and Venus shells (*Venerupis* spp) reach their maximum size in up to 5 years of age. In general, it can be assumed that a period of at least 5 years (and possibly up to 14 years) may be required for some of the slow-growing components of the marine community to achieve their full biomass after initial recolonisation has occurred.

***Glycymeris glycymeris* Age/Size data**

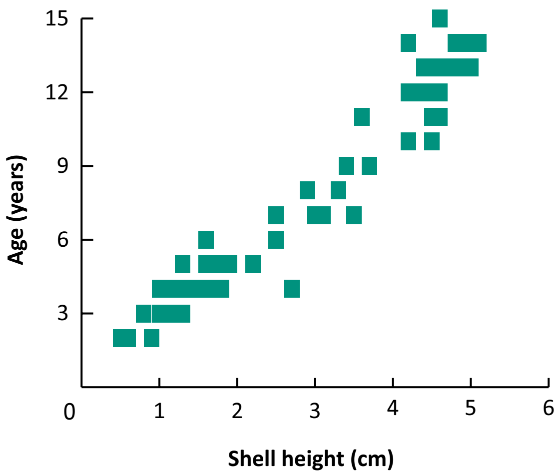


Fig 7.2 Graph showing the relationship between the shell height (cm) and age (years) of the dog cockle, Glycymeris glycymeris, from deposits in the East Channel Region in August 2001. Based on Newell et al. (2004a).

Fig 7.3 The dog cockle, Glycymeris glycymeris, and Queen scallops, Aquipecten opercularis (Courtesy of MES Ltd).

The situation is complicated by the fact that many species do not recolonize deposits immediately after cessation of dredging, so the time required for recovery of community composition is not necessarily the same as the time required for a species to achieve its full size (biomass). Some require the presence of other species, or adults of the same species, to induce settlement whilst others such as the dog cockle and King scallop (*Pecten maximus*) have an intermittent breeding and recruitment success that reflects seasonal and other factors.

The frequency of successful recruitment can be determined by analysis of the frequency of occurrence of individuals of different sizes in a population. Figure 7.4 shows the percentage occurrence of different-sized dog cockles in a population from gravel in the West Bassurelle area in the English Channel (from Newell *et al.*, 2004a). There were clearly maxima in the successful recruitment for individuals of 2cm shell height and 5cm shell height. Comparison with the data in Figure 7.2 shows that successful recruitment of dog cockles in this particular gravel habitat evidently resulted in large numbers of individuals of about 4 years of age (2cm) and 14 years of age (5cm). That is, at intervals of about 10 years.

This species could therefore take as much as 10 years for successful recruitment to take place, and a further 15 years for the biomass of the bivalve to be restored as a component in the mature gravel community. Whilst recruitment of the majority of the species that comprise the community undoubtedly occurs well within this time, it is clear that a period of between 15 and 25 years could be required for some of the larger slow-growing bivalve components to recolonize and then achieve their maximum biomass.

Glycymeris glycymeris Size Frequency

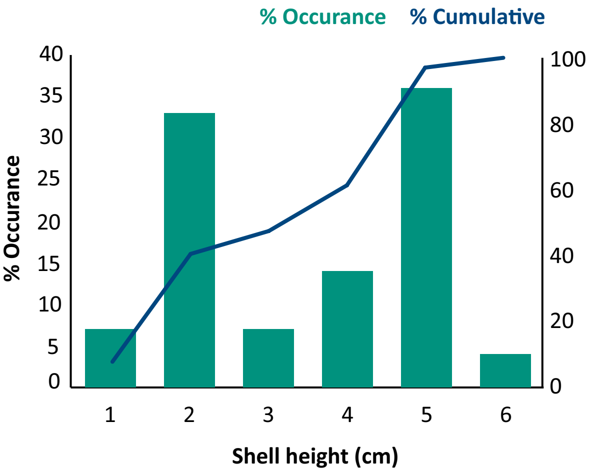


Fig 7.4 Size-frequency histograms and cumulative curve showing the percentage occurrence of different sized Glycymeris glycymeris in deposits of the East Channel Region in August 2001. Based on Newell et al. (2004a).

Knowledge of the population dynamics of the organisms that comprise the benthic community thus allows some estimates of the likely time-course of recolonisation and subsequent recovery of community composition of benthic communities following cessation of dredging. A generalised sequence showing the nature and likely rate of recolonisation of benthic macrofauna in coastal deposits following cessation of dredging is shown in Figure 7.5.

This shows that initial recolonisation by many of the typical components of the deposits can be very fast (within months) in sublittoral muddy sand. The community in these habitats is characterised by a relatively small number of opportunistic ('*r*-selected') species. However, the time for initial recolonisation increases to at least one year in coarse sand and gravel deposits. As shown above, it can be considerably more than this for some of the larger bivalve species with an intermittent recruitment success.

Initial recolonisation is then followed over a period of time by an increase in species diversity and population density (shown in blue) which reaches a peak in muddy deposits after about 1 year, but may take as much as 16 years in coarse gravel deposits. This reflects the slow recruitment and growth of the larger ('*k*-selected') equilibrium species and is accompanied by a gradual increase in biomass (shown in green) indicated by the increasing width of the green portion of the histogram.

For the most part, coarse gravels such as those that occur in the central and eastern English Channel, including the Hastings Shingle Bank, do not require screening to achieve a suitable cargo. Hence there is generally no significant alteration in substrate type following cessation of dredging, provided that a suitable thickness of deposit remains on the seabed. In these cases the impacts on biological communities that have been reviewed above are confined strictly to the footprint of dredging in the Active Dredge Zones (ADZs) with no significant impact on community composition outside the boundaries of the dredge site.

Habitat Restoration and Enhancement

We have seen that relatively long-term alterations in the physical properties of the substrate can occur at dredge sites where sand has been returned to the seabed by screening, and that this is commonly associated with long-term changes in community composition in the active dredge zones. Some studies have therefore been carried out to assess the feasibility of restoration of the

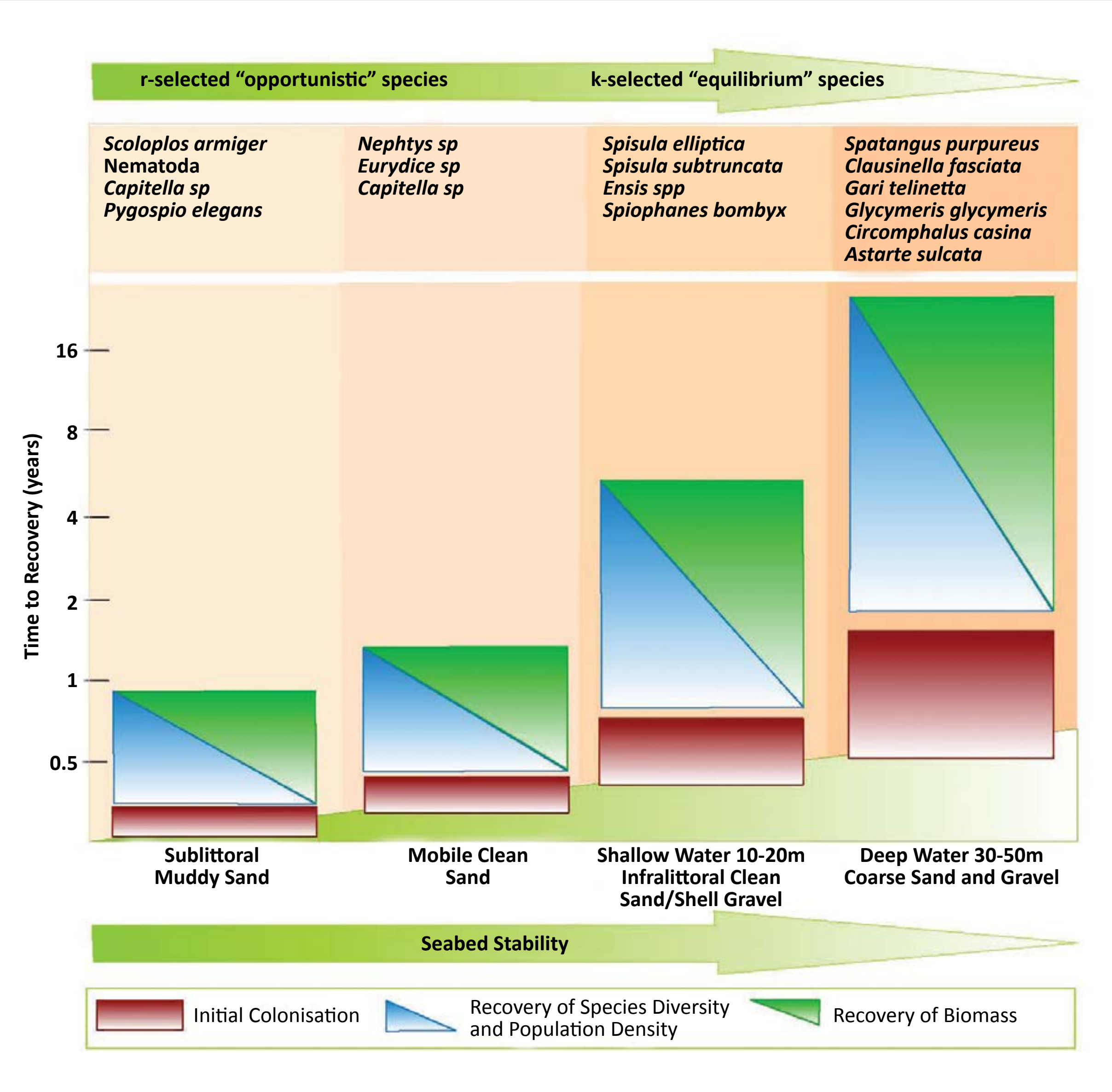


Fig 7.5 Generalised sequence showing the nature and likely rate of recolonisation of benthic macrofauna in coastal deposits following cessation of dredging. Note that recovery is likely to be achieved within 12 months in muddy deposits that are characterised by mobile ‘opportunistic’ species. In shallow water sands and gravels, recovery of diversity and biomass is achieved within 4-6 years. In deep water stable habitats substantial recovery is achieved in 4-6 years but restoration of the biomass of the slowest-growing members of the community may take 15-20 years. From Newell et al. (2004a).

particle size composition of deposits at sites where dredging has ceased, to determine whether this results in a restoration of the community that occurred at the site prior to dredging.

A review of the options for marine aggregate site restoration has been carried out by Emu Ltd (2004) who collated reports on impacts and possible remediation options based on examples for a variety of industries from the terrestrial quarrying environment, the intertidal and coastal environments. They used these to form the basis for a set of guiding principles that could be applied to remediation following cessation of aggregate dredging.

A review of the concepts and terminology used in the restoration of a variety of marine and coastal ecosystems has also been carried out by Elliott *et al*. (2007). They point out that whilst recovery techniques can have some success in marginal habitats such as coastal bays and fringing habitats on the coastline, they have less relevance to open coastal and marine habitats such as those targeted for aggregate dredging. They conclude that the best option available in open coastal habitats is to remove the stressor (in this case aggregate dredging), prevent other stressors such as use of heavy bottom gear by fishing vessels, and allow the system to recover over time through natural processes. This option is distinguished as 'active-passive' recovery and has generally been the one that has been adopted at aggregate sites after the cessation of dredging.

This process can be facilitated by the use of a series of relatively small Active Dredge Zones that are exploited fully within the licence area and then left to recover whilst the dredger moves to another zone. This is generally regarded as preferable to a lower intensity of dredging over the whole of the licence area for a long period, because in this case the seabed deposits are impacted for the duration of the licence without an opportunity to recover until the licence is relinquished.

The main problem with allowing 'active-passive' recovery to occur in licence areas after the cessation of dredging is that the deposition of sand during screening may result in a quasi-permanent change in deposit type at sites where there is limited natural sand transported as bedload. In this case, as shown in Chapter 6, the community is likely to revert from one which is rich in biodiversity and with a relatively high proportion of long-lived species to one with lower species diversity and components that are short-lived mobile organisms. Such communities may achieve some of the ecosystem functions that were performed by the community prior to dredging, and there needs to be a sound argument for intervention if an active restoration programme is to be considered.

Some attempts have been made to enhance the recolonisation process by placement of waste shell 'culch' on the seabed in areas where dredging has ceased. Collins and Mallinson (2007) studied the recolonisation of the seabed at two dredged sites to the east of the Isle of Wight (Licence Areas 395 and 351). Within each area some 200kg of crushed whelk and scallop shells were placed about 20m apart on mixed sand and gravel seabed at a depth of 18m. Whelk shell material proved to be too mobile for successful enhancement, but scallop shell promoted fast colonisation by epifauna being settled after only 7 months by 70% of the species found on dredged aggregate areas after > 5 years of recolonisation. The species diversity was enhanced within 7 months by 14 species on the scallop material that were not found on the aggregate area after > 5 years. Thus whilst the use of shell culch has the capacity to enhance biodiversity after cessation of dredging, the community is clearly not one which is 'restored' to its original community composition. There is also some concern that this technique could transfer pathogens or invasive species from one site to another.

Cooper *et al*. (2011a) have recently carried out an experimental study at Area 408 in the southern North Sea where, as has been shown in Chapter 6, dredging and deposition of fine sand from screening has resulted in an increase in fine sands and a change in community composition in the active dredge zones. They surveyed a site where dredging had ceased using a combination of acoustic, camera and grab techniques two months before deposition of 4,444m^3 of gravel-rich sediments. They then carried out surveys at zero, 12 and 22 months after gravel seeding had taken place. The results of this preliminary trial suggested that deposition of a relatively thin layer of gravel-rich deposit over the surface of the

Table 7.1 Cost of restoration by zone, and for the site as a whole. The total cost for each zone is made up of separate costs for: Restoration Works, Licensing, GHG Emissions and Survey work. From Cooper *et al*. (2011b).

		Restoration Works			Licensing	Carbon Footprint		
Zone	Description	Dredging	Capping	Bed Levelling		CO_2e (tonnes)	Cost "traded" price	
1	Dredge depressions	-	-	£77,000	-	25.21		£356
2	Trough	-	£64,855	-	£2,156	8.36		£118
3	Dredge tracks	-	-	£112,500	-	36.84		£519
4	Sand waves	£193,763	-	£19,500	£12,808	69.82		£984
5/6	Rippled sand and Sand ribbons/streaks	-	£441,987	-	£19,850	76.60		£1,080
7	Rippled sand	-	£146,998	-	£4,886	18.86		£266
	Total (ex zones 5/6)	**£193,763**	**£211,853**	**£209,000**	**£19,850**	**159.1**	**£2,243**	**£2,243**
	Total (inc zones 5/6)	**£193,763**	**£653,840**	**£209,000**	**£39,700**	**235.7**	**£3,323**	**£3,323**

sandy deposits left in the dredge site after dredging had ceased did result in some restoration of the deposit type. Further, the community that colonised the superficial gravels in the treatment site showed an increased similarity to that in non-dredged areas over the study period of 22 months.

A wider study was subsequently carried out by Cooper *et al*. (2011b) at an abandoned aggregate dredge site at Licence Area 222 in the outer Thames estuary. This study area comprised seven separate zones within an overall area of 1.4km^2 in which some zones (zones 1-4) were associated with topographic changes to the seabed whilst others (zones 5-7) were associated with changes in sediment composition. This allowed investigation of the feasibility and costs of remedial works to restore both seabed topography and sediment composition. Restoration options for seabed topography included bed levelling to reduce dredge trails and changes in bathymetry from trailer dredging and disposal of dredged material in pits left from static anchor-dredging. Restoration of sediment composition in areas where the original mixed gravels had reverted to sandy deposits was investigated using gravel seeding techniques and proved to be successful in promoting recolonisation by some species characteristic of coarser deposits.

The results of this comprehensive desk study of all aspects of potential restoration works at this site are of considerable interest, although it should be pointed out that feasibility and costs estimated for Area 222 in the Thames estuary may be very different at other licensed sites.

Table 7.1 shows that the total costs of restoration at site 222 were estimated to be between £712,143 and £1,189,660. These costs were primarily incurred by restoration works (86%), survey work and monitoring (10%), licensing (3%) and greenhouse gas emissions (<1%). Restoration of all the zones would involve the relocation of 202,528 tonnes (135,019m^3) of sand, and seeding of 291,097 tonnes (168,264m^3) of gravel, which is equivalent to about 2.85% of the 10.2 million tonnes of aggregate extracted from the site.

The costs are not only high, but account has to be taken of the environmental impacts of extraction of over 290,000 tonnes of gravel from another site (a 'borrow' site) for seeding purposes and the cost of relocation and disposal of over 2,000 tonnes of sand from the remediation site. There is a risk in this case that the impact of aggregate extraction is merely being transferred from the remediation site to the gravel 'borrow' site at comparatively high cost. The general conclusion from this study was that at this particular area, the benefits of seabed restoration do not warrant the high costs of remediation works.

In general the objective of management of the aggregate dredging industry is to identify environmental resources of conservation or economic significance at an early stage prior to dredging and ensure that they are properly protected through an appropriate mitigation and on-going monitoring programme. This underpins the comprehensive baseline and pre-dredge surveys for fisheries, benthic ecology, archaeology and other seabed features that form an integral part of the Environmental Impact Assessment (EIA) and consent process.

In this sense, an unacceptable residual impact at sites where dredging has ceased would mark a failure of the regulatory and management regimes and is something that the industry would wish to avoid, quite apart from the very high likely costs of remediation works based on the figures shown in Table 7.1. ■

	Survey			Total Cost	% of total cost (inc restoration zones 5/6)	Cost/m
	Baseline	1st post-restoration survey	2nd post-restoration survey			
	£9,139	£3,433	-	£89,928	13 (8)	£0.33
	£9,139	£3,433	-	£79,701	11 (7)	£0.81
	£9,139	£3,433	-	£125,591	18 (11)	£0.31
	£9,139	£3,433	-	£239,627	34 (20)	£3.49
	£9,139	£3,433	£14,600	£12,572-£490,08	2 (41)	£0.02-£0.94
	£9,139	£3,433	-	£164,729	23 (14)	£0.74
	£54,834	**£20,600**	**-**	**£712,143**		
	£54,834	**£20,600**	**£14,600**	**£1,189,661**		

8 SOCIO-ECONOMIC APPRAISAL

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Introduction

This chapter considers the role of socio-economic appraisal in the management of the marine aggregate extraction industry. Socio-economic appraisal in this context aims to maximise the net benefits to society from marine aggregates extraction through socio-economic analysis that identifies, quantifies and compares both positive and negative impacts. Positive impacts include supply of resources, knowledge gained, employment and revenues, while negative impacts can include disturbance of the seabed, noise, pollution and damage to marine biota, and exclusion of other marine activities. Economics enables comparison of these different impacts, facilitating the best judgements possible about the trade-offs involved.

