AGGREGATE EXTRACTION: A REVIEW ON THE EFFECT ON ECOLOGICAL FUNCTIONS

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1 Introduction

In the last decades, extraction of marine aggregates (sand and gravel) used for industrial purposes, reclamation and coastal protection has steadily increased in European Countries. The industrial need for sand and gravel has been fairly constant for the last ten years and marine sources contribute less than 10-15% of the industrial demand. In contrast, the amount of sand used for coastal protection and beach replenishment has recently increased significantly. There are no alternatives to marine sand mining and reuse of sediment from maintenance dredging. More than 20 Mm$^3$ or 40% of the total amount of aggregates extracted mainly in the North Sea in 2002 was used for beach replenishment (ICES, 2003).

The expected possible sea level rise due to global warming will increase coastal erosion and therefore is can be expected that large-scale sand mining for coastal protection in many European countries is needed in the future. Therefore the effects of large scale sand mining on morphological, but also ecological characteristics should be investigated.

The main objectives of the EU-project SANDPIT are to develop reliable prediction techniques and guidelines needed to optimise the location and dimensions of sand extraction areas, both in shallow and deep areas. As part of this, an assessment is made of morphodynamic processes in extraction areas and adjacent shorelines. With the morphological changes caused by aggregate extraction also the habitat for the associated biota will be modified and possibly destroyed. The ecological implications depend among other factors of the spatial scale and frequency of aggregate extraction and the temporal scale in recovery of the seabed habitat and the benthic communities. As part of the SANDPIT project, an inventory is made of the ecological effects of aggregate extraction based on existing knowledge.

The expected major increase in marine aggregate extraction in the future will increase the spatial and temporal environmental impacts. Coastal zone management and interdisciplinary surveys and assessments will become increasingly important in order to minimise impacts of large-scale sand mining on marine resources and to resolve conflicts against other legitimate uses of the coastal zone.

The physical and biological effects of dredging and aggregate extraction have been described in a large number of surveys and subject for recent reviews (ICES, 1992, ICES, 2001, Newell et. al., 1998, Boyd et al., 2003a). Guidelines for preparation of Environmental Impact Assessment of aggregate extraction were included in ICES (2001). These guidelines have recently been revised and adopted by OSPAR (ICES, 2003). The revised guidelines emphasised an ecosystem approach as a principle in assessment and management. It was also stressed that the potential effects on ecologically sensitive species or habitats which are not subject to specific protection according to national legislation and international agreements should be assessed (ICES, 2003).

Use of Ecological Quality Objectives as a management tool of human impacts on marine ecosystems is adopted by OSPAR (Skjoldal et al., 1999). The feasibility of this approach in relation to assessment and management of aggregate extraction is currently explored by ICES and the Working Group on the Effects of Extraction of Marine Sediments on Marine Ecosystem (WGEXT) is expected to submit a report in 2005 including this issue (ICES, 2003).
This inventory addresses the following topics, which are of relevance for assessment and management of ecological effects of large-scale sand mining:

- Physical and chemical effects of aggregate extraction
- Ecological effects of aggregate extraction
- Guidelines for assessment and management of marine sediment extraction
- Management framework and use of ecological state indicators.
2 Physical and chemical effects of aggregate extraction

2.1 Amounts extracted and methods used

Extraction of marine aggregates (sand and gravel) used for industrial purposes, reclamation and coastal protection has increased in European Countries from 30 Mm$^3$ to about 60 Mm$^3$ in the last 10 years (Figure 2-1).

![Aggregate extraction in 1992-2002](image)

Figure 2-1 Aggregate extraction in European countries in 1992-2002. Based on (ICES 2003)

The nature and effect of the physical disturbance of the seabed due to this dredging activity depend among other factors on the methods used to extract the sand and gravel. Two methods are commonly used: trailer suction hopper dredging and static suction hopper dredging.

![Trailer suction dredger](image)

Figure 2-2 Trailer suction dredger

Trailer suction hopper dredging is based on extraction with one or two backwards directed pipes while the ship is moving slowly (Figure 2-2). The upper layer of the sediment is
removed and 1-2m broad and 20-50 cm deep tracks are left in the seabed. Trailer dredging is by far the most common method used in the North Sea and the only suitable method in areas with shallow resources of sand and gravel.

Static suction hopper dredging use one forward directed pipe while the ship is anchored (Figure 2-3). Static dredging leave cone shaped holes in the seabed, which may be up to 20 m deep and 75 m wide (ICES, 2003). This method is commonly used in areas where the resources are deep and/or spatially limited. Static dredging is the only suitable method in areas where the wanted resource is covered by or contains embedded unsuitable layers of fine sediment or organic matter (e.g. peat).

Trailer and static dredgers could normally operate to maximum water depths of about 30 m. Removal of the seabed during dredging creates sediment plumes due to spill of fine sediment which is embedded in the targeted aggregates. Sediment spill in the surface water is caused by the overflow when the water in the hopper is displaced by sediment. Sometimes screening is used to adjust the wanted ratio between the fine and coarse fraction and reject of normally fine sediment, but occasionally also coarse fractions are another source of spillage. Movement of the draghead and the suction during trailer dredging may stir and suspend fine sediment but this bottom plume is generally insignificant compared to the surface plume caused by the sediment spill.

### 2.2 Physical effects on seabed morphology

The change in seabed morphology is an immediate effect of aggregate extraction and the size of areas affected depends on the method used. Extraction of 1 Mm$^3$ by trailer dredging will in theory remove the top 0.2-0.5 m of an area of 2-5 km$^2$ of the seabed assuming that the tracks are non-overlapping. Extraction of a similar amount of aggregates by static dredging will affect a much smaller area but the seabed will be left with patches of 5-10 m or even deeper pits often interconnected and distributed in a confined area.

The post-dredging changes of sediment composition and seabed morphology depend of a combination of many site-specific factors. These factors includes the morphology of the affected area, the sediment type (sand or gravel) and stability of the surrounding unaffected seabed, which may be related to the origin (relics or recent) of the resource and the local hydrodynamic conditions (waves and currents).

Examples of short and long term effects of aggregate extraction of gravel and sand respectively are summarised below.
2.2.1 Gravel

Gravel (Figure 2-4) is a finite resource in the North Sea. An irreversible change of gravel beds into sandy habitats due to aggregate extraction are concerning because of the high diversity of benthic communities associated with habitats of consolidated gravel and the potential importance of gravel habitats as spawning grounds for herring.

Gravel accounts for 80% of the aggregate extraction in UK (ICES, 2003). Southeast of England and in the Channel, mixed sediments with a high percentage of gravel are common. Consolidated gravel is a stable substrate and movement of gravel is limited even in high dynamic environments.

Experimental trailer dredging in a mixed gravel and sand substrate off North Norfolk (UK) resulted in 1-2 m wide and 0.3-0.5 m deep tracks. Estimates suggested that 70% of the surface sediment was removed but the seabed was lowered up to 2 m in patches dredged repeatedly. The gravel fraction of the sediment has increased after extraction due to exposure of deeper layers more rich in gravel. Sand was mobilised during dredging and 1-2 cm sand ripples were developed in the tracks shortly after cessation (Kenny & Rees, 1994). Weathered tracks were still visible after one year and further eroded. After two years they were just visible on side-scan sonar (Kenny & Rees, 1996). Equilibrium in sand transport was reached after three years where the sediment was similar to pre-dredging (Kenny et al., 1998).

An industrial dredging site off Dieppe (France) with a heterogeneous substrate of gravel and coarse sand was exploited in 1980-1994. The seabed has been lowered up to 5 m and the substrate at the extraction site changed as it was progressively dominated by fine sand due to overflow and/or bedload transport (Desprez, 2000). Similar deposits of fine sand 200 m North and 200 m South of the dredging site originated probably from the overflow. The existence of strong currents in the area was witnessed by megaripples of sand in deep furrows. Weathered tracks were still visible four years after cessation of commercial dredging and interconnected pits adjacent to the dredging area were at least nine years old.

A dredging area in the Channel was exploited for 25 years by trailer dredging and screening of sand. The area recently subject to high dredging intensity contained more sand and less silt than the low intensity dredging area and far less silt than a reference area. The high content of sand could be natural and/or caused by screening (Boyd et al., 2003b).

Ongoing commercial dredging without screening at two sites East of the Isle of Wight has not resulted in an increase of sand even in 10 m deep holes created by static dredging (Boyd & Rees, 2003). However, a zone of sandier gravel extends 1500-2000 m east of the dredging
sites in the predominant direction of the tidal current and may be a result of dredging disturbances (Hitchcock & Bell, 2004).

### 2.2.2 Sand

**Figure 2-5** Distribution of mud, sand and gravel in the Northsea. Adapted from De Wolf, 1990.

The North Sea contains large but uneven dispersed resources of sand (Figure 2-5). Sediments dominated by sand are common along the eastern shores of the North Sea and in the Channel. Sand is a finite resource in the Baltic (ICES, 2003). Large amounts of sand are used for beach replenishment. In the Netherlands, beach replenishment accounts for 80% of the aggregate extraction (ICES, 2003).

The recovery of the seabed after sand extraction is highly variable depending on methods of extraction, bedload transport and the local hydrodynamic conditions. Reported recovery times range from one month to more than 15 years (ICES 2001). In general recovery is fast after trailer dredging in mobile sand in highly dynamic areas and extremely slow and sometimes incomplete in deep pits in calm environments.

In-filling of deep pits after static dredging on tidal flats in the Dutch Wadden Sea lasted more than 13-16 years. The sediment accumulated in the pits was finer compared to the surrounding sediments and contained high concentrations of organic matter. Sedimentation in pits in tidal channels and watershed was faster because of a higher sub-tidal sediment transport. In tidal channels, the in-filling of pits lasted more than four years. In a watershed the in-filling lasted only one year. The sediment in these pits was almost similar and only slightly finer than the surroundings (Van der Veer et. al., 1985). In contrast to the slow inter-tidal deposition in the Wadden Sea, the yearly rate of sedimentation in the Wash (UK) was high and in-filling of two intertidal pits were nearly complete after three and half years and four years respectively (McGrorty & Reading, 1984).

The seabed was lowered between 5 m and 12 m in the CNEXO experimental pit in the Seine estuary in 1980. Fifteen years later there was no in-filling in the deeper part of the pit and only a limited in-filling with finer sand enriched with silt in the shallow part of the pit due to bedload transport and/or slumping of pit walls (Desprez, 2000).
In the shallow inner Danish Waters, static dredging is the predominant dredging method used. The pits created act as traps for fine sediment and organic matter. Accumulation of organic debris, resulting in anoxic conditions in the bottom of 10 m deep pits was observed seventeen months after cessation of static dredging in the Baltic (Norden-Andersen et al., 1992). Sand ripples indicated that the effect of current and waves was limited to the top seven metres of the pits. Oxygen was depleted in the bottom water of the pits during periods of stratification in the summer.

Intensive trailer dredging could create depressions in the seabed up to 2 m deep. Two metres is the maximum allowable impact on seabed morphology by trailer dredging in Dutch waters (ICES, 2003). Depressions in the seabed are caused by a common practice of dredging which is often confined to small sub-areas within authorised dredging sites. This is illustrated by data from the UK in 2001. The area in which over 90% of the extracted material was taken was less than 10% of the area where extraction activities was actually done and less than 1% of the authorised (licensed) areas (ICES, 2003).

In a sand extraction area off the West coast of Jutland, the seabed was locally lowered more than 1 m as a cumulative effect of five years of dredging in a same sub-area of the borrow site. The grain size and the content of organic matter of the sediment remained unchanged after yearly dredging with fairly low intensity. However, the overall sediment composition changed significantly in the extraction area after an intensive dredging campaign, which removed more than 50% of the surface area (VKI, 1999).

Dredging in fine sand in the western Mediterranean created up to 2 m deep pits covered with 5-20 cm layers of silt three month after cessation. The silt content of the sediment was still 27% one year after dredging (Van Dalfsen et al., 2000). Tracks were filled with fine sediment and enriched with organic matter just after trailer dredging of a sand bank composed of coarse to fine sand in the western Mediterranean along the Catalan coast. The pre-dredging composition of the sediment was restored in less than one year (Sarda et al., 2000).

Trailer dredging in the Baltic lowered the seabed 1.5-2 m. The tracks were eroded but still visible 17 month after cessation and the lowering of the seabed was unchanged (Norden-Andersen et al., 1992). No changes in sediment composition were observed after trailer dredging and extraction of 1.3 Mm$^3$ of sand and an estimated removal of 50% of the surface of the extraction area at Kriegers Flak in the Baltic in 1996-98 (DHI & TOXICON, 2000).
2.3 Sediment spill, sediment plumes and deposition

Sediment spill, generation of surface plumes (e.g. Figure 2-6) and deposition depends on several factors including the method of extraction, sediment composition in the extraction area, the rate and amount of sediment spill and the local hydrodynamic conditions. Coarse fractions of the spill will accumulate close to the dredging location and finer fractions could accumulate at greater distances.

