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Sediment dynamics in relation to sediment trend monitoring

Maria J. Belzunce • Bernard Boutier • Hanneke Gieske

Jean Louis González • Per Jonson • Claire Mason

Els Monteyne • Stefan Schmolke • Birgit Schubert

ICES International Council for the Exploration of the Sea

CIEM Conseil International pour l'Exploration de la Mer

International Council for the Exploration of the Sea
Conseil International pour l'Exploration de la Mer
H. C. Andersens Boulevard 44–46
DK-1553 Copenhagen V
Denmark
Telephone (+45) 33 38 67 00
Telefax (+45) 33 93 42 15
www.ices.dk
info@ices.dk

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Contents

1 Introduction

This report discusses the underlying processes of sediment dynamics in the North Sea, the Baltic Sea, and several estuaries in order to indicate the broad range of conditions that exist within the ICES Area. It is important to be aware of these processes when designing monitoring programmes in order to ensure that the data collected can be the foundation of a more meaningful interpretation. This introductory section does not seek to define which monitoring strategies should be used, but demonstrates that it is necessary to consider the sediment dynamics present in the area being studied when designing a monitoring programme.

Time-trends in contaminant, nutrient, and carbon concentrations in sediments are usually inferred from sediment cores or from surface sediments taken during repeated sampling exercises. Physical, chemical, and biological processes, all components of sediment dynamics, can affect the concentration of contaminants.

Physical processes include erosion, transport, deposition, and resuspension. These processes are driven by various different forces, such as isostatic movement, tidal and wind-driven currents, and density currents. For example, in the Baltic Sea, increased eutrophication may lead to deep-water oxygen deficiency that subsequently causes the creation of laminated sediments, and these apparently allow a strong down-core time-control on contaminant input. However, these down-core trends may be distorted by several processes, including the increased input of clean sediment resulting from increased wind-driven erosion of glacial clays that are subject to isostatic uplift. In the North Sea, the upper 10 cm of sediment in a sandy area may reflect contaminant input during the most recent months, or even days, because of the constant reworking of the sediment and potentially large bulk-sediment movement, while the upper 10 cm of sediment in a muddy depositional area with a slow deposition rate may represent accumulation over the last 25–50 years or more.

There are several different systems of classifying bottom types, based on their physical and chemical properties. The following sediment classification system (Håkanson and Jansson, 1983) has been used in this report.

- **Depositional (i.e. accumulation) areas** – dominated by the continuous deposition of fine materials with grain sizes of <60 μm.
- **Transportational areas** – characterized by the discontinuous deposition of fine particles/aggregates, i.e. periods of accumulation are interrupted by periods of resuspension and transportation.
- **Erosional areas** – where erosion of sediment predominates.

Any classification is a simplification of reality, and gradations between the three types occur.

Chemical processes affecting contaminant accumulation and profiles in sediment include early diagenetic processes, such as redox processes and authigenic formation of minerals. Inflow of oxic water into the Baltic Sea may cause changes from anoxic to oxic conditions, resulting in a release from the sediments of easily mobilized metals, such as Cd, into the overlying water mass, possibly leading to increased Cd concentrations in biota at that time.

Biological processes include bioturbation, eutrophication, and degradation of organic matter. Bioturbation in the muddy areas of the North Sea causes a strong mixing of the sediment, effectively obliterating fine-scale, down-core time-trends. An oxic event in the Baltic Sea, such as that described above, could lead to benthic recolonization, causing bioturbation of the upper centimetres of the laminated sediments and mixing of the sedimentation record over a period of years.

This background information concerning the importance of knowledge of sediment dynamics for design and interpretation of monitoring data is amplified in subsequent sections. Sediment dynamic processes and their effect on the sediment composition are elaborated for the North Sea (Netherlands continental shelf; Section 2) and the Baltic Sea (Section 3). Possible changes in sediment dynamics as a result of climate change in the Bay of Biscay are discussed in Section 4. Sediment dynamics in several estuaries are considered and discussed using case studies in Section 5. The conclusions are summarized in Section 6, and references are listed in Section 7.

2 North Sea (Netherlands continental shelf)

2.1 Description of the sediment dynamics and sedimentological characteristics in the North Sea

2.1.1 Depositional areas

There are few areas of sediment accumulation in the North Sea. The main depositional areas are the Oyster Grounds, German Bight, Outer Silver Pit, Kattegat, Norwegian Trench, and Skagerrak. These are found in hydrodynamically less energetic environments, below the fair-weather wave base, where tidal currents are weak (e.g. near amphidromic points). Muddy fine sands occur, and sediment accumulation rates are low (e.g. 2–4 mm $year^{-1}$ for the Oyster Grounds).

2.1.2 Transportational areas (no net deposition or erosion)

In the Dutch coastal zone, waves and tides determine the hydrodynamic conditions to a depth of 20 m. The sands are usually coarse, with a maximum mud content of 1–2%. Wave and storm action dominate at the upper shore face. A sand-bar system occurs near the shore. When wave action is dominant, the orbital water movement moves the sand grains to and fro, forming thin sediment laminae in the seabed. Waves stir up the sediment during storms, and the sand subsequently settles out of suspension, the coarser grains first, resulting in a graded deposit called a "storm deposit". In the deeper parts of the foreshore, tidal currents move sand grains in the direction of the main axes of the tidal ellipse. The net residual current along a large part of the coast is directed northwards (Figure 1). Sand transport by tidal currents may result in thin, inclined (sometimes bidirectional) sediment layers. The interaction between waves, storms, and tides results in complex sedimentological structures, but subsequent bioturbation often obliterates these completely.

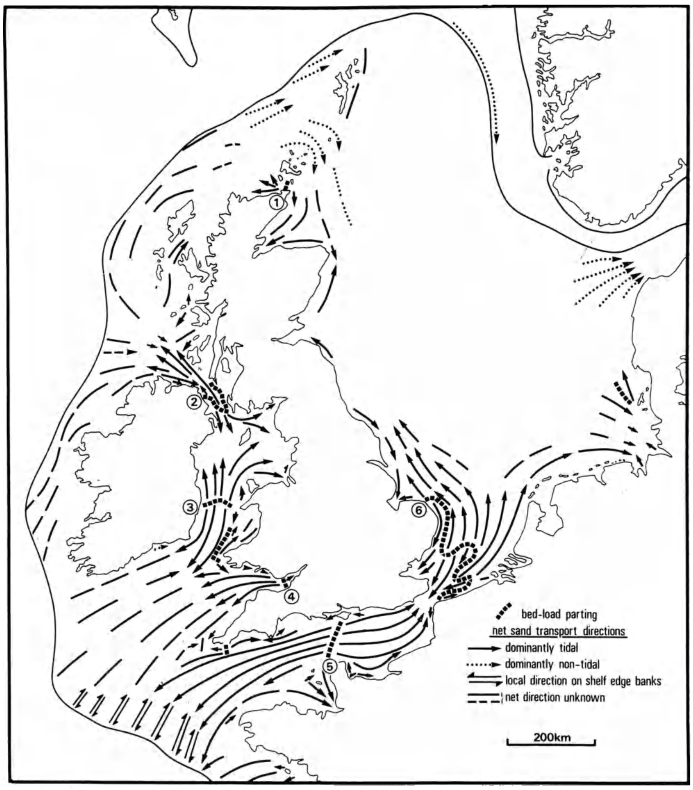

Figure 1. Net sand transport directions in the North Sea (Johnson *et al.*, 1982).

In the shallow shelf waters (20–30 m depth), the hydrodynamic conditions are determined by tides and occasionally by storms. Here, an extensive sand-wave field occurs, with megaripples on one or both sides. These bedforms result from bedload transport of sand grains by dominantly unidirectional (residual) tidal currents, whereby the sand grains are deposited at the lee side of the bedform. The sand waves typically range from several hundred metres to more than a kilometre in length and are up to 8 m high. The superimposed megaripples are typically several decimetres long and from several decimetres to 2 m high. In some areas, the sand waves move several metres each year in the direction of the net residual current (Figure 1). In other areas, when ebb and flood currents are of equal strength, the sand waves merely oscillate about a mean position. The megaripples built up during summer on one or both sides of the sand waves are usually washed away during winter storms. The creation of these bedforms results in thin, inclined sediment layers, the so-called "cross bedding". Storm waves may occasionally touch the seabed, and storm deposits may be formed. Sand banks also occur, but these do not seem to play a significant role in sediment transport.

2.1.3 Erosional areas

Locally, areas occur where net erosion takes place, exposing older, Pleistocene deposits at the seafloor. These erosional areas are found in the coastal zone, as well as in the sand-wave field.

2.2 Dynamic processes affecting contaminant concentrations

2.2.1 Transport of suspended matter

Suspended matter is the main carrier of contaminants. Transport of suspended matter is closely related to the circulation of water masses in the North Sea, which is generated by residual tidal currents (Figure 2). Sources of suspended matter include (estimates from various authors and OSPAR, 2000): Channel water (14 and 44 Mt year^{-1}), North Atlantic water (11–13 Mt year^{-1}), Baltic (0.5 Mt year^{-1}), erosion of English coast (Holderness, 1.4–2.6 Mt year^{-1}; Norfolk and Suffolk, 0.7–6.3 Mt year^{-1}), seabed erosion (Flemish banks, 1–2.4 Mt year^{-1}; all, 9–13.5 Mt year^{-1}), input from rivers (4.8 Mt year^{-1}), primary production (1 Mt year^{-1}), and atmospheric deposition (1.6 Mt year^{-1}). Concentrations of suspended particulate matter (SPM) in winter are about twice those measured in the quieter summer.