Application of economics to such environmental considerations is only as effective as the environmental and other data available to the analysis. While gaps and uncertainties remain, both environmental economics techniques and knowledge of the marine environment (as reflected in other chapters of this book) have been improving constantly over recent decades. Together these have enhanced the way that socio-economic impacts of marine aggregates extraction can be identified, quantified and included in decision-making.

The term ‘socio-economics’ is sometimes used interchangeably with ‘economics’, since much of the content of economic analysis can contribute to social analysis. A broader definition is proposed here that regards social analysis as an important, linked but distinct element of the analysis. For example, economic analysis should capture the distribution of impacts in terms of affected activities (including marine industries), geographical locations (such as local communities, national populations), and interest groups (e.g. environmental NGOs and their members). This information can be used to extend the economic analysis into socio-economic analysis that goes beyond calculation of net impacts, both in terms of the impacts on different affected groups today, and in terms of the balance of impacts for current and future generations.

This chapter outlines recent developments in the socio-economic appraisal of the marine environment in the UK, and the decision-making processes that require inputs from socio-economic appraisal. It then describes socio-economic appraisal concepts and methods, along with some examples of their application to the seabed. It aims to help readers understand how socio economic analysis, in its broadest definition as above, can be consistently applied to activities that impact the marine environment now and in the future.

Appraisal of activities affecting the seabed means the use of methods that help inform decision-making. Economic appraisal does this using techniques that capture, as far as possible, impacts on human welfare, expressing them in monetary terms. It is an explicitly anthropocentric approach, reflecting people’s preferences regarding the current and future use and preservation of the marine environment.

The purpose of this chapter is to summarise available techniques and their applications in socio-economic appraisal of impacts of marine activities on the seabed, in particular marine aggregates extraction. It covers the latest thinking on socio-economic appraisal concepts and methods, and describes how they have developed sufficiently to start to become a practical tool for decision-making in relation to marine aggregate extraction.

Background

This section describes recent developments in the socio-economic analysis of the marine environment in the UK, some recent developments in marine decision-making processes that create demand for socio-economic analysis, and finally specific developments in relation to the marine aggregates sector.

Socio-economic Analysis of the Marine Environment

Socio-economic analysis of the UK marine environment has progressed through a number of recent studies and methodological developments.

Firstly, socio-economic data relating to marine activities have been defined in detail and published in comprehensive reports. Most recently the Productive Seas Evidence Group (PSEG) report has been produced as part of the work under Charting Progress 2 (UKMMAS, 2010). Prior to this, detailed data on “Socio-economic Indicators of Marine-related Activities in the UK economy” were also published by Pugh (2008). Attempts have also been made to look at changes to socio-economic values into the long term future (Dickie *et al*., 2011).

Much of the science and socio-economic baseline data available for the UK marine environment is weaker than for terrestrial ecosystems. However, the disparity is being reduced, and the UK's evidence base is stronger than for many other marine areas, including some other European waters.

Secondly, marine socio-economic analysis has benefited from developments in applying environmental economics techniques to resource management issues in general. Important recent developments have included:

- The emergence of the ecosystem services frameworks, through global studies such as the Millennium Ecosystem Assessment (MEA) and The Economics of Ecosystems and Biodiversity (TEEB), and its application in the UK (notably through the UK National Ecosystem Assessment – the UKNEA;
- An improved (but still limited) literature on the economic value of the UK marine environment, e.g. through studies such as (Beaumont *et al*. (2008); SAC, 2008; SAC and University of Liverpool, 2008) commissioned to inform the UK Marine Act and other policy developments (see below); and
- An improving ability to exploit the available literature and evidence, through improved scientific-economic collaboration using the ecosystem services framework, and the use of value transfer methods (eftec (2010)).

The ecosystem services framework is now used widely in UK Government policy development processes, being applied to such diverse areas as analysis of the impacts of improving air quality (e.g. RoTAP, 2010 ongoing) and assessment of the benefits of achieving Good Ecological Status (GES) under the Marine Strategy Framework Directive (eftec, forthcoming 2012). Guidance on the methods involved and appropriate use of the ecosystem services framework has been published in the UK by Defra, (2007 and 2010).

More recently in 2011 the UK's first National Ecosystem Assessment (UKNEA) provided a basis for using ecosystem services analysis in a wide range of policy contexts. Other recent marine applications of the ecosystem services framework include its use in the Impact Assessments required by UK Government for the designation of marine protected areas (originally developed by eftec (2007) for JNCC and in eftec (2010, discussed further below).

Decision-making for the Marine Environment

Use of socio-economic analysis to support decision-making in relation to the marine environment has increased in recent years. Coupled with continued advances in the application of environmental economics (e.g. MEA, UKNEA, TEEB, described above), this has helped the decision-making techniques involved improve. Key recent and current developments in appraisal of marine resources include:

New objectives for sustainable development of the marine environment

The way natural resources are used in all ecosystems is becoming increasingly accountable to the needs of society. These needs are encapsulated in the objective of sustainable development, as reflected in the UK's Marine Policy Statement (MPS, HM Government *et al*., 2011). The MPS is the framework for preparing Marine Plans and taking decisions affecting the marine environment. It aims to contribute to the achievement of sustainable development in the United Kingdom marine area, and the vision of having '*clean, healthy, safe, productive and biologically diverse oceans and seas*'.

Increased designation of marine protected areas

The legislation most pertinent to protecting marine species and habitats in UK waters are:

The EU Habitats Directive (Council Directive 92/43/EEC) and Birds Directive (Council Directive 2009/147/EC), under which the UK is required to: maintain or restore listed habitats and species; and contribute to a coherent European ecological network (the 'Natura 2000 network') of protected sites by designating and managing Special Areas of Conservation (SACs) for listed habitats. Similar measures are also to be applied to Special Protection Areas (SPAs) classified under Article 4 of the Birds Directive. The exceptional circumstances in which projects affecting the Natura 2000 network may still be permitted include when there are imperative reasons of overriding public interest. Such reasons are often based on socio-economic arguments, and therefore require detailed socio-economic evidence to be clearly presented to prove this 'overriding public interest'.

The UK Marine and Coastal Access Act, 2009; Marine (Scotland) Act 2010. Powers in these Marine Acts enable the designation of Marine Conservation Zones (MCZs) in UK waters (referred to as Scottish MPAs (Marine Protected Areas) in Scotland). Their purpose is to halt the deterioration of the UK's marine biodiversity, promote recovery where appropriate and support healthy ecosystem functioning.

Work to extend the UK's network of marine protected areas of different types was initiated during the 2000s (e.g. with JNCC work to designate offshore SACs), and continues at present through further Natura 2000 site and MCZ identification and designation. Economic analysis plays a role in each of these processes, being required as part of the 'Impact Assessments' (see HM Government, 2011b) that must accompany policy decisions such as the adoption of the Marine Act and the designation of marine Natura 2000 sites.

The Marine Strategy Framework Directive (MSFD)

The MSFD is a complex framework Directive governing the use of European seas. It includes an explicit role for socio-economic analysis in marine management and decision-making through considerations such as:

- The Cost of Degradation of the marine environment;
- That measures to manage the marine environment do not have disproportionate Costs (regarded as a political decision based on comparisons of costs to benefits or the distribution of costs across stakeholders);
- Cost-Effectiveness Analysis (CEA estimates how much of a given outcome is delivered for each pound spent and/or what is the cheapest way of delivering a given outcome (the two are not necessarily the same), and
- Social Analysis, that considers the distribution of impacts across different parts of society in detail.

These considerations of sustainable development, protected areas and the MSFD overlap extensively and draw on economic analysis in different ways.

For example, distributional analysis is a necessary, though not always sufficient, input to social analysis and is one basis for the assessment of disproportionate costs.

Appraisal of Marine Aggregate Extraction Activity

Improvements in socio-economic analysis techniques and the relevant evidence for the UK and the marine policy context noted above have implications for all marine activities. The marine aggregate extraction sector is no exception, and has been subject to several studies that have developed the application of socio-economic appraisal. For example, Lockhart-Mummery *et al.* (2009) looked at the methods that could compare the socio-economic impacts of extracting marine and terrestrial aggregates. Another example, that responds to the policy drivers to include the impacts of marine aggregate extraction on other marine users, is the appraisal tool developed by eftec (2010a) funded by the ALSF. The results of this study are considered in more detail in the case studies at the end of this chapter.

Socio-Economic Appraisal Concepts

Developing appropriate, evidence-based policies for managing the marine environment requires a more comprehensive understanding of the impacts of uses of the marine environment on ecosystem services and socio-economic activity. Such understanding and supporting data will increasingly need to be incorporated into decision-making to help determine how the marine environment and its ecosystem services are allocated amongst competing and/or conflicting economic uses. Economic valuation techniques are a powerful tool for doing this, allowing the expression of different physical, economic and social impacts in a common monetary metric. This allows non-market effects such as environmental impacts to be taken into account on a more even footing with marketed goods and services, in terms of their respective net contributions to human wellbeing.

Economic valuation is a three stage process of: i) qualitative, ii) quantitative, and iii) monetary, assessments. The first two steps are made more comprehensive by the use of ecosystem services analysis.

Ecosystem Services

The fundamental insight of the ecosystem services framework is that we can understand the role of the environment in supporting human life and wellbeing as composed of a number of specific goods and services provided by natural environments. These can be classified (following the MEA) as:

- *Provisioning services:* raw materials, food, and energy.
- *Regulating services:* natural regulation of ecosystem processes and natural cycles;
- *Cultural services:* benefits associated with experiences of natural environments;
- *Supporting services:* ecosystem functions that support and enable the maintenance and delivery of other services.

These services influence human welfare directly, through human use or experience of the service (these may be called 'final services'), or indirectly, via impacts of supporting and regulating services on other services and environments (these may be called 'intermediate' services). Note that the marine environment also has cultural values from historical assets (e.g. marine wrecks) and marine archaeological sites, which are conserved through the Protection of Wrecks Act (1973) and Scottish Historic Marine Protected Areas.

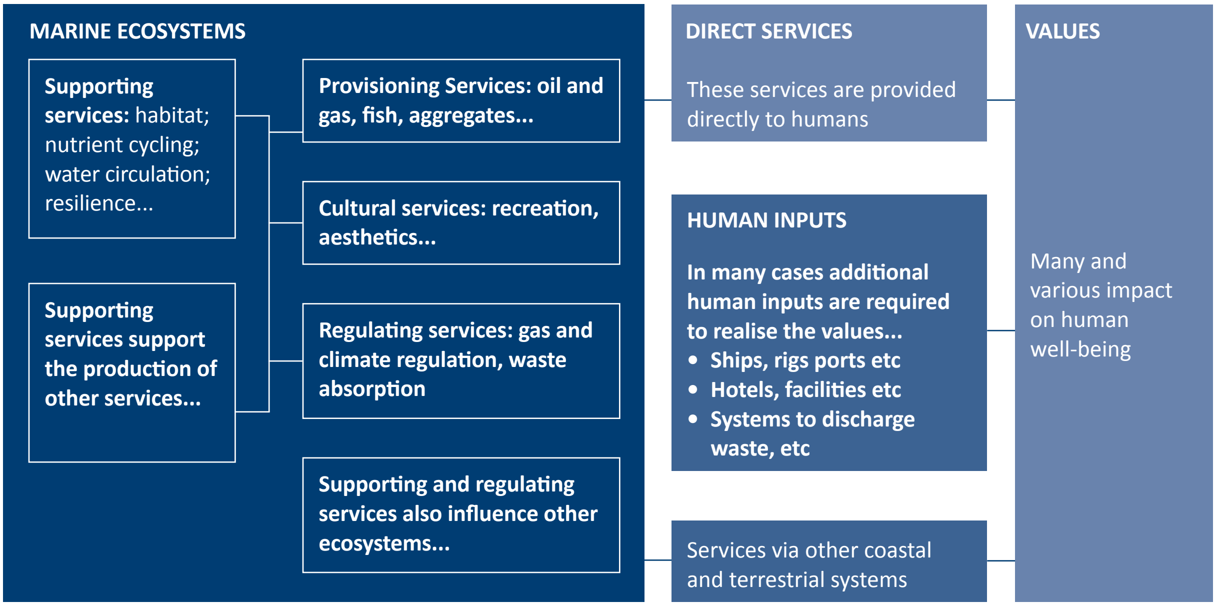

Fig 8.1 Marine ecosystem services and human values.

The concept of ecosystem services is addressed, for example, in the Millennium Ecosystem Assessment (2005), in previous work (e.g. Daily, 1997), in many subsequent publications (e.g. Silvestri and Kershaw, 2010; Turner and Daily, 2008; Boyd and Banzhaf, 2007), and in the recent work of The Economics of Ecosystems and Biodiversity programme (TEEB, 2010) and UK National Ecosystem Assessment (UKNEA, 2011). These cover the services of the marine environment in some detail. We do not repeat this catalogue here, but give examples in Figure 8.1, showing how marine ecosystem services influence human values both directly and via their impact on other marine, coastal and terrestrial systems, with or without the addition of human labour and manufactured capital.

Any ecosystem processes or services contributing to the maintenance of healthy ecosystems and human well-being can be considered ‘valuable’ to humans. Nevertheless, when assessing the value to humans of changes in the marine environment, we would typically focus only on the final services directly influencing human welfare, because the values of the intermediate services are already reflected via the final services or benefits that they support[1].

Similarly, services are often enhanced by human inputs (labour, market networks) and manufactured capital (ships, ports) or other resources (fuel). To avoid over-counting benefits we need to account for the costs of these inputs when calculating the net value of environmental goods and services.

Concepts of Economic Value

The ecosystem services framework focuses on the flows of valuable goods and services provided by the stock of natural resources. The same ideas are applied to man-made capital (e.g. an aggregates dredging vessel) and environmental capital (or resources) (e.g. fish stocks). Flow values are the values that the stock can support during a period (usually one year) (e.g. the volume of aggregates the dredger can extract, or the catch of fish).

Economic value is an expression of the values individuals hold for the changes in the environment that affect them – in other words their demand for such changes. This is expressed in monetary terms either as their willingness to pay (WTP) to avoid environmental degradation or to secure an improvement, or as their willingness to accept (WTA) (monetary) compensation to tolerate environmental degradation or to forgo an improvement.

For decision making, both these expressions of economic value are valid because they can be related to the marginal value of the change being decided on. Marginal value is the additional value gained or lost by an incremental change in the flow of services or a stock: for example, the benefit of extracting one more tonne from a site.

[1] This does depend on the boundaries of the assessment: where the ‘supported’ services are outside the boundaries – for example, where marine services support terrestrial services that the analysis does not cover – there is no double-counting involved in valuing these supporting services, and they should be included.

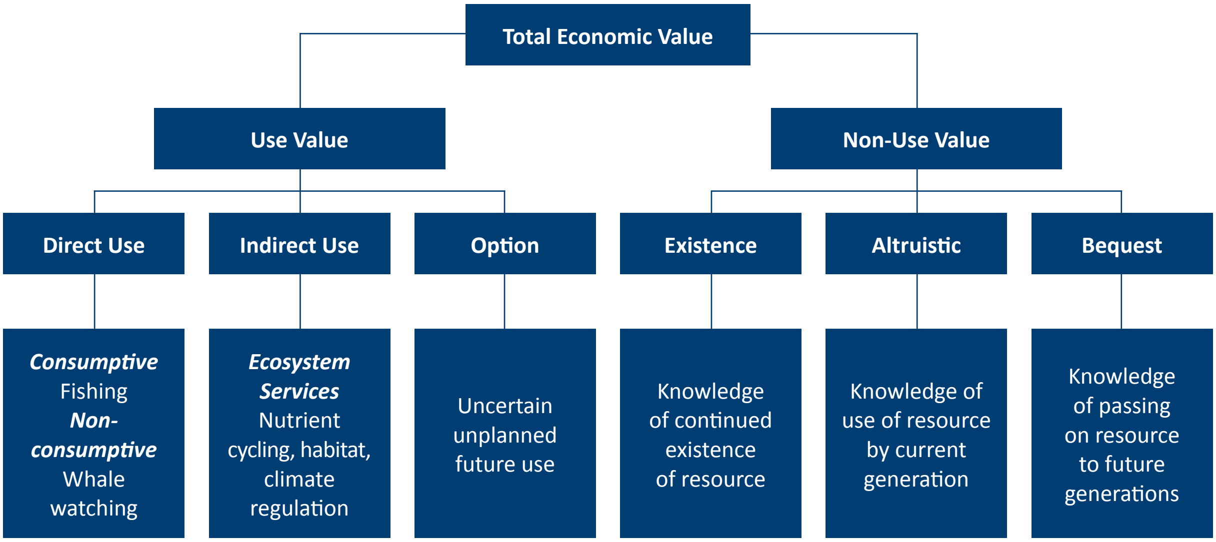

Fig 8.2 Total Economic Value framework (TEV) (adapted from Defra, 2007).

The reasons why individuals hold such values are presented in the Total Economic Value typology used in environmental economics (see Figure 8.2).

Individuals may have positive WTP (WTA) values because they make use of an environmental resource and its services directly (direct use value) or indirectly (indirect use value). They may also value the possibility of using the resource in the future (option value). Finally, they may not make use of the resource now or plan to use it in future, but may value the knowledge that it exists (existence value), it is used by others now (altruistic value) or is available for future generations (bequest value).