2.3.1 Sediment spill

Sediment spill due to overflow was measured regularly during three years of sand extraction by trailer dredging at Kriegers Flak in the Baltic. The average sediment spill was 2.8% of the total amount of sand extracted (2.5 Mt) and well below the limits stipulated by the Authorities (DHI & TOXICON, 2000). The sediment in the extraction area was fine to medium sand and the content of silt and clay was about 0.5%. It means that at least 80% of the spill was sand. Distribution of sediment plumes and deposition of spill was simulated. According to the simulations the maximum deposits exceeded 20 mm in patches inside the extraction area, 8 mm adjacent to the boundary of the extraction area and was insignificant one km from the extraction area (Water Consult, 2000).
The sediment spill from overflow and reject of sand due to screening (Figure 2-7) may be very high during gravel extraction. According to a detailed survey of Hitchcock & Drucker (1996) the total loss of sediment was 1.9 times the amount retained. Reject through screening accounted for 90% of the sediment loss when the rest of the sediment loss was due to the overflow. The particle size of the sediment in the discharges was predominantly sand in the reject chute, whereas silt (<0.063 mm) and very fine sand (0.063-0.125 mm) contributed 38% and 14%, respectively of the proportion of the overflow. Static dredging in a gravel bed without screening was estimated to reject 1.6 t of sediment for a cargo loading about 2000 t (Boyd & Rees, 2003). This corresponds to a sediment spill of less than 0.1% of the amount extracted.

2.3.2 Sediment plumes

The plume generated by a sediment spill was tracked downstream on the basis of water sampling and use of Acoustic Doppler Current Profiler (Hitchcock & Drucker, 1996). The total concentration of suspended matter within the plume was high (500-600 mg/l) close to ship, but decreased rapidly to background levels (5-10 mg/l) at a distance of less than 300 m from the discharge. The maximum concentration of silt was 30 mg/l and background concentrations of silt were already reached 500 m from the ship. Rapid flocculation and formation of larger aggregates with higher rates of sedimentation could explain the fast decrease of silt content within the plume.

A similar rapid decay of sediment plumes was recorded during static dredging in gravel with no screening. The maximum concentration of suspended matter was very high (5.5 g/l) close to the dredging site. The settled sediment extended as a dense near bed plume 3-4 m thick more than 800 m from the site (Hitchcock & Bell, 2004).

In situ measurements of grain size spectra of particles in a dredging plume of lime in Øresund proved that small sized particles disappeared due to flocculation at a distance of 1500 m from the source after an excursion lasting approximately 50 minutes (Mikkelsen & Peirup, 2000). The settling velocity of non-flocculated and flocculated particles was found only to vary approximately a factor 1.7. This was due to the counteracting effect of decreasing density with increasing particle size. This effect was confirmed by determination of in situ settling velocity in similar dredging plumes where the settling velocity was almost constant (Edelvang, 1998). Flocculation time depends of many physical-chemical
characteristics of the water and could vary from a few minutes to days according to information cited in Mikkelsen & Peirup (2000).

Distinct lime plumes with concentrations of suspended matter more than ten times higher than background concentrations (1-3 mg/l) extended at least 2 km downstream a dredger in Øresund. The plume was visible at even greater distance from the source (Figure 2-8; Jørgensen and Edelvang, 2000).

In Moreton Bay, Australia, large scale dredging on a sandbank of medium to fine sand with 6-10% silt created a long and distinct sediment plume of about 200 m wide. Maximum concentration of suspended matter in the plume was 20-25 mg/l above background and reached after 0.5 hour. The background level of 3 mg/l was reached after 2 hours (Poiner & Kennedy, 1984). Deposition in a 200m narrow corridor at 500m intervals south of the extraction area over a period of 2 years and dredging of 14 Mm$^3$ was calculated. The simulated depositions at increasing distances were: 23 mm (500 m), 16 mm (1000 m), 12 mm (1500 m), 8 mm (2000 m) and 6 mm (2500 m) (Poiner & Kennedy, 1984).

A visible plume characterised by a surface sheen was observed far behind the 300-500 m, where the background levels of suspended matter was attained and back-scatter using ADCP was recorded more than 3 km astern the dredger (Hitchcock & Drucker, 1996). Organic matter and lipids from destroyed animals in the outwash from aggregate extraction was suggested as a probable explanation of the surface sheen and this explanation was supported by theoretical calculations based on benthic biomass in extraction areas and direct measurements in discharges (Newell et. al., 1999). Unfortunately measurements of the excursion of the sediment plumes and discharges of organic matter was not done simultaneously or in the same area. The average discharge of organic matter that was calculated on the basis of direct measurements (1.5 g AFDW/l) was 30 times higher than the theoretical estimate based on benthic biomass. Discharge of organic matter from aggregate extraction was forwarded as a probable explanation of the surface sheen of sediment plumes.
and likely to be sufficient to account for enhanced diversity and biomass of benthic invertebrates noted outside the boundaries of extraction sites (Newell et al., 1999).

The generation and decay of sediment plumes from overflow during trailer dredging of sand in Hong Kong was described based on a detailed field and modelling approach (Whiteside et al., 1995). The total loss of sediment via the overflow was estimated to be 26% of the load retained and silt accounted for 55-58% of the lost amount. Ten minutes after the overflow, the calculated mass in the plume was only 15% of the amounts discharged and silt only accounted for less than 30% of the remaining amount in the plume. The rapid decline of sediment concentrations in the plume was explained by a short dynamic phase lasting 5-10 minutes where the overflow mixture was entrained into the water column as a density current and hit the seabed near the dredger. The plume was diluted due to turbulent mixing during descend but the majority of the spill including the silt fraction settled on the seabed in a narrow zone astern the dredger. The length of the deposition zone during the dynamic phase was affected by several factors including the water depth, rate of discharge, density of overflow and dredging speed. The settling distance during the dynamic phase was 270m and 720m 10 minutes after discharge at a dredging speed of 0.45 m/s and 1.2 m/s, respectively. The dynamic phase was followed by a passive phase where the silt content in the plume gradually decreased to background levels during the next two to three hours due to sedimentation. Modelling of the plume in the passive phase simulated the spatial excursion of the plume in agreement with the measurements but overestimated the silt content and the lifetime of the plume (Whiteside et al., 1995). A simple sedimentation of silt was assumed in the model and flocculation might explain the faster sedimentation rates measured in the field.

2.3.3 Deposition

Direct tracks of deposits originating from sediment spill versus bedload transport and other sources of similar sediments are difficult to distinguish. Sediment traps and analysis of grain size distribution of surface layers of core samples collected in natural sedimentation areas were used in Øresund. The colour and the known size distribution of the lime spill were used as tracers. At a time when 181,000 t was spilled light-coloured unconsolidated layers 2 mm thick were recorded at the sediment surface in natural deposition areas closest to the dredging sites (Edelvang, 1998).

2.4 Chemical effects

Liberation of organic matter and reduced substances such as sulphides during dredging could reduce the oxygen concentrations in the overlying water and potentially harm benthic fauna. The organic matter and nutrient content of the sediment is usually an inverse function of the particle size of the sediment. Deposits of sand and gravel in dynamic areas have normally a very low content of organic matter and nutrients and are therefore usually well oxygenated. Direct environmental impacts of release of organic matter, inorganic nutrients, sulphides and other reduced components from the interstitial water during aggregate extraction will therefore in most occasions be insignificant.

The indirect effects of dredging on oxygen concentrations are more serious and result from changed hydrodynamic conditions in the area caused by the changed morphology. Oxygen depletion in the water phase is a function of the oxygen consumption and residence times of the water. The oxygen consumption of the seabed is a function of the organic matter content and temperature. In sheltered areas, sediments usually have a higher organic matter content due to the settling of organic particles. The degradation of the organic matter could lower
the oxygen concentration to a critical level for fish and benthos (ICES, 2001). In deep pits, residence times of the water could increase, especially during the Summer time when the water in the pit can become stratified. High residence times of the water in combination with high degradation rates could cause anoxic conditions in the water near the seabed. Accumulation of organic matter and anaerobic conditions may develop in the bottom of deep pits and local impacts in the water column of renewed extraction may not be disregarded. However, dredging operations are generally of limited spatial extent and only of short duration, and this limits any chemical impact (ICES, 2001).

2.5 Conclusions

- Tracks after gravel extraction may remain two to four years after cessation and at least nine years old pits have been recorded. Sediment spill from overflow and/or screening of sand may change the sediment composition and increase the ratio of sand as an irreversible effect of prolonged extraction in gravel beds.

- Recovery of the seabed after sand extraction is extremely variable depending on method of extraction and the local environment. Recovery times between one month and more than 15 years have been recorded. Minimum in-fill time for intertidal and subtidal pits was 3-4 years and one year, respectively.

- Long-term changes in sediment type and development of anoxic conditions were recorded in deep subtidal pits in the Baltic and intertidal pits in the Wadden Sea. Accumulation of silt and organic matter was also observed in shallow tracks in the Western Mediterranean.

- The sediment loss of the amounts retained is variable depending on method of extraction and seabed composition. Sediment spill from 0.1-26% due to overflow and 190% due to screening of sand has been recorded.

- A major fraction of the sediment spill by weight can be expected to deposit close to the dredging sites. Background levels of suspended matter may be attained 300-500m down current dredging sites but near bed plumes of settled sediment may extend even further. Visible plumes caused by suspended fine sediment and/or organic matter, suggested to originate from destroyed benthic animals, may extend several km downstream.

- The concentrations of organic matter, nutrients and oxygen consuming compounds is normally low in sand and gravel and direct chemical impacts during aggregate extraction are limited and transient in most occasions. However, oxygen deficiency may develop in the bottom water of deep pits due to stagnation of the water and decay of accumulated organic matter.
3 Ecological effects of aggregate extraction

The physical and chemical changes in the seabed habitat and the water column due to aggregate extraction may directly or indirectly affect the ambient ecosystem. The ecological effects are characterised in relation to extraction areas, sediment plumes and deposition of sediment.

3.1 Extraction areas

The seafloor within an extraction area is not only composed of sand or gravel, but many living organisms live in and on top of the seafloor (e.g. Figure 3-1). The immediate effect of aggregate extraction is the direct destruction of the sedentary benthic communities and organisms associated with the uppermost layers of the seabed habitat removed. The direct mortality during dredging may be enhanced by burial of organisms in the remaining sediment due to excessive deposition of sediment from overflow, screening and/or sliding of track or pit walls. As a side effect, animals living adjacent to the disturbed sediments may be exposed and subject to an increased predation from e.g. demersal fish species during and after the dredging.

The number of macrobenthic species (species richness) is in general highest in stable substrates of gravel, lower in mobile sand and lowest in areas with low and/or fluctuating salinity irrespective substrate. A comparison of the diversity of different habitats is not easy because the number of species recorded is a function of the sampling effort. Moreover the number of samples collected may be inadequate in rich communities with an even distribution of the abundance of the species, see Newell et al. (2001).
A total of 394 taxa were recorded in 31 samples (3.1 m$^2$) collected in a mixed substrate of gravel, sandy gravel and sand east of the Isle of Wight (Boyd & Rees, 2003). As a comparison 85 taxa were recorded in 76 samples (5.7 m$^2$) collected in mobile medium to coarse sand along the west coast of Jutland (DHI, 2000b) and only 18 taxa in 30 samples (3 m$^2$) in fine to medium sand at Kriegers Flak in the Baltic (DHI, 2003). In addition to sediment dwelling species (in-fauna) the high diversity on stable gravel substrate is caused by a diverse component of encrusting species (epi-fauna) that are not found in sandy habitats. A high natural level of disturbance and instability of the substrate explains the rather low diversity of benthic communities in mobile sand.

The immediate (short term) loss in species richness, abundance and biomass and changes in community structure depends primarily of the spatial dredging intensity expressed as the percentage of seabed habitat actually removed during dredging. The impact may range from almost total defaunation to insignificant changes depending on the ratio between disturbed and undisturbed seabed.

![Figure 3-2 Schematic diagram showing the likely recolonisation rates for the benthic community of estuarine muds, sands, gravels and rocky reefs (Newell et al., 2004b)](image)

The post-dredging recovery of the benthic communities is related to the spatial and temporal scale in recovery/changes in seabed habitat, the mode of re-colonisation including transport of adults and juveniles and survival of recruits from adjacent undisturbed sediments or settled from the water column (Figure 3-2).

Reviews of relevance for re-colonisation, succession and structure of soft bottom benthic communities in relation to physical disturbance, sediment type and pre- and post-settlement processes are found in Hall (1994), Snelgrove & Butman (1994) and Olafsson et al., (1994).

### 3.1.1 Gravel

In a small dredging site off the coast of North Norfolk (UK), 70% of the surface area composed of mixed gravel and sand was removed during experimental dredging. The structure of the community changed significantly and the benthic fauna was very dissimilar.
in the dredging site as a response of a patchy distribution of disturbed and undisturbed seabed (Kenny & Rees, 1994). One month after cessation, the number of species, abundance and biomass of the macrobenthic fauna were reduced by 66%, 95% and 99%, respectively. The number of species and the abundance, but not the biomass increased rapidly during the following month due to recruitment of the pre-dredging dominant epi-benthic species (*Dendrodoa grossularia* and *Balanus sp.*). Eight month after cessation the number of species, abundance and biomass was 65%, 30% and 6% of reference and the community structure has approached the structure of the benthic community at the reference site. The species richness recovered after one year, but abundance, biomass and community structure was still affected two years after cessation (Kenny & Rees, 1996). The abundance but not the biomass was below reference values after three years. However, the community structure at dredging and reference sites was similar and at both sites the structure has changed compared to the pre-dredging structure (Kenny et al., 1998).