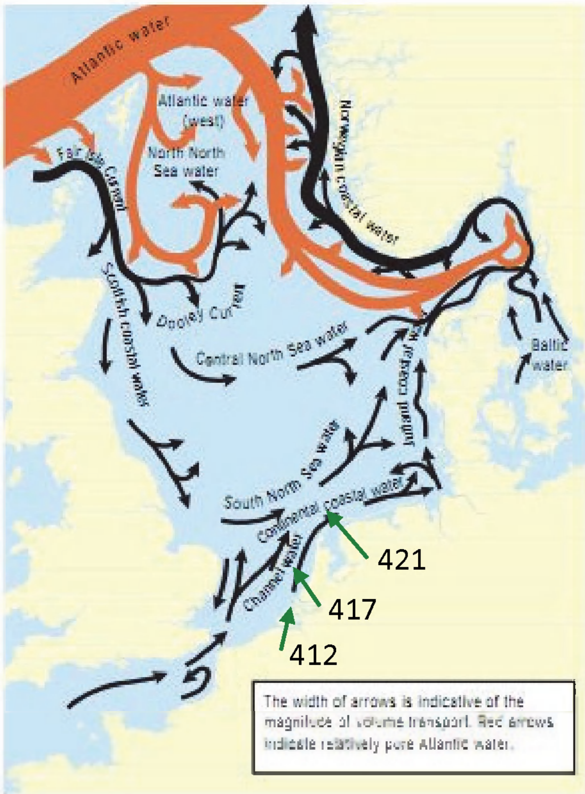

Figure 2. Circulation of water masses in the North Sea (OSPAR, 2000). Locations of cores 98dw412, 417, and 421.

2.2.2 Exchange of mud between the water column and the sediment in the transportational area

The upper sediment layer that is reworked by wave and tide action is defined as the "active layer". The depth of the active layer can be determined using its sedimentological and geochemical characteristics; for example, the active layer usually shows a uniform concentration of Pb, Zn, and Pb isotope ratios, whereas the sediment below the active layer usually shows background concentrations for these components. Typical profiles for the sandy area are shown in Figures 3 and 4. It appears that the active layer is usually at a depth between 15 and 40 cm in the transportational area (Gieske *et al*., 1999). This suggests that the upper, most recently deposited sediment layer in the coastal area and sand-wave field probably reflects the very recent deposition of mud present in the water column. Deposition occurs over a shorter time-scale (days to months) than the changes in the contaminant load on the suspended mud.

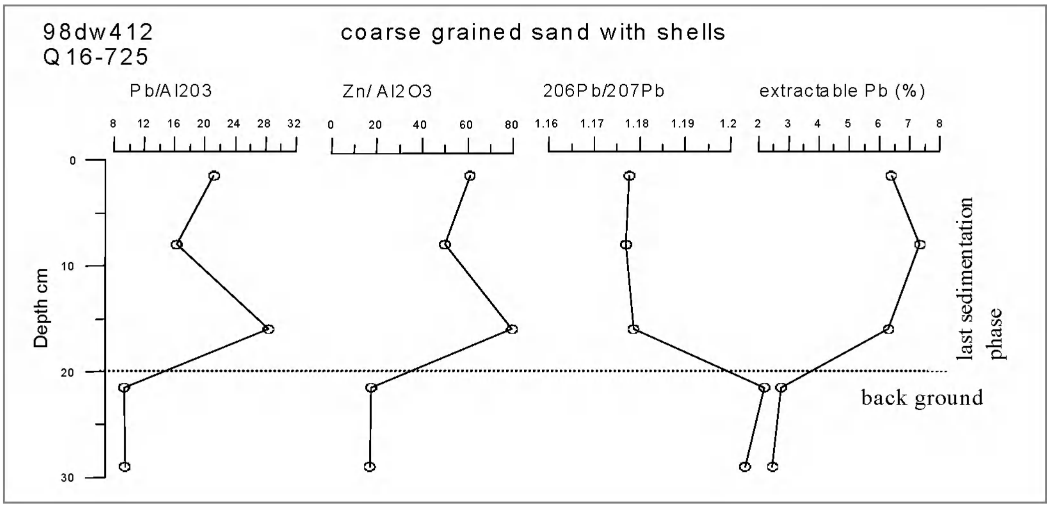

Figure 3. Pb and Zn, normalized to Al_2O_3, and Pb isotopic ratios in a core in the coastal area (transportational area).

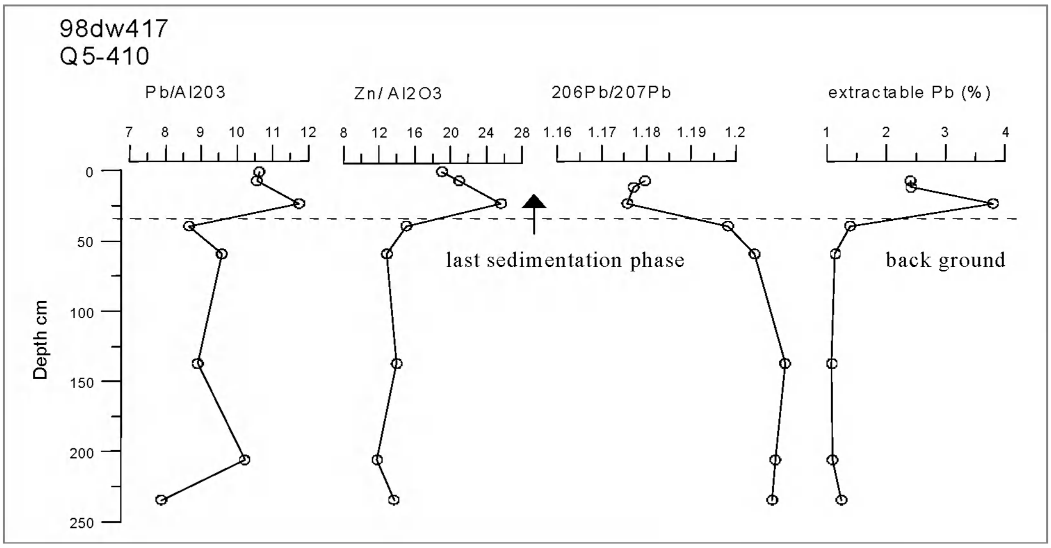

Figure 4. Pb and Zn, normalized to Al_2O_3, and Pb isotopic ratios in a core in the sand-wave area (transportational area).

2.2.3 Bioturbation in the depositional area

Bioturbation occurs everywhere in the North Sea, but is especially important in muddy areas. In the muddy sediments of the Oyster Grounds, a gradual decrease in background concentrations of Pb, Zn, and the Pb isotopes was found at a depth of approximately 40–50 cm (Gieske *et al.*, 1999). This was attributed to bioturbation. A typical profile for the depositional area is shown in Figure 5 .

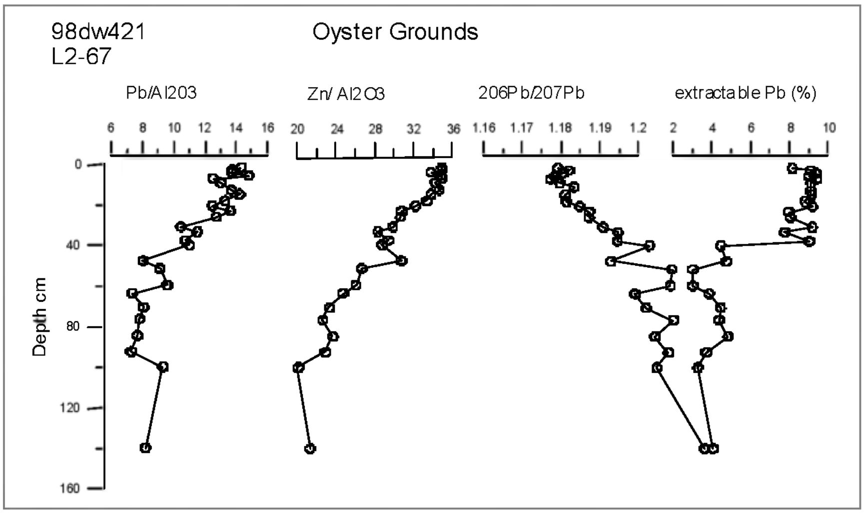

Figure 5. Pb and Zn, normalized to Al_2O_3, and Pb isotopic ratios in a depositional area (the Oyster Grounds).

2.2.4 Redox status

All sediments off the coast of the Netherlands are oxic in the upper centimetres and occasionally to a depth of 20 cm. Owing to the low organic carbon concentrations (<0.05% in the sandy areas, <1% in the depositional area), the reduction capacity is relatively small, although remobilization of Fe and Mn at a depth of several cm occurs as well as formation of Fe and Mn oxides at the sediment–water interface (Slomp, 1997). Redox-driven mobilization and precipitation are considered to be minor influences on the concentrations of metals in the sediments.

Table 1. Characteristics of North Sea sediments.

Characteristic	Transportational Area	Depositional Area
Grain size	200 - 500 µm	100 - 150 µm
Mud content	0 - 2%	10 - 50%
TOC (total organic carbon) content	0 - 0.05%	0.1 - 1%
Redox conditions	Upper cm to dm: oxic	Upper cm: oxic
Dynamics	Upper 15 - 40 cm: mechanically reworked	Sedimentation rate (Oyster Grounds): 0.2 - 0.4 cm year^{-1} Upper 40 - 50 cm: bioturbated
Distribution of heavy metals	Homogeneous in the active layer	Slow decline to background values

2.3 Implications for time-trend monitoring

The implications for time-trend monitoring in the North Sea can be summarized as follows.

- **Depositional areas**. Time-trend monitoring can be undertaken in these areas using cores or repeated sampling. However, because of the rather slow sedimentation rates and strong bioturbation, it is difficult to establish precise links with inputs of contaminants. To a degree, these can be mitigated by the selection of a particular sampling strategy, such as sampling only the upper few millimetres of sediment.
- **Transportational areas**. Here, the upper 15–40 cm reflects the latest quality status of the mud. Data from subsequent sampling exercises can be used for time-trend monitoring.

- **Erosional areas**. Data from these areas will not be useful in the context of correlations between current inputs of contaminants and concentrations in sediments. Repeated sampling and time-trend monitoring can show how conditions experienced by benthic organisms at the sampling site change with time, but they cannot be linked to current pollution and are not amenable to improvement through control measures.