"Total" in Total Economic Value does not imply the "value of the entire resource", but rather the "sum of all types of economic value" for the resource. Since the decisions we have to make generally involve incremental changes (improvements or deteriorations) in the provision of environmental goods and services, we are usually interested in the (marginal) TEV of these changes, rather than the (total) TEV of whole resource stocks. On a practical level, marginal values are usually much easier to estimate than total values.

The natural environment is also considered to have an 'intrinsic' value independent of the services it provides to humans. Such a value is fundamentally beyond human knowledge. Both Total Economic Value and ecosystem services concepts are human-centric perspectives of the environment and how we interact with, depend on and impact upon it.

They do include non-use values associated with conservation, bequest to future generations and so on, but these remain human values. Note that this human focus is not in conflict with moral or ethical arguments for conservation: the arguments are often used together.

Economic Valuation Methods

There are three main groups of valuation methods that are used for primary research: market based, revealed preference, and stated preference. Cost of damage from environmental degradation or cost of correcting such degradation is also used even though these measure costs, not values. All but stated preference methods measure use values only as the data they analyse are linked to the uses made of the environment. Non-use values can only be measured through stated preference methods as will be explained below. Where primary research is not possible, value transfer is used to apply existing value estimates to new contexts. The rest of this Section provides an overview of economic valuation methods.

There are also a number of methods available for assessing and taking into account the ways in which ecosystems are valuable to humans, without using the concept of economic value. These include deliberative methods such as focus groups and citizens' juries, and various participatory methods in which stakeholders become more intimately involved in the planning, and management decisions. Although sometimes seen as conflicting, economic and deliberative or participatory methods can work well together. In fact, at least some of the economic valuation methods also make use of focus groups or other techniques as part of the valuation process.

Market-price Based Methods

Market-price based methods use evidence from markets in which environmental goods and services are traded directly, or enter into the production functions for traded goods and services, or markets for alternatives or substitutes for the environmental service.

Market prices can be used for traded goods, for example aggregates, and for some non-traded goods where there is a market in a closely related good (see 'Revealed Preference methods, below).

However market price is not equal to value:

- It is necessary to correct for market distortions such as subsidies or taxes;
- There is usually some additional consumer surplus, the value to the consumer over and above the price paid;
- Prices include the resource cost (for example the cost of ships, fuel, and labour) that does not form part of the value of the ecosystem service provided. This is often dealt with by reporting 'value added', i.e. price net of costs;
- A full analysis using price and consumption data from markets requires estimation of a demand curve and a supply curve, explaining how values and costs change with quantity;
- If the exploitation of a specific resource is not sustainable – as is the case for non-renewable resources such as aggregates, or when fish-stocks are over fished and cannot maintain their population – there is an additional cost associated with degrading the natural resource that may not be reflected in prices.

Production functions can be used for ecosystem services that are inputs for the production of man-made products or services. They use statistical analysis to determine how a change in the quality or quantity of an ecosystem service changes the cost or quantity of a good or service which has a market price or the value of which can be estimated using another method. The primary difficulty in this method is the paucity of scientific knowledge and/or data that can link the service input with the product output.

Cost-based methods are measures of costs rather than value. They differ from value for similar reasons to why market prices do not reflect value (discussed above), but are used as a proxy for value when other methods cannot be applied.

- Cost of illness method links environmental quality to human health and used in particular to estimate the cost of illness associated with air pollution. The cost of illness includes medical expenses, wiliness to pay to avoid pain and suffering and economic cost of work days lost.
- Avoided cost method values an ecosystem service by calculating the costs that would be incurred if the service was no longer available or delivered.
- Replacement cost method estimates the cost to replace an ecosystem function or service. This is usually applied to replacing specific ecological functions with human-engineered alternatives (e.g. the cost of providing hard flood defences in place of natural defences) but can also be applied to entire ecosystems (e.g. the cost of providing new habitat to compensate for habitat losses).

Revealed Preference Methods

Revealed preference methods infer the value of ecosystem services from interpreting observations of human behaviour. They estimate demand for an ecosystem good or service through statistical analysis of individuals' willingness to incur the costs associated with benefiting from the good or service. There are two main methods:

Travel cost method analyses the data on the costs of travelling for recreational activities (both market costs, e.g. fuel, and non-market costs, e.g. personal time), participation rates, population characteristics, and characteristics of the recreational site and alternatives. It is particularly relevant for cultural ecosystem services.

Hedonic pricing analyses property sale data and estimates the premium paid for environmental characteristics by comparing the price differentials between properties with different characteristics. This method can be used, for example, to estimate the benefit associated with a sea view, or the disbenefits associated with proximity to industrial sites.

Stated Preference Methods

Stated preference methods survey representative samples of those affected by a change. The survey gives the respondents an opportunity to trade off environmental changes against income and express their willingness to pay or willingness to accept compensation. The methods are very widely applicable, used for example for biodiversity, and the only techniques capable of capturing non-use values. Careful design and pre-testing of the questionnaire used for the survey is vital to ensure responses are focused accurately on the ecosystem service change of interest. The two variations of stated preference methods are:

Contingent valuation elicits willingness to pay (or willingness to accept) for a specified change directly (e.g. are you willing to pay £x?)

Choice experiments present different options for the responses to choose from, whereby each option provides ecosystem services at different levels with different price tags attached. The method then infers willingness to pay (or willingness to accept) for each service from the choices made.

Both methods also collect information about the uses respondents make of the ecosystem and/or service, their opinions and socioeconomic characteristics. Stated preference methods require extensive primary data gathering (e.g. as described in eftec, 2006). This can be prohibitively costly and time-consuming, so a more practical approach can be to attempt to use value transfer.

Value Transfer

Primary valuation methods (e.g. as described in eftec, 2006) for non-market costs and benefits may be a long term option for addressing gaps in the data. However, a more practical approach to attempt to use value transfer, for which best practice is described in eftec (2010b).

Value transfer can be used to estimate the economic value of a change in the provision of ecosystem services by combining:

i. *A reliable estimate of the economic value* – ordinarily in terms of 'willingness to pay' in market data or estimated in relevant primary valuation studies;
ii. *A description of the change in the provision of the good under consideration* – this may be presented in qualitative and/or quantitative terms;
iii. *Knowledge of how the economic value (i) changes due to the change in provision of the good (ii)* – what is the relationship between the level of provision of the good and willingness to pay for marginal changes in the good (i.e. constant or non-constant)?; and
iv. *Knowledge of which factors influence the economic value* – particularly in terms of the population affected by the change, their use of the environmental resource, their socio-economic characteristics (e.g. income, age, gender, education and so on) and substitute goods and services.

Economic Impact Measures

Some assessments of the "economic value" of ecosystem services focus on contributions to local or national economies. This is especially the case for tourism and recreation, and extractive industries such as the aggregates industry. Expenditure is not the same as economic value, for similar reasons to why market prices are not the same as value (discussed above). But expenditure measures can serve different purposes, in particular assessing impacts on local communities, or securing funding from organisations with a focus on economic development. Other indicators may also be used, in particular employment.

When estimating expenditure measures, there are several additional factors that are often taken into account. These depend on defining a spatial boundary for the impact, and this often depends on who is taking the decision. Local authorities, for example, may be interested only in impacts within their boundaries, which may not reflect national interests.

The key factors to consider in using expenditure methods are:

Multiplier effects: direct expenditure within an area will lead to additional indirect and induced spending, leading to further economic and employment benefits. These are typically accounted for using multipliers on the basic spend.

Displacement: where an increase in spending/employment in one area arises at the expense of a reduction elsewhere.

Leakage: where part of the benefits accrues outside the target area, this may be netted out of the calculations.

Complicating Factors in Marine Valuation

In applying economic valuation methods to the marine environment, as with environmental resources more generally, there are a number of complicating factors that need to be considered. These are described briefly here:

Uncertainty: in marine ecosystem services assessment and valuation this can be due both to imperfect knowledge of ecological and economic relationships in the marine environment and to fundamental and irreducible randomness (for example, flood events or random climate effects on fish stock-recruitment relationships). In practical terms, economic valuation and cost-benefit analysis deal with risk (i.e. where probabilities are known) reasonably well, and with ambiguity (known outcomes, unknown probabilities) to some extent, through calculation of expected values and various forms of sensitivity analysis. However, economic methods are more limited where possible outcomes are unknown. In these cases, concepts of 'safe minimum standards' can be used for aspects of the natural environment that need to be safeguarded because they have critical functions that cannot be substituted (Atkinson, 2009).

Cumulative impacts: if the same resources or services are subject to multiple on-going pressures, or to combinations of threats (such as storms and disease outbreaks), then analysis of values focusing on just one pressure could miss the dangers associated with the overall impacts. For example, when determining the impacts of aggregates extraction on fisheries it may be necessary to consider not only the direct impacts on fish habitats, but the bigger picture of threats facing fish populations, including overfishing, climate change and the availability of alternative habitats.

Scale: Calculations at different spatial scales can give different results for units of the same resource. For some services, such as carbon storage, values for carbon storage in different locations are constant when making decisions about international climate policy. Other services however show very rapid changes with area: for example recreation, where the provision of the first few sites (beach access, parking, hotels, marinas) brings substantial benefits, but adding more and more in the same area soon adds relatively little to total values. The appropriate decision over permitting aggregates extraction at a specific site may be highly dependent on the amount of permitting already in place in the surrounding sea areas.

Value transfer methods (discussed above) must be mindful of, and can attempt to correct for, the influence of these factors, taking into account the levels of substitute resources and thresholds in value transfer functions. Where resources allow, explicitly spatial modelling is a better solution, allowing for more accurate consideration of such effects.

Social Analysis

As described in the introduction, there are overlaps between the social and economic aspects of socio-economic analysis. However, social analysis brings in distinct considerations such as the distribution and fairness of impacts.

Social impacts can be defined as the consequences to human populations of actions that alter the ways in which people live, work, play, relate to one another, organize to meet their needs and generally cope as members of society (International Association for Impact Assessment, 2003).

As this description illustrates, social analysis contains a number of different aspects. Firstly, the distribution of the costs and benefits is an important consideration. Social analysis produces awareness of differential distribution of impacts among different groups in society, particularly the impact burden as experienced by vulnerable groups (Vanclay, 2003).

Secondly, social analysis recognises the importance of social assets and different groups' access to them. Change in either the quantity of a social asset, or access to it, induces a social impact. Social assets include:

- Public services
- Cultural heritage
- Education
- Natural environment
- Community cohesion/integration
- Social capital
- Employment
- Political empowerment
- Crime
- Health

Marine aggregate extraction potentially has indirect relevance to all these assets through providing materials for construction. However, the scope of analysis can be more pragmatically defined in relation to the main assets that it will have direct relevance to: employment, cultural heritage and the natural environment. There is overlap between cultural services assessed within the ecosystem services framework, and social impacts arising from changes in cultural heritage assets.

For more details and guidance on social analysis and other qualitative evaluation methods see Chapter 8 of the magenta book (HM Treasury, 2011).

Appraisal Methods

The economic value estimates from the methods described above can be used in a wide range of contexts, for example to help decide on aggregates permitting decisions, to determine where and how much of the marine environment to protect, to formulate resource management policies, to determine compensation payments for damage to marine features, and so on.

Within these contexts, they need to be part of an appraisal method that provides a way or organising the relevant information for decision-makers.

The main methods relevant to marine aggregates extraction are:

Cost-benefit analysis (CBA) is a decision support method which compares, in monetary terms, as many benefits and costs of an option (project, policy or programme) as feasible, including impacts on environmental goods and services. Its application is limited by the availability of the necessary data. CBA targets two of the most crucial appraisal question (1) Is the objective worth achieving? and (2) if it is, what is the most efficient way of doing so?

Cost-effectiveness analysis (CEA) is a decision support method which relates the costs of alternative ways of producing the same or similar outcomes to a measure of the outcomes. CEA can answer the question of the cheapest or most cost-efficient way of achieving a given objective, but not whether an objective is worth attaining.

Multi-criteria analysis (MCA) develops a set of criteria for comparing policy or management options, evaluates the performance of each of the options against each criterion, weights each criterion according to its relative importance, and aggregates across options to produce an overall assessment. Often one or more of these steps is implemented with stakeholder participation.

Impact Assessment (IA) is a framework for complete assessment of a proposed policy or decision, covering appraisal, implementation and ex-post evaluation; valuation evidence can be integrated at each of these stages.

Within these methods, the use of economic valuation methods should be guided by the following principles:

Proportionality: the methods and level of detail that are appropriate will be determined by the decision-making context, legal requirements, characteristics of the policy options, location, habitats, services, human populations and scale of the impacts;

Uncertainty: it is necessary to consider uncertainties and gaps in scientific data and valuation evidence, often through formal sensitivity analysis where this is proportionate to the decision context.

Transparency: it is essential to maintain a clear audit trail of methods, data, consultations, assumptions, limitations, omissions and uncertainties.

Decision-support: appraisal and valuation methods involve approximations and it is rarely possible to specify all costs and benefits in monetary terms, so other information will usually be relevant. The methods aid the structuring of data and evidence and are very useful for decision support, but they are not a replacement for deliberation or consideration of other evidence.

Application of Economic Valuation and Appraisal Methods to Impacts on the Seabed

This Section presents four examples of applying economic appraisal and valuation methods described above to impacts on the marine environment:

- Recently developed tools for combining science and economics in analysis of the marine environment
- The inclusion of the effects of aggregates extraction in an Impact Assessment concerning the designation of marine protected areas;
- A tool for appraising the socio-economic impacts of aggregates extraction on other marine users for inclusion in aggregates licensing decision making, and
- A detailed case study describing use of the tool for a hypothetical but realistic aggregate extraction site in the Thames Estuary.

Example 1. Tools for Analysing Impacts on Ecosystem Services

The recent advances described in both science and economics means that changes in ecosystem services due to an economic activity are considered in a more equal footing to the financial costs and benefits the of activity. Two notable examples that are relevant for the marine environment are ARIES (ARtificial Intelligence for Ecosystem Services)[2] and the InVEST (Integrated Valuation of Ecosystem Services and Trade-offs)[3] projects.

Both InVEST and ARIES map the provision and beneficiaries of multiple ecosystem services, and can estimate monetary values. ARIES assigns ecosystem service provision and value directly according to the habitat and management characteristics, with the ecosystem service provision and values drawn from other site-based studies. InVEST determines ecosystem service provision and value via ecological and economic production functions, linking spatially explicit maps of habitat types to specific service outputs. The production functions include a biophysical component, where supply of the service is quantified; a use component, where demand for the service is quantified; and an economic component for valuation in monetary terms. The Marine InVEST tool quantifies how climate, management, and policy scenarios, specified by users, impact on ecosystem processes. Resulting predictions of ecosystem service provision can be used to compare the values arising in different scenarios.

The first marine ecosystem service modules to be included in ARIES include coastal flood protection, sedimentation, subsistence fisheries and recreation. Production functions currently available within Marine InVEST include food from commercial fisheries and from aquaculture, coastal vulnerability, protection from coastal erosion and flooding, wave energy generation, recreation, habitat risk assessment and aesthetic quality.

These spatial modelling approaches can help to demonstrate the spatial relationships between ecosystem services, and to identify management options that optimise service provision across the range of services considered, and over time. The use of stakeholder-derived scenarios can help to combine science and economic knowledge with local, user-based knowledge of the situation and trends.

Example 2. Impact Assessment of a Marine Protected Area: Dogger Bank Special Area of Conservation (SAC)

Economic appraisals of recent designations of marine Natura 2000 sites in UK waters have included analysis of marine aggregates extraction. This example is taken from the actual Impact Assessment (IA) for Dogger Bank Special Area of Conservation (JNCC, 2011).

Dogger Bank is the largest single continuous expanse of shallow sandbank in UK waters, located in the Southern North Sea. It lies in the Humber marine dredging region, which in 2010 was licensed for permitted removal of approximately 5 million tonnes, with actual landings of approximately 730,000 tonnes (The Crown Estate, 2011).

The impact assessment identifies current human activities and environmental characteristics of the site, including the ecosystem services it provides. The current and expected future condition of these provides a baseline against which the impacts of designation are assessed.

When the site was being designated, no aggregate extraction licences had yet been approved at the site, but two licences had been applied for with an expected

[2] *Under development by the University of Vermont, Conservation International, Earth Economics, and UNEP-WCMC (**http://www.ariesonline.org**).*

[3] *Natural Capital Project, a partnership of the Woods Institute for the Environment at Stanford University, The Nature Conservancy, and World Wildlife Fund. InVEST 2.2.0 was released in December 2011. **http://www.naturalcapitalproject.org/download.html**.*

average annual extraction of 700,000 tonnes pa. In order to undertake economic appraisal of the impacts of designating the Dogger Bank, the following implications for the aggregates dredging industry/regulator were assumed:

- For applications within the Dogger Bank area, it is likely that a more in-depth knowledge of the area will be required for EIA purposes. It is estimated that designation may raise costs faced by the industry in terms of environmental survey work and appropriate assessments by 10-50% (approximately £60,000 to £300,000 per licence).
- Restriction on screening could increase the operating costs of extracting the aggregates. Not being able to screen would in certain cases make dredging significantly more costly and possibly unviable.
- If extraction applications are turned down or companies perceive that the relevant authority will judge that future dredging will adversely affect the integrity of the SAC, this could lead to a failure to exploit potential resources.

In the short term supplies would be expected to be met from alternative sources, but in the long term the UK could face aggregate resource constraints.

Through these assumptions the Impact Assessment attempts to make a realistic assessment of the costs of designation on the aggregates extraction sector. The costs to all sectors are collated and compared to the overall expected benefits of designating and managing the site to achieve its conservation objectives. While the costs of designation can be broken down by the user sector (e.g. costs to aggregate extractors), the benefits arise for the whole site and cannot be apportioned to each controlled activity. As such, the benefits are likely to arise from the improvements to the following services:

- Provisioning services: The Dogger Bank is important as a spawning ground for a number of commercial fish species, including plaice.
- Regulating services: which are not analysed as their value is considered to be minimal at a site level.
- Cultural services: such as impacts on the archaeological interest of the site (during the last ice age, Dogger Bank ("Doggerland") connected Britain, The Netherlands, Germany and Denmark, and bottom trawlers have recovered important archaeological pieces from the area in the past (Coles 1998; Gaffney *et al* 2009).