The recovery at the North Norfolk experimental dredging site was characterised by an initial rapid phase of re-colonisation of pre-dredging dominant species with an opportunistic behaviour. The benthic biomass and the abundance remained low in the second phase lasting two years. The prolonged re-colonisation phase is attributed to an increase in amounts of sand in transport responsible for erosion of tracks and scouring of epi-benthic species. After two years the sand transport approached pre-dredging equilibrium and the benthic biomass (but not the abundance) increased significantly in a third phase of recovery (Kenny et al., 1998).

The recovery of the seabed habitat and the benthic community took three years after cessation of a small experimental dredging in a gravel habitat off North Norfolk. The original fauna was diverse but not rich and characterised by a dominance of opportunistic epi-benthic species adapted to a certain level of natural disturbance.

An industrial dredging site along the French coast of the Eastern English Channel was used in 1980-94. The number of species was reduced by 80% and abundance and biomass by 90% as a maximum impact recorded in 1993 (Desprez, 2000). The original heterogeneous substrate of gravel and coarse sand was progressively replaced by fine sand in the tracks due to overflow and/or bedload transport. Species richness was similar at dredging and reference site sixteen months after cessation but the abundance and biomass of the benthic fauna was only 56% and 35%, respectively. The biomass increased rapidly in the following year and approached the reference level 28 months after cessation but the abundance was still lowered. The post-dredging re-colonisation and structure of the macrobenthic community was closely linked to the sediment type and there was a gradient of impact from west to east of the dredging area. The community in the western section of the dredging area with an intrusion of mobile coarse sand resembles the reference area with a high percentage of species characteristics of coarse sediments. The diversity, abundance and biomass was lower in the eastern section of the dredging area and the community structure has changed radically from a dominance of species characteristic of gravel habitats to a dominance of erratic species of polychaetes characteristic of fine sand (Desprez, 2000).

The re-colonisation of benthic macrofauna at a dredging location off the Southeast coast of England was examined fours years after cessation of commercial extraction of gravel and screening of sand for 25 years. The effect on the benthic community was assessed in relation to different levels of dredging intensity and compared with a nearby reference site (Boyd et al., 2003b). The number of (non-colonial) species and the abundance was significantly lower in the area recently subject for the highest dredging intensity compared to the area with a low intensity of dredging and the reference site. The abundance was also reduced in the low intensity dredging area compared to the reference area. The community structure in the three areas (high and low intensity dredging areas and the reference area) was
significantly different after four years. However, the structure of the low intensity dredging area has approached the structure of the reference area and these areas were both clearly separated from the high intensity dredging area in which the replicates were dissimilar as an indication of a prolonged biological effect of the disturbance of the seabed. The sediment in the high intensity dredging area contained more sand than the low intensity and reference areas. However, the silt/clay content of the sediment at both dredging sites were far less than at the reference site probably because of dispersal of fine spill outside the boundaries of the extraction area. The dredging intensity was the single most important factor correlated to the community structure but sorting of sediment and % of sand was also of importance. The dissimilarity of the benthic fauna in high and low intensity dredging areas and the reference area was attributed to a number of species. Epi-benthic polychaetes (*Pomatoceros triquetra*) were abundant and a tube building reef forming polychaete species sensitive to dredging induced disturbance (*Sabellaria spinulosa*) were common at the reference site but absent or scarce at the dredging sites. The fauna at the high intensity dredging area was characterised by adult polychaetes typically associated with sand and newly settled polychaetes (Boyd et al., 2003b). The mobility of the sand and unstable sediment probably contribute to the low rate of recruitment, low diversity and abundance and the prolonged perturbed state of the benthic community in the high intensity dredging area. The changes in sediment composition and the increase of sand are probably irreversible and a permanent change of the community to a structure dominated by sand dwelling species of benthic in-fauna are likely.

Two sites in the central English Channel east of Isle of Wight with ongoing trailer and static dredging of gravel without screening were studied. The structure of macrobenthic communities showed significant changes from the centre of intensive dredging and downstream up to a distance of 5000 m (trailer dredging) and 1000 m (static dredging) (Boyd & Rees, 2003). The number of species was significantly lowered in the centre of both trailer and static dredging, but the spatial pattern in abundance and species composition differed. The abundance of benthos was highest in the centre and at the margin of intensive trailer dredging due to elevated numbers of barnacles (*Balanus crenatus*) and an amphipod (*Leptochirus hirsutimanus*). The abundance was highest 500 m and 1000 m downstream of intensive static dredging and lowest outside the boundary of the dredging site at a distance of 2000 m. Sedentary filter feeders (*Crepidula, Balanus, Pomatoceros and Dendrodoa*) were abundant. However, the spatial pattern is unlikely to be an effect of organic enrichment from overflow due to the low biomass in dredging sites subject for repeated intensive dredging (Boyd & Rees, 2003). Dredging has not changed the sediment type and spatial patterns in the structure of macrobenthic assemblages were mostly correlated to dredging intensity and methods of dredging.

Studies at the same two sites east of the Isle of Wight in 1999 showed that the benthic fauna was strongly reduced inside anchor dredging sites but little affected in the vicinity. The suppression of the fauna lasted for at least 18 months after cessation. The overall community structure was not affected by low intensity trailer dredging and recovery of species and abundance but not biomass was faster than areas affected by anchor dredging (Newell et al., 2004a).

### 3.1.2 Sand

The biomass of macrobenthic in-fauna in deep pits in tidal channels in the Dutch Wadden Sea with a rapid in-filling was similar to the biomass of the fauna in the surroundings one to three years after cessation of dredging (Van der Veer et al., 1985). The rapid increase and recovery in the benthic biomass was most likely caused by immigration and/or transport of adult bivalves able to cope with the sediment accretion in the pit. The recovery of the
Benthic fauna was slower in a pit at a watershed and the biomass was only 40% of the surroundings four years after cessation of dredging. The composition of the fauna in the pits was similar to the surrounding but the number of species was still lower in some of the pits. In contrast the in-filling of pits on tidal flats was incomplete after 13-16 years and species of benthic in-fauna were absent due to accumulation of silt and development of a black and nearly anaerobic surface layer in the pit (Van der Veer et al., 1985).

The density of benthic invertebrates was low in unconsolidated sediments during early stages with rapid in-fill of inter-tidal pits at the Wash (UK). The abundance in the pit of similar species dominant outside the pit exceeded pre-dredging values four years after cessation of dredging and six month after completely infilling and consolidation of the surface sediment (McGrorty & Reading, 1984).

The number of species, abundance and biomass of the macrobenthic fauna was 2-3 times higher in the CNEXO pit than in the reference area fifteen years after the dredging. Silt has accumulated in the shallow part of the pit and mud-dwelling species of crustaceans dominated in the pit in contrast to sand-dwelling species of polychaetes in the reference site. Echinoderms was a dominant component of the biomass in both areas (Desprez, 2000).

A re-colonisation of mud-snails (*Hydrobia sp.*) and other mobile species were recorded on video in the top seven metres of 10 m deep pits in the Baltic one year after cessation of static dredging. There were no animals in the bottom of the pits due to poor oxygen conditions caused by accumulated and decaying organic detritus resulting in oxygen deficiency in the bottom water during periods of saline stratification (Norden-Andersen et al., 1992).

The number of macrobenthic species was restored in areas subject for intensive trailer dredging in the Baltic 17 month after cessation. However, the abundance and the biomass in areas with the highest dredging intensity were 40% and 25% below unaffected surroundings, respectively (Norden-Andersen et al., 1992).

No effects of trailer dredging were recorded on the macrobenthic fauna at Kriegers Flak in the Baltic during the dredging period or eight months after cessation (VKI & TOXICON, 1997, VKI & TOXICON, 1998 and DHI & TOXICON, 2000). The actual dredging proved to be confined to small sub-areas not adequately covered by the sampling grid used before, during and after the dredging. This fact and the very limited sediment spill (2.8%) probably explain the lack of any measurable biological effect of dredging in or adjacent to the extraction area.

The structure of the macrobenthic community in mobile sand off the west coast of Jutland was not affected by low intensity trailer dredging estimated to remove 11% of the surface of the dredging area. Similar low dredging intensity had no cumulative effect on the benthic fauna over a period of four years. However, the benthic biomass was reduced significantly immediately after a large scale dredging estimated to remove 50% of the surface of the extraction area (VKI, 1995, VKI, 1996 and DHI, 2000). The decline in biomass was caused by destruction of large (old) specimens of the bivalve *Spisula solida* characteristic of coarse sand. A prolonged recovery time is likely because of irregular recruitment and the slow growth rate of this species.

The number of species, abundance and biomass was not affected one year after a small scale trailer dredging estimated to have removed less than 30% of the surface area of an extraction area of coarse sand off the west coast of Jutland (VKI & DCA, 1997). The seasonal and year to year variation was profound in this area due to intense recruitment of
bivalves during spring and summer and high mortality during autumn and winter caused by natural disturbance of the seabed and predation.

Similar large seasonal and inter-annual variations of the macrobenthic community were observed in a sand extraction area at Terschelling in the North Sea. The abundance and the biomass of the benthic in-fauna were reduced ten months after cessation of dredging. The decline in biomass was attributed to an elimination of bivalves (*Donax vittatus* and *Tellina sp.*) and adult echinoderms (*Echinocardium cordatum*). It lasted four years before the number of adult echinoderms were similar in extraction and reference sites. Opportunistic species of polychaetes (*Spio filicornis* and *Spiophanes bombyx*) increased in numbers in early stages of re-colonisation. The structure of the benthic community changed from year to year. Recovery was complete four years after cessation. The structure of the benthic community was similar in extraction and reference sites but the structure has changed and was different from the pre-dredging community (van Dalfsen et al., 2000).

In the western Mediterranean (Costa Daurada), the number of species was not affected three month after cessation of trailer dredging. In spite of an accumulation of 5-20 cm of silt the abundance increased 4 times due to a rapid re-colonisation of a few opportunistic species of polychaetes (*Capitella capitata* and *Malacoceros sp.*). Populations of commercially exploited species of molluscs (*Callista chione*, *Murex sp.*, *Cerastoderma edule* and *Ensis siliqua*) were almost eliminated. The increased content of silt in the sediment will probably delay the re-colonisation of molluscs. Recovery of the formerly abundant bivalve *Callista chione* may take at least four years based on experience of fishermen with similar dredging along the Spanish coast (van Dalfsen et al., 2000).

Pre-dredging surveys along the Catalan coast in the western Mediterranean showed that the macrobenthic community in coarse to fine sand in 10-30 m depth was characterised by a distinct seasonal cycle. A rapid increase in abundance and biomass after the spring recruitment was followed by a steep decline during the summer (Sarda et al., 2000). The site was almost defaunated just after trailer dredging except for a few polychaetes (*Capitella sp.*), probably feeding on organic matter accumulated together with fine sediment in depressions left in the seabed. The pre-dredging composition of the sediment on the sand bar was restored in less than one year. The re-colonisation of the benthic fauna was fast during the first year and the abundance and biomass exceeded pre-dredging levels due to intense recruitment of the polychaete *Ditrupa arietina* and the bivalve *Spisula subtruncata* in the spring and the lancelet (*Branchiostoma lanceolata*) in late summer and autumn. Pre-dredging abundance and biomass was restored two years after cessation. However the abundance and biomass of commercial exploited bivalves including the important and slow growing *Callistes chione* was reduced and the yield of artisanal fishery on bivalves steadily decreased and showed no sign of recovery three years after cessation (Sarda et al., 2000).

### 3.2 Sediment plumes

Elevated concentrations of particulate suspended matter and increased turbidity of the water in a sediment plume may effect different functional levels of the ecosystem. The potential effects include primary production, filter feeding, migrations and/or movements of fish, survival of pelagic egg and larvae of fish and forage opportunities of visual predators like fish, seabird and mammals.
3.2.1 Shading

The effect of reduced light regime in the sediment plume on primary production of phytoplankton and macrophytes (seagrass and seaweeds) depends on the temporal and spatial scale of the exposure for reduced availability of light, nutrient concentrations in the plume and the light requirements of the plants. Potential impact on phytoplankton is insignificant due to the transient exposure in the sediment plumes and the limited area and volume of the photic zone affected. Reduced primary production within the plume could result in increased nutrient availability at the edge of the plume. This could enhance primary production in the area, where light is not limiting.

![Figure 3-3](image)

Seagrass and macroalgae need sunlight to grow.

Macrophytes (and microbenthic algae) may be affected by prolonged exposure for sediment plumes and the impact of shading due to light extinction in the water column may be augmented by fine sediment settling on the plants (Figure 3-3). The excursion of dense sediment plumes generated by aggregate extraction with no screening is rather limited and impacts of shading caused by sediment plumes and deposition of spill is most likely in and close to the dredging areas.

The shoot density and the biomass of eelgrass (*Zostera marina*) was reduced close to dredging areas in Øresund due to large scale dredging and prolonged exposures of eelgrass beds for lime plumes (Øresundskonsortiet, 2000). Inter-tidal populations of eelgrass (*Zostera noltii*) have almost disappeared in the Dutch Wadden Sea since mid sixties. A reduced transparency of the water is a probable cause and aggregate extraction and other dredging work may have contributed to the development (Giesen, et al., 1990).
### 3.2.2 Filter feeders

![Typical filter feeding polychaete Sabella pavonina](image)

High concentrations of particulate matter in the sediment plumes may affect filter feeders due to clogging of the filtering apparatus or by diluting the organic food suspension by inorganic particles (Figure 3-4). Inorganic suspended matter reduce the average quality of the filtered material and filtering organisms have to invest more energy in food selection and feeding becomes less efficient. Only benthic filter feeders will be considered due to the confined exposure in time and space of filter feeding organisms in the water column (e.g. copepods).