3 The Baltic Sea

3.1 Depositional areas

Compared with the North Sea, large areas of the Baltic Sea are classed as depositional area for fine material. Although it may vary in different parts of the Baltic Sea, an average of 30% of the bottom in offshore areas is considered to be of this type. In general, depositional areas are found at depths greater than 75–80 m, although deposition can occur at shallower depths in topographic depressions and at depths of as little as 50 m in wind-exposed areas. The deposition rate of the surficial sediment is generally between 0.1 and 0.4 cm year^{-1}.

The depositional areas may be divided into areas of (i) bioturbated sediments, and (ii) azooic laminated sediments. In the bioturbated sediments, animals cause a more or less effective mixing of the upper sediment column over depths ranging from millimetres to several decimetres. Concentration profiles in the sediments may become more or less obscured owing to the abundance and bioturbating activity of the benthic fauna.

3.2 Transportational areas

Approximately 40% of the bottom area of the Baltic Sea is classed as transportational areas. These areas may be characterized as the transition zone through which eroded/resuspended sediments are transported to the final depositional areas in the deep offshore parts of the Baltic. Owing to the large proportion of erosional and transportational areas in the Baltic Proper (Brydsten, 1993; Christiansen *et al.*, 1997), there may be a substantial time-delay before contaminant changes are manifested in the deep depositional areas (Eckhéll *et al.*, 2000). A contaminated riverine particle that is finally deposited in the offshore depositional areas may have passed through a number of resuspension events, lasting years, if not decades, after it initially entered the sea, before being trapped in the deep anoxic sediments. Particle-associated contaminants may be retained in long-term transportational areas until high-energy input from waves, currents, or submarine slides resuspends the sediment many years after its initial deposition. Temporary accumulation in transportational areas may delay changes in contaminant concentrations found in sediments of the deep depositional areas.

3.3 Erosional areas

In the Baltic Sea, erosion is a significant process in coastal areas, as well as in shallow offshore areas, and erosional areas are estimated to constitute approximately 30% of the total bottom area. This percentage varies widely between different parts of the Baltic Sea. In some areas in the southern Baltic, erosion causes extensive damage to clayey/silty and sandy sediments along the shoreline.

Christiansen *et al.* (1997) found that resuspension occurred in shallow waters near the coasts for 15–35% of the year, whereas the bottom sediments in deeper areas were resuspended for <3% of the year. Brydsten (1993) showed that resuspension in the Gulf of Bothnia decreased dramatically with increasing depth. Sediment at depths of 0–30 m had a mean resuspension frequency of >5–300-fold year^{-1}. In deeper areas (>30–60 m), the bottom sediment was resuspended 0–5-fold year^{-1} on average.

Suspended matter derived from wave-induced resuspension has been shown to be important to sedimentation processes (Axelsson and Norrman, 1977; Brydsten, 1990;

Jonsson *et al.*, 1990; Brydsten, 1993; Christiansen *et al.*, 1997). By using Al, Fe, and Ti as markers to calculate the proportion of primary settling matter and resuspended sediment, Blomqvist and Larsson (1994) found that the resuspended portion commonly exceeded 50% of the total sedimented matter in a coastal area of the Baltic Sea. Eckhéll *et al.* (2000) found that erosion/resuspension accounted for an average of 70% of the deposited matter in the open northwestern part of the Baltic Proper between 1969 and 1993. During individual windy years, the eroded/resuspended portion may increase to 85%. Eroded sediment constitutes a major fraction of the material that is finally deposited in the deep depositional areas.

3.4 Lack of bioturbation causes laminated sediments

The benthic fauna bioturbate sediment under normal oxygen conditions. This results in a more or less homogeneous sediment without any clear structures. In areas with poor oxygen conditions (<2 mg O_2 l^{-1}) in the overlying water, the benthic fauna is eliminated, and laminated sediments are consequently often created. Without the bioturbating macrobenthic fauna, the normal seasonal changes in the composition of sedimenting matter are preserved in the sediments as more or less distinct annual varves, or laminae. In the Baltic, the high rate of resuspension and deposition of minerogenic particles deriving from glacial and post-glacial clays during winter is normally manifested by a light layer in the sediment profile, overlaid with a darker (often black) layer with a higher organic content, representing deposition in spring and summer.

The elimination of the benthic fauna is often a gradual process. In the sediments, this can often be represented as a few, more or less diffuse laminae overlying homogeneous bioturbated sediment (Figure 6). This is often overlaid with a bioturbated layer, indicating a shorter or longer period of conditions suitable for the benthic fauna. Finally, this development is characterized by distinct lamination, often to the top of the sediment column.

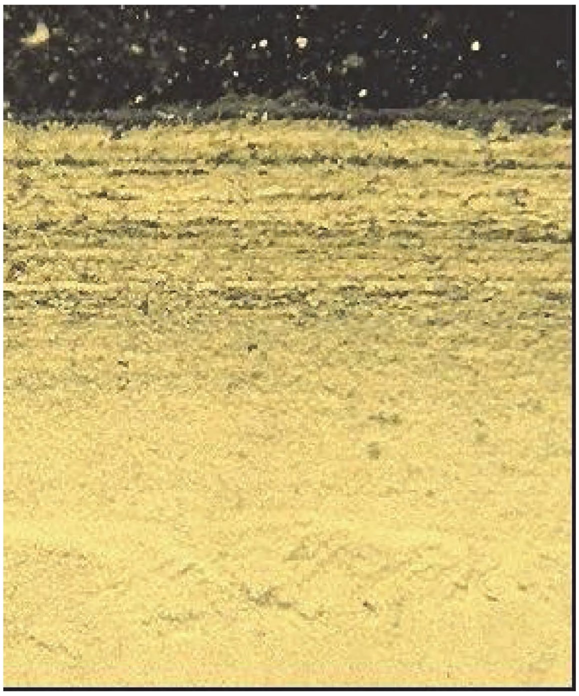

Figure 6. A typical laminated sediment from the open northern part of the Baltic Proper. *In situ* image taken with a sediment-profile imaging camera from a depth of 125 m. The total length of the image is approximately 10 cm.

Several studies in the Baltic Sea have demonstrated highly variable sediment accumulation rates in deep areas, averaged over periods ranging from decades to thousands of years (Table 2; Östlund and Hallberg, 1991; Blomqvist and Larsson, 1994; Kunzendorf and Christiansen, 1997; Neumann *et al.*, 1997).

Table 2. Characteristics of the Baltic Sea sediments in depositional areas, in brief.

CHARACTERISTIC	DEPOSITIONAL AREAS
Grain size	Mainly < 60 µm
Mud content	>90%
TOC content	2–10%
Redox conditions	Upper cm: temporarily oxic, temporarily anoxic
Dynamics	Sedimentation rate offshore: mean 0.1–0.3 (range 0.05–2) cm year^{-1}. Sedimentation rate archipelago: mean 1.7 (range 0.11–7) cm year^{-1}.

In the deepest parts of the major basins of the open part of the Baltic Proper, laminated sediments have been deposited on anoxic bottoms for more than a hundred years, indicating natural oxygen deficiency in these areas (Jonsson *et al.*, 1990). During recent decades, the opportunities for detecting interannual changes of contaminant concentrations in sediment have substantially improved over large areas in the Baltic Proper owing to a large-scale expansion of areas of anoxic/hypoxic laminated sediments (Jonsson *et al.*, 1990). The area of laminated sediments has expanded since the 1940s and, in the late 1980s, approximately 30% of the Baltic Proper at >75–80 m depth had laminated surficial sediments. During the 1960s and early 1970s, the macrobenthic fauna was eliminated from an average of approximately 3000 km^2 annually. This has been attributed to a substantial increase in the sedimentation of autochthonous organic matter caused by increased eutrophication of the Baltic Sea (Jonsson and Carman, 1994).

As a result of the significantly better time-resolution available from laminated sediments, anoxic sediments may be considered much more sensitive than bioturbated sediments as indicators of contaminant load changes. In areas where both types of sediment occur, this would suggest that the laminated sediments are better suited for time-trend monitoring.

However, it is important to bear in mind that the lamination is not a static or permanent phenomenon. In 1993, a major inflow of saline water occurred through the Danish Sounds into the Baltic Sea, which deepened the halocline in the northern part of the Baltic Proper to the extreme depth of 110–120 m and improved the near-bottom oxygen concentrations (Helsinki Commission, 1996) over extensive areas above this depth. The oxygenation of the seabed allowed recolonization by benthic fauna and led to bioturbation down to a couple of centimetres below the sediment surface. During the rest of the 1990s and until 2002, anoxic/hypoxic conditions in the deep water have caused mass mortality of benthic fauna in the recently colonized areas and an expansion of the area of laminated sediments. The oxic episode after 1993 is reflected in the sediment column as a bioturbated layer 1–2 cm thick, overlaid by laminated sediments.

3.5 Isostatic processes cause resuspension of large amounts of uncontaminated sediment

The isostatic uplift of land since the last glaciation in Scandinavia is causing large relocalization of material (Axelsson and Norrman, 1977; Jonsson *et al.*, 1990). Areas of seabed that were formerly below the wave base gradually become exposed to wave action, and large quantities of glacial and post-glacial clays were eroded. Estimates suggest that 50–80% of the material finally deposited in the deep areas of the Baltic is derived from this process (Jonsson *et al.*, 1990; Jonsson, 1992; Blomqvist and Larsson, 1994; Eckhéll *et al.*, 2000). The interannual changes in the amount of material eroded are significant. Anthropogenic inputs of nutrients and contaminants are, therefore, diluted to a variable degree by a large input of uncontaminated eroded old clays.

3.6 Storm-induced erosion causes changes in sediment accumulation rates

From long-term observations of waves along the German Baltic coast, it has been shown that the annual frequency of storm waves increased from 1831 to 1990, with substantial differences between years and decades (Baerens and Hupfer, 1994). From detailed studies of laminated sediment cores from the northwestern part of the Baltic Proper, Eckhéll *et al.* (2000) demonstrated that the sediment accumulation rate varied substantially between years/decades (Figure 7). They demonstrated a strong correlation between the annual rate of dry matter deposition and the frequency of windspeeds ≥14 m s^{-1} at a nearby weather station.