Enhancements to these services result in both use and non-values to people. However, there is insufficient evidence to quantify the changes in ecosystem services as a result of managing the site, and to place monetary values on these changes. Therefore, the changes to ecosystem services are assessed qualitatively, using a framework that ensures explicit consideration of the baseline situation and importance of the ecosystem services, the range of possible changes to them resulting from management of the site, and the level of confidence placed in the analysis.

The value of expected changes to marine aggregates extraction and ecosystem services provision are reported as part of the IA's conclusions. The IA approach explicitly requires that key monetary and non-monetary impacts are clearly reported. It also provides for sensitivity analysis and identification of the groups impacted by the expected changes.

Example 3. A Tool for Analysing the Socio-Economic Impacts of Marine Aggregate Extraction

Through a project funded by the Marine Aggregates Levy Sustainability Fund (MALSF), Dickie *et al*. (2010a) designed a tool to allow marine aggregates extraction options to be analysed using socio-economic information. The tool shows the interactions between different uses of the marine environment at both local and regional levels and the data requirements for such a framework.

The tool was designed primarily for use in a site level Environmental Impact Assessment (EIA) decision-making context. This was considered to be of most practical use to the wider industry and other stakeholders, including the Marine Management Organisation (MMO) and the marine aggregates industry, and reflects an increasing need for including socio-economic concerns within the EIA process.

The tool is designed to work alongside marine spatial planning of aggregates extraction activity. Based on spatial planning considerations it is possible to determine whether spatial conflicts exist between aggregates extraction and other uses of the sea. Where they do exist, approaches for measuring environmental and social impacts need to be applied.

The tool consists of two parts. Firstly a decision tree to help structure the analysis, and secondly, a framework for undertaking that analysis.

1. Decision-Tree

The decision tree identifies different economic sectors for which different methods and/or detail of analysis are judged appropriate. This judgement is based on the level of interaction between marine aggregates extraction and other uses/industries of the marine environment, and the likely data availability for analysing that interaction. Three levels of interaction between marine aggregates and other uses are defined:

Interaction 1 is for the industries (such as the laying of telecommunication cables and oil and gas pipes on the seabed; the interests of national security, i.e., military exercise areas; and energy provision, from potential oil and gas reserves) that are considered to be of higher planning priority than aggregates extraction by virtue of the previous investments that have occurred.

Interaction 2 is for other uses/industries that may be impacted directly or indirectly by aggregates extraction (marine conservation, recreation, and heritage) for which it may be difficult to find data to estimate the costs.

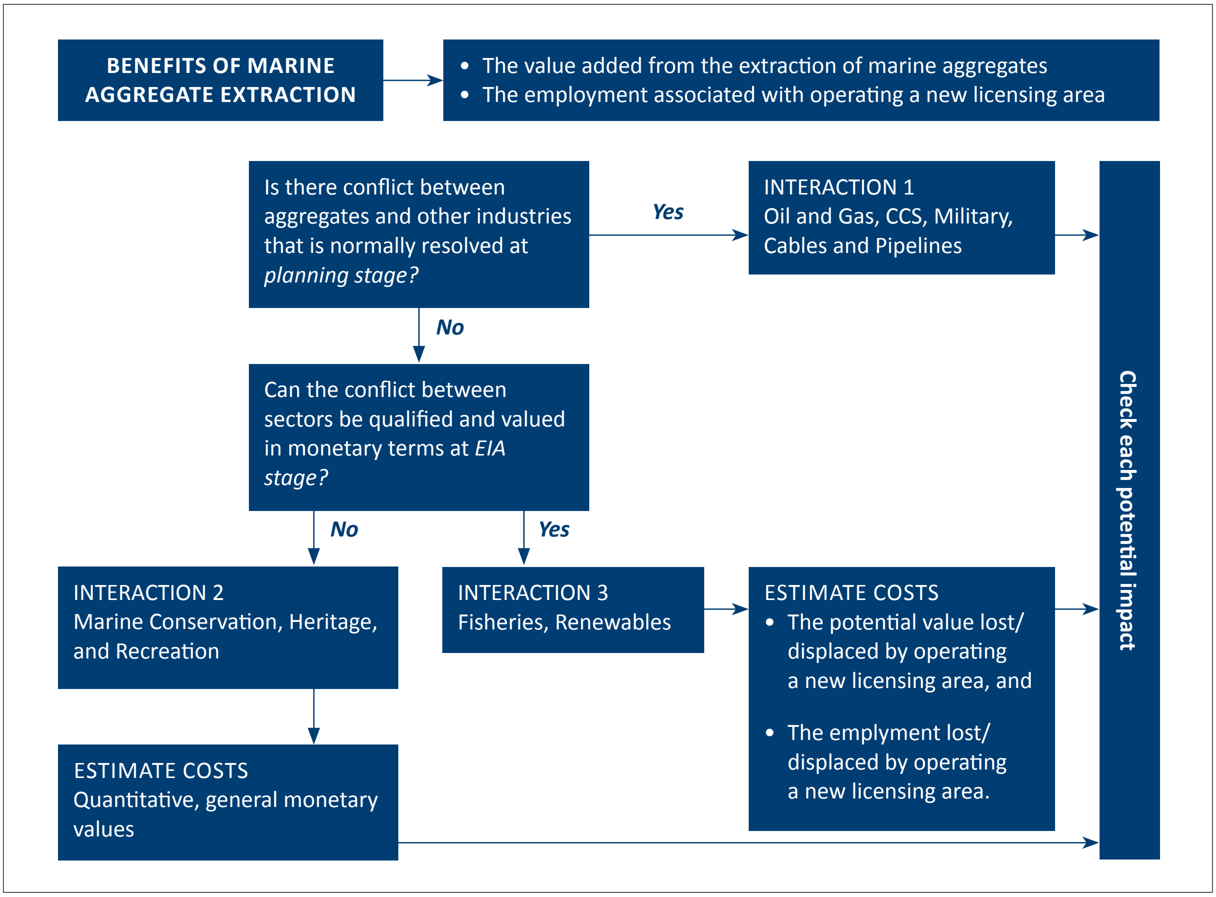

Fig 8.3 Decision Tree Determining Approaches to Socio-Economic Analysis of Different Interactions between Marine Aggregates Extraction and Different Marine Activities.

Interaction 3 (fishing and renewable energy provision) which aggregate extraction could impose costs on and for which it is likely to be easier to find data. The three levels of this decision tree are illustrated in Figure 8.3.

Several methods for calculations and different indicators of costs and benefits can be used to determine the potential costs and benefits to different industries associated with a new licensing area. The most appropriate methods to each sector depend on both the interactions, described above, and the data available for the case in question.

2. Process of Analysis

In its second part, the tool defines a process for estimating the socio-economic implications of a newly licensed area. The process starts by determining whether conflicts exist at the 'site' level and whether any quantitative evidence is available, either at local level or from averages based on larger scale datasets and their associated caveats.

The next stage is to conduct analysis of costs and benefits. Cost estimates are made where marine interactions mean that aggregate extraction imposes costs on other users or on the marine environment. Benefits are mainly associated with marine aggregate extraction sector activity.

A summary template is suggested for reporting the outputs of analysis in order to make the different interactions and socio-economic impacts more transparent. The application of the framework will depend on the time, resources and data available, and may be particularly useful in areas where multiple conflicts exist or large changes are proposed.

Example 4. A Case Study of Applying the Tool for Analysing the Socio-Economic Impacts of Marine Aggregate Extraction in the Outer Thames Estuary

The Outer Thames Estuary was chosen as the case study site because it was a relatively typical aggregates extraction location and had relatively good data availability. In particular data were available from reports such as the Regional Environmental Scoping Report (ERM *et al*., 2008); Natural England's work on the Margate and Long Sands draft Special Area of Conservation (Natural England, 2010), and from a broad range of other data on the activities taking place or planned in the area.

These data included aggregate dredging licences, application, option and prospecting areas; the values of fish landings according to the ICES rectangles in the Outer Thames Estuary (for which permission was obtained to use in the study) and studies looking at wind farms operating, under construction and proposed in this area (Greater Gabbard, Gunfleet Sands, Thanet and Kentish Flats), which are accompanied by detailed environmental statements. There were still gaps in the available data, with regional and local data being less available, and gaps existing in relation to heritage and wider environmental issues.

To enable the illustration of different calculations throughout this case study the potential marine aggregate licence was deliberately sited in an area that would result in conflicts with other marine activities. For simplicity the benefits from aggregates extraction are assumed to be constant over time, and a licence period of 15 years is used. More details of the calculations behind the results reported here can be found in Dickie *et al*. (2010b).

Figure 8.4 shows the 'fictitious' area ("site F") being considered for marine aggregates licensing in this case study. The size of site F is based on the mean of all current licensed aggregates areas within the Outer Thames Estuary.

It was assumed that the proportion of site F actually dredged, and the yield of aggregate per km^2 was the same as the average for the existing areas in the Outer Thames Estuary. This allowed an estimate of the expected volume of aggregate extracted from site F and sold into different markets (UK and European construction and beach nourishment). For each market a sale price was estimated using price data taken from (Pugh, 2008), giving a price of between £6.39 and £12.80 per tonne in 2008 prices for the UK construction market.

This gave an expected annual sales value of £3.80-5.96 million. From this, Gross Value Added (GVA[6]) was calculated using the GVA ratio of 0.47 reported in (Pugh, 2008), at £1.79-£2.80 million per year.

Fig 8.4 Map showing the total licensing area of current dredging sites in the case study area (areas in red)[4] and the 'fictitious' new licensing area (in purple)[5].

[4] Shape files are available from The Crown Estate: **http://www.thecrownestate.co.uk/energy-infrastructure/downloads/marine-aggregate-downloads/**

[5] *The actively dredged areas within each licensing area are smaller in size.*

[6] *GVA is the added value of outputs of goods and services from an activity compared to inputs.*

Fig 8.5 A map showing the current licence areas (red and purple) and MPA boundary (green).

Assuming this benefit is constant over 15 years, and using the standard discount rate of 3.5%, means the present value[7] (PV) is estimated at £22.4-£35 million. This result was subject to sensitivity analysis by shortening the licensing period to 10 years. Doing so decreases the present value of the extracted aggregate by 25% to £16.7-£26.0 million.

In addition to this contribution to UK economic activity, the socio-economic impacts of the aggregates extraction from site F would also include employment. The direct employment of 22 assuming it is worked by a single vessel operated by at least two crews (Highley *et al*., 2007) of 11 (Ian Selby, The Crown Estate, pers. comm. October 2011) based in the UK.

Further indirect employment is supported, through jobs associated with the wharves where the aggregates are landed. This was calculated based on an estimated 48 jobs per million tonnes of marine aggregates landed in the UK, resulting in an estimated 28 jobs for site F producing 0.59 million tonnes. Combining the 22 direct and 28 indirect jobs gives an estimate of 50 jobs supported by the operation of the site F.

[7] *This is the total value of all the costs over the assessment period (in this case 15 years) discounted at a rate of 3.5% to reflect society's preference to defer costs to future generations (and to receive goods and services sooner rather than later).*

These socio-economic benefits of the marine aggregates extraction activity were compared to impacts of the licence on other marine activities, through the three interactions defined in the tool (see Figure 8.3).

Interaction 1 is for activities that are generally prioritised above aggregates extraction within marine planning. In the Outer Thames Estuary case study site, maps were scrutinised that confirmed there were no significant interactions for the following activities:

- No currently licensed areas for oil and gas are affected by the potential aggregates licensing area;
- Cables and pipelines in the area are not affected by the potential aggregates licensing area;
- Navigational routes and port authority uses are also unaffected but are close to these areas (see ERM *et al*., 2008, for maps);
- There are some caveats with regard to military exercise areas and munitions dumps which are likely to be on a case by case basis. If conflicts arise between The Crown Estate and the Ministry of Defence with regard to sensitive/restricted areas, it is likely that licensing conditions will reflect any agreement between these parties, and
- There is currently no publicly available information on any potential areas that are currently being explored for the purpose of carbon capture and storage.

Interaction 2 is for marine uses/industries that may be impacted directly or indirectly by aggregates extraction, and involved assessment of impacts on recreation, marine conservation and heritage in the Outer Thames Estuary.

Two main types of recreation that take place are: sea angling and boating. Both of which may incur direct costs related to their displacement due to aggregates extraction. Sea angling intensity and value within the Outer Thames Estuary are difficult to estimate as statistics relating to participation are only available at a relatively high level.

Similarly there are relatively little data on the exact location of boating recreation within the Outer Thames Estuary. Levels of general activity are implied by data from two sources. The Watersports and Leisure Participation Survey (2009), which gives the sailing and yachting participation of UK residents at approximately 3.3% of those that reside within the London, South East and Eastern England. The Charter boat directory, lists the number of registered vessels in Kent, Essex and Suffolk. However, it is not possible to determine an economic value for the impact of the potential licensing area on these activities.

Site F overlaps with a newly designated marine protected area (MPA), and therefore could affect marine nature conservation values. The overlap is shown in Figure 8.5.

Using Geographical Information Systems (GIS) allows calculation of the overlap between the aggregate extraction area and the MPA. There will clearly be an effect on part of the MPA should dredging be carried out within its boundaries or within close proximity to it. Whether this impact is of significance to the conservation of the site or in economics terms is very hard to determine, and would require detailed site level ecological analysis.

The potential licensed area would be subject to checks in relation to both wrecks within/near to site F, along with geological surveys to determine whether the proposed site was one of significant 'archaeological' potential. In the case of the Outer Thames Estuary there are a number of different wrecks across the area (ERM *et al*., 2008) with at least three within the potential licensed area. In this case the protocol established to preserve both wreck and landscape of archaeological potential would expect to be followed. In the absence of quantification of damage and economic value estimates, it is not possible to estimate the economic implication of this potential impact – even when it cannot be avoided.

Interaction 3 is for the fishing and renewable energy provision sectors on which aggregate extraction could impose significant costs and for which it is likely to be easier to find data.

The potential to generate electricity at marine aggregates extraction site relates to waves, tides or currents (wet renewables) and wind power. For site F there is only potential energy generation from wind power.

The potential cost to the wind farm of not being able to generate electricity from the area where it overlaps with site F was calculated. This was based on expected generation capacity for the area involved (taking into account load factors) and a range of the expected price of electricity. It resulted in an estimated present value of £2.9-£4.8 million of electricity generation lost over 15 years. A reduction in employment of approximately 15 jobs during the construction phase of the project was also estimated. An alternative scenario in which the entire wind farm construction was delayed resulted in very large costs (a PV of £1.88 billion) so is not considered realistic.

Analysis of the interaction of site F with fisheries used activity data that had originally been used within analysis for the Margate and Long Sands SAC in 2008. These data are now slightly out of date and so results should be treated with caution.

For the ICES rectangle containing site F, the average value of catches for different types of fishing where calculated and summed. This gave an estimated value of £5,393 per year for the expected catches from the area of active extraction within site F, and £16,210 per year from the whole of the licensed area of site F. Using the ratio of 0.4 reported in JRC (2009) gives an estimated GVA of £2,160 to £6,480 per year, and a PV of £27,000 to £81,000 over a 15 year licensing period.

It should be noted that some of this catch would be expected to be displaced, so the loss of fisheries activity would be less than this. Fish caught within this ICES rectangle but landed in ports outside of the UK are not included within these estimates.

A number of sensitivities can be tested in relation to these figures. Firstly, a 1km buffer zone can be included around the licensing area of site F to account for the increased turbidity caused by active dredging. A 1km buffer was chosen after referring to the impact on sediment transport as discussed in a number of environmental statements produced for marine aggregate areas. This gave an estimated value of £26,320 per year for the expected catches from the area, an estimated GVA of £10,530 per year, and a PV of £131,000 over a 15 year licensing period. These results suggest that the impact of any buffer area is potentially significant. However, it should be noted that assuming fishing is excluded from the whole licensed area and the buffer of 1km is not realistic.

Secondly, the method used to calculate the per km^2 value of all fisheries could be adjusted by excluding areas that are already actively dredged or have other restrictions effectively preventing fishermen from fishing. In the case of the Outer Thames Estuary this recalculation increases results by 2.1%, so is not significant.

As well as these potential direct costs in terms of fish landings, there are possible indirect effects through the impacts of marine aggregates extraction on the marine environment. Firstly, the quality of the fishery may not recover immediately after aggregates extraction ends. To allow for this a recovery period of three years can be added to the calculations. This increases this cost by 13% to a PV of £30,600 to £91,800.

Thirdly, if the aggregates extraction impacts on the life cycle of commercial species, and therefore the availability of fish stocks, this could result in costs that are greater than the current value of landings. Data available for spawning/nursery grounds in the area (provided as part of the EIA) were examined to determine whether site F overlaps with these areas and if so to what extent. The MALSF (2008) provide maps for the nursery areas for several commercial fish species including: herring, mackerel, lemon sole, sandeel, sprat, sole and whiting, plaice and cod and spawning grounds for sole, lemon sole, sandeel and herring.

Site F overlaps with the spawning grounds of lemon sole, sole and sandeels and the nursery areas of herring, mackerel, lemon sole, sandeel and sprat. However, in all cases the spawning/nursery areas affected cover a large part of the Outer Thames Estuary, thus for this case study we assumed that there are no additional stock effects.

If fisheries impacts are potentially significant at a site, more detailed analyses can be carried out. This can use: the COWRIE dataset (ABPmer, 2009) (likely to give a better indication of where fishing effort is concentrated), use data on inshore fisheries from the MMO, conduct a site-specific survey, and contact the relevant authorities including the MMO and harbour masters (these are discussed in the assumptions section but are not considered further within this example).

ICES data can also be used to examine which fish species and which fishing methods have the greatest commercial importance in the area. Socio-economic effects can be examined through estimated the employment supported in proportion to the value of fisheries activity (Seafish, 2007). However, for the an individual site like the hypothetical site F here, the fisheries activity potentially affected equates to less than one job in the sector.