Filter feeding bivalves are adapted to cope with large natural variations in ambient concentrations of suspended matter. Bivalves were able to select food particles in mixed suspensions of algae and sediment and to maintain an unaltered rate of ingestion and absorption of food at suspended sediment concentrations from zero to 56 mg/l (Kiørboe et al., 1980a). Low concentrations of suspended sediment may even improve the growth rate of common mussels (*Mytilus edulis*) compared to situations with no suspended sediment at all (Kiørboe et al., 1981). A grinding function of the sediment, which will improve the mechanical treatment of organic particulate matter, has been suggested to contribute to the growth enhancing effect (Navarro et al., 1996). The growth rate of common mussels increased in a field experiment, where the mussels were regularly exposed for silt concentrations between 200-250 mg/l in a plume originating from dumping of dredged spoil during a period of five weeks (DHI, VKI & Geografisk Institut, 1993). The high concentrations did not effect the survival of mussels. Mussels can protect themselves from overloading by closing the valves and the closing response depends on the size of the mussels. Common mussels in a estuary with a natural range in suspended matter between 5-35 mg/l stopped filtering and closed the valves, when the concentrations was around 250 mg/l (small mussels: 3 cm) and around 350 mg/l for 7 cm large mussels (Widdows et al., 1979).
Filter feeding epi-benthic species supposed to be unable to select food particles and possessing no protective means should in theory be more sensitive than bivalves to sediment plumes. The impact on rate of filtration of epi-benthic species was surveyed in silt concentrations varying from 0-30 mg/l (Lisbjerg et al., 2002). A sponge (*Haliclona urceolus*) was not affected but the filtration of a solitary ascidian (*Ciona intestinalis*) declined in higher concentrations. The growth rate of a bryozoan (*Electra crustulenta*) and a colonial ascidian (*Botryllus schlosseri*) was high and not affected by a continued exposure to a concentration of 26 mg/l of silt during seven days in a flume. The survival of the bryozoan *Electra crustulenta* and the ascidian *Ciona intestinalis* was not affected by high concentrations (30 mg/l) of silt or very fine sand during 48 hours. A proportion of the bryozoans stopped filtering and became inactive during exposure in very fine sand because the size of the sand particles (but not silt) exceeded the size of the mouth opening of the individuals (Lisbjerg et al., 2002).

### 3.2.3 Migration of fish

Sediment plumes may affect migration and movement of fish. Avoidance behaviour of herring (*Clupea harengus*) and cod (*Gadus morhua*) was recorded in a large flume with sediment plumes of equally sized particles of clay or lime in concentrations between 2 mg/l and 8-9 mg/l (Westerberg et al., 1996). The background concentration of suspended matter was less than 0.4 mg/l. Surprisingly pelagic herring and demersal cod were equally sensitive and the avoidance threshold was around 3 mg/l in plumes of both clay and lime. This threshold was far below the 10 mg/l determined as avoidance limit for herrings in relation to suspended concentrations of dredged spoil (Johnston & Wildish, 1981).

Exposure of cod in the night showed a similar response as in daytime and this suggest that there was an important non-visual component in the response. This was further supported by the direct observations. The avoidance was never based on vision of the plume alone but was preceded by an excursion into the plume (Westerberg et al., 1996).

The implications of the experimental findings, when the fish encounter a sediment plume in the field are difficult to predict. The behaviour of the fish may be different when they experience a gradient of suspended matter changing from background to maximum concentrations in the centre of the plume. However, the low threshold (3 mg/l) found in the experiments may be an absolute value in cases where the plumes are very distinct. Potential avoidance response of herrings was taken into account in the spatial and temporal dredging schedule during construction of the fixed Link across Øresund because this strait is a major migration route for the important Baltic herring stock (Øresundskonsortiet, 2000).

Fish often aggregate at the interface between turbid and clear water, at the edge of plumes. They hide from potential predators like birds in the turbid water from where they penetrate in the clear waters for foraging.

### 3.2.4 Buoyancy of pelagic egg and development of egg and larvae

Cod and a number of other important commercial fish species (e.g. plaice and flounders) have pelagic egg. In static experiments, it was shown that the sinking rate of cod egg was fairly linear with time and increased with the concentration of silt (Westerberg et al., 1996). This is a pure mechanical effect due to adherence of silt to the surface of the eggs. The response will be similar on pelagic egg of other species. A faster sinking rate of pelagic eggs may increase the mortality if the eggs hit the bottom before the pelagic phase of the development is completed. The mortality of cod eggs was not affected after three days in 20
mg/l of clay or lime but the mortality increased significantly when the concentrations were 200 mg/l (Westerberg et al., 1996). The mortality and embryonic development of herring egg was not affected by prolonged exposure (10 days) in concentrations of suspended silt between 5-300 mg/l and was not affected by short-term exposure in a 500 mg/l suspension of silt (Kjørboe et al., 1981b).

Newly hatched larvae of cod were more sensitive than cod egg. The mortality of larvae was about 50% after one day of exposure in 200 mg/l of silt. The mortality of the larvae increased with the duration of the exposure and lime concentrations as low as 10 mg/l affected the mortality after 6 days (Westerberg et al., 1996).

### 3.3 Deposition of sediment

Recent surveys on decay of sediment plumes suggest that most of the sediment in the overflow settle rapidly as a density current below and close astern the dredger (Whiteside et al., 1995). The effect on biota of burial depends on several factors including rate of sedimentation, sediment type and the ability of the benthic organisms to cope with a rapid accretion of sediment. Impact of deposition during extraction in sandy habitats is in general believed to be less than the impact of extraction in gravel habitats with many sessile and encrusting epi-benthic species (Boyd & Rees, 2003). In addition, screening of sand often used during gravel extraction will result in a highly enlarged deposition on the seabed compared to gravel extraction without screening and sand extraction.

The sensitivity of benthic invertebrates to burial is species specific. Mobile species of polychaetes, bivalves, gastropods and crustacean were able to migrate between 2-26 cm during eight days after an acute burial by 32 cm of sand. The migration of the species in silt was less with the exception of the gastropod species (*Ilyanassa obsoleta*) used in the experiment. The mortality of most species was rather low in sand but high in silt after the exposure (Maurer et al., 1981a, Maurer et al., 1981b, Maurer et al., 1982).

The survival of species depends on the rate of sedimentation, the duration of the burial and the type of sediment. The bivalve *Macoma balthica* with long siphons was unaffected by sediment accretion up to 7 cm per month but only 80% of the specimens survived when the accretion was 10.2 cm per month. The tube building crustacean *Corophium volutator* was more sensitive than the bivalve *Macoma balthica*. The survival of *Corophium* was 56%, 18% and 0.4% when the monthly sediment accretion was 2.3 cm, 7 cm and 10.2 cm, respectively (Turk & Risk, 1981).

Changes in the structure of benthic communities are expected to be a more sensitive measure of the impact of burial than mortality response of individual species. An inter-tidal assemblage of nematodes was capable to migrate in experimental deposits of native muddy and non-native sandy sediment. The impact and changes in the structure of the assemblage was most severe when the same amount of sediment was deposited in one large dose instead of several smaller doses (Schratzberger et al., 2000).

*In situ* burial experiments in deeper water approach reality but are difficult to conduct for obvious reasons. The response of an epi-benthic community on a mixed bed of sand and gravel buried by 3-5 cm of sand was followed during fourteen months (Lisbjerg et al., 2002). The water depth was 15 m and conspicuous members of the community counted during the experiment included several species of sponges, solitary sea anemones, sea urchins, solitary and colonial ascidians, sedentary polychaetes and bivalves. The protruding part of the abundant horse mussel *Modiolus modiolus* was buried by the experimental treatment. During to first two months, where compacted sand remained in the experimental
lots, the density of *Modiolus* was reduced by about 45%. The burrowing sea anemone *Sagartia trogloodytes* was unaffected by the burial and the mobile urchin *Strongylocentrotus droebachiensis* emigrated from the area. The urchins returned into the area and reached almost initial densities after the sand has disappeared during the winter. The structure of the epi-benthic community changed significantly after the treatment and the community remained in a perturbated state until the end of the experiment and one year after the sand has gone (Lisbjerg et al., 2002).

![Figure 3-5](image)

**Figure 3-5** Photographs showing the depth structure of the seabed deposits during the investigation of the impacts of overboard screening on benthic biological communities. Left hand photographs show box-core profiles and the right hand photograph was taken *in situ* (from Newell et al., 2004)

Excessive sedimentation (e.g. Figure 3-5) in extraction areas will enlarge the mortality of organisms remaining in non-disturbed sediment adjacent to the tracks and aggravate the immediate impacts of dredging. Impacts of deposition of sediment spill adjacent to extraction areas depend on the magnitude and type of the deposits and the content of organic matter, which may serve as a nutritional input to the surroundings and affect the composition of the benthic community.

The benthic community in sand deposits 200m north and south of the extraction area was more disturbed and the number of species, density and biomass of benthic fauna was lower than in the extraction area sixteen months after cessation of dredging. Like the most affected part of the dredging area the community in the deposit area was dominated by species characteristic of fine sand and species characteristic of coarser sediment were scarce or absent (Desprez, 2000).

The number of species and the abundance of the benthic fauna were very low in the dredging area and also depleted 200-400 m south of the boundary of the dredging area probably due to sediment instability caused by sliding and deposition of spill in the current direction. At further distance there was a noticeable enhancement of the biota and the scale of the effect was in the order of 1500 m to 2000 m. There was significant correlation between the enhanced abundance of the benthic fauna and the estimated total deposition south of the dredging area. This and similar findings in the literature suggested that the enhancement effect probably was a response of the biota to an increase in nutritional resources generated by dredging and transported by the plume (Poiner & Kennedy, 1984).

The content of organic matter is normally low in sediments of sand and gravel. Fragmented animals discharged in the outwash is suggested as a probable source of organic enrichment and measurements support that the concentrations of organic matter can be high at least during dredging in non-exploited deposits (Newell et. al, 1999). However, the source is probably of minor importance in commercial dredging areas where the benthic biomass is depleted due to repeated dredging (Boyd & Rees, 2003).
Benthic invertebrate communities in sand and gravel are in most occasions the primary target of burial effects but other components of the ecosystem in the vicinity of dredging sites are also vulnerable to deposition of sand. Impacts on macrophytes (e.g. seagrass) of burial are confounded with the shading effect. Response to sediment accretion is species specific. Seagrass may be able to cope with sedimentation rates of 2-13cm/year but sedimentation during a two month period should probably not exceed 5cm for any species (Vermaat et al., 1996).

Known spawning grounds of herring (*Clupea harengus*) are in general of limited spatial size and the egg adhere to the surface of coarse substrate such as gravel and stones. The survival and development of herring eggs appears to be rather insensitive to even high concentrations of suspended sediment (Kiørboe et al., 1981b). However, deposition of sediment is expected to be detrimental unless the sediment is removed rapidly by currents. Due to the limited excursion of sediment plumes impacts of deposition of sand adjacent to dredging areas will in most occasions be of limited spatial size compared to direct destruction of possible spawning grounds in dredging areas.

The lesser sandeel (*Ammodytes marinus*) is an important species of the North Sea ecosystem and subject for the largest single species fishery (Wright et al., 2000). The species is also a key food item for many seabirds and seals (Furness, 2002). Adult sandeel is stationary and buried in the sand except when feeding on zooplankton during daytime. The species appears to prefer clean sand with less than 2% silt/clay and decline in abundance with increasing content of fines and is absent in sediments with more than 10% silt/clay (Wright et al., 2000). The preferred depth range is 30-70m but important fishing grounds are also located in more shallow water especially along the West Coast of Jutland (Jensen et al. 2002). In addition to depth the content of silt/clay is a limiting factor for the distribution of sandeel. Deposition of silt/clay from the dredging overflow may affect the suitability of sandeel habitats in the more shallow reaches of the distribution of the species adjacent to sand extraction areas.

### 3.4 Conclusions

**Extraction areas**

- The number of species increases fast during the first year after cessation of gravel extraction but recovery of abundance, biomass and community structure may take two to four years. Increase in sand due to overflow and/or screening prolongs consolidation and colonization of the seabed habitat and the benthic community may change irreversibly.

- Recovery of the biomass in deep pits may last one to more than four years. Development of stratification and periodic oxygen deficiency in the bottom water prevents re-colonization.

- The number of species and abundance may restore during one year after intensive sand extraction by trailer dredging. Post-dredging colonization of opportunistic species of polychaetes was rapid but recovery of the benthic biomass dominated by adult long living bivalves and echinoderms takes at least four years in the North Sea and in the Western Mediterranean.

**Sediment plumes**
- A shading effect should be considered in case of large scale dredging and prolonged spill generating sediment plumes and increased sedimentation in shallow areas with dense sensitive communities of seagrass and perennial macroalgae.

- Due to the rapid decline in the concentrations of suspended matter in sediment plumes potential impact on benthic filter feeding organisms will be confined to the near field as a combined effect of excessive concentrations of suspended matter and increased deposition on the seabed.

- Herring and cod avoid low excess concentrations of suspended matter under experimental conditions. The response of fish species in nature is difficult to predict but sediment plumes may potentially affect migration and movement of herring and cod (and probably other fish species) in the far field.