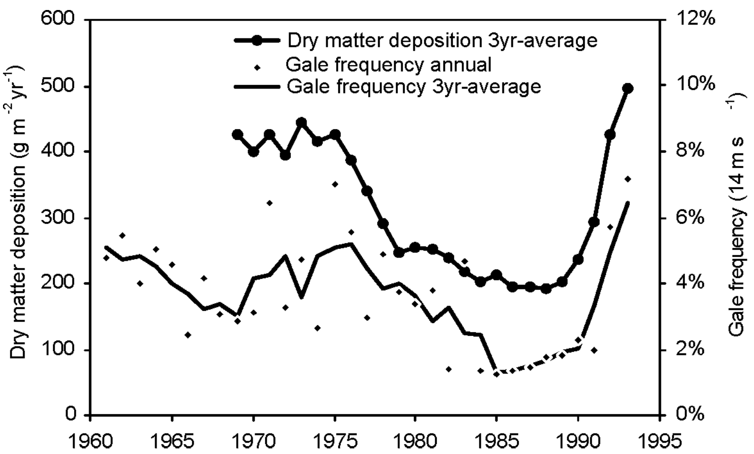

Figure 7. Dry matter deposition (3-year running mean) in a core ($n = 3$) and the frequency of wind velocities ≥ 14 m s^{-1} (gale force; individual years and 3-year running mean) for the period 1969–1993 (Eckhéll *et al.*, 2000).

In the Baltic Proper, the 1950s to 1970s were characterized by a higher frequency of gales than the 1980s. In the early 1990s, the gale frequency increased dramatically and reached a maximum in 1993, which resulted in a large saltwater intrusion from the Kattegat into the Baltic. The dry matter deposition rates were significantly higher in the 1970s and early 1990s than in the 1980s, which may be considered as a calm decade in this area. The authors suggested that sediment accumulation rates in offshore areas of the northwestern part of the Baltic Proper can be predicted from this correlation with windspeed. Similar results have been obtained from the Swedish St Anna archipelago and the Stockholm archipelago (Persson and Jonsson, 2000). Although interannual changes in sediment accumulation rate are difficult to detect in sea areas where bioturbated sediments predominate, it is likely that similar variations occur in these areas.

Interpretation of time-changes in monitoring data in the Baltic must consider the substantially increased sediment accumulation rate during stormy years, and the fact that storm frequency may be useful in data analysis.

3.7 Resuspension of old clays affects sediment organic carbon content

Numerous investigations have shown that the sediment organic carbon content is of great importance for the concentrations (and burial) of contaminants, particularly hydrophobic organic contaminants (HOC). Therefore, processes/mechanisms that can alter the organic carbon content must be considered in trend monitoring.

Total organic carbon (TOC) concentrations were analysed in the cores studied by Eckhéll *et al.* (2000). The dry matter deposition rate decreased by approximately 50% in the 1980s, and this was reflected in an increase in TOC content from 3–4% to 7–8% during the same period (Figure 8). When the dry matter deposition rate increased in the early 1990s, the TOC content decreased. This is interpreted to mean that the erosion/resuspension of mainly minerogenic matter from glacial and post-glacial clays is greater during windy years, whereas, in calmer years, the carbon input from primary production becomes more dominant and dry matter deposition rates are lower.

A study of down-core trends of HOCs in a Canadian lake with laminated sediments (Stern *et al.*, 2005) revealed a substantial decrease in bulk sediment accumulation rate coinciding with an increase in TOC content, which obscured trends of HOCs in the sediment in relation to changes in industrial sources of the different pollutants studied. These findings complement the results from the Baltic Sea (Figure 8) and emphasize the importance of considering changes in bulk sedimentation accumulation rates when interpreting sediment monitoring data.

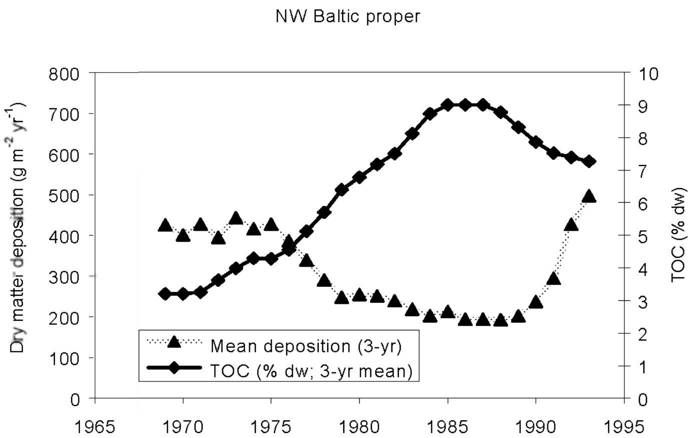

Figure 8. Dry matter deposition and TOC content vs. time; 3-year running average of the core means (Eckhéll *et al.*, 2000).

3.8 Chemical redox processes

3.8.1 Metals

Jonsson (1992) suggested that the occurrence of laminated sediments in the offshore part of the Baltic Proper caused increased trapping of contaminants (metals and organic pollutants) in the sediments. Although the mechanisms are not fully understood, changes in burial efficiency must be considered when interpreting time-trends in laminated sediments.

Remobilization processes within the sediment may cause interpretation problems. Differences in the vertical distribution of metals, particularly of Zn, indicated the significance of mobilization processes within the sediment at two sampling sites in the Baltic Proper (Tervo and Niemistö, 1989). Therefore, detailed interpretation of retrospective trace element studies of Baltic sediments should be regarded with due reservation.

Redox changes may cause differences in the efficiency with which metals can be trapped in sediments. This is a well-known phenomenon for a number of elements (e.g. Fe and Mn). Also, trace metals, such as Cd, Pb, Zn, Hg, and Cu, have been shown to be more effectively sequestered in anoxic Baltic sediments. Borg and Jonsson (1996) found high correlations between all of these metals and the degree of anoxia described in areas of laminated sediments. This indicates an increased redox-induced trapping for these sulphide-binding metals in the laminated sediments. At sites where laminated sediments have accumulated continuously over hundreds of years, the metal concentrations have increased gradually, but steadily, during recent decades. As no dramatic redox changes seem to have occurred in the naturally laminated bottoms, sediment cores from this type of bottom probably contain the best retrospective information about the pollution history of metals in the Baltic Proper.

In the ICES/HELCOM Sediment Baseline Study, substantially lower concentrations of these metals, especially Cd, were detected in surficial sediments in the northern part of the Baltic Proper in June 1993. In the early 1990s, progressively larger saltwater inflows from the Kattegat were registered, reaching a maximum in January 1993 and leading to substantially improved oxygen conditions in the deep water to 115–120 m depth (Axelsson and Norrman, 1977). The change from anoxic to oxic conditions, with a subsequent recolonization of benthic fauna, obviously caused a release of the easily mobilized metals (e.g. Cd) into the water mass. Increased Cd concentrations have been detected in biota along the Swedish coast of the Baltic Proper in the 1990s (Bignert, 2001). This increase may, to a certain extent, have been caused by mobilization of Cd from the sediments.

3.8.2 Organic compounds

Sediment profiles of chlorinated compounds (e.g. extractable organochlorines (EOCls), polychlorinated biphenyls (PCBs), dichlorodiphenyltrichloroethanes (DDTs), polychlorodibenzodioxins and -furans (PCDD/Fs)) indicate substantially increased sequestering in the Baltic Proper sediments from the 1950s and onwards, coinciding in time with the expansion of laminated sediments and clearly increasing organic content of the sediments (Niemistö and Voipio, 1981; Perttilä and Haahti, 1986; Jonsson, 1992). These studies indicate that, because of the turnover from oxic to hypoxia/anoxia conditions close to the sediment–water interface, the sequestering efficiency has increased in the sediments. A pilot study, aimed at comparing the burial efficiency of PCBs in laminated sediments and in bioturbated sediments from the Stockholm archipelago (P. Jonsson, pers. comm.), showed an average 40% increase in concentrations when the sediment changed from bioturbated to laminated conditions. This may be attributed to increased eutrophication causing stagnant conditions in the near-bottom water.

3.9 Possible changes in sediment dynamics in the Baltic Sea caused by climate change

3.9.1 Present-day sedimentation situation

This section is largely derived from information supplied by P. Jonsson (pers. comm.). As discussed above, the main sources of the bulk sedimentation in the Baltic Sea are riverine inputs, primary production, erosion/resuspension of old glacial and post-glacial clays, and, to some extent, atmospheric deposition.

The Baltic Sea area is subjected to a considerable isostatic uplift owing to crustal rebound after the last glaciation of Scandinavia. It varies from 0 mm year^{-1} in the southern Bothnian Sea to 9 mm year^{-1} in the northern Bothnian Sea (Figure 9). This has resulted in a gradual exposure of old glacial and post-glacial clays to stronger waves and currents, and substantial erosion along the Baltic coastal areas. Jonsson (1992) highlighted the major role played by the erosion of uplifted old sediments in the formation of recent fine deposits in the Baltic Sea (cf. Axelsson and Norrman, 1977; Blazhchishin, 1984). It has been estimated that as much as 50–80% of the bulk accumulation of fine material in the Baltic Sea is derived from relocalization of old sediments (Blomqvist and Larsson, 1994; Jonsson *et al.*, 2003).

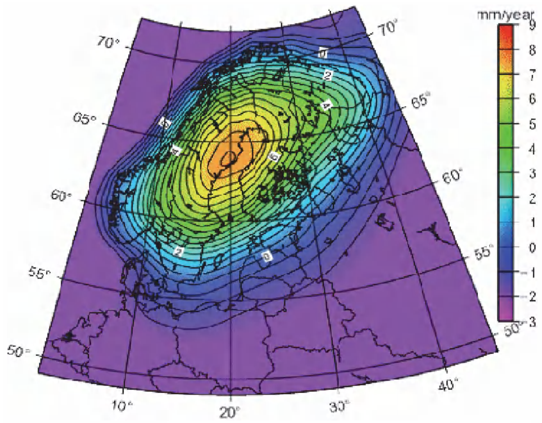

Figure 9. Apparent land rise in the Baltic Sea area (mm year^{-1}; Land-rise model NKG2005LU (RH 2000 LU) 200; Lantmäteriet, Sweden, www.lantmateriet.se).