Table 8.1 summarises the socio-economic impacts for site F in the Outer Thames Estuary described above. The table includes all quantifiable estimates of benefit, i.e., the financial gains associated with a new licensing area to the marine aggregates industry; and costs associated with impacts on other marine users along with a comment column where details of employment impacts are given. The table also summarises whether qualitative information is available for any of the sectors analysed and identifies those areas in which conflict at the site level is unlikely to take place.

Conclusions

This chapter has reviewed what socio-economic appraisal methods are and how they can be applied (albeit imperfectly) to the seabed and the services it provides,

Table 8.1 Summary of analysis of a fictitious site F in the Outer Thames Estuary.

Benefits				
Aggregates	**N/A**		**£22.4m-£35m**	**50 jobs**
Costs				
Oil and gas, carbon capture and storage	N	-	-	These uses have overriding priority such that potential extraction areas that conflict with these interests will be filtered out in planning and will not reach the EIA stage.
Military training grounds	N	-		
Navigational routes	N	-	-	
Cables and pipes	N	-	-	
Interaction 2				
Recreation	Y	Y	N	Data can show importance of these activities, but cannot be used to assess impacts of aggregate extraction at site F.
Heritage	Y	Y	N	
Marine Conservation areas	Y	Y	N	
Interaction 3				
Renewable energy	Y	Y	£2.9m-£4.8m	Loss of construction phase jobs.
				Maximum impact of stopping Windfarm development: cost of £1.9 billion, loss of over 6300 temporary jobs considered unrealistic.
Fisheries	Y	Y	£27,000-£81,000	<1 job.

Table 8.2 Table summarising the range of factors that should be considered in the socio-economic appraisal of seabed resources.

Key factors	Guidance
Use data from a range of sources and stakeholders, and be explicitly interdisciplinary.	Ecosystem services thinking improves the links between scientific knowledge and socio-economic outcomes.
Adopt a clear framework to bring together different sources of information in a systematic manner.	The tool described in Section 8.3 provides a suitable option.
Information on the economic value of the marine environment can be generated through a range of valuation techniques.	It is important to understand the nature of these techniques when interpreting the evidence they provide.
Make analysis proportionate to the resources and values in question.	Regional-scale analysis can inform appraisal of different strategic options for resource management. Its results can also guide whether and how much socio-economic analysis of local or site-level decisions is appropriate.
Recognise that socio-economic appraisal of marine resources will face data gaps and therefore will not provide unequivocal answers.	Use it as a tool to input useful information to decision-making.

and to decisions about resource use. This suggests a range of factors that should be considered when using socio-economic appraisal for seabed resources. These are presented in Table 8.2 along with guidance on how to implement them.

The value of applying socio-economic appraisal comes from the way the results of interdisciplinary work can be collated within an economics framework, in particular by using ecosystem services concepts. However, it does take some effort to get the right data at an appropriate spatial scale, and while methods are being applied in practice, there is room for advances in data management and analysis to improve the process considerably.

Appraisal is not just about numerical results and does not make, but contributes to, decisions. It is a process and aims to make the assumptions, information and analysis that go into it transparent and thereby enable stakeholders' interests to be fairly represented. This in turn can help stakeholders engage with one another and negotiate optimal outcomes.

For aggregate extraction the available methods make socio-economic appraisal possible at different spatial scales. As the case studies show, using powerful spatial analysis through GIS, analysis can be undertaken at the level of individual extraction licences. This can help inform decisions over sensitive marine management issues, such as measures to conserve marine protected areas. However, detailed analysis for individual cases may not always be proportionate to the resources at stake, and may miss important factors such as the cumulative nature of impacts across an area of sea. Therefore, socio-economic analysis may be the most appropriate approach to inform appraisal of strategies for aggregates resource exploitation at a regional spatial scale.

More powerful GIS analysis could certainly improve socio-economic analysis further, and as more data become held systematically in GIS tools, the costs of using the methods discussed in this chapter can be expected to fall. Greater spatial organisation of data is also anticipated as a result of more explicit spatial planning of the marine environment, for example due to the recent establishment of the Marine Management Organisation in the UK. This mirrors trends in terrestrial analysis (e.g. of river and forest management) where more specific spatial data are supporting more spatially refined socio-economic analysis and contributing to the understanding and appraisal of environmental impacts across smaller areas to enable decision-making at local scales.

While better spatial data allow greater distinction of impacts on the marine environment, this only supports better socio-economic appraisal if it can be combined with information about how people value different outcomes. As the case studies demonstrate, data availability is very variable for different ecosystem services. The greatest gaps in knowledge relate to values of the non-market benefits society gains from marine resources, both in terms of:

- The supporting and regulating ecosystem services that are essential to, but not fully valued as part of, market goods and services (e.g. providing fish spawning grounds and assimilating pollutants), and
- Individuals' preferences for protection of the marine environment for all the services it provides.

More interdisciplinary primary research is needed in both these areas.

Despite these weaknesses in data, the ecosystem services approach aids appraisal of marine aggregates management decisions. It helps place the impacts involved in context, relative to both the wider provision of the services involved, and the relative scale of one service compared to another. ■

9 REGULATION AND MANAGEMENT

By R.C. Newell, Richard Newell Associates

Introduction

The marine aggregate industry operates within a tight regulatory framework which has been supplemented in recent years by a comprehensive series of industry-led initiatives developed in the UK through the British Marine Aggregate Producers Association (BMAPA) and elsewhere in Europe through the European Dredging Association (EuDA). BMAPA is the trade association for the marine aggregate industry in the UK and represents eleven members who collectively produce about 90% of the marine sand and gravel that is dredged from our coastal waters. The EuDA is the official interface between the European dredging industry and the European institutions.

The main policy drivers for the statutory regulatory regime in the UK include compliance with the OSPAR Convention 1992 and a number of European Directives as well as a raft of recent procedures and regulations initiated through the new Marine Management Organisation (MMO). European regulations that affect the UK marine aggregates industry include the Conservation of Wild Birds Directive (Council Directive 79/409/EEC), the EC Marine Strategy Framework Directive (Council Directive 08/56/EC), the Conservation of Natural Habitats and of Wild Fauna and Flora (Council Directive 92/43/EEC) and the Environmental Impact Assessment Directive (Council Directive 85/337/EEC). Essentially these require a proper assessment of environmental resources that are likely to be affected by infrastructure developments, together with specific proposals on how impacts can be minimised.

Industry-led initiatives include a BMAPA Sustainable Development Strategy, a comprehensive protocol for the reporting and protection of assets of historical and archaeological significance and a series of Regional Environmental Assessment (REA) surveys. These have played an important part in defining resources of conservation significance in areas that are either subject to aggregate dredging, or might be dredged in the future. More recently, and in support of a sustainable development strategy for the industry, BMAPA have launched a Biodiversity Action Plan (BAP) aimed at managing dredging activities so that environmental impacts are minimised and biodiversity is sustained.

The proposals in the BMAPA BAP reflect the significant advances in our understanding of the environmental impacts of dredging that have been achieved in recent years in part through work supported by the Aggregate Levy Sustainability Fund (ALSF) between 2002 and 2011.

The UK Regulatory Regime

The regulatory regime in the UK that is relevant to the marine aggregate industry reflects a number of policy documents including '*Safeguarding our Seas*' (Defra, 2002), and the UK transposition of the EU Marine Strategy Framework. This has recently led to the development of a Marine Policy Statement (MPS) which was published by the UK Government in 2011. The MPS sets out the framework for preparing Marine Plans and taking decisions that affect the marine environment in a more holistic way than had been achieved in the past. It has the aim of contributing to the achievement of sustainable development in the UK marine area from mean high water out to the boundaries of the Exclusive Economic Zone in line with the Marine and Coastal Access Act 2009.

The Marine and Coastal Access Act 2009 received Royal Assent on 12th November 2009. This Act is the key to the UK Regulatory regime and led to the vesting of the MMO in April 2010 which (with the exception of oil and gas projects) now carries out the licensing and enforcement functions on behalf of the Secretary of State for the English inshore region and all English, Welsh and Northern Ireland offshore regions. The regulatory requirements for marine aggregate dredging in England and Wales have been recently summarised by Ware and Kenny (2011).

The regulatory regime ensures that environmental impact assessment includes a wide range of heritage and cultural issues as well as more traditional factors such as potential impacts on living resources of conservation or economic significance and assets of historic and archaeological significance.

Once dredging permission is granted, the licence contains a schedule of conditions that specify mitigation and monitoring measures that are designed to minimise the environmental impacts of dredging. These conditions are site-specific and depend to a large extent on the resources of conservation and economic significance that have been identified in the Environmental Impact Assessment process that is required as a precursor to the application for a licence. A generic set of conditions commonly includes:

- *Pre-dredge monitoring:* This to be carried out after a licence has been granted and before dredging starts (a pre-dredge survey). It allows the pre-dredge conditions to be accurately determined and provides a 'baseline' against which the impacts of dredging can be assessed.

- *Electronic Monitoring System (EMS):* This is installed on all dredging vessels and allows a record of the ship's position while dredging is taking place
- *Operational Monitoring:* This commonly includes assessment of impacts on the bathymetry and benthic ecology of the seabed, as well as to assess impacts on archaeological sites and features.
- *Substantive Reviews:* These comprise a collation and analysis of the operational monitoring data at intervals of 5 years. This is designed to assess the effectiveness of the monitoring that has taken place, and includes recommendations on any variations in the dredging operations and monitoring that might be required better to protect the marine environment.

The impacts of aggregate dredging are thus not only assessed at the EIA stage, but are regularly monitored as part of an environmental surveillance programme that is designed to confirm whether predictions made during the predictive EIA process are valid, and (importantly) to modify the dredging activity if this proves to be necessary. An 'Adaptive Management' approach has thus now been incorporated as an integral part of the new consents procedure.

Regional Environmental Assessment (REA)

One of the difficulties with the Environmental Impact Assessment and licensing process in the past has been that potential impacts have been assessed without a detailed knowledge of environmental resources over a wider area than the immediate licence area and surrounding seabed. Hence it has been difficult to assess the 'context' against which potential impacts should be judged. The fact that several licence applications might be made in adjacent areas by different operating companies has also led to a considerable duplication of effort and difficulty in taking 'in-combination' and 'cumulative' impacts over time properly into account.

The lack of information for wider areas of seabed than individual licence areas has led to support for a series of Regional Environmental Assessment (REA) surveys funded through a consortium of operating companies, and designed to provide comprehensive information on the environmental resources within broad areas of seabed that are likely to be the subject of licence applications. This information then provides a common background against which Environmental Impact Assessments for individual licence applications can be carried out.

A Regional Environmental Assessment document (**www.jncc.defra.gov.uk/pdf/rea framework guidelines_final.pdf**) provides guidance and recommendations on a framework for Regional Environmental Assessments for the marine minerals sector from the perspectives of nature conservation and the historic environment.

An example of the huge amount of data that has been provided through the industry-led REA programmes can be seen on **http://www.eastchannel.info** for the East Channel Association. This association was formed in 2001 voluntarily to commission an REA to investigate the potential cumulative and in-combination effects of dredging in ten licence application areas in the Eastern English Channel, approximately 30km south of Beachy Head. Since then, work has been completed on Regional Environmental Assessments for marine aggregate dredging areas in the Outer Thames estuary (ERM Ltd., 2010), off the East Coast (EMU Ltd., 2012) , the Humber and Outer Wash region (ERM Ltd., 2012) and the South Coast (EMU Ltd., 2012).

Part of the REA project is a commitment to provide a legacy of data for industry and regulators and for this to be placed in the public domain. This new information provides a comprehensive database against which the impacts of aggregate dredging and other impacts of man on the coastal environment can be assessed both now and in the future. It also provides a basis for regional management (including mitigation and monitoring) and avoids duplication of effort for activities taking place in the same sea area.

Biodiversity Action Plan (BAP)

Environmental impact assessment (EIA) has in the past mainly focused on single industries or point sources of disturbance on individual environmental features, rather than on impacts on ecosystem function or on the complex array of organisms (Biodiversity) that comprises natural communities. Complex communities with a large diversity of species are generally regarded as being more stable, and less likely to suffer catastrophic collapse than communities that are represented by relatively few species, even if these occur at high population densities. Larger individuals with a greater stored biomass are also thought to stabilise a given ecosystem over longer time periods with a greater variety of environmental cycles. Hence there has been an increasing recognition that maintenance of both a high biodiversity and a mature population structure is important in retaining the stability of ecosystem function upon which food webs depend.

The UK became the first country to produce a national BAP in 1994, following the Earth Summit held in Rio de Janeiro in 1992. The summit agreed on a programme of 'sustainable development' which meant that the needs of society were

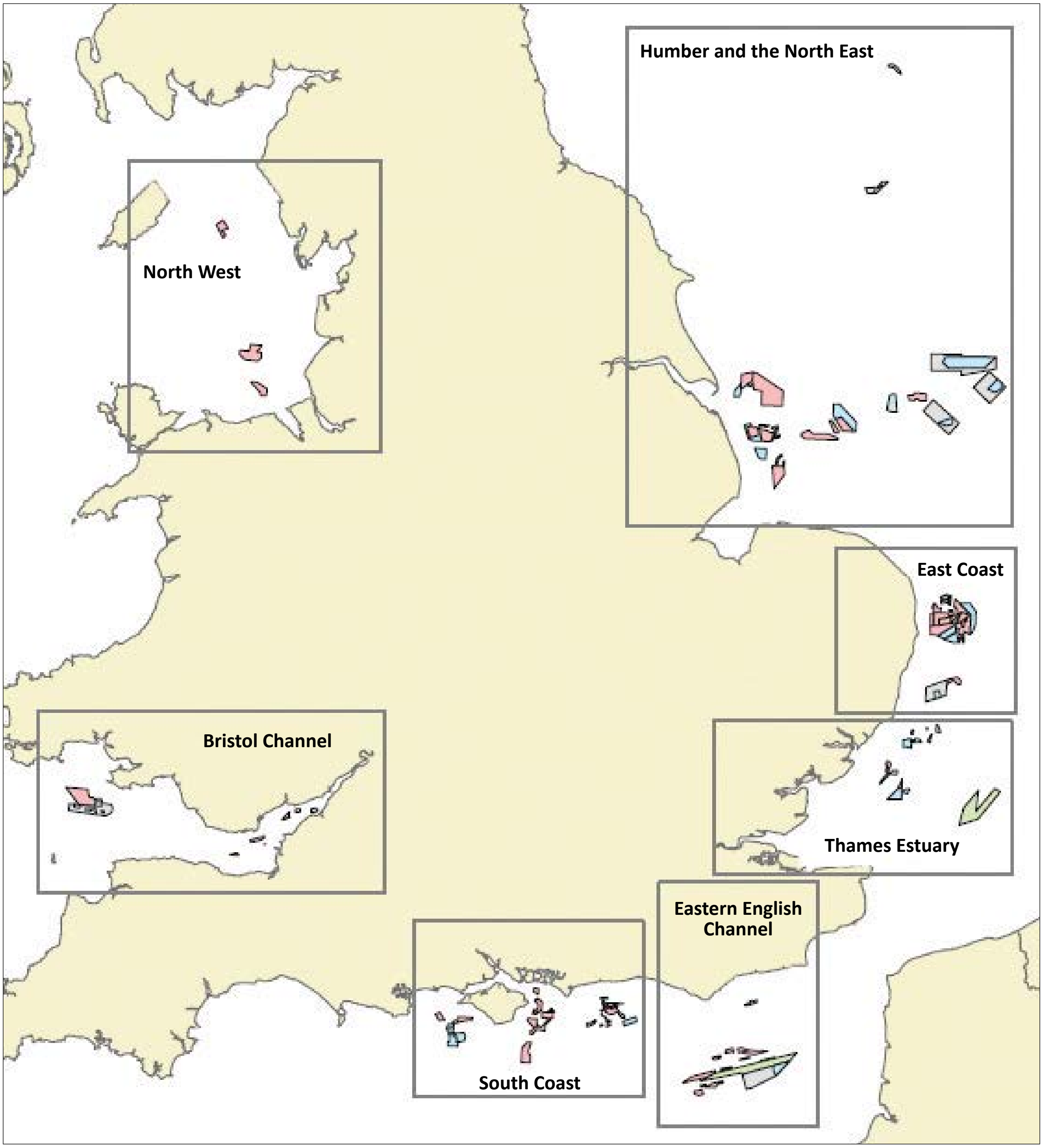

Fig 9.1 Regions for which Biodiversity Action Plans (BAPs) are in the process of development or have been implemented through an initiative by the UK marine aggregate industry. Courtesy of Mark Russell of BMAPA.

met whilst at the same time leaving a healthy and viable world for future generations. The Convention on Biological Diversity that developed as a result of the summit meeting called for national strategies and action plans to identify, conserve and protect biological diversity and to enhance it wherever possible. The management, maintenance and enhancement of biodiversity has since become a central part of approaches to sustainable development and corporate responsibility by both governments and industry.

There have been a number of iterations of the UK BAP, the latest being '*Biodiversity 2020: A strategy for England's wildlife and ecosystem services*' (Defra, 2011). This outlines a biodiversity strategy for the UK over the next decade. It includes a more integrated large-scale approach to conservation on land and sea, putting people at the heart of the biodiversity policy, reducing environmental pressures and improving knowledge. The marine aggregates industry has, through BMAPA, also recently developed a Biodiversity Action Plan that places the needs of the natural environment at the heart of social, economic and corporate development in the sector, thereby enhancing sustainability and best use of natural resources.

The BMAPA BAP strategy document was published in 2011 and aims to establish biodiversity issues within the centre of the Sustainable Development Strategy of the Association. It also aims to provide aggregate producing companies with practical and pragmatic management tools to develop the most sustainable working practices, and to improve the biodiversity management of the industry, based on research and development (R&D) that has been carried out in recent years. This is central to the industry approach to addressing R&D issues and links to Regional Environmental Assessment and regional management programmes.