- The mortality of pelagic egg and fish larvae may increase in sediment plumes. However, the short-term exposure in the plumes and the small volumes of water affected by increased concentrations of suspended matter will limit the impact of aggregate extraction compared to natural mortality factors, especially predation.

- Demersal eggs of herrings tolerate high concentration of suspended matter but extraction in the vicinity of spawning grounds should be avoided because deposition is expected to be detrimental for the development of the eggs unless the sediment is removed rapidly by current.

**Deposition**

- The impact of deposition is species specific but benthic in-fauna is in general tolerant to burial. The effect of sand is less than silt and a gradual deposition has less effect than a similar but acute amount. Increased mortality caused by aggregate extraction will mostly be confined to the near field. An increase in the benthic fauna observed in some occasions at further distance from the boundary of extraction sites is suggested to be an enhancement effect of organic matter released during dredging.

- Epi-benthic communities in gravel habitats are more sensitive to burial than soft bottom in-fauna. Immediate reduction of the fauna due to acute burial may be followed by a prolonged recovery phase where the benthic community remains in a pertubated state more than one year after the sediment has gone.

- In addition to negative impacts on herring spawning grounds in the near field deposition of silt in the far field may affect the suitability of clean sand habitats preferred by sandeel.
4 Guidelines for assessment and management of marine sediment extraction

4.1 Introduction

Aggregate extraction affects the environment and the activity is included in Annex II of the “Directive on Assessment of the Effects of Certain Public and Private Projects on the Environment” (85/337/EEC). The directive has later been amended by Directive 97/11/EC. The member states define when an Environmental Impact Assessment (EIA) is needed and prepare guidelines.

ICES has prepared “Guidelines for Preparation of Environmental Impact Assessment Evaluating the Effects of Seabed Aggregate Extraction on the Marine Environment” (ICES, 2001). The Guidelines has been amended and has taken comments forwarded by OSPAR into account in the revised “Guidelines for the management of marine sand extraction (ICES, 2003).

OSPAR has prepared a Draft Agreement on Sand and Gravel and expressed that ICES Guidelines was sufficient to cover OSPAR’s requirements. OSPAR therefore agreed that the Contracting Parties should take ICES Guidelines into account within their procedures for authorising extraction of marine sediments (ICES, 2003).

Helsinki Commission adopted HELCOM Recommendation 19/1 on 23 March 1998 concerning Marine Sediment Extraction in the Baltic Sea. The Commission recommends to the Governments of the Contracting Parties to the Helsinki Convention that an EIA should be carried out in all cases of sediment extraction according to the Guidelines in Attachment 1. Attachment 1 emphasise the need to restrict extraction in “Sensitive areas”, to conduct “Extraction practice” with minimum negative impacts on the marine environment inclusive BAT or BET and to include “Environmental monitoring” as a component of every kind of extraction activities (www.helcom.fi/recommendations/rec19_1.html).

The ICES and HELCOM Guidelines are comprehensive lists of physical, chemical and biological issues relevant for assessment of potential impacts of aggregate extraction. The lists are useful in the first phase of the EIA process, where the scope of the surveys and information necessary for a specific dredging area are defined in consultation of the issuing Authorities and the Applicant. The EIA should be structured and tailored to the specific surroundings. The scope of large-scale sand mining in diverse and sensitive areas could be comprehensive.

In addition to physical/chemical and biological/ecological impacts in the marine environment large-scale sand mining may have direct or indirect socio-economic impacts on coastal communities with potential conflicts between tourism and fishery. This emphasises the possible complex and interdisciplinary nature of assessments of large-scale dredging projects.

The Guidelines provide less guidance in the following and crucial steps of the EIA process, which includes predictions of potential physical, chemical and ecological impacts in time and space, mitigation measures and design of appropriate monitoring programmes.
4.2 Assessment of potential impacts

Tools are available to predict physical impacts of specific dredging scenarios on plumes and sedimentation in the near field and coastal morphology in the far field. Possible impacts on oxygen, transparency and eutrophication in both water and seabed communities in response of release of oxygen consuming compounds and nutrients may also be simulated. However, assessment of the most common impacts of sand mining on benthic invertebrates must rely on conceptual models on succession of disturbed soft bottom communities and available threshold limits for exposure to suspended sediment and deposition.

Assessment of direct and indirect impacts of sand mining on other components of the surrounding ecosystem is hampered by inadequate knowledge on the importance of potential aggregation extraction areas as habitats, feeding, spawning and nursery areas for fish. Information on migration routes of fish and possible importance of potential extraction areas for seabirds and marine mammals, e.g. as breeding place for harbour porpoise is not readily available.

4.3 Mitigation measures

Experience gained from past and current use of aggregate extraction areas should be summarised and used in strategic and integrated management of large-scale sand mining in the future with the aim to avoid impacts on valuable resources and sensitive habitats and communities.

In addition, only suitable resources of sand and gravel should be exploited with the aim to avoid or minimise on board screening and reject of large amounts of sediment, which may change the sediment type and the benthic community in the dredging areas and the surroundings.

The potential of an extensive dredging strategy affecting large areas of the seabed with a low frequency versus an intensive strategy affecting small areas repeatedly with a high frequency as a potential mitigation measure need to be analysed.

4.4 Monitoring


A major problem in design of a monitoring programme is to elaborate the verbal statements of predicted ecological impacts in the EIA into operational criteria. Operational criteria and monitoring with the aim to ensure compliance may be related to predicted and predefined impact zones realising that impacts of dredging is inevitable in confined areas. Monitoring is necessary because of the uncertainty of predictions of ecological impacts in the EIA. If possible a feedback option should be included in a monitoring programme in order to prevent unforeseen effects by adjusting the dredging in time. An efficient use of the
feedback approach is based on sensitive key species directly affected by the dredging work and quickly responding variables easily measured. Predefined threshold limits in relation to known natural seasonal variations of the variables used must be defined and compliance is assessed on the basis of frequent monitoring during the dredging work.

A feedback approach and compliance monitoring of eelgrass and common mussels was a component of the environmental management system implemented during construction of the fixed Link between Denmark and Sweden. The effectiveness of the approach was confirmed by follow-up surveys (Øresundskonsortiet, 2000).

4.5 Conclusions

- A review of operational criteria and conceptual framework used in the Environmental Impact Assessment process and guidance on how to conduct structured assessments would be a useful amendment to the existing Guidelines. An update of possible mitigation measures including an analysis of extensive versus intensive extraction strategy and possible application of feedback approaches in monitoring of large-scale sand mining would also be beneficial. An annex with relevant references and links would be most useful.
- The continued work on the Cooperative Research Report planned in 2005 address these issues and the report is expected to improve the basis for assessment and management of extraction activities in the future. Recent surveys on the effect of aggregate extraction will be included and ICES will also address the use of threshold values or Ecological Quality Objectives (EcoQOs) in assessment.
5 Management framework and ecological state indicators

5.1 The management context

Large sand mining is envisioned to be 10’ to 100’ of millions of cubic meters per location. Sand mining of this scale has potentially a number of direct and indirect physical and ecological impacts and may also affect other uses and priorities of the coastal zone including recreation, fishery, navigation, offshore installations, protected habitats and endangered or threatened species.

Management of marine environments is obviously difficult due to the inherent structural and functional complexity of the ecosystems and various human impacts of different spatial and temporal scales. A sector-based management approach is deemed to be inadequate to protect the overall performance and health of the marine environment and this has been recognised for many years.

In the last decades several attempts have been made to establish a cohesive framework for assessment of impacts and management of the coastal zone based on an ecological (holistic) approach both nationally and in later years internationally by OSPAR and EU.

Ecological indicators have been developed in the Netherlands by different sectors responsible for management of territorial waters of the North Sea but the use of the approaches in management and policy making has been limited (Erftemeijer et al., 2002). A number of organisations with different geographical coverage and policy-making roles have been involved in management of the North Sea over the years. One conclusion based on a review is that a strong co-ordinating body is needed in order to avoid duplication and to improve to use of scientific information in management (Ducrotoy & Elliot, 1997).

An ecosystem approach and development of Ecological Quality Objectives (EcoQOs) for the North Sea was initiated in the late 1990s under the auspices of OSPAR and ICES (Erftemeijer et al., 2002). A joint workshop in 1999 agreed on definitions of EcoQOs and Ecological Quality (EcoQ) and proposed ten sets of issues for EcoQOs for the North Sea (Skjoldal et al., 1999). Several EcoQOs are subject to a test in a pilot project in the North Sea and progress will be reviewed by OSPAR in 2005 (Erftemeijer et al., 2002). Derivation of Ecological Quality Standards (EcoQS) and EcoQOs in analogy with previously used Environmental Standards and Environmental Objectives was discussed in Elliot (1996) and applied in management of nutrients and potential eutrophication (Elliot & Jonge, 2002).

CEFAS held a “Workshop on Ecological Quality Objectives for Aggregate Extraction Areas” in 2001 and EcoQOs as a management cool in aggregate extraction will be considered by the ICES working group (ICES, 2003).

EcoQ is defined as “an overall expression of the structure and function of the aquatic system” and EcoQO is “the desired level of the EcoQ relative to the reference level”. The reference level is a level of EcoQ where the human influence is minimal (Skjoldal et al., 1999). The conceptual framework and use of the term “desired level” and reference to
minimal human influence require a clarification from science and political decisions due to the economic implications.

A review of Elliot et al. (1999) evaluate the impact of EU Directives on coastal science and management including the recently proposed Water Framework Directive (WFD), which aim to produce a sustainable water policy. One of the most important aspects of WFD is the concept of Ecological Status defined as “an expression of the quality of the structure and functioning of aquatic systems associated with surface waters; it takes into account the physico-chemical nature of the water and sediment, the flow characteristics of the water body, but it concentrates on the biological elements of the ecosystem” (Elliot et al., 1999).

Several types of Ecological Status to be achieved by the environment have been defined. Natural (theoretical status achieved by absence of human activity), high (demonstrated not to be significantly influenced by human activity) and good (demonstrated to be significantly influenced by human activity, but still has a rich, balanced and sustainable ecosystem) (Elliot et al. 1999).

WRD states that three types of parameters are measured as pointers of Ecological Status: biological, hydromorphological and chemical. The biological (indicators of presence and composition of particular organisms as indicator of ecological quality, whereas the two others indicate those elements affecting the health of the biological community (Elliott et al., 1999).

## 5.2 Potential effects and management of aggregate extraction

### 5.2.1 Pre-dredging procedures

Aggregate extraction is strongly regulated and the activity is confined to extraction areas delineated by the Authorities. The spatial regulation makes it possible to minimise potential impacts of sand mining at the planning stage. Protected areas and sensitive habitats (e.g. herring spawning grounds) should be avoided and the distance from appointed extraction areas should be judged from the prevailing currents. Moreover aggregate extraction in a specific area requires an Environmental Impact Assessment (EIA) if the extraction described in the application exceed predefined amounts per year and/or in total or otherwise requested by the Authorities in cases where significant impacts on adjacent protected or sensitive areas may occur.

Methods of extraction, amount and quality of the planned extraction, the dredging area(s) and the duration of the work is specified in the Authorisation. Maximum spill rate and average spill of sediment may also be stipulated and combined with spatial and/or temporal zoning with the aim to protect sensitive areas in critical seasons e.g. growth of seagrass, spawning, migrations and fishery.

### 5.2.2 Spatial scale of sediment disturbance caused by extraction and trawling

The immediate ecological impact of aggregate extraction is proportional to the actual surface area of the seabed habitat removed. Current registration of accurate positions during dredging using “black boxes” makes it possible to map the size, location and depth of the
actual dredging areas. The amount and type of aggregates extracted and the actual size of
the seabed removed is key figures essential for management. These figures makes it possible
to assess the development in amounts and total areas of the seabed directly affected relative
to the size of the used and appointed dredging areas and relative to other activities
disturbing the seabed. An estimate based on 1986 data suggested that physical disturbance
affected about 57% of the seabed in the North Sea and that aggregate extraction affected
0.03% of the area and fishing 54% of the area (de Groot, 1996). The estimate is crude and
includes activities not strictly comparable. However, regular updated figures on areas
affected by sand mining and bottom trawling are useful summary indicators that illustrate
the proportions of the seabed habitat disturbed directly by different activities.

Aggregate extraction, maintenance dredging, dumping of dredged spoil and bottom trawling
are the main activities directly disturbing the seabed and affecting the benthic communities.
Aggregate extraction has significant immediate impacts at a local spatial scale confined to
the extraction areas and the adjacent surroundings.

The immediate impacts of bottom trawling on benthic communities are less than the effect
of aggregate extraction. However, repeated trawling in large areas of the North Sea over
almost a century has changed the structure of the benthic invertebrate communities at a regional spatial scale in the North Sea. The physical damages of invertebrates on the seabed
following the trawling and the huge discard of invertebrates and fish caused the changes.
The long-term changes are characterised by an increased numbers of opportunistic fast
growing species and robust scavengers and predators (e.g. hermit crabs, swimming crabs,
whelks and sea stars) and a decline of several species of slow growing bivalves (e.g. the threatened Arctica islandica).

The effects of bottom trawling on marine communities in reviewed in (NIOZ 2-ref. follow).
The impact of bottom trawling and discard on different components on benthic fauna and
long term changes in benthic communities is described in e.g. (Rumohr & Kujawski, 2000,
et al., 2000).

The trawling intensity is very high in some places especially in the southern North Sea and
trawling frequency in sand extraction areas should be recorded because of possible
cumulative impacts.