3.9.2 Climate-change scenarios

P. Jonsson (pers. comm.) discussed how climate change may affect the sedimentation process in the different parts of the Baltic Sea. As a basis for these estimates, he used various climatic scenarios (Figures 10 and 11) and compared them with the present situation.

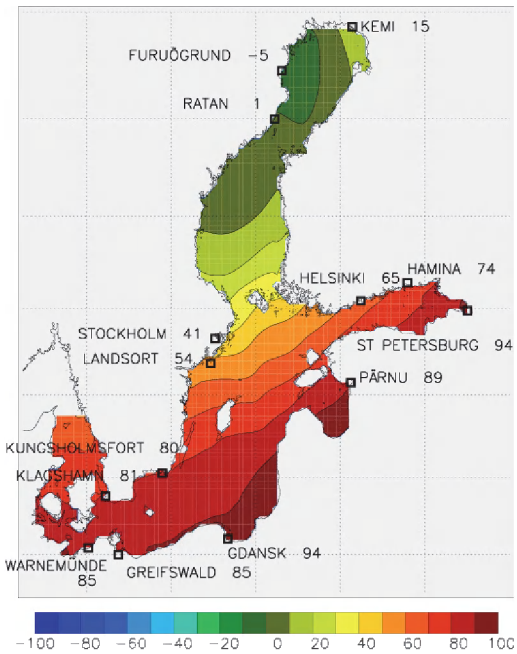

Figure 10. The High case scenario, assuming a global average sea-level rise of 88 cm. This figure presents sea-level changes (cm) in the year 2100, taking into consideration uplift caused by crustal rebound after the last glaciation (Meier, 2006).

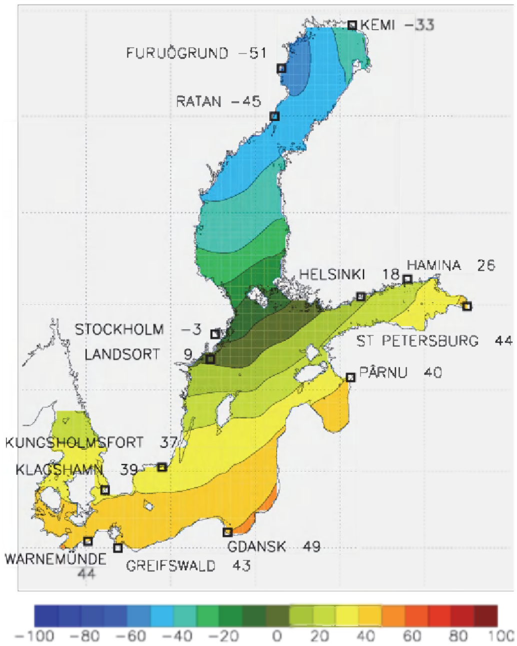

Figure 11. The Average case scenario, assuming a global average sea-level rise of 48 cm. The figure shows sea-level changes (cm) in the year 2100, taking into consideration uplift caused by crustal rebound after the last glaciation (Meier, 2006).

If the resulting regression of the shoreline decreases, halts, or even turns into a transgression (when water level rises) as a result of climate-induced melting of ice or eustatic changes, the sediment input from relocalization of old clays may change drastically and lead to significant changes in the sediment composition in depositional areas. In the conservative estimates below, it is assumed that 75% of the present bulk sediment accumulation is derived from erosion/resuspension of old sediments.

In the High case scenario, large changes occur, and the bulk deposition rate decreases approximately fourfold in all areas of the Baltic Sea (Figure 12). In the Average case scenario, the decrease is approximately 30% in the Bay of Bothnia and in the Bothnian Sea, while the decrease in the Baltic Proper is again expected to be fourfold.

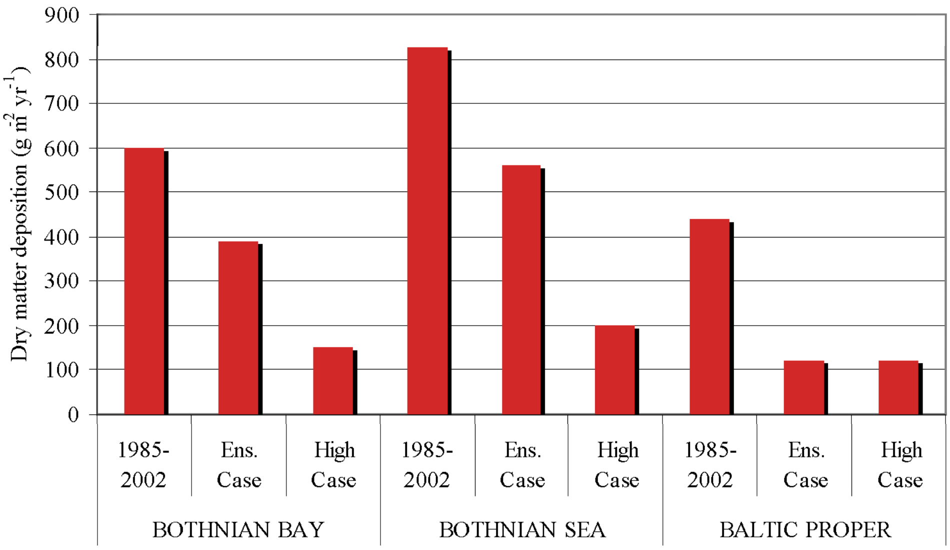

Figure 12. Current dry matter deposition in different parts of the Baltic Sea compared with the High case and Average case projections for the year 2100 (P. Jonsson, pers. comm.).

The predicted decreases in the input and deposition of mineral material would lead to a substantially higher carbon content in the sediments, owing to the relatively greater importance of carbon derived from riverine inputs and primary production. In the High case scenario, the carbon content gradually increases from a current average of approximately 7% to 25% around the year 2100 (Figure 13). In the Bay of Bothnia and in the Bothnian Sea, the increase would be somewhat smaller, but would still be approximately threefold.

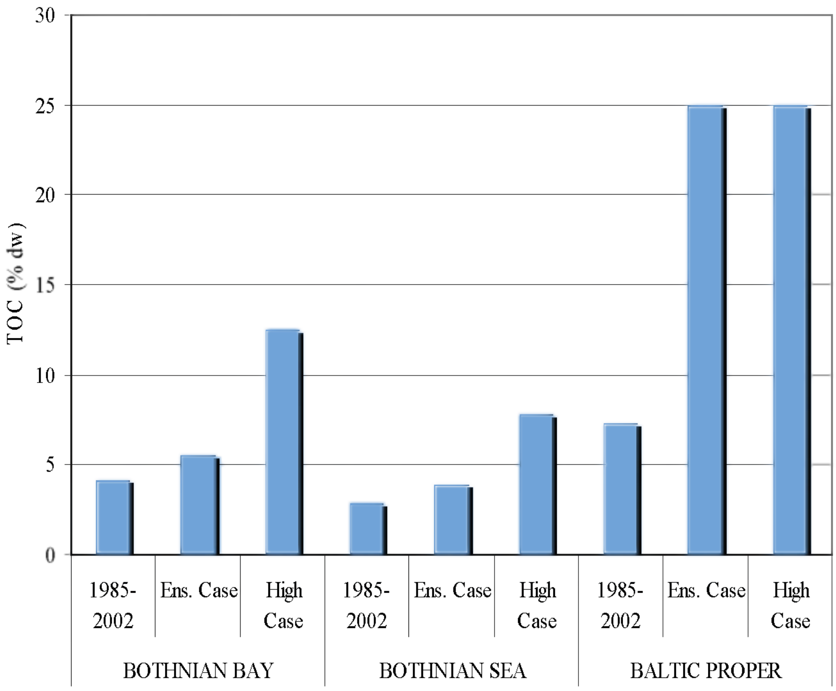

Figure 13. Current total organic carbon (TOC; % dry wt) in sediments from different parts of the Baltic Sea compared with the High case and Average case projections for the year 2100 (P. Jonsson, pers. comm.).

Such large changes will alter many critical processes in the sediment–water interface and also change the environment for benthic organisms. It will probably affect the turnover of nutrients and also change the transport and fate of organic and inorganic contaminants in the Baltic ecosystem. It will also certainly change the pattern of nutrient and contaminant concentrations and, therefore, will be a relevant consideration when interpreting sediment monitoring data.

4 Bay of Biscay

4.1 Dynamic processes affecting distribution of sediment concentrations

The information in this section is derived primarily from Ferrer (pers. comm., 2008), González *et al.* (2008), and the Proceedings of the XI International Symposium on Oceanography of the Bay of Biscay (Borja, 2008).

It is well known that the distribution of suspended sediment in the water column and close to the seabed off river mouths can be highly variable. Sediment distribution depends on the behaviour of the plumes, whose dynamics are a function of the mixing processes within the coastal sea, the strength of the discharge, the circulation, and wind and tide regimes (Arnoux-Chiavassa *et al.*, 1999). The expansion, contraction, and longshore orientation of surface plumes are often influenced by winds, waves, and tides (Stumpf *et al.*, 1993; Liu *et al.*, 1999).

The injection of fluvial sediments into the coastal and offshore areas can easily be recognized in satellite or aerial images by the plumes of suspended sediment near the river mouths. Numerical models are used to simulate the behaviour of river plumes in order to further understand their influence on the dispersion of solid materials and on sedimentation patterns. In the case of the Bay of Biscay, a Lagrangian Particle Tracking Model (LPTM), coupled to the Regional Ocean Modeling System (ROMS), was used to simulate the behaviour of river plumes in the southern margin of the bay (González *et al.*, 2008). The ROMS model is driven by hydrodynamic variables: winds, air temperature, precipitation rate, relative humidity, and long- and short-wave radiation fluxes. These variables permit the air–sea heat and momentum fluxes to be calculated. Tidal forcing data were obtained from the OSU TOPEX/Poseidon Global Inverse Solution version 5.0 (TPXO.5).