The BAP sets high-level goals for the UK aggregates industry. These objectives are now planned to be implemented through data collection and analysis of information to assess which of the UK habitats and species of conservation significance occur within each of the seven aggregate-producing areas shown in Figure 9.1, their sensitivity to disturbance and best practice methodology to minimise impacts on the environment.

A detailed Extraction Management Reporting Programme has already been implemented for the East Channel Association and covers multiple aggregate licence areas in the Eastern English Channel. It includes a series of Regional Monitoring Reviews and the results of the East Channel BAP reported in 2010 (see **http://www.eastchannel.info**).

A good deal of the information on the distribution of resources of conservation significance required to inform the regional BAPs for other blocks of licence areas will be drawn from REC and REA surveys, and will be supported by survey and monitoring data for individual licence areas. This information will be combined with the improved understanding of the 'footprint' of impact of aggregate dredging on seabed resources and the nature and rate of recovery processes, to provide appropriate management options for minimising the environmental impact of dredging operations, and to comply with Marine Planning requirements.

Sustainability in Action – Examples of Industry 'Best Practice'.

Reduction of the Carbon 'Footprint' of Aggregate Dredging Vessels

A key part of the Sustainable Development Strategy and BAP for the marine aggregates industry is to translate what we now know of the potential sources of impact on the environment into sound practical management measures to reduce the footprint of aggregate dredging on the environment. One such source of impact is the carbon footprint of dredging vessels from burning fossil fuels during transit to and from the dredge site, and during the dredging operations themselves. Since 2006 the industry has therefore reported total fuel and related Key Performance Indicators (KPI) under its Sustainable Development initiative.

Since the introduction of a Sustainable Development strategy by the marine aggregates industry in 2006, they have reported on a number of KPI's against a series of objectives defined to determine performance in terms of climate change and energy issues.

Against the objective '*Reduce the impact of atmospheric emissions released through the production and transport processes*', the industry reports annually on KPI's for the fuel oil consumed per tonne landed and the CO_2 emissions per tonne landed. Both also include the total consumption/ emissions across the sector – based on data provided by all producing member companies. In 2010, 2.75kg of marine gas oil were required for every tonne of marine sand and gravel delivered to a wharf – equivalent to 8.20km CO_2/tonne.

Against the objective '*Maximise the efficient use of the dredging fleet*', the industry reports on the tonnes landed per km steamed, which includes the total distance steamed by the dredging fleet.

This gives a good indication of the economies of scale of dredging operations – a lorry transporting 20 tonnes over a 40km round trip would result in 0.5t being delivered per km travelled. By contrast, marine aggregate dredging operations are transporting 11.59t/km steamed (based on 2010 data).

This information has now been consistently reported for 5 years, so that changes in the overall performance of the sector can be assessed – both as a result of good practice, but also as a result of changing market conditions (particularly with the recession).

Emissions from shipping have been under scrutiny since the early 1990s with an initial focus on SO_2 emissions and this was followed by pressure to reduce nitrous oxides

Fuel use in kg per tonne of aggregate

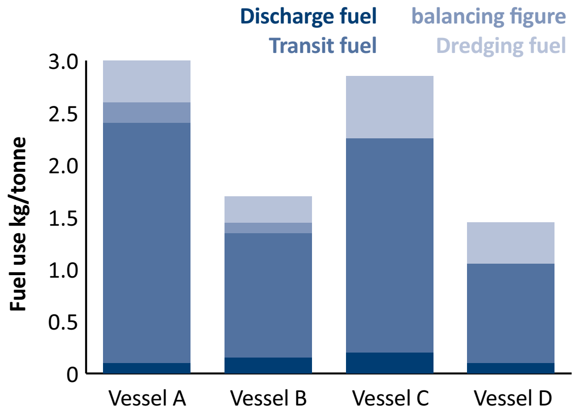

Fig 9.2 Overall fuel use per tonne of product. From Hasselaar and Evans (2010).

Fuel use and transit time

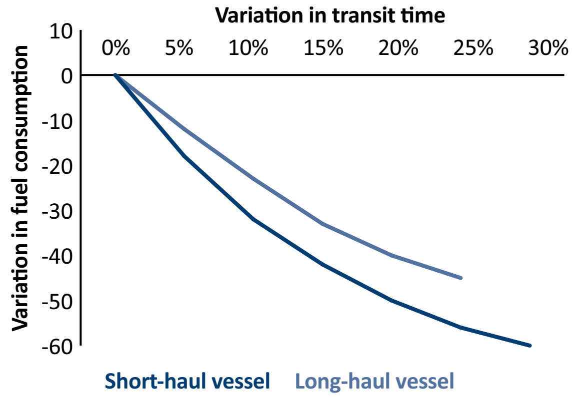

Fig 9.3 Transit versus fuel consumption. From Hasselaar and Evans (2010).

Fuel use and ship speed

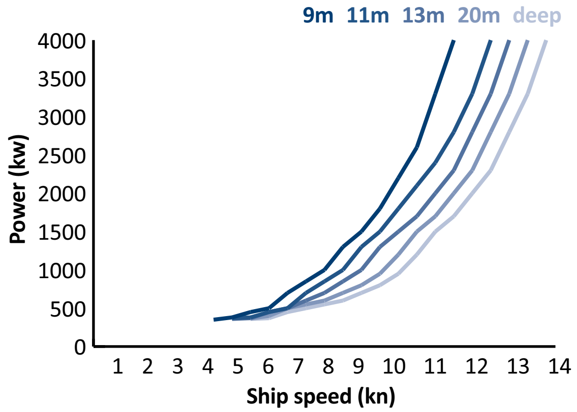

Fig 9.4 Speed and power in shallow water for long-haul vessel. From Hasselaar and Evans (2010).

(NOx) in emissions from shipping. More recently moves have been made to control the CO_2 emissions from shipping following the European Union commitment under the 2005 Kyoto Protocol to reduce greenhouse gas emissions by up to 20% by 2020 and by 80% by 2050. Improvements in ship's performance can make a serious contribution to the reduction of greenhouse gas emissions, and also result in major savings in fuel by operating vessels.

A study by Kemp (2008) has shown that by far the largest amount of fuel used by aggregate dredging vessels is during transit to and from the dredge site. Figure 9.2 shows the fuel use in kg per tonne of aggregate for four different dredgers. It is clear from the histogram that fuel used in transit accounts for 65-75% of the total fuel used during the dredging cycle. Improvement in ship's performance during transit operations is therefore likely to be the most effective way of reducing emissions and saving costs.

A comprehensive analysis of factors that affect dredger performance, fuel consumption and resultant carbon footprint has subsequently been carried out by Hasselaar and Evans (2010) and more recently by Hasselaar *et al*. (2011). They showed that fuel consumption was heavily dependent on ship speed, water depth and roughness of the hull, as well as propeller design. A combination of relatively small changes to the operation of the dredger, especially during transit to and from the dredge site could result in significant reduction in CO_2 emissions and savings on fuel.

Figure 9.3 shows an example of the savings in fuel consumption that can be made by a reduction in ship speed. The speed reductions are expressed as the percentage time loss relative to a benchmark service speed of 12 knots for a larger long-haul dredger (100x19.5 x7.8m) and 11.0 knots for a smaller short haul vessel (67x13.4x4m).

The graph shows that relatively large savings in fuel consumption (and CO_2 emissions) can be made by reducing the speed by a small fraction of a knot – a reduction that would be unnoticeable from the bridge. For example a reduction of speed by a short-haul vessel from 11.0kn down to 10.45kn (5%) results in a reduction in fuel consumption by as much as 17%. Hasselaar *et al*. (2011) point out that a delay of as little as 7 minutes on a 6 hour transit voyage is equivalent to an 8% reduction in fuel consumption and CO_2 emissions.

Water depth under the keel of a vessel also has a significant effect on fuel consumption. Figure 9.4 shows the increase in fuel consumption as a function of ship speed and water depth.

From this it can be seen that in a water depth of only 11m and at a speed of 11.5kn, the fuel consumption increases by about 19% compared with the corresponding fuel consumption in deep water at this hull speed. Observations on operating vessels suggest that it is common practice to decrease speed only slightly, down to 90% of operating power in shallow water as the dredger

Table 9.1 Predicted fuel and CO_2 reduction from in-situ hull cleaning. From Hasselaar *et al*. (2011).

Dredging cycle:		*36h*
Time in transit		*25h*
Fuel usage per cycle (transit)		*10-13 metric tonne*
Fuel price MGO		*960 US/metric tonne fuel (2 Mar 2011)*
Exchange rate		*1 USD = 0.613 GBP (2 Mar 2011)*
CO_2 conversion rate		*3.2 Tonne CO_2/metric tonne fuel*
Hours sailing per year		*7560 (45 weeks per year)*
6 months	*8% saving fuel*	*85 Tonne fuel/2 years*
	CO_2	*272 Tonne CO_2/2 years*
	GBP	*£50,072 Per ship/2 years*
Costs in-situ hull cleaning by divers:		*£10,00 Per ship*

approaches land. The high speed that is maintained results in unnecessary losses of energy. It is clear that operating speeds should be significantly reduced below 90% power in shallow water, provided that other factors such as the 'tidal window' available for the vessel to approach land with a favourable tidal current do not override the advantages of reduced speed.

The hull roughness due to bio-fouling by algae and barnacles, and from damage to the paintwork on the hull can also have a significant effect on the ship performance and energy budget. The hull roughness on the front 25% of the length of the ship from the bow has been estimated to account for about 40% of the total increase in resistance. Hasselaar *et al*. (2011) calculated the costs associated with hull roughness based on a cleaning schedule at intervals of 1.5 years and with a dry-dock frequency of 2 years. The results of their estimates for reduction of fuel consumption and CO_2 emissions from in-situ hull cleaning are shown in Table 9.1.

This indicates that an 8% saving in fuel consumption for a period of 6 months compared with an un-cleaned hull can result in a saving of about 85 tonnes of fuel. This is equivalent to 272 tonnes of CO_2 emissions (equivalent to 2% of the total greenhouse gas emitted per year) and a total saving of £50,000 over a 2 year period. This far outweighs the costs of £10,000 incurred in cleaning the hull and is an obvious option to assist fuel efficiency of the vessel.

Finally, detailed analysis of propeller and operating data for a 100m hopper dredger suggests that a 5-10% saving in power can be achieved by operating the propeller on constant pitch, rather than constant rpm. Fitting of a head-box and nozzle to the propulsion system can result in additional savings of the order of 15-20% in fuel consumption and CO_2 emissions.

This detailed study of the performance and fuel consumption of operating dredgers has thus given valuable insight into how ships can be managed to reduce fuel consumption and greenhouse gas emissions. The sum of the relatively small incremental increases in efficiency reviewed in the project point clearly to a range of strategies to improve operational performance of dredgers, and to greatly reduce greenhouse gas emissions. An improved sustainability of dredging operations can thus be achieved with very little effect on performance and transit times, whilst at the same time reducing operating costs.

Protection of Resources of Historic and Archaeological Significance – Antony Firth

Our understanding of the nature and distribution of resources of historic and archaeological significance has been revolutionised over the past decade in part due to improvements in remote sensing and software for interpreting details of the seabed, and to funding for research funded through the ALSF between 2002 and 2011. This has facilitated the development of sound management practices that are designed to ensure that seabed resources of archaeological and historic significance are appropriately recorded and protected within the framework of a Sustainable Development Strategy for the aggregates industry.

The Marine Aggregates Industry Protocol

As discussed in Chapter 4, marine archaeology has been managed as an integral concern through the MAREA process and through individual EIAs. The principal means of mitigating impacts to the historic environment is through exclusion zones around important or sensitive sites, and the implementation of the Marine Aggregate Industry (MAI) Protocol (Wessex Archaeology, 2011).

The MAI Protocol offers an effective safety-net for dealing with discoveries that first come to light in the course of dredging. All reasonable efforts are made in the course of EIA to identify important, sensitive archaeological features in advance of the dredging licence being granted, so that impacts can be mitigated by exclusion zones or some other method in advance of dredging. However, the marine environment – and our knowledge of what it contains – is such that despite massive improvements in capabilities, it is not possible to identify everything in advance. On land, an archaeological safety net is provided by 'watching briefs' whereby archaeologists stand over plant and machinery, watching for any unexpected archaeological material and recording, recovering or sampling anything that comes to light. In most cases, watching briefs do not offer a reasonable form of mitigation for dredging, because the process is such that the excavated area cannot be seen and there are very few opportunities to examine the dredged material. Watching briefs on 24/7 marine operations may also be disproportionately expensive relative to their likely outcome.

The MAI Protocol has shown that it can offer a practical, effective alternative to continuous watching briefs. Rather than putting archaeologists in place, the MAI Protocol relies on the observations of industry staff within their day-to-day workplace.

The MAI Protocol is also innovative because it was initially introduced in 2005 by BMAPA on a voluntary basis across the whole of the operations of its member companies, who also seek its adoption on non-BMAPA wharves and vessels in their dealings with them. Being industry-wide, the MAI Protocol is not tied to specific areas or licences. Irrespective of the precise legal and management framework governing any ship, wharf or area, industry staff know that the Protocol applies in exactly the same way. Although not dependent on individual licences, most recent licences require implementation of the MAI Protocol as a condition, so it has teeth also. Additionally, by satisfying the MAI Protocol, staff and companies also meet their statutory obligations to report 'wreck' under the Merchant Shipping Act 1995.

Fig 9.5 Participants in the BMAPA/English Heritage/The Crown Estate Protocol Awareness Program. Courtesy of Wessex Archaeology.

There are three principles underlying the MAI Protocol:

- It should be straightforward and unambiguous for industry staff to use;
- Industry staff should be acknowledged for their reports and provided with feedback about what they have found, what they should do next, and how their information will be used;
- Industry staff should be made aware of and kept informed about the Protocol and how best to implement it.

These three principles are given effect through the three main components of the MAI Protocol, which are as follows:

The Protocol itself is set out as a simple hierarchy of actions, with flow charts, that makes clear what each person should do. The Protocol has four main tiers: staff on board or at the wharf; a 'Site Champion' for each vessel and wharf; a 'Nominated Contact' for each BMAPA company; and the archaeologist who deals with the report.

The Protocol is accompanied by an Implementation Service, which hosts the archaeologists who deal with reports. The Implementation Service maintains contact with both the Nominated Contact and with various agencies, including English Heritage, the Receiver of Wreck, local authority Historic Environment Records, the Portable Antiquities Scheme, and The Crown Estate. The Implementation Service also draws on a wide range of specialists in different artefact types, and in finds recording and conservation. Consequently, the Implementation Service ensures a quick response to initial reports, seeks any clarifications that might be necessary, informs the relevant agencies, and provides feedback in the form of a 'wharf report' back to the member of staff who reported the discovery.

Support for the overall operation of the Protocol is provided by an Awareness Programme, which is based around visits by archaeologists to industry staff to introduce them to the operation of the Protocol, to alert them to the range of material that can be discovered, and to provide guidance about recording, photographing, handling and storing their discoveries. Presentations and hand-outs are also made available over the web, and a DVD has been produced for distribution to crews working on dredging vessels. The Awareness Programme is also responsible for the Protocol Newsletter, *Dredged Up from the Past*.

The MAI Protocol has been highly successful. In the first six years of operation, 245 separate reports have been submitted, totalling over 830 individual finds. The discoveries represent a very wide range of material: fossil bones and teeth of mammals that roamed the Continental Shelf hundreds of thousands of years ago; prehistoric flint artefacts; structure, cannonballs and personal items lost from ships of different centuries; aircraft remains from WWII and later; and a range of domestic debris thought to have been dumped at sea. Some of these discoveries have been very important in their own right, as discussed in Chapter 4; other finds are less immediately significant, but the gradual accrual of information reveals broader distribution patterns that are important in regional and licence-specific assessments. Some discoveries have led directly to additional mitigating actions to safeguard sites that still lie on the seabed. Extensive documentation for the MAI Protocol – including details of all the discoveries that have been reported – can be found at: **http://www.wessexarch.co.uk/projects/marine/bmapa/index.html**

The most striking success is, however, the level of engagement with the Protocol exhibited throughout the marine aggregate industry and more widely. There is genuine interest and enthusiasm for finding out about the historic environment at sea from the finds that are made during dredging; and clear acceptance of the responsibility for dealing with the discoveries properly. In wharf reports and newsletters, archaeologists acknowledge the contribution of individuals, wharves, vessels and companies; and many specialists in a wide range of museums and other institutions lend their expertise freely to help identify and understand what is being found. To further recognise best practice, BMAPA awards annual prizes for the Best Find, Best Attitude by a Wharf and Best Attitude by a Vessel. Yet wider recognition was achieved in 2008 when BMAPA and Hanson Aggregates Marine Limited shared the prize for Best Archaeological Discovery at the biennial British Archaeological Awards with Mr. Jan Meulmeester for the Palaeolithic artefacts from Area 240.

Sustainability in Action – A European Perspective

In recent years an increasing number of clients and stakeholders have recognised the importance of sustainable development, which means the adoption of practices that meet the needs of the present without compromising the needs of future generations. As a consequence, environmental and ecological aspects of dredging activities in Europe have become strategic issues of key importance in sustaining markets and securing new ones in the face of competition in a global marketplace.

As a consequence, members of the European Dredging Association have been actively involved in improvement in ship design to provide cleaner and more efficient dredgers that can operate with minimal impacts on the environment. They have also participated in an innovative 'Building with Nature' programme in which the dynamics of marine systems are integrated into the development and design processes for major coastal infrastructure projects.

In this respect the approach has shifted from one where the environment is regarded as a constraint on infrastructure projects to one where natural processes become a driving force behind the project.