5.2.3 Sediment spill, plumes and deposition

The immediate and direct destruction of the seabed habitat and the associated species caused
by aggregate extraction may be enhanced by burial due to sediment spill via overflow and/or
screening. The potential ecological effects of sediment plumes and deposition are site
specific and depends on the spill rate, the total amount of spill and the type of sediment in
the overflow. The spill of silt/clay and fine fractions of sand is normally limited during
dredging in clean sand or gravel but onboard treatment (screening) can increase the amount
significantly.

The ecological effect of a low spill rate is in general insignificant due to a rapid decay of the
plumes and the limited rate of deposition. However, release of fines during large-scale sand
mining may potentially change the sediment type and effect the recovery of benthic
communities. Screening and reject of large amounts of sand will in most occasions
eventually change a habitat of mixed gravel and sand with a diverse epi-fauna to a habitat
dominated by sand and a less diverse benthic in-fauna (Newell et al, 2004a).
Regular onboard measurement of the amount and type of sediment spill in absolute terms and relative to the amounts extracted is therefore recommended as a requirement in an Authorisation. This requirement can be used as a pro-active management tool to ensure that BAT or BET is implemented and that the quality of the aggregates exploited are suitable for the purpose. The aim is to reduce the sediment spill and associated ecological effects and to preserve valuable resources.

The area of the seabed habitats affected by dredging, the amount of aggregates extracted and the sediment spill are summary indicators directly related to the physical disturbance of sand mining and of importance for assessment of the magnitude of the ecological effects.

5.2.4 Ecological effects and post-dredging changes

Aggregate extraction results in a fragmentation of the habitat and divide the dredging area in a mosaic of (1) defaunated tracks, (2) patches with reduced fauna due to burial, immediate sediment instability due to sliding of track or pit walls and increased predation of exposed animals and (3) unaffected patches. The immediate impact of dredging is a reduction in summary community attributes (number of species, abundance and biomass) and changes in the structure of the benthic community in the dredging area.

The scale of immediate impacts and post-dredging re-colonisation in different habitats (sand or gravel) are related to the spatial and temporal dredging intensity. Intensive dredging and disturbance of larger areas of the seabed habitat enlarge the immediate impact and re-colonisation is further delayed by frequent extraction in the same area. Repeated dredging will eventually deplete the resource and the habitat may change irreversibly due to increased depth and sedimentation of silt and sand from overflow and/or screening. These changes may prolong re-colonisation and an altered post-dredging benthic community may develop.


Benthic architecture is a concept summarising diverse small-scale physical and biogenic features on the seabed (e.g. boulders, mounts of tubeworms and shells) which enhance benthic diversity. Some of the factors structuring benthic communities are related. There is a dynamic interaction of hydrographic regime, sediment type, sedimentation of organic matter and supply of larvae and recruits (Snelgrove & Butman, 1994).

The structuring factors will be affected directly or indirectly by aggregate extraction and impacts on benthic communities differ depending on dredging strategy (shallow or deep) and habitat type (sand or gravel) as suggested in Table 5-1

<table>
<thead>
<tr>
<th>Important factors structuring benthic communities</th>
<th>Shallow extraction</th>
<th>Deep extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sediment type/quality</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Hydrography/disturbance regime</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Nutrient/organic matter flux</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Depth</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Benthic architecture</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Supply of recruits</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>
According to a common paradigm disturbance of the seabed initiate a succession where an abundant re-colonisation of small fast growing, early reproducing and short living opportunistic species (e.g. polychaetes) gradually will be succeeded by larger slow growing, late maturing species with a long life cycle (e.g. bivalves and echinoderms).

Bivalves and echinoderms are dominant components of the benthic biomass and recovery in benthic biomass takes longer than recovery of number of species and normally also abundance. However, the early stages of recolonisation depend on several local factors including the importance of immigration of adults and recruits respectively, which in turn may be affected by the size of disturbed patches relative to undisturbed patches.

Re-colonisation by immigration of adults was of less importance than supply of recruits in a study of scale-dependant benthic re-colonisation dynamics (Whitlatch et al., 1998). However, rapid recovery in benthic biomass in a dredged channel and in pits in tidal channels was based on rapid immigration and lateral transport of adults (Bonsdorff, 1980, Van der Veer, 1985). Mobile species of crustaceans are also capable of rapid post-dredging re-colonisation.

Larval supply and recruitment of benthic invertebrates depends on a complex sequence of pre-settlement, settlement and post-settlement processes and factors (Todd, 1998). The pelagic life stage may last from seconds to months and the settlement and recruitment process from minutes to hours (Todd, 1998). Local changes in sediment and hydrodynamic in disturbed patches may affect nearbed transport of larvae and modify cues involved in substrate election and actual settling such as flow regime, sediment texture, biofilm and presence of similar species (e.g. gregarious species as barnacles). However, tracks and depressions left in the seabed may enhance deposit of organic matter (potential food source) and recruits and thus facilitate re-colonisation.

Larvae of soft bottom species are able to suspend settling and lateral transport of early recruits is possible. In contrast, settling of epi-benthic species is irreversible except for some species of bivalves able to limited movements in younger stages. A low larval supply may have a structuring affect on epi-benthic communities but in most occasions larval supply is abundant and post-settlement processes such as competition for limited resources (space and food) and predation is of major importance.

**Summary of impacts and recovery after shallow dredging in sand**

The grain size of sand extraction areas range from fine to very coarse sand. The different sand fractions may relate to diverse hydrodynamic impacts and morphological structures on the seabed (e.g. crests and troughs of sand waves). The content of silt/clay and organic matter in the sediment is often low (<1%) and highest in the most coarse and stable sediment fractions in dynamic areas. Repeated dredging may lower the seabed but changes in sediment type and accumulation of fines is normally limited. The seabed may recover during one year in areas with active sand transport but recovery of the seabed may take more years in calm environments with limited bedload transport and deposition of sand.

The number of species and abundance of the benthic fauna in clean sand in dynamic areas are in general low and often dominated by adult species with a short life cycle (e.g. polychaetes and crustaceans) and juvenile bivalves and echinoderms. Bivalves and echinoderms with a long cycle are dominant components of the biomass.

The initial impact and the rate of re-colonisation are affected by the dredging intensity and the area of the seabed disturbed. No cumulative effect on benthic fauna effect was measured...
in the Baltic and the North Sea when yearly extraction removed less than 50% of the surface area. However, the biomass was reduced significantly when a yearly dredging affected more than 50% of the area. Post-dredging recovery times in affected areas range from one year (in number of species) to 2-4 years (abundance, biomass and community structure). However, recovery of slow growing species of bivalves of commercial importance in the Western Mediterranean may last even longer.

**Summary of impact and recovery of shallow dredging in gravel**
Gravel extraction areas are characterised by heterogeneous sediment of silt/clay, sand and gravel. The silt/clay content can exceed more than 10% in consolidated deposits. Exploitation reduces the silt/clay fraction of the sediment and increases the sand fraction. Prolonged extraction and screening of sand will in most occasions eventually change the habitat from gravel sand to sandy gravel or sand.

The benthic fauna may be very diverse due to a large number of epi-benthic taxa. The stable solid surfaces with encrusting species and other biogenic structures such as shells of epi-benthic species (e.g. the partly buried horse mussel, *Modiolus modiolus*) contribute to the benthic architecture and increase the diversity of sessile and mobile epi-benthic species.

Removal of gravel and associated epi-benthic species impair the benthic architecture and reduce the diversity of encrusting species due to a permanent loss of available substrate. Increase in sand will favour re-colonisation of benthic in-fauna. Instability and movements of the sand may further delay or hamper re-colonisation of epi-benthic species due to scouring and/burial of remaining solid substrate. A recovery of the benthic community has been recorded three years after of small scale gravel extraction without changes in sediment type but at a commercial site the benthic community was still pertubated four years after cessation of dredging.

**Summary of impact and recovery of deep dredging and pits**
The rate and time of in-filling of deep pits are highly variable and may last from one year to more than 15 years depending on local hydrodynamics and transport of sand. In-filling during one year with sediment similar to the surroundings was recorded in the Wadden Sea. Deposit of finer sediment was observed in early stages of an infilling lasting 3-4 years but the uppermost sediment of the filled pit consolidated and approached the surrounding sediment. Deposition of silt and organic matter may be extremely slow in calm environments. Development of harmful anoxic conditions in the bottom water was recorded in pits in the Baltic and the Wadden Sea.

Development of benthic communities in pits depends on rate of sedimentation and the types of deposits. Juveniles are more sensitive than adult and deposit of silt is more problematic than sand. Probably an extreme case is the development of sediment and benthic fauna in the deep crater “Figge Maar” in the German Bight created by gas eruption during exploration drilling in 1963 (Thatje et al., 1999). The crater is 400 m wide and the bottom was originally 30 m below seabed and 65 m below surface. The crater act as a trap and the average rate of sedimentation was 50 cm/year until 1992-96, where studies of sediment and benthic fauna were conducted. The sediment in the crater was much finer than the surroundings and silt/clay accounts for about 50%.

The abundance and the biomass of the benthic fauna were higher in the crater than in the surrounding seabed. The benthic community in the crater differed from the surrounding seabed and was totally dominated by juvenile echinoderms (the heart urchin *Echinocardium cordatum* and the brittle star *Amphiura filiformis*). The crater trap pelagic larvae and newly settled demersal drifters but the survival of juveniles are low. However, organic enrichment
in the crater was beneficial for the survivors and the number of adult echinoderms was in
general higher inside than outside the crater (Thatje et al., 1999).

5.3 Coastal zone management and ecological state indicators

Coastal State Indicators (CSI's) have been developed for Coastal Zone Management
purposes in the Netherlands. A CSI is defined as “a quantitative concept of the actual state
of the system as a basis for objective and transparent decision making”; or “a well defined
physical and/or ecological variable quantifying a socio-economic functional use of the
coastal zone”.

The physical impacts of large-scale sand mining on relevant CSI’s will be quantified in
SANDPIT on the basis of scenario testing and expressed as near and far field output
parameters.

As a supplement to the physical indicators a number of Ecological State Indicators, which
may be affected by sand mining, has been suggested in Table 5-2 and Table 5-3 for the near
and far field, respectively.

Table 5-2: Coastal and Ecological State Indicators for sand mining and Near Field output parameters.

<table>
<thead>
<tr>
<th>Function/uses</th>
<th>Coastal and Ecological State Indicators</th>
<th>Near Field – output parameters</th>
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<tbody>
<tr>
<td>Sand mining</td>
<td>Areas subject to shallow sand mining</td>
<td>Inside boundaries of sand mining areas:</td>
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<tr>
<td></td>
<td>(sandbanks)</td>
<td>Total amounts extracted and spilled</td>
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<tr>
<td></td>
<td>Areas subject to deep sand mining (pits)</td>
<td>Shallow dredging: Total surface area of seabed</td>
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<td>removed (Max 50% of area removed every</td>
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<td>fourth year is suggested)</td>
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<td>Shallow dredging: Total area affected by</td>
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<td>deposition exceeding 5 cm (suggested threshold</td>
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<td>for short term burial effects on epi-benthic</td>
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<td>species)</td>
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<td>Deep pits: Total area affected by deposition</td>
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<td>&gt;1 mm/day (1 mm/day suggested as a threshold</td>
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<td>for viable recruitment)</td>
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<td>Ecosystem</td>
<td>Areas of Habitats (appointed according to</td>
<td>Magnitude of and Area affected by changes in:</td>
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<td>Habitat and Bird Directives)</td>
<td>Current Waves</td>
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<td>and temporal zoning (access to fishing</td>
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<td>Fishery</td>
<td>Herring spawning areas</td>
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<td>Fishing grounds</td>
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</table>

Table 5-3: Coastal and Ecological State Indicators for sand mining and Near Field output parameters.

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<th>Near Field – output parameters</th>
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<td>Deep pits: Total area affected by deposition</td>
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<td>Sand mining areas subject to spatial</td>
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<td></td>
<td></td>
<td>and temporal zoning (access to fishing</td>
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<td>grounds)</td>
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</tbody>
</table>
Table 5-3  Coastal and Ecological State Indicators for sand mining and Far Field output parameters.