Freshwater discharges of the main rivers, such as the Adour (in France) and the Nervión, Oria, Deba, Urola, and Urumea (in the Basque Country), were incorporated into the model simulations. These data were provided by the French National Database for Hydrometry and Hydrology (HYDRO) and the Provincial Councils of Bizkaia and Gipuzkoa.

Figure 14 shows freshwater discharges from the rivers Adour, Nervión, and Oria, from 1 March to 6 April 2007. Analysis of these data shows that there were noticeable peaks of discharge by the Spanish rivers on 8 March (maximum value for the Oria River of approximately 308 $m^3 s^{-1}$) and 24 March (maximum value for the Nervión River of 372 $m^3 s^{-1}$), with an increase in mean freshwater runoff during the period between 20 March and 6 April. The discharge behaviour of the Adour River was similar, but the maximum discharge occurred on 2 April, with a value of 372 $m^3 s^{-1}$.

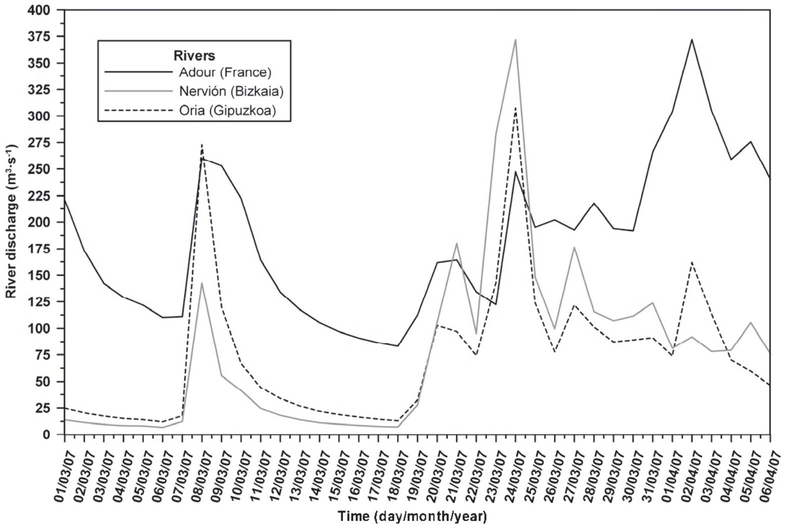

Figure 14. Daily freshwater discharges at the mouths of the rivers Adour (France), Nervión (Bizkaia), and Oria (Gipuzkoa) from 1 March to 6 April 2007.

Figure 15 shows the fine silt and clay concentration in bottom sediments obtained from field measurements carried out for the Basque Country region. The maximum concentrations are located between the Urola River and the western area of the Urumea River. The grain-size distributions agree well with the results from the simulations performed with the LPTM, fed by the hydrodynamic information obtained with ROMS. The results show that the coastal jet and the grain-size composition of the river discharges play fundamental roles in the final sedimentation patterns, especially in extreme events such as the two observed during March 2007.

The model explains the sedimentation patterns obtained from field measurements, especially in extreme events. The results show that the dispersion of river plumes is determined by the buoyancy of the effluent, tides, and the windfield in the upper part of the water column. The coastal jet related to the plumes and the grain-size composition of the riverine particles influence the dispersion of material offshore and the final sedimentation patterns.

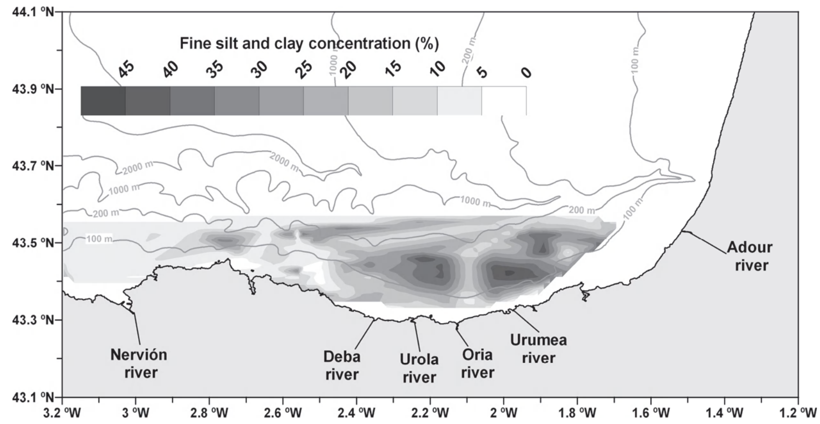

Figure 15. Fine silt and clay concentrations (%) in the sediment for the Basque Country region, obtained from field measurements.

In summary, the reasonably good correlation between field and modelled data demonstrates the suitability of these models to reproduce the physics of the ocean. The combination of observational data and numerical modelling provides tools for monitoring several phenomena in real time, such as sediment transport.

5 Estuaries

5.1 The purpose of monitoring in estuaries of the Northeast Atlantic

European estuaries are typically sites of human settlement and industrial development; consequently, relatively high levels of contaminants from both diffuse and direct sources are common in the water, sediments, and biota. Contaminant concentrations in offshore marine sediments are usually lower, and trends in pollution levels may consequently only be detected over a relatively long time-frame. Time-trends closer to the source of contamination are usually much larger and easier to detect. However, the complex hydrodynamic processes in estuaries may give rise to short-term variations in contaminants and, therefore, should be considered when designing monitoring programmes or assessing monitoring data from estuaries. For trend monitoring, contaminant concentrations are usually normalized according to Technical Annex 5 of the JAMP Guidelines for Monitoring Contaminants in Sediments (OSPAR, 2002) in order to correct for variations in contaminant concentrations resulting from the physical heterogeneity of sediments (e.g. grain-size distribution).

5.2 Characteristics and typology of estuaries

Although estuaries all share some common features, they vary widely in size and in tidal range. Estuaries can be characterized by their length, catchment area, tidal range, degree of stratification, river discharge, and input of SPM from the river. Their length may vary from a few kilometres to more than 100 km.

Sediment dynamics are mainly determined by tidal currents and river discharge. The bottom topography is an important means of identifying present-day sediment dynamics, namely areas of deposition and erosion, and transport routes.

Estuaries, or transitional waters, mark the transition between marine and freshwater environments. They extend from the sea into the river valley up to the limit of tidal influence. Within an estuary, three distinct areas can be distinguished.

- The **lower reaches**, which are connected directly to the open sea via the mouth.
- The **middle reaches**, which are an area of intense interaction and mixing of marine and fluvial water masses and steep physicochemical gradients.
- The **upper reaches**, which are dominated by freshwater inflow from the river, but are still subject to daily tidal action.

Both ends of the system, i.e. the fluvial and marine water bodies, are characterized by a unique chemical, physical, and biological composition. As the fluvial water flows through the middle reaches of the estuary, its composition is changed by complex processes until it resembles that of the marine water. In this respect, the estuary could be regarded as a filter (Chester, 2002).

The estuarine system is driven by a continuous input of energy and material from tidal currents and river discharge. The SPM plays a major role in estuarine processes. The shift from a fluvial to a marine composition involves the interaction of dissolved and particle-bound matter. Depending on the key conditions of pH, redox potential, salinity, and temperature, SPM can serve as either a sink or a source for chemical components in the water phase.

The estuary filter system acts differently for individual chemical components. Some components behave conservatively during transport through the estuary, and their concentration profile in the water phase along the estuary behaves linearly with salinity. Other components are removed by flocculation, adsorption, and sedimentation processes. Also, remobilization of components from sediments resulting from high energy input and/or changing redox conditions, as well as biological uptake and remineralization, must be considered. The interaction of these processes results in a turbidity zone with high concentrations of SPM. Bioproduction and degradation also contributes significantly to the SPM concentration in turbidity zones. These zones may extend up to several tens of kilometres, and their extent and location are influenced by river discharge. The retention time of particles in estuaries, especially in the turbidity zone, may be quite lengthy; for example, in the Gironde estuary of the Bay of Biscay, it is approximately two years (OSPAR, 2000). However, under riverine flood conditions, large amounts of particulate matter may be flushed out to the sea relatively quickly.

Within the OSPAR region, a wide range of estuary types occurs and it is, therefore, not sensible to produce a single description for monitoring purposes. Under the European Water Framework Directive (WFD, 2000), Member States are required to produce a typology covering the transitional waters that come under their jurisdiction. Some examples are described below (for terminology of typology, see European Union, 2000).

5.2.1 Germany

In Germany, all three estuaries (Ems, Weser, and Elbe) fall into a single category: fully mixed and mesotidal. Upstream, they are all limited by tidal weirs. Average river discharges vary from 79 $m^3 s^{-1}$ (Ems), to 325 $m^3 s^{-1}$ (Weser), and to 720 $m^3 s^{-1}$ (Elbe), and the lengths of the estuaries are 82, 90, and 142 km, respectively. The input of fluvial SPM to the estuary in the Ems (~60 000 t $year^{-1}$) is small relative to the Weser (600 000 t $year^{-1}$) and the Elbe (800 000 t $year^{-1}$).

Upstream transport of marine sediments or SPM in all estuaries is significant, and sediment dynamics are prominent. Marine sediments contribute >90% of the sediment in the Ems estuary, which is distributed throughout almost its entire length, whereas the percentage of marine sediments in the Elbe and Weser estuaries decreases from the mouth of the estuary to the tidal weir.

5.2.2 Portugal

In Portugal, all of the rivers typically experience dry and flood seasons. The freshwater runoff is not particularly strong at the Atlantic coast of the Iberian Peninsula. The main contributors of freshwater runoff north of 41°N are the rivers Douro and Minho. Although there are differences between the Portuguese estuaries, in general, they receive sandy sediments from the sea and export finer sediments (i.e. silt and clay) to the sea.

The Douro River has a greater discharge than other Portuguese estuaries and has an artificial upstream end (Crestuma Dam) only 22 km from the mouth. The presence of this obstruction probably determines the dynamic behaviour of the estuary and causes the standing character of the tidal wave. As a rule, the estuary behaves as a salt wedge controlled by river inflow, such that average winter inflows may be high enough to push the salt wedge out of the river mouth. It is mesotidal with a coarse sand substratum. The Tagus River, one of the largest estuaries in Europe (80 km long), is partly to well mixed, mesotidal, and has a predominantly sand and mud substratum. Sediment dynamics of both estuaries are high, especially in winter at times of high rainfall.