The aims of this programme are stated as follows:

*'Building with Nature is a five-year innovation and research programme (2008-2012) carried out by the Foundation EcoShape (**www.ecoshape.nl**). This 30 million Euro program is initiated by the Dutch dredging industry, while partners represent academia, research institutes, consultancies and public parties. The program aims to develop knowledge for the sustainable development of coasts, deltas and rivers by combining practical hands-on experience with state-of-the-art technical and scientific knowledge on the functioning of the ecosystem and its interaction with infrastructures. Key is that infrastructure solutions are sought that utilise and at the same time enhance the natural system, such that ecological and economic interests strengthen each other.'*

A thorough understanding of the hydrodynamics of coastal systems can, for example, assist in the formation of man-made sandbanks and islands that are subsequently maintained and enhanced by natural processes of sediment transport and accretion. Sandbanks and other offshore structures required to minimise coastal erosion can then enhance biodiversity by provision of self-sustaining habitats for marine life. Thus by integrating key disciplines such as engineering, ecology and socio-economic requirements, 'Building with Nature' and other programmes based on a sustainable approach to infrastructure developments give the opportunity to build, whilst using natural processes and ecosystem dynamics to sustain and enhance the local environment (see also Aarninkhof *et al*., 2010).

Developments like the UK industry BAP and the 'Building with Nature' programme, which are based on the principles of environmental sustainability, are in their infancy. Corporate responsibility and accountability for protection of the environment by the aggregate dredging industry is, however, likely to form an increasingly important component of the 'Life-Cycle Analysis' that is now a significant factor in the selection of raw materials by clients in the construction industry. There is therefore no doubt that programmes designed to enhance biodiversity and minimise impacts on the environment will become a driving force behind the continued successful development of the marine aggregate dredging industry both in the UK and in continental Europe. ■

10 CURRENT UNDERSTANDING AND FUTURE DIRECTIONS

By R.C. Newell, Richard Newell Associates

Recent research, (particularly that funded through the marine Aggregate Levy Sustainability Fund (ALSF) between 2002 and 2011, and through the industry-led Regional Environmental Assessment (REA) programme) has resulted in a greatly improved understanding of the nature and extent of impacts of aggregate dredging on resources of conservation and economic significance in the coastal waters near to aggregate dredging sites.

In particular we highlight the following key areas where recent research has assisted in providing a sound evidence-base upon which advice to both regulators and management can be given:

Importance of the Receptor

A key issue in the Environmental Impact Assessment (EIA) process is to have a thorough understanding of the nature and distribution of environmental resources of conservation and economic significance. This has been severely hampered in the past by the fact that the most detailed information available for seabed resources was mainly restricted to surveys over a relatively small area of seabed carried out for specific licence application areas. Thus whilst we had detailed information for isolated survey areas, there was very little information on the context or 'significance' of those resources in relation to those in the surrounding seabed.

The Regional Environmental Characterisation (REC) surveys supported through the ALSF and the industry -led Regional Environmental Assessment (REA) surveys have significantly improved our knowledge of the nature and distribution of environmental resources over relatively wide areas of seabed that are currently under licence for aggregate dredging or may be so in the future (see **http://www.cefas.defra.gov.uk/alsf.aspx**).

As a result of this work we now have an improved understanding of the nature of the seabed deposits and underlying geology and its relation to biotope composition, as well as greatly improved information on resources of archaeological and historic potential on the seabed (see Chapter 4).

The Nature and Significance of Impacts

A second key issue in the Environmental Impact Assessment (EIA) process is the need for an understanding of the nature and scale of potential impacts from aggregate dredging. Recent research reviewed in this book points to the following common features of the impacts of aggregate dredging:

- Removal of the seabed sediments can result in a significant loss of benthic fauna, depending mainly on the intensity of dredging within the licence area. Overall losses from an Active Dredge Zone (ADZ) can result in a 40-80% reduction in population density and biomass of benthic invertebrates within the very small area of seabed that is under the path of the draghead.
- Removal of coarse material from the deposits and return of excess sand during the screening process results in a progressive fining of the seabed deposits, which therefore become sandier over time in the immediate vicinity of the Active Dredge Zone.
- Impacts on sediment composition can extend outside the boundary of the dredged area as material mobilised by the dredging process is carried by seabed currents along the axis of sediment transport. Most studies show that even in areas of strong seabed transport, the 'footprint' of sand deposition does not extend beyond 2-3km from the site of initial deposition in the vicinity of the dredger. This gives some information on the size of an 'exclusion zone' that might be required if resources of particular conservation or sensitivity are located near to a proposed aggregate dredge site.
- A change in sediment composition from coarse sandy gravels towards sandier deposits is reflected in changes in the community composition of the benthic fauna. Commonly there is a reduction in species diversity and an alteration in species composition in sandy deposits compared with mixed sands and gravels.
- Where the deposits are loaded as an 'all-in' cargo, without excess sand being returned to the seabed during the screening process, the evidence to date suggests that the footprint of dredging is strictly confined to the ADZ itself, with little or no impact outside the boundaries of the dredge site.
- We also have an improved understanding of the effects of dredging on scouring and deposition processes on the seabed and this has allowed a better definition

of the size of 'exclusion zones' that may be required around seabed features such as reefs and wrecks of conservation significance.

Recovery of Seabed Resources

One characterising feature of the seabed environment is that it is regularly disturbed by waves and currents, as well as by episodic events such as storms. The biological communities that inhabit the sands and gravels that are dredged for aggregates are well-adapted to recolonise and recover following disturbances of this kind. Recent research reviewed in this book suggests that there are some common patterns in the recovery process:

- If the deposits remain similar in composition following cessation of dredging to those in the non-dredged parts of the licence area, then recovery of a similar community is likely by recruitment and settlement from the plankton and by lateral invasion of mobile species. Some species can initially colonise within weeks or months, but others which have a less mobile colonising phase may take much longer. Recovery of the biomass of organisms depends on the growth rate of component species. In some cases recolonisation is intermittent and growth rates are slow, leading to a 'recovery' time of several to many years, but most common components of the seabed community of sands and gravels can recolonise and grow to maturity well within this time.
- If the deposits become sandier within a dredge site due to the removal of coarse gravels and return of sand to the seabed, then the animals capable of colonising the deposits will be different from those which originally inhabited the deposit of mixed sand and gravel. This can be a quasi-permanent change in seabed sediment composition and associated biological community within the relatively small area of seabed that lies within an ADZ.
- In some sites where seabed currents are strong, the recently-deposited surface sand can be removed or 'winnowed' away leaving the coarser deposits exposed on the surface of the seabed. This provides a potential mechanism for 'recovery' of the physical features of the substrate over time, and the potential for recolonisation by organisms more typical of coarse mixed sands and gravels. This is likely to be a long-term process and has not been well-documented in surveys to date.
- Studies on potential remedial options such as laying of shell 'culch' or of gravel 'seeding' to promote the growth of gravel communities at sites that have become sandier following aggregate extraction have resulted in some enhancement of communities typical of coarse deposits, but the costs are very high and are likely to be prohibitive for a relatively low-value product such as sand and gravel.

Best Use of Data

Recent work reviewed here has highlighted the value of surveys that provide information on seabed resources over a wider area than is required by just the marine aggregates sector. Quite apart from their importance to the aggregate sector itself, information gained through the REC and REA programmes provides important information for infrastructure projects such as offshore renewable energy structures, cables and pipelines and help to provide a robust evidence-base for management of the seabed around our coastline.

The work supported through the ALSF has also shown the value of the data gathered for multiple uses including analysis of seabed sediments and associated biotopes, identification of historic wrecks and potential ancient land surfaces of archaeological significance. The principle of 'gather once, use many times' can result in significant savings on ship time and associated costs when offshore surveys are carried out with multiple use of the data in mind. Experience gained through the REC and REA programmes provides an important lesson in the value of science-led research which is both flexible and capitalises on the best use of data that can be used for multiple end-products.

Areas of Uncertainty

The recent work that has been summarised in this book illustrates the value in understanding the nature and scale of impacts of aggregate dredging on the marine environment, but also points to gaps and uncertainties in our knowledge which to some extent limit our ability to manage multiple uses of the marine environment. We are able, for example, to make some realistic predictions on the nature and extent of impacts from individual licence areas, but can be much less certain of how the impacts from one licence area interact with potential far-field impacts from adjacent sites and over time. 'Cumulative' impacts of this type are difficult to study partly because biological communities on the seabed undergo regular (and often abrupt) changes over time in response to episodic disturbance even in the absence of dredging activities. The situation is further complicated by the 'in-combination' effects of other activities such as the use of heavy bottom gear by commercial fishing vessels, so that it is often difficult to distinguish the potential long-term impacts of aggregate dredging on seabed communities from natural, and other sources of disturbance.

We have even less information on the 'ecosystem function' performed by different types of communities on the seabed and the extent to which changes in community composition in the small areas that are dredged might have on nutrient cycling, carbon flux and the food webs leading to commercially exploited fish stocks and higher trophic levels in the food web including seabirds and mammals. These areas are much more difficult to investigate and interpret yet they remain of central importance in assessing the effects of the many pressures that our coastal seas are likely to experience in the future.

The ALSF programme achieved a remarkable amount in the period between 2002 and 2011 when the fund came to an end. It illustrates the value of highly-targeted science-led research aimed to resolve clearly-defined issues related to marine aggregate dredging.

The definition of key priority research themes has been assisted by a close interaction between representatives from the industry, regulators and their scientific advisors and by rigorous insistence on genuine practical and useful outcomes from the projects that were supported through the ALSF. The outputs of this work are all in the public domain, and the original research data is also available free of charge for use by Third Parties.

Reports of all projects funded through the MEPF can be accessed at the following website: **http://www.cefas.defra.gov.uk/alsf.aspx** and those for archaeology through the Archaeology Data Service (**http://archaeologydataservice.ac.uk**). A search engine that assists in identifying relevant projects can be accessed at **www.marinealsf-navigator.org.uk**.

The research is necessarily complex and technical. We hope that this summary and review of some of the key results of the marine ALSF programme and associated work supported through the industry and other sources will assist the non-technical reader in an understanding of the huge variety of resources that surround our coastline, and the efforts that have been made by UK marine scientists to understand and protect them for future generations. ■

GLOSSARY

The reader is referred also to 'Marine Aggregate Terminology: A Glossary' by The Crown Estate and the British Marine Aggregate Producers Association (BMAPA), 2010. ISBN: 978-1-906410-13-1. 93pp.

Accretion – The accumulation of material on the seabed or shore.

Acoustic Backscatter – A form of image commonly obtained with an Acoustic Doppler Current Profiler (ADCP) and used to detect changes in salinity, current speed and suspended solids in the water column.

Active Dredge Zone (ADZ) – A zone within a licence area that is intensively-dredged to exhaustion before being left to recover whilst the dredger moves to another ADZ.

Active-Passive Recovery – The process of leaving dredge sites to recover by natural processes after cessation of dredging, rather than by active intervention.

Adaptive Management – The management of dredging activities based on the results of operational monitoring, and allowing dredging to be adapted to minimise environmental impacts.

Aggregates – A mixture of sand, gravel, crushed rock or other bulk minerals used in construction and civil engineering.

Aggregate Levy – A tax imposed on the sale of primary aggregate resources.

Aggregate Levy Sustainability Fund (ALSF) – A fund that used a proportion of the money generated by the Aggregate Levy to reduce the environmental impacts of the extraction of aggregates, both on land and from the sea, and to deliver benefits to areas subject to these impacts.

Algae – Plants that can be either large Macrophytes ('seaweeds') that are attached to rocks and stones, or microscopic plants (Diatoms) that comprise the phytoplankton confined to the water column.

All-In Cargo – A cargo of aggregate that is loaded into the hopper without the need to adjust the gravel:sand ratio by screening.

Anchor Dredging – Dredging activity usually undertaken over thick, spatially constrained aggregate deposits, whereby the dredging vessel remains stationary.

Anthropogenic Disturbance – Disturbance of the environment by Man, as opposed to natural events.

Anticline – Folded rocks where the oldest strata are in the middle of the fold structure.

Artefacts – Objects of historic or archaeological significance such as from wrecks or at sites occupied by early man.

Ascidians – Soft-bodied animals that include sea-squirts.

Barnacles – small crustaceans encased in a calcareous shell, usually attached to rocks and shells on the seabed.

Baseline Monitoring – Surveys designed to define environmental conditions and resources in an area prior to disturbance by Man.

Bathymetry – The depth and topography of the seabed, usually measured from the sea surface.

Beach Drawdown – the loss of beach material by wave and current action to replace material removed from the seabed offshore.

Beach Replenishment (Beach Nourishment) – The process of placing new sediment onto beaches to replace sediment lost through erosion.

Beam Trawl – A trawl that is held open by a beam – commonly used for fish and shellfish on the surface of the seabed and in near-surface sediments.

Bedform – Sand sheets, ribbons and sand waves on the seabed.

Bedload – The sediments that are transported at the seabed by waves and tidal currents.

Benthic Fauna – Animals that live on the seabed, both on the surface (benthic epifauna) and within the deposits (benthic infauna).

Benthic Boundary Layer – A zone of elevated suspended solid concentrations at the sediment-water interface caused by sediments mobilised by the dredging process and transported by seabed currents.

Benthos – The community of animals and plants that live on the seabed.

Biodiversity – The range of species that characterise a particular community or habitat.

Biodiversity Action Plan (BAP) – A plan to protect and enhance biodiversity in regions that are subject to disturbance by Man.

Biogenic Reefs – Reef structures that are formed by organisms such as mussels, Ross worm, serpulid worms and maerl. They form biotopes of considerable complexity that can support increased biodiversity and population densities compared with more uniform sandy deposits.

Biological Traits – The sum of a number of characteristics of an animal such as body size, mobility, feeding guild, fecundity and other features which affect its ecological function within a biotope.

Biomass – The mass (weight) of organisms in a community.

Biotope – The distinctive community of interdependent organisms that characterise a particular habitat type.

Biotope Mapping – The geo-referencing of distinct biotopes (or habitats) on the seabed.

Bivalves – A group of molluscs that includes oysters, scallops and clams.

BMAPA – The British Marine Aggregate Producers Association – the trade organisation for the marine aggregates industry and part of the Mineral Products Association.

Boomer Sub-Bottom Profiler – Equipment that emits a seismic (acoustic) signal used to survey sub-seabed sediment and rock structures.

Borrow Site – An area of seabed from which deposits are removed to replace those lost elsewhere, such as for coastal defence schemes.

Bottom-Up Biotope Classification – A system of biotope classification in which the living communities are matched with environmental variables and then used to define biotopes.

British Marine Aggregate Producers Association (BMAPA) – The representative trade body for marine aggregate producers in the UK.

Byssus Threads – Threads secreted from the foot of bivalve molluscs such as mussels to attach themselves to the substrate.

Capital Dredging – Removal of sediment from the seabed as part of an engineering or navigational project, usually for a port development or approach channel.

CBI – Cost Benefit Analysis: an analysis of the benefits and costs of an option.

CEA – Cost Effective Analysis; an analysis of the costs of alternative ways of producing an outcome.

CEFAS – The Centre for Environment, Fisheries and Aquaculture Science. Statutory scientific advisors to the regulator (the Marine Management Organisation).

Clamshell Grab – A large grab commonly used by the dredging industry to obtain a representative sample for evaluation of the quality of aggregate resource on the seabed.

Coastal Impact Study (CIS) – A study (often using mathematical models) used to predict the impacts of dredging and infrastructure developments on coastal processes such as waves, sediment transport and coastal erosion.

Cohort Analysis – Analysis of the frequency of occurrence of different-sized individuals in a population to estimate growth rate, age and recruitment.

Colonial Organisms – Organisms produced asexually and which remain attached to one another to form a colony.

Communities – The assemblage of animals and plants that live in a particular habitat.

Community Composition – The biodiversity, population density and biomass of animals and plants that comprise a biotope.

Computation Fluid Dynamics (CFD) – A mathematical modelling tool used to predict changes in water flow, sediment suspension and deposition at the seabed.

Concrete – Construction material made through the combination of cement, sand, gravel and water.

Consent Process – The regulatory process by which consent for a dredging licence is obtained.

Crustaceans – Shellfish such as crabs, lobsters and prawns.

Cumulative Impacts – The impacts of multiple activities in combination or impacts over time.

Cypris Larva – The late larval stage of a barnacle prior to settlement from the plankton.

Data Corruption Zone – The zone at the sediment-water interface where interference at the seabed may mask the turbidity plume from acoustic backscatter methods.

Debris Field – An area of seabed where material from a wrecked vessel is scattered.

Defra – The UK Government Department for Environment, Food and Rural Affairs.

Deposit-Feeders – Animals that feed on particulate organic matter deposited on the seabed or within the deposits.

Dog Cockle – The common name for the bivalve *Glycymeris glycymeris* which is a long-lived and slow growing component of gravel communities.

Draghead – Equipment on the end of suction pipe (dredge pipe) that is in contact with the seabed during dredging.

Dredger – A generic term describing a ship capable of removing material from the seabed.

Dredging Footprint – The area of seabed that is affected by dredging

Dredging Intensity – The frequency that a particular area of seabed is dredged.

Dynamic Plume – The phase of discharge where material is forced to the seabed by the speed of overboard discharge.

Echinoderms – Animals such as starfish, sea urchins and sea cucumbers.

Ecosystem – A community of organisms and their wider physical environment acting as an ecological unit.

Ecosystem Function – The functions performed by an ecosystem such as carbon capture, nutrient cycling.

Ecosystem Services – Ecosystem functions that are of perceived value to Man.

Electronic Monitoring System (EMS) – A monitoring system aboard a dredger that records the position and activity of the vessel to ensure that dredging is only undertaken within permitted zones.

Emergence Tube – The delicate tube formed by Ross worm (*Sabellaria spinulosa*) during the process of emergence to the surface of deposits after burial.

English Heritage (EH) – the Statutory Body responsible for the historic environment in England.

Environmental Impact Assessment (EIA) – An assessment of the environmental resources, their sensitivity to disturbance and proposals to minimise impacts as required under the EU Environmental Impact Directive.

Epifauna – Animals that live on the surface of the seabed either attached to the surface of boulders and stones, or as mobile animals that feed at the surface of the seabed.

Equilibrium Species – Organisms with a slow rate of growth and reproduction that are often controlled by complex interactions with other species in the community.

European Dredging Association (EuDA) – The official interface between the European dredging industry and the European institutions.