<table>
<thead>
<tr>
<th>Function/uses</th>
<th>Coastal and Ecological State Indicators</th>
<th>Far Field – output parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recreation</td>
<td>Beach width</td>
<td>Distance between MLW and MHW</td>
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<tr>
<td></td>
<td>Beach quality (sediment characteristic)</td>
<td>Median grain size (D$_{50}$) near shore</td>
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<tr>
<td></td>
<td>Swimmer safety</td>
<td>Max current velocities and direction near shore</td>
</tr>
<tr>
<td></td>
<td>Transparency of water</td>
<td>Max wave height &amp; direction near shore</td>
</tr>
<tr>
<td></td>
<td>Smothering of beaches</td>
<td>Areas affected by sediment plumes and reduced clarity of the water (A Secchi depth &gt;1m is a criteria for bathing water)</td>
</tr>
<tr>
<td>Ecosystem</td>
<td>Areas of Habitats (appointed according to Habitat and Bird Directives)</td>
<td>Magnitude of and Area affected by changes in:</td>
</tr>
<tr>
<td></td>
<td>Seagrass beds</td>
<td>Current</td>
</tr>
<tr>
<td>Fishery</td>
<td>Herring migration routes</td>
<td>Waves</td>
</tr>
<tr>
<td>And</td>
<td>Herring spawning areas</td>
<td>Water depth</td>
</tr>
<tr>
<td>And</td>
<td>Shellfish culture</td>
<td>Sediment characteristics</td>
</tr>
<tr>
<td>Mariculture</td>
<td>Aquaculture</td>
<td>Areas affected by increased rate of sedimentation (&gt;0.8 mm/day during a period of 2 month suggested as a threshold for seagrass)</td>
</tr>
<tr>
<td></td>
<td>Fishing grounds</td>
<td>Areas affected by sediment plumes (frequent exposure for plumes with concentrations of suspended sediment &gt;3 mg/l may affect migration of herring and movement of sensitive fish species)</td>
</tr>
</tbody>
</table>

5.3.1 Management and Ecological State Indicators in the near field

Extraction of large amounts of sand by shallow dredging will directly affect the benthic community in large seabed areas. A spatial and temporal zoning of the dredging activity will enhance physical and biological recovery of the disturbed seabed and minimise restrictions to other users of the sea, especially fishery. The seabed area removed and the frequency of dredging are two interrelated factors of decisive importance for the short and long term impact on the benthic community. Regulation of these factors individually or in combination enables an efficient and transparent management of shallow dredging. It is recommended to divide large extraction areas intended for shallow dredging in four sub-areas. As a starting point it is suggested that maximum 50% of the seabed surface of a sub-area should be removed every fourth year. This strategy will minimise the immediate impact of dredging and in most occasions also enable re-colonisation of long living species of bivalves and echinoderms. A “good” quality status in the sense of WFD may be achieved in the dredging areas following this strategy.

Monitoring in the extraction sub-areas and nearby similar reference areas should be used with the aim to optimise the extraction strategy in specific areas. It may be feasible to adjust the relation between percentage removal of the seabed habitat and the frequency of dredging. Monitoring should include measurements of the biomass of the benthic fauna. Biomass is indicative of the presence of large slow growing species and related to the production of the benthic community. Multivariate techniques (e.g. MDS) should be used to assess spatial impacts and temporal changes and the need of possible adjustments of the extraction strategy in specific areas. Multivariate methods are more sensitive than univariate measures and robust in the sense that rigorous and time-consuming identification to a species level is not needed.

Benthic in-fauna is in general tolerant to sediment spill and burial but may suffer from excessive deposition in undisturbed patches. Benthic epi-fauna is more sensitive and modest
acute deposition may reduce the abundance of e.g. horse mussels (*Modiolus modiolus*). However, coarse substrate with epi-benthic species and potential herring spawning grounds should be avoided in the near field of sand extraction areas.

Fishery is normally not allowed inside extraction areas during ongoing sand extraction. Spatial and temporal zoning is therefore a mean to minimise the restrictions imposed on fishery. Information on the frequency of bottom trawling in extraction areas and associated reference areas in non-dredging periods must be available for a proper assessment of post-dredging re-colonisation.

The post-dredging changes in sediment type after shallow dredging in sand extraction areas are likely to be rather limited but accumulation of silt must be expected in deep pits in most occasions. Post-dredging re-colonisation in deep pits depends on the rate of sedimentation and the oxygen condition in the bottom water. Deep pits trap larvae and recruits of benthic invertebrates and a few mobile species of echinoderms are able to survive sustained high rates of deposition. Development of unstable communities dominated by juveniles is a likely post-dredging scenario in deep pits.

### 5.3.2 Management and Ecological State Indicators in the far field

The possible ecological effects of sand extraction beyond the boundaries of extraction areas depend on excursion of surface and near bed sediment plumes and deposition of sediment. According to recent experience sediment plumes decay rapidly and deposition decreases fast with increasing distance from the source of sediment spill. However, long excursion of silt plumes and deposition of fines may potentially affect sensitive and/or prioritised components of the surrounding ecosystem and uses such as recreation, fishery and mariculture in the far field, cf. Table 5-3.

Potential impacts are related to concentrations of suspended sediment in the plumes and the frequency and duration of the exposure. The response of communities and populations to increased turbidity of the water and increased rate of deposition are site and species specific. The threshold limits suggested in Table 5-3 for survival of seagrass due to burial and migration of herrings must be regarded as tentative and may not be relevant or adequate for other species, specific areas or seasons.

In addition to direct and indirect effects of dredging in the far field overall changes in current, waves, depth and sediment characteristics may have subtle and not easily detectable effects on the structure of the benthic communities.

### 5.4 Conclusions

- Management and prediction of ecological effects of large scale sand mining based on present experience may be inadequate because the spatial and temporal scale of most studies are small compared to the possible scale of extraction activities in the future and precautions are advised.

- Large scale sand mining based on shallow dredging are in general characterised by short-term effects of large areas of the seabed. Advantages of shallow dredging are that (1) alteration of the seabed morphology and sediment type is reduced and (2) conditions for recovery of the seabed habitat and the benthic fauna are improved and (3) seabed suitable for trawling. A management approach based on spatial and temporal zoning
may further reduce the biological effects. The disadvantages of shallow dredging are (1) that extensive areas of the seabed are affected and (2) possible impacts on wave and current pattern.

- Large scales sand mining based on deep dredging are in general characterised by long-term effects of small sized areas of the seabed. Disadvantages of deep dredging are that pits (1) acts as trap for silt and organic matter, (2) enhance the possibility for stratification and development of oxygen deficiency in the bottom water, (3) hamper re-colonisation due to rapid infilling, siltation and poor water quality, (4) prolong recovery of the seabed habitat and change benthic community and that (5) seabed morphology is unsuitable for trawling in addition to (6) possible effects on wave and current pattern.

- Management tools are available to predict physical, chemical and biological impacts of sand extraction and to map physical changes of the seabed habitat with high resolution in the near field. The ecological effects are caused by the physical changes but biological monitoring based on sampling and analysis of biota is still necessary to assess changes in community attributes (species, abundance and biomass) and benthic community structure in relation to simulated output parameters.

- Prediction and management of potential ecological effects in the far field is complicated due to inadequate information on potential resources, which may be affected by sand extraction and the fact that potential impacts of simulated output parameters may interact with other sources of disturbance.
6 References


DHI, VKI & Geografisk Institut (1993). Environmental Impact Assessment of planned deepening of the access channel to the harbour of Esbjerg in the Danish Wadden Sea. Report to Harbour Authority of Esbjerg (in Danish).


# A Glossary of biological and ecological terms

In this appendix an overview is given on biological and ecological terms that are used in this report.

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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</thead>
<tbody>
<tr>
<td><strong>Abundance</strong></td>
<td>The number of organisms in a population, combining 'intensity' (density within inhabited areas) and 'prevalence' (number and size of inhabited areas).</td>
</tr>
<tr>
<td><strong>Benthic</strong></td>
<td>Occurring at the bottom of a body of water, for example, a seabed, riverbed, or lake bottom.</td>
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<tr>
<td><strong>Benthos</strong></td>
<td>In freshwater and marine ecosystems, the collection of organisms both attached to or resting on the bottom sediments and burrowed into the sediments. In terms of size, benthos are generally divided into three categories: meiobenthos, the organisms that pass through a 0.5 millimeter sieve; macrobenthos, those that are caught by grabs or dredges but retained on the 0.5 millimeter sieve, and epibenthos, those organisms than live on rather than in the seabed.</td>
</tr>
<tr>
<td><strong>Biogenic</strong></td>
<td>Formed by the action of biological organisms</td>
</tr>
<tr>
<td><strong>Biomass</strong></td>
<td>The total weight of all living organisms in a biological community</td>
</tr>
<tr>
<td><strong>Bivalve</strong></td>
<td>A mollusc with a bilaterally symmetrical two-part external shell that completely encloses the body (including clams, oysters, and mussels).</td>
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<tr>
<td><strong>Community</strong></td>
<td>The species that occur together in space and time.</td>
</tr>
<tr>
<td><strong>Demersal</strong></td>
<td>Living at or near the sea floor but having the capacity for active swimming</td>
</tr>
<tr>
<td><strong>Echinoderm</strong></td>
<td>Any of a phylum (Echino-dermata) of radially symmetrical coelomate marine animals including the starfishes, sea urchins, and related forms</td>
</tr>
<tr>
<td><strong>Epi-fauna</strong></td>
<td>Animals living on the surface of the bottom or floor of a water body</td>
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<tr>
<td><strong>Fauna</strong></td>
<td>Plant life</td>
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<tr>
<td><strong>Flora</strong></td>
<td>Animal life</td>
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<tr>
<td><strong>In-fauna</strong></td>
<td>Benthic organisms that dig into the sea bed or construct tubes or burrows. They are most common in the subtidal and deeper zones</td>
</tr>
<tr>
<td><strong>Invertebrates</strong></td>
<td>An animal without a backbone, such as snails, worms, and insects.</td>
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<tr>
<td><strong>Lipids</strong></td>
<td>An essential structural component of living cells, lipids are a class of oily organic compounds which are insoluble in water but soluble in</td>
</tr>
</tbody>
</table>
fats and oils. The lipid class of molecules mainly consists of fats, oils and waxes.

**Macroalgae**  Multicellular, large algae, resembling vascular plants but lacking advanced reproductive and water management systems (e.g., kelp).

**Macrofauna**  Animals large enough to be seen with the naked eye.

**Mortality**  The number of organisms lost or the rate of loss.

**Pelagic**  Free swimming throughout the water column (not restricted to specific micro-environments like the sea floor).

**Photic zone**  The surface zone of the sea or a lake having sufficient light penetration for photosynthesis.

**Phytoplankton**  One of two groups into which plankton are divided, the other being zooplankton. Phytoplankton comprise all the freely floating photosynthetic forms in the oceans.

**Polychaetes**  Any of a class (Polychaeta) of chiefly marine annelid worms (such as clam worms), usually with paired segmental appendages, separate sexes, and a free-swimming trochophore larva.

**Primary production**  The biomass produced through photosynthesis and chemosynthesis in a community or group of communities.

**Recruitment**  Additions to a population, either through birth or immigration, or, in the case of net recruitment, the differences between such additions and the losses resulting from death or emigration.

**Sessile organism**  Literally a 'seated' organism. One whose position is fixed in space except during a dispersal phase, e.g. a rooted plant, barnacles, mussels (*Mytilus*), corals.

**Taxon (taxa)**  Any organism or group of organisms of the same taxonomic rank; for example, members of an order, family, genus, or species.
### Dredging site and surveys

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Depth</th>
<th>Dredging method</th>
<th>Amount and size of extraction area</th>
<th>% of surface area removed</th>
<th>Sealed</th>
<th>Benthic fauna</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine sand (125-154 µm), 1-8 (30%) silt Inter- and sub-tidal Anchor with overflow.</td>
<td>0.15 – 1 mio m³</td>
<td>Pins up to 10 m deep</td>
<td>Time of in-filling: Tidal flat: &gt;13-16y (fine sediment with high content of silt. Black and almost anaerobic sediment); Tidal channel: 1 &gt;4y. Watershed: 1y (sediment only slightly finer than surroundings.)</td>
<td>S: Tidal flat: 0%. Tidal channel: 57-88%. Watershed: 86%. B: Tidal flat: 0%. Tidal channel: 67-120%. Watershed: 40%</td>
<td>S: Species composition similar to surroundings. Tidal flat: fast recovery (&gt;1y) probably caused by immigration of adults.</td>
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### The Wash (SE England). Dredging of outer (1975) and inner (1972) borrow pits. Pre-and post-dredging surveys 1975-1979 of outer pit 4 years post-dredging survey of inner pit