The Guadiana estuary, another large estuary in Portugal (70 km long), is partly mixed, mesotidal, and with predominantly sand and mud (at the margins) substratum. Sediment dynamics are usually low, except in winter when rainfall is higher.

5.2.3 United Kingdom

In the UK (WFD Ecoregion 1 (North Sea) and Ecoregion 4 (Atlantic)), which has a long and variable coastline, six different types of transitional waters have been defined.

- **Type 1**. Partly mixed or stratified, tending to be mesohaline or polyhaline. These sheltered estuaries are strongly macrotidal, and the intertidal or shallow subtidal areas have a predominantly sand and mud substratum, e.g. the Parrett estuary.
- **Type 2**. Mixed or stratified, tending to be mesohaline or polyhaline. These sheltered estuaries are strongly mesotidal, and the intertidal or shallow subtidal areas have a predominantly sand and mud substratum, e.g. the Tees and Dart.
- **Type 3**. Fully mixed and predominantly polyhaline. These sheltered estuaries are macrotidal, and tend to have extensive intertidal areas with a sand or mud substratum, e.g. the Dee, Severn, and Thames.
- **Type 4**. Fully mixed or stratified, tending to be predominantly polyhaline. These sheltered estuaries are mesotidal, and the intertidal or shallow subtidal areas have a predominantly sand and mud substratum, e.g. the Solway Firth, Plymouth Sound, Orwell, and Stour.
- **Type 5**. Transitional sea lochs (fjords). These sheltered bodies of water are predominantly polyhaline, sometimes stratified, and mesotidal, e.g. Loch Eil, Loch Linnhe, and Loch Etive.
- **Type 6**. Transitional lagoons. These sheltered bodies of water are partly mixed or stratified, oligohaline to polyhaline, and shallow with a predominantly mud substratum. They are widespread around the UK coasts.

This classification applies to many European estuaries and provides a description of the main characteristics and relative importance of particular processes in different types of estuaries. In turn, these can be used to guide the planning of cost-effective monitoring programmes and the interpretation of results.

5.2.4 Bay of Biscay

Characteristics of estuaries in the Bay of Biscay are described by Borja and Collins (2004). Uriarte *et al.* (2004) describe sediment supply, transport, and deposition relative to contemporary and Late Quaternary evolution. The fine-grained material transported by the river systems in suspension is: (i) stored within the estuaries; (ii) transferred to the shelf waters; and (iii) dispersed in response to the prevailing winds and currents (see also González *et al.*, 2004). It has been estimated that, on average, 30% of the sediments carried in suspension by the main rivers discharging out from the French coast into the Bay of Biscay remain permanently in the estuaries (OSPAR, 2000). The suspended material discharged by the Gipuzkoa and Bizkaia rivers into the Cantabrian Sea is approximately 1.57×10^6 t year^{-1}, an amount comparable to that of the Gironde (France).

The shelf mud patches (west and south) of the Gironde have been studied in some detail (Lesueur *et al.*, 1996, 2001, 2002). Less information is available on the extent and controlling mechanisms of the buoyant plumes in the Basque Country estuaries and/or their associated shelf deposits. However, research on plume characteristics has been undertaken within the context of the spawning of the Bay of Biscay anchovy (*Engraulis encrasicolus*).

Coarse-grained sediments originating from the rivers and transported as bedload constitute part of an exchange system with the inner part of the continental shelf. Hence, during high river discharges, riverine material is supplied and moved seawards; in turn, this is transported landwards in response to wave/current activity.

5.3 Depositional areas

In estuaries, deposition over several decades can occur in areas of low energy, such as tidal flats and branches of estuaries, close to the mouths of small tributary rivers and creeks, or close to groynes and other structures. In such areas, fine sediments predominate. Sediment accumulation rates depend on the rate of supply of material and the hydrodynamics of the system. However, erosion may occur as a result of storm tides or extreme river discharges. Under such circumstances, the deeper sediment layers (a surface layer greater than a few centimetres thick) are consolidated and show stratification. Sediment accumulation rates should be taken into account when using samples from these areas for time-trend monitoring. Usually only the upper few centimetres will reflect present-day conditions. However, these cores may be used for retrospective monitoring. Diagenetic processes should be considered when assessing retrospective core data, because deeper sediment layers tend to be anoxic.

5.4 Transportational areas

In the main body of estuaries, hydrodynamic conditions and sediment dynamics reflect the tidal currents and river discharge at the tidal limit. During slack water, SPM tends to settle out temporarily and then be resuspended partly or completely during flood and ebb tides. The continuous sedimentation and erosion processes result in a permanent exchange between sediments and suspended matter. No stratification of bottom sediments is expected.

Particulate matter is transported bidirectionally and represents a mixture of varying percentages of marine and fluvial sediments. It tends to be well mixed and homogeneous within the limits of the tidal movement. Owing to the permanent mixing processes, the particulate matter is predominantly oxic, and remobilization of metals is unlikely.

5.5 Dynamic processes affecting contaminant concentrations

The hydrodynamic conditions prevailing at each sampling site within an estuary should be considered when assessing the trend in contaminant concentrations. Contaminant concentrations should be normalized in order to minimize variation caused by physical heterogeneity of sediments (e.g. grain-size distribution).

The main factors influencing normalized contaminant concentrations in estuarine sediments and suspended matter are:

- load of particulate matter of fluvial origin and associated contaminant concentrations entering the estuary;
- load (amount) of marine sediments transported upstream and associated contaminant concentrations;
- potential contaminant sources within the catchment area of the estuary;
- potential resuspension of stable and possibly highly contaminated long-term sediment deposits; and
- dredging and removal of dredged sediments or their disposal within the estuary.

Depending on their location in estuaries, contaminant concentrations may vary widely owing to the bidirectional tidal sediment transport. Sediments or suspended matter may consist of both often heavily contaminated fluvial sediments that have been transported downstream across the tidal limit and lightly contaminated marine sediments that have been transported upstream from the sea.

Transport and mixing of fluvial and marine particulate matter is influenced mainly by:

- ebb and flood current velocities;
- limits of ebb and flood currents; and
- river discharge.

The ratio of these sediment types may vary widely in space and time, particularly in the mixing zone of fluvial and marine sediments, depending on hydrodynamic processes. Consequently, large variations in contaminant concentrations, which are not related to changes in pollution levels, may be observed in recently deposited sediments at a fixed sampling site. The amplitude of these variations usually depends on river discharge, the ratio of marine/fluvial sediments, and the location of the sampling site in relation to the mixing zone. When river discharges are high, contaminated fluvial sediments are transported farther downstream, whereas low river discharges support upstream transport of normally less contaminated marine sediments. This is shown in a qualitative model for the German Elbe estuary (Figure 16; Ackermann, 1998), in which Zn concentrations in the <20-μm fractions of fluvial and marine sediments are up to 1400 mg kg^{-1} and 200 mg kg^{-1}, respectively.

Sampling sites in the lower reaches of the estuary tend to be less affected by river discharge than those in the upper reaches. In combination with continuous mixing resulting from sediment dynamics, sediments are relatively chemically homogeneous (cf. Elbe estuary; Figure 17; Ackermann, 1998, 2004). Contaminant concentrations measured in samples from the lower reaches of estuaries are generally representative of a larger area.

In some cases, such as the German Ems estuary, fine particulate matter of marine origin predominates, and contaminant concentrations are quite uniform along the whole estuary. This results in low time and spatial variability of contaminant concentrations (Figures 18 and 19; Ackermann, 1998, 2004).

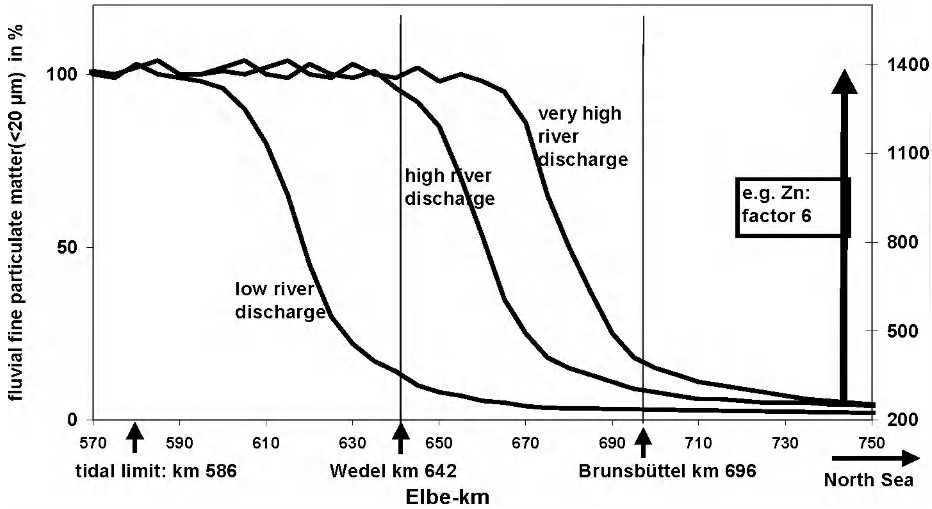

Figure 16. Qualitative scheme for the mixing of fluvial and marine fine-grained particulate matter in the Elbe estuary (Ackermann, 1998).