Exclusion Zone – A zone surrounding a feature of conservation significance (such as a wreck) within which dredging is not permitted.

Fecundity – The abundance of eggs and larvae produced by a species.

Feeding Guild – The type of feeding that characterises an animal – such as filter-feeder, deposit-feeder, or predator.

Filter-Feeders – Animals that feed by filtering suspended particulate matter from the water column.

Fines – fine-grained particles such as sand and silt discharged or mobilised by the dredging and screening process.

Fishing Effort – A measure of the type of fishing gear and man-hours spent catching fish. Catches are commonly expressed per unit of fishing effort to compare the yields for different fishing activities.

Fluvial deposits – Marine aggregate that was deposited by a river associated with a former land surface and now submerged.

Food Web – A term used to describe the food relationships between members of a community.

'Footprint' – The area that is affected by an activity such as aggregate dredging.

Gastropod – A group of molluscs that includes the snails.

Genus – The taxonomic discrimination comprising the first half of the scientific name of an organism.

Geogenic Reefs – Reef structures that are of geological origin (cf. Biogenic Reefs).

Geomorphology – The nature and topography of the seabed.

Geophysical Surveys – Surveys of the seabed using remote sensing equipment to define the physical and geological properties of the seabed.

Geo-Referenced Charts – Charts where the distribution of marine resources and potential anthropogenic pressures are superimposed as layers on a GIS chart to assess potential conflicts of seabed use.

Glacial deposits – Marine aggregate that was deposited by a glacier or ice sheet.

Glacial maximum – A period when polar ice sheets reach their maximum extent – often referred to as an 'Ice Age'.

Global Information Systems (GIS) – the recording of geo-referenced data as information 'layers'.

Global Positioning System (GPS) – A method of determining geographical position using satellite signals. Differential GPS (dGPS) is an accurate form of geo-positioning system.

Grab Sampling – A survey method used to acquire data describing the character of the seabed and the resident organisms using a mechanical grab system.

Gravel – Sediment with a particle diameter of 2-64mm on the Wentworth Scale.

Gravel Seeding – The process of depositing coarse gravel material on the surface of deposits where these have become sandy after cessation of dredging.

Ground-Truthing – The acquisition of a sample of seabed to inform the results of a geophysical survey.

Growth Ring – A method of estimating the age of an organism based on annual variations in growth.

GVA – The Gross Value Added: added value of outputs of goods and services from an activity compared to inputs

Habitat – The physical features of the environment in which animals and plants live.

Habitat Restoration – The process of actively changing the physical features of the habitat to promote enhanced biodiversity after cessation of aggregate dredging.

Hamon Grab – A type of grab that takes a quantitative sample of seabed sediment for analysis of particle size composition and associated biological community composition.

Hastings Shingle Bank – A site of coarse gravels off the south east coast of England that is of importance for gravel extraction as well as for a brown crab fishery and other targeted fish species.

High Energy Environments – Sites that are disturbed by strong currents or wave action.

Honeycomb Worm – A tube-dwelling worm (*Sabellaria alveolata*) that generally occurs on the shore, and occasionally in the sub-tidal zone where it is replaced by the related ross worm (*S.spinulosa*).

Hopper – The area within the hold of a dredger that aggregate is loaded during dredging.

Hydrodynamics – The wave, tidal and current regime.

Hydrothermal Vents – Sites on the seabed where volcanic activity results in the emission of hot mineral-rich material that can provide an energy source from hydrogen sulphide which fuels a food web that is independent of sunlight and photosynthesis by plants.

Hydroids – Colonial and solitary polyps that live in tubes attached to the seabed.

ICES – The International Council for the Exploration of the Sea.

Infauna – Burrowing or tube-dwelling animals that live beneath the surface of the seabed.

Interglacial Period – A relatively warmer period between glacial maxima ('Ice Ages').

Invertebrates – Animals without backbones – worms, shellfish and starfish etc.

InVEST – Integrated Valuation of Ecosystem Services and Trade-offs.

King Scallop – The common name for the large scallop *Pecten maximus* which lives on the surface of gravel deposits.

JNCC – The Joint Nature Conservation Committee.

Knot – A unit of ship's speed roughly equivalent to miles per hour, but measured in nautical miles per hour (I nautical mile equals 1 minute of longitude – a feature that is central to celestial navigation).

Licence – The legal commercial agreement whereby the landowner grants permission to a dredging company to extract aggregate from a prescribed area of seabed. Aggregate licences are granted through The Crown Estate.

Licence Area – The area of seabed within which aggregate extraction is permitted.

Lithology – The chemical and geological nature of the particles that comprise sediments.

Macrofauna – Animals generally larger than 1mm body diameter.

Macrophytes – The larger seaweeds that are attached to rocks and stones on the seabed.

Maerl – Seabed deposits formed from fragmented calcareous algae that reproduce vegetatively and can for complex reef-like structures.

Magnetic Anomaly – A change in the magnetic field caused by an object made of iron and detected by a magnetometer towed behind a survey vessel.

MALSF – The Marine Aggregate Levy Sustainability Fund. A research fund delivered through Defra aimed at improving knowledge of the impacts of marine aggregate dredging, and reduction of environmental impacts: www.cefas.defra.gov.uk.

MALSF Navigator – A search tool available to assist location of reports and data available through the MALSF.

MAREA – Marine Aggregate Regional Environmental Assessment (see also REA).

Marine Aggregate Industry Protocol – A protocol for reporting finds of archaeological interest, developed through the British Marine Aggregate Producers Association (BMAPA). The Crown Estate and English Heritage.

Marine Transgression – A warmer period in the geological cycle (inter-glacial period) when sea levels rise.

Marine Management Organisation (MMO) – From April 2010 this organisation now carries out the licensing and enforcement functions (with the exception of oil and gas projects) on behalf of the Secretary of State for the English inshore region and all English, Welsh and Northern Ireland offshore regions.

MCA – Multi-Criteria Analysis: a set of criteria developed to compare different policy options.

MCZ – Marine Conservation Zones.

Marine Protected Areas (MPAs) – A conservation designation that includes Marine Protected Areas (MPAs), Marine Nature Reserves (MNRs), Marine Conservation Zones (MCZs), Special Areas of Conservation (SACs) and Special Protected Areas (SPAs).

MPS – Marine Policy Statement.

MSFD – The Marine Strategy Framework Directive.

MEPF – The Marine Environment Protection Fund. A part of the Marine Aggregate Levy Sustainability fund that was administered through Cefas: www.cefas.defra.gov.uk.

Megaripples – Small sand waves on the seabed.

Metocean Surveys – Oceanographic surveys that are combined with meteorological data.

MEA – Millennium Ecosystem Assessment.

MIRO – The Mineral Industry Research Organisation.

Mitigation Measure – Measures taken to reduce the environmental impact of an anthropogenic activity such as aggregate dredging.

Molluscs – A large phylum of animals that include bivalve shellfish, snails and squid.

Monitoring Programmes – Surveys designed to define environmental conditions and biological communities during and after disturbance by man. These are increasingly part of the conditions attached to the Consent for aggregate extraction and form the basis for assessing impacts and potential remedial action.

Moraine – deposits accumulated either at the sides (lateral moraines) or the end (terminal moraines) of a melting glacier.

Multibeam Sonar – A method of bathymetric survey in which multiple sonar signals are used to measure water depth at multiple points across a swathe of seabed.

Multidimensional Scaling (MDS) – A statistical method that illustrates the similarity between communities in space and time.

Multivariate Analysis – A statistical procedure that compares the similarities and differences between communities using many different features including the number of species, population density and biomass.

Multi-Variate Index – An index of community composition based on several combined attributes of community composition such as biodiversity, population density, biomass, body size and feeding guild.

Mussel Beds – Communities of the blue mussel (*Mytilus edulis*) or horse mussel (*Modiolus modiolus*) that can form a dense covering on the seabed and provide a complex biotope that is available for other species.

Natura 2000 – A European network of Special Areas of Conservation (SACs), Special Protected Areas (SPAs) and other protected sites.

Nauplius – The early stage larva of Crustacea such as shrimps and barnacles.

NGO – Non-Governmental Organisation.

Niche – A micro-habitat within a biotope that may provide special conditions for a distinct species or group of animals.

NMR – The National Monuments Record. Amongst other data the NMR contains details of shipwrecks on the seabed.

ODPM – Office of the Deputy Prime Minister (now replaced by the Community and Local Government (CLG) Department.

Operational Monitoring – Monitoring of the physical and biological features of a dredge site to ensure that environmental impacts are controlled and minimised.

Opportunistic Species – Small fast-growing organisms with a high rate of growth and reproduction that rapidly recolonize deposits after disturbance.

Optically-stimulated Luminescence (OSL) – A method of dating material obtained in seabed samples.

Overflow Spillways – Openings at the top of the cargo hopper that allow excess water and suspended sediment to flow back into the sea during cargo loading, thus maintaining stability of the dredger.

Overspill – The water and sediment released from the spillways as the hopper fills during dredging.

Palaeo-channel – A channel formed by an ancient river system.

Passive Plume – The phase of a plume discharged from a dredger when natural dispersion by gravity, waves and tidal currents occurs.

Pelagic Organisms – Organisms that live in the water column as opposed to those that live on the seabed (benthic organisms).

Permafrost – Frozen soil in polar regions that are subject to permanently frozen conditions.

Photosynthesis – The process by which plants convert carbon dioxide to complex sugars using energy from the sun.

Phylum – A major taxonomic group of animals or plants such as Echinoderms, Crustaceans and Molluscs.

Physical Recovery – The restoration of seabed features such as bathymetry and particle size composition of deposits after cessation of dredging.

Plankton – Small animals (zooplankton) and plants (phytoplankton) that drift in the surface waters of the sea.

Plume – The visible material settling to the seabed following discharge from a dredger.

Plymouth Routines in Multivariate Environmental Research (PRIMER) – a widely-used software package used to analyse community composition and identify characterising species.

PMRA – Protection of Military Remains Act.

Polychaete Worms – A group of marine worms with numerous bristle-like chaetae.

Population Density – The number of organisms in a community.

Population Dynamics – The attributes of a population that allow estimation of the rate of recolonisation, growth and restoration of biomass.

Present Value (PV) – The total value of all the costs over the assessment period.

Primary Components – Those members of a community that are directly dependent on the physical features of the habitat for their occurrence.

Primary Impacts – Immediate impacts of dredging on environmental resources under the footprint of the drag-head within the Active Dredge Zone.

Pseudofaeces – The silt-like material filtered from the water column by suspension-feeding molluscs like mussels and rejected prior to ingestion. This material can form a thick silt layer that forms part of a mussel bed biotope.

Pycnogonids – A group of sea spiders that are commonly found attached to hydroids and other sessile epifauna.

Quantitative – Factors that can be measured in a precise way, in contrast to qualitative factors that can only be measured in a more subjective way.

Quaternary Period – The second period of the Cenozoic Era, from the end of the Tertiary Period through to the present – including the Pleistocene and Holocene periods during which humans first appeared.

Queen Scallop – The common name for the bivalve *Aequipecten sp*. which often occurs in large numbers on the surface of gravel deposits.

Recolonisation – The process of restoration of biodiversity by settlement of algal spores, larvae or by mobile animals in areas of the seabed where disturbance by Man has ceased.

Recovery – The time required for a community to regain a similar community composition to that present prior to dredging. Note that there a several views on how ‘recovery’ should be defined in a system that is subject to major change in biodiversity and population density over time in the absence of disturbance by Man.

Recruitment – The colonisation and successful subsequent growth of organisms in a particular habitat.

Reefs – Geological (bedrock reefs) or biogenic structures that are distinct from the surrounding deposits and which provide a hard substratum and complex habitat compared with the surrounding seabed.

Reference Site – An area that remains undisturbed and serves as a comparison with sites that have been impacted by dredging.

Regional Environmental Assessment (REA) – A process by which the potential cumulative and in-combination effects of regional marine aggregate extraction proposals are investigated.

Regional Environmental Characterisation (REC) – A survey to broadly describe the nature of the seabed habitats and associated species that exist within a region.

Rehabilitation – The recovery and restoration of seabed sediments, topography and biological communities.

Relict deposits – Sediment deposited by processes, and under physical conditions that no longer exist. They are also known informally as fossil sediments.

Remediation Works – Works that are carried out to restore a habitat after disturbance by episodic environmental events or the impact of Man.

Remotely Operated Vehicle (ROV) – Self-propelled survey equipment controlled from a ship and used for underwater imagery and to obtain samples.

R&D – Research and Development supported by Government and industry.

Revealed Preference Methods – Methods of valuation of ecosystem services using observations of human behaviour.

Risk Assessment – A formal process in which the nature and scale of potential impacts by Man are assessed against the distribution and vulnerability of living resources.

Ross Worm – The common name for the tube worm *Sabellaria spinulosa* which can form biogenic reef structures and crusts on the seabed.

Sabellid Worms – Worms that live in a tube in the deposits and filter food from the overlying seawater through a crown of feathery tentacles.

Sabellaria spinulosa – a worm that builds a tube from sand grains and which can form a 'biogenic reef' from dense aggregations of tubes. See also Ross Worm.

SACs – Special Areas of Conservation designated under the EU Habitats Directive.

SPAs – Special Protection Areas designated under the EU Habitats Directive.

Sand – Sediment with a particle diameter of 0.063-2mm on the Wentworth Scale.

Sand Banks – Deposits that are distinct from the bathymetry of the surrounding seabed and range from coarse sandy gravel through to muds.

Sand Wave – A seabed sediment dune formed by the action of waves and tidal currents.

Screening Tower – Rotating towers located on the side of the hold of a dredger where the proportion of sand and gravel to be retained as cargo can be controlled.

Seabed Imagery – The use of camera systems to record the communities that live on the surface of the seabed.

Seabed Topography – The surface relief of the seabed which may be left as a series of ridges and grooves in areas of intensive dredging.

Secondary Aggregate – Material generated as a by-product of another production process which may be utilised for lower specific end uses such as land fill or road sub-base.

Secondary Components – Those members of a community that are dependent on other (primary) components of the community for their occurrence.

Secondary Impacts – Impacts of aggregate dredging on environmental resources outside the immediate boundaries of the Active Dredge Zone.

Sediment Plume – A zone of elevated suspended solids in the water column caused by overflow from the dredger, rejection of screened material, and disturbance of the seabed from the drag-head during dredging.

Sediment Transport – The process, driven by hydrodynamic forces such as waves and tidal currents that mobilises and transports sediment particles.

Sediment Transport Pathway – The route along which sediment transport occurs.

Self-Discharge – The ability of a dredger to unload cargo without the need for shore-based unloading equipment.

Serpula – A polychaete worm that builds a calcareous tube and can form distinct reef-like communities in some sheltered areas, although it also occurs as isolated tubes on stones, shells and buoys.

Sheer-Bed Stress – the features imposed on the seabed by current speed.

Shellfish – A general term that includes molluscs (whelks, scallops, mussels, cockles etc) and crustaceans (crabs, lobsters and shrimps).

Shoreface – the surface of the shore between high water and low water (the 'beach').

Side-Scan Sonar – Survey equipment that uses acoustic energy to generate information about the texture and characteristics of the seabed surface.

Species – The specific identification name of a particular organism.

Species Diversity – A measure of the variety of species in a particular sample or community.

Stressor – A pressure on biological resources from either environmental factors or Man.

Sublittoral – The seabed that is below the low water mark and is permanently covered by the sea.

Substantive Review – A review of the results of monitoring data at intervals of 5 years to ensure that environmental impacts of dredging remain within permitted limits. Such reviews form the basis upon which a licence may be extended.

Substrate – The type of material on the seabed (rocks, cobbles, gravels, sands etc).

Suction Pipe – Equipment through which water and sediment is drawn from the seabed to the dredger.

Suction Pump – The pump that is used to draw seabed deposits up through a suction pipe into the hopper of the dredger.

Syncline – Folded rock structure where the youngest rocks are in the centre of the fold.

Taxon (Taxa) – A distinct category of organism such as family, genus or species.

TEEB – The Economics of Ecosystems and Biodiversity

Thalli – The ‘leaves’ of macrophytes (‘seaweeds’). They can be green, brown, red or calcareous.

The Crown Estate – The organisation responsible for the management of assets owned by The Crown Estate, including the seabed.

Top-Down Biotope Mapping – The classification of marine biotopes based on identification of the physical characteristics of the habitat and the associated organisms.

TEV – Total Economic Value: the sum of all types of economic value of a resource.

Trailer Dredging – A dredging technique whereby the vessel moves slowly forward, with the dredge pipe and drag-head trailing behind.

Traits – Features of the biology of an organism such as the size, age, reproductive biology and feeding type.

Transit – The distance or time taken for a vessel to get from one point to another.

Trawl – A method of sampling the surface-dwelling invertebrates and fish using a net, the mouth of which is held open by either a beam (beam trawl) or by otter boards (otter trawl).

Trophic Groups – Animals grouped together in terms of their feeding strategies such as filter-feeders, detritus-feeders and predators.

Uni-Variate Indices – Single indices of community composition such as number of species (biodiversity), number of individuals (population density) and biomass (weight).

UKHO – The UK Hydrographic Office. This organisation maintains a wreck index along with oceanographic and seabed data.

UKNEA – The UK National Ecosystem Assessment.

Veliger – The planktonic larva of many types of mollusc including snails and bivalves.

Venus Shells – The common name for a group of burrowing bivalves belonging to the family Veneridae. They are common shallow-burrowing components of mixed sand and gravel deposits.

Vessel Monitoring Data (VMS) – Automatic monitoring data of the tracks of fishing vessels in UK waters outside of the 3nM near-shore fishing limit.

Vibrocore – Equipment used to acquire a 10cm diameter core sample of the seabed – commonly down to several metres.

Wave Refraction – The alteration in direction of waves imposed by obstacles such as sandbanks or man-made structures.

Winnowing – The process of removal of fine-grained particles by seabed currents, leaving coarser gravel deposits on the surface of the seabed.

WTA – Willingness to accept (an economic burden).

WTP – Willingness to pay an economic burden.

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