<p>| Outer pit: Fine sandflat with 2-4% org. matter. Inner pit: Silt-clay mudflat with 12% org. matter | Outer: ? | Outer pit: 0.5 mio m³ 0.074 km² Inner pit: 0.02 km² | In-filling of outer pit: 1 y: rate 2-4 m³y 2 y: 69% filled (rate 1-1.5 m³y of Anaerobic silt) &gt;2 y: mostly fine sand. 3.5 y: Completely in-filled. Inner pit: 4y: almost in-filled with soft (unconsolidated) sand, but coarser than flat. | Outer pit: S: 4y: almost 100%. A: 4y: &gt;100%. CS: Increased dominance of previous dominant species. Inner pit: S: 4y: 100%. A: 4y: &gt;100% | Only <em>Nephys hombergi</em> during early in-filling. After 2y followed by a dominance of <em>Macoma, Cardium and Pygospio</em>. Inner Pit: dominance of opportunistic species (<em>Tubificoides benedeni)</em> | McGregor &amp; Reading, 1984 |</p>
<table>
<thead>
<tr>
<th>Dredging site and surveys</th>
<th>Substrate</th>
<th>Depth</th>
<th>Dredging method</th>
<th>Seabed Impact on seabed</th>
<th>Seabed Recovery or change of seabed</th>
<th>Benthic fauna Effects on: S: species; A: abundance; B: biomass; CS: Community structure</th>
<th>Recovery of S: species; A: abundance; B: biomass; CS: Community structure</th>
<th>Recovery or change of dominant species</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNEXO. Experimental pit 1980. 15 years post-dredging survey in 1995</td>
<td>Fine sand</td>
<td>22 m.  Ref. 17 m</td>
<td>Anchor</td>
<td>Lowered 5-12 m</td>
<td>No in-fill in deeper part (12 m). Limited in-fill and slumping of pit wall of shallow part (5 m) of fine muddy sand with 2.9% silt vs. 0.6% silt in Ref.</td>
<td>15 years: SAB: (200-300% of Ref.). CS: dominance of mud-dwelling species (sand-dwelling species in Ref.)</td>
<td>Dominant mud-dwelling species: Crustacea Echinoderm (presence of fish and crabs)</td>
<td>Desprez, 2000</td>
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<tr>
<td>Baltic Sea (Koge Bay). Dredging: 1987-88. Surveys 1987-1989</td>
<td>Fine sand</td>
<td>12-16 m</td>
<td>Anchor and Trailer</td>
<td>3 mio m³</td>
<td>Anchor: pits: up to 10 m. Trailer: seabed lowered up to 1.5-2 m</td>
<td>Anchor: Sand ripples in the top 7 m of pits. Accumulation of debris and anoxic conditions in the bottom of pits. Trailer: 17 m. Tracks eroded but clearly visible with finer sediment and small sand ripples. Seabed still lowered 1-1.5 m</td>
<td>Anchor: Normal fauna in the top 6-7 m of the pits. Trailer: 7 m. Scoloplos armiger abundant and some lugworms S: 17 m (100%). A: 17 m (20-85%) B: 17 m (20-70%)</td>
<td>Nortdalen andersen et al., 1992</td>
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<tr>
<td>Dredging site and surveys</td>
<td>Substrate</td>
<td>Depth</td>
<td>Dredging method</td>
<td>Amount and size of extraction area</td>
<td>% of surface area removed</td>
<td>Seabed</td>
<td>Benthic fauna</td>
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<tr>
<td>The North Sea. The west coast of Jutland off Thorsminde. Dredging: 1993. Surveys: 1994 and 1995 (1 and 2 years post-dredging)</td>
<td>Fine to coarse sand</td>
<td>16-18m</td>
<td>Trailer</td>
<td>0.25 mio m³</td>
<td>About 30%</td>
<td>1 year post-dredging: No effect of dredging</td>
<td>I year post-dredging: No effect on SAB. Increase in abundance of opportunistic polychaetes</td>
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<td>Western Mediterranean. Dredging Sep.-Dec. 1993. Survey: Before and 3 month post-dredging</td>
<td>Fine sand (100-150 µm)</td>
<td>16-20m</td>
<td>Pin up to 2m</td>
<td>2.6 mio m³ 2mo: 5-20cm layers of silt (16-18µm). Ly: 27% silt in sediment</td>
<td>Pin up to 2m</td>
<td>Commercial molluscs almost completely eliminated</td>
<td>3mo: Dense populations of opportunistic polychaetes, no molluscs Capitella capitate; Malaespera sp.</td>
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</table>

References:
Van Dalen et al., 2000
<table>
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<tr>
<th>Dredging site and surveys</th>
<th>Substrate</th>
<th>Depth</th>
<th>Dredging method</th>
<th>Amount and size of extraction area</th>
<th>% of surface area removed</th>
<th>Impact on seabed</th>
<th>Seabed Recovery or change of Effects on S: species; A: abundance; B: biomass; CS: community structure</th>
<th>Benthic fauna Recovery of S: species; A: abundance; B: biomass; CS: Community structure</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western Mediterranean, Dredging: 1994. Survey: before (1992) and 1 and 2 years post-dredging (1995 and 1996)</td>
<td>Medium to coarse sand, M&lt;sub&gt;2&lt;/sub&gt; 575µm and 0.25% silt</td>
<td>10-30m</td>
<td>Trailer?</td>
<td>0.15 km&lt;sup&gt;2&lt;/sup&gt;</td>
<td>50%</td>
<td>Increase in fine fraction (silt) + organic matter. &lt;1 y: recovery to pre-dredging (coarser) grain size</td>
<td>Almost complete defaunation (only a few Capitella capitata in tracks)</td>
<td>&lt;1 y: fast recovery above normal spring recruitment (A, B &gt;100%). 2 y: normal recruitment. &gt;2 y: recovery of all species. Post-dredging bivalve fisheries reduced 50%</td>
<td>Sarda et al, 2000</td>
</tr>
<tr>
<td>Baltic Sea (Raisio Bay), Dredging of navigation channel: Sept. 1976. 2 years post-dredging surveys</td>
<td>Mud</td>
<td>8-9m</td>
<td>0.8 mio.m&lt;sup&gt;2&lt;/sup&gt;</td>
<td>100% (channel 200 wide)</td>
<td>Lowered from 2-5 m to 8-9 m</td>
<td>None – Access channel</td>
<td>Benthic fauna eliminated</td>
<td>&lt;1 y: colonization (similar to reference)</td>
<td>N. diversicolor (adult). Oligochaeta (larvae). C. vulnator (adult + juveniles). Macoma balatica (immigration of adults in less than 1 y)</td>
</tr>
<tr>
<td>Baltic Sea (Degersand Bay)</td>
<td>Sand</td>
<td>Small scale dredging</td>
<td>S: 1 y: 85% A: 1y: 80% B: 1y: 85% 5y: full recovery</td>
<td>Bonsdorff et al, 1986</td>
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<tr>
<td>Dredging site and surveys</td>
<td>Substrate</td>
<td>Depth</td>
<td>Dredging method</td>
<td>Amount and size of extraction area</td>
<td>% of surface area removed</td>
<td>Seabed</td>
<td>Recovery or change of seabed</td>
<td>Effects on: S: species; A: abundance; B: biomass; CS: community structure</td>
<td>Recovery of S: species; A: abundance; B: biomass; CS: dominant species</td>
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<tr>
<td>Bay of Brest. Dredging 1977-Aug 1978. Survey: 3 years post-dredging (May 1978 to April 1981). (Low diversity 44 species recorded)</td>
<td>Sandy mud</td>
<td>4.3 mio m²</td>
<td></td>
<td></td>
<td></td>
<td>Silt increased from 47-70%. Re-deposition due to changed currents (reclamation). Organic matter 8.7% (affected of nearby effluent). Progressive oxidation of surface sediment in parallel with re-colonisation (bioturbation)</td>
<td>S: 2-30.1 m²: A: 100.1 m²: B: 2 g/m². Almost defaunated except for a few Abris abu and Nephtys hombergi</td>
<td>S: 15 y: 7/0.1m²: S: 2.5 y: 20.01 m²: A: 1 y: increased 30 times. A: 2 y: &gt; 30 times increase. B: 1 y: 7g/m². B: 2 y: 11g/m². Apparently further increase in SAB after 3 years. CS: quantitative changes of the same community. No qualitative changes (unstable community naturally dominated by opportunists)</td>
<td>S: ~50% A: ~60% Enhancement of S: (+118%) and A (+32.3%) up to 2000m from the dredging area</td>
</tr>
<tr>
<td>Moreton Bay (Australian). Dredging 1981-83. Survey 1982</td>
<td>Medium to fine sand (6-10% silt)</td>
<td>10-20m</td>
<td></td>
<td>14 mio m²</td>
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</table>
### Summary tables gravel

<table>
<thead>
<tr>
<th>Dredging site and surveys</th>
<th>Substrate</th>
<th>Depth</th>
<th>Dredging method</th>
<th>Amount of area removed</th>
<th>Seabed</th>
<th>Benthic fauna</th>
<th>Effects on: S: species; A: abundance; B: biomass; CS: community structure</th>
<th>Recovery or change of dominant species</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Norfolk. Experimental dredging including Ref. site in April 1992. Survey: Early post-dredging (1-8 months)</td>
<td>Mixed gravel and sand. (30% gravel)</td>
<td>Trailer</td>
<td>25,000 m³ 0.135 km²</td>
<td>Tracks 1-2m wide and 0.3-0.5m deep. Seabed lowered up to 2m</td>
<td>0.5 m. Mobile 1-2 cm sand rippled. Increase of sand granule fraction to 50% due to exposure of deeper layer of gravel</td>
<td>S. 1 mo. -66%. A: 1 S: 8 mo. 65% Ref. A: 8 mo. 30%. Ref B: 8 mo. 6% Ref. CS: 8 mo. Approach Ref and pre-dredging S: 1mo. separate clusters and increased variance.</td>
<td>Recovery of: S: species; A: abundance; B: biomass; CS: Community structure</td>
<td>8 mo. Dendrodoa Balanus (recruits same dominant opportunists species as pre-dredging)</td>
<td>Kenny &amp; Rees, 1994</td>
</tr>
<tr>
<td>North Norfolk. Dredging: April 1992. Survey: 1 and 2 years post-dredging</td>
<td>Mixed gravel and sand. (30% gravel)</td>
<td>Trailer</td>
<td>25,000 m³ 0.135 km²</td>
<td>Tracks 1-2m wide and 0.3-0.5m deep. Seabed lowered up to 2m</td>
<td>1 y: weathered tracks still visible; 2 y: tracks further eroded and just visible (side scan sonar)</td>
<td>S: 1 y (67% = Ref.). A: 2 y (30% Ref.). B: 2 y (&lt;10% Ref.). CS: clusters 1 y + 2 y are similar no further recovery (due to destabilised sediment and sand scouring of epibenthos on gravel)</td>
<td>Lower post-dredging abundance and lower mean size of the two dominant species</td>
<td>Kenny &amp; Rees, 1996</td>
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<tr>
<td>North Norfolk. Dredging: April 1992. Survey: 3 years post-dredging</td>
<td>Mixed gravel and sand. (30% gravel)</td>
<td>Trailer</td>
<td>25,000 m³ 0.135 km²</td>
<td>Tracks 1-2m wide and 0.3-0.5m deep. Seabed lowered up to 2m</td>
<td>3 y: sediment composition similar to 2 y post-dredging</td>
<td>S: 3 y (100% Ref.). A: 3 y (30% Ref.). B: 3 y (70% Ref.). CS: 3 y Dredging and Ref. site are similar and both sites have changed</td>
<td>Dominant species similar before and after dredging (indicate high natural disturbance)</td>
<td>Kenny et al, 1998</td>
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<td>Dieppe (eastern English Channel). Commercial site used in 1980-1994 Monitoring since 1979 and post-dredging surveys in 1995-97</td>
<td>Heterogeneous gravel and coarse sand</td>
<td>Trailer</td>
<td>15 m 0.2-0.4 m³/yr. 1986-94: 50 m³/yr. 1980-85: 1.5 km²</td>
<td>Lowered up to 2m. Progressively dominated by fine sand in tracks due to overflow of bed load transport. Similar sand deposits 200 m North and South of dredging site. Megaripples of sand in big furrows (Trawling efficiency reduced because of uneven seabed. No dredging in Oct.-Feb. to protect Herring fishery.</td>
<td>1993: S: -63%. A: 86% B: -83%</td>
<td>Dredging site: S: 16 mo. (100% of Ref.). A: 28 mo. 60% of Ref.). B: 28 mo. (75% of Ref.). CS: Changed completely to dominance of errant polychaetes. Sedimentation area 200 m North is more disturbed than dredging site.</td>
<td>Community changed from species affiliated to coarse sand (Branchiostoma) to species characteristic of fine sand (Ophiola, Nephtys, Spiophiene, and Pomatoceros on gravel)</td>
<td>Desprez, 2000</td>
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<td>Dredging site and surveys</td>
<td>Substrate</td>
<td>Depth</td>
<td>Dredging method</td>
<td>Amount and size of extraction area</td>
<td>% of surface area removed</td>
<td>Sealed</td>
<td>Effects on: S: species; A: abundance; B: biomass; CS: community structure</td>
<td>Benthic fauna</td>
<td>Recovery or change of dominant species</td>
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<td>English Channel (east of Heterogeneous 10-20m Isle of Wight): Ongoing on dredging in Area 122/3 (1968) and Area 351 (1989): Transect study in sandy gravel and sand</td>
<td>Gravel and sand</td>
<td>4-10m</td>
<td>No screening</td>
<td>Area 351: 250,000 m³ in 1999; Area 122/3: 70,000 m³ in 1999. Reject of anchor dredging 0.08%</td>
<td>Centre: &gt;100%</td>
<td>Area 122/3: lowered up to 8-10m</td>
<td>S: High 25% of Ref (Low = Ref.). A: High 12% and Low 54% of Ref. B: High 3% of Ref. CS: High cluster separate from Ref. Low: intermediate. Dredging intensity the most important single factor, especially in 1995.</td>
<td>trailer: Fauna disturbed in centre. Filter feeders abundant 500-1000m downstream due to settlement of organic matter (enrichment ?).</td>
<td>Trailer: Balanus crenatus abundant inside dredging area.</td>
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<tr>
<td>English Channel (east of &gt;50-60% Isle of Wight). Area 122/3: Dredging since 1989. Survey in 1990 inside and outside anchor and trailer dredging sites</td>
<td>Gravel and sand</td>
<td>4-10m</td>
<td>No screening</td>
<td>Anchor: 150,000 m³/y (mainly Anchor). 4-10m deep and 50m wide holes</td>
<td>Anchor: 100%</td>
<td>Physical impact limited to 300m downstream (including deposition). ADCP: near bed plume 2.4 m thick a few tens of meters wide</td>
<td>Anchor: Fauna disturbed by anchor. Anchor: 1-18m S; &lt;13% A: -88 to 82%. B: -98 to 36%. Trailer: 1-3m S: -38 to 7%. A: -69 to 85%. B: -87 to 36%. SAB: Zone 0.6m upstream and 2km downstream with enhanced S (148%), A (262%) and B (419%). Organic enrichment ?</td>
<td>Anchor: Dominance of opportunistic Polychaetes (Notopterus, Capitellum).</td>
<td>Hitchcock &amp; Bell, 2004</td>
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