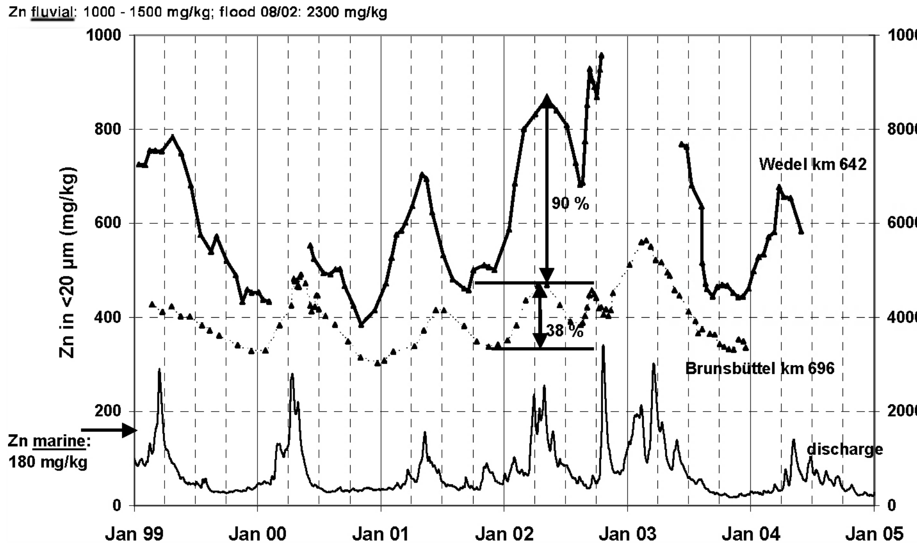

Figure 17. Variability of Zn concentrations in the Elbe estuary. Wedel km 642: 86 km from the Elbe mouth; Brunsbüttel km 696: 32 km from the Elbe mouth (Ackermann, 1998).

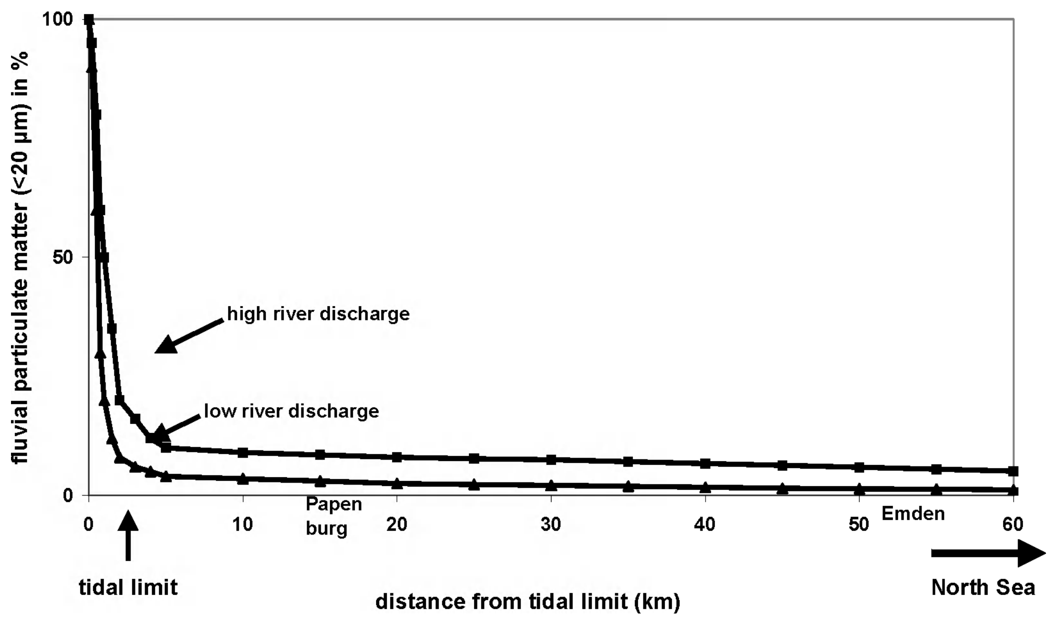

Figure 18. Qualitative scheme for the mixing of fluvial and marine fine-grained particulate matter in the Ems estuary.

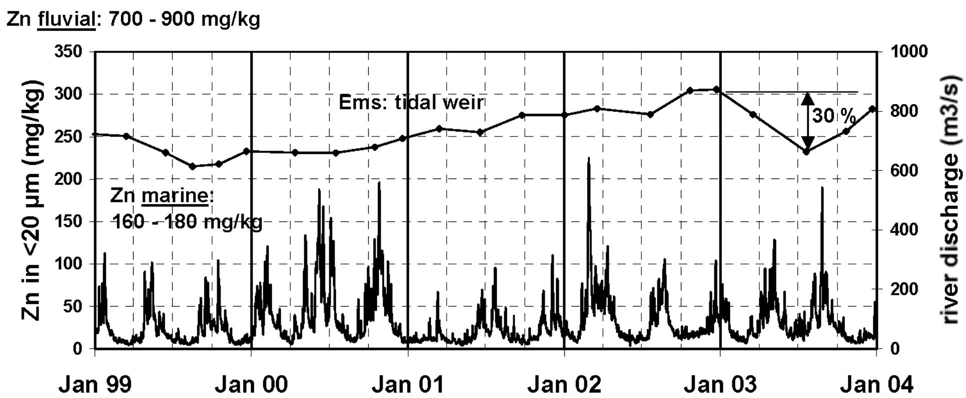

Figure 19. Variability in Zn concentrations at the tidal weir in the Ems estuary.

5.6 Implications for time-trend monitoring

The lower reaches of estuaries are less affected by river discharge than the middle and upper reaches. As marine sediments dominate, variations in normalized contaminant concentrations are much smaller than in the upper reaches of estuaries. Accordingly, sampling in the lower reaches can be less frequent (e.g. once or twice per year). However, the prevalence of marine solids with low contaminant concentrations, which often do not exceed those in marine sediments, makes the detection of a decrease in contaminant input more difficult.

In contrast, an adequate record of time-trends in the upper reaches may require more frequent sampling (e.g. monthly) in order to keep track of variations caused by changes in river discharge.

In the middle reaches, or transportational zone, of estuaries, the upper layers of sediment (10–20 cm) are likely to be well mixed by continuous deposition and erosion processes. Consequently, the upper layers tend to reflect the current contamination status of mobile particulate matter. Measurement of contaminant concentrations in the SPM can be used for monitoring overall trends in sediment contamination as well, owing to the near-continuous exchange between the sediment phase and SPM. Sampling of suspended matter at variable time-scales may be easier to achieve than sediment sampling, which could be important when extreme hydrodynamic events are being investigated.

In depositional areas, the upper layers may be reworked by bioturbation. However, if this bioturbation is from recent periods, the deeper layers may be consolidated and show a distinct stratification. Therefore, provided that layers can be dated, sediment cores from estuarine depositional areas may be appropriate for retrospective time-trend monitoring.

5.7 Impact of human activities

In addition to natural hydrodynamics, human activities must be considered when assessing time-trends in contamination concentrations owing to changes in contaminant input.

The deepening of navigation channels or other alterations to the morphology of estuaries (e.g. by engineering works such as building dams or jetties), may change the balance between flood and ebb current velocities or even alter the current regime and the hydromorphology in the lower estuary. Enhanced upstream transport of marine particulate matter could be induced by increased floodstream velocity. This may lead to decreasing contaminant concentrations, even without any changes in contaminant load. An example of this is given in Fettweis *et al.* (2007) in relation to Zeebrugge, where most of the depositions of mud are relatively uncontaminated and have been introduced by anthropogenic operations such as dumping, deepening of the navigation channels, construction, and extension of the port. The area around Zeebrugge where fresh mud is deposited now extends farther offshore than it did 100 years ago.

A changing current regime may change a former depositional area into a transportational area. This could have a significant effect on the stratification of the sediment deposits. Older sediment horizons with high levels of contamination could be brought to the surface, and resuspension of this material could falsely indicate increased contaminant loads.

If not limited by a weir, the tidal limit could be displaced upstream by dredging and sand extraction. Furthermore, disposal of dredged material is often carried out in estuaries and may influence contaminant concentrations within the estuary, as well as at the disposal site offshore.

6 Conclusions

Sediment dynamics are defined by a combination of the physical, chemical, and biological processes occurring in an area. From the evidence presented in these case studies, it is clear that it is essential to define the specific pattern of sediment dynamics in an area prior to designing a monitoring programme and attempting to interpret the data collected.

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8 Author contact information

Maria J. Belzunce
AZTI-Tecnalia, Marine Research Division
Muelle de la Herrera, Recinto Portuario s/n
20110 Pasajes, Spain
jbelzunce@pas.azti.es

Bernard Boutier
Ifremer, Centre de Nantes
BP 21105, 44311 Nantes Cedex 01, France
bernard.boutier@ifremer.fr

Hanneke Gieske
Hoogheemraadschap van Delfland
Postbus 3061
2601 DB Delft, The Netherlands
hgieske@hhdelfland.nl

Jean Louis González
Ifremer, Département Polluants Chimiques, Centre de La-Seyne-sur-Mer
Z.P de Bregaillon
83507 La-Seyne-sur-Mer, France
gonzalez@ifremer.fr

Per Jonson
Naturvårdsverket (Swedish Environmental Protection Agency)
SE-106 48 Stockholm, Sweden
Per.jonsson@naturvardsverket.se

Claire Mason
Centre for Environment, Fisheries and Aquaculture (Cefas), Lowestoft Laboratory
Pakefield Road
Lowestoft, Suffolk NR33 0HT, UK
claire.mason@cefas.co.uk

Els Monteyne
Management Unit of the North Sea Mathematical Models (MUMM),
Laboratory Marchem
Oostende, Belgium
E.monteyne@mumm.ac.be

Stefan Schmolke
Bundesamt für Seeschiffahrt und Hydrographie
(BSH; Federal Maritime and Hydrographic Agency)
Wustland 2
22589 Hamburg, Germany

Birgit Schubert
Bundesanstalt für Gewässerkunde (BfG; Federal Institute of Hydrology)
Am Mainzer Tor 1
50068 Koblenz, Germany
Schubert@bafg.de

9 List of abbreviations

DDT	dichlorodiphenyltrichloroethane
EOCl	extractable organochlorides
HOC	hydrophobic organic contaminants
LPTM	Lagrangian Particle Modeling System
PCB	polychlorinated biphenyls
PCDD	polychlorodibenzodioxin
PCDF	polychlorodibenzofuran
ROMS	Regional Ocean Modeling System
SPM	suspended particulate matter
TOC	total organic carbon