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The North Sea: An Overview [and Discussion]

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The North Sea: an overview

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An overview is given of the natural systems of the North Sea: water-circulation, topography and geology of the sea floor, sediment transport, influx of trace constituents (nutrients, trace metals, organic compounds), biological systems and their interrelations. The effects of pollution and other human activities are discussed as well as the difficulties in assessing them where they are obscured by natural changes.

1. Introduction

The North Sea, with a surface area of approximately 575000 km^2 and a total volume of seawater of *ca.* 54000 km^3, has a long geological history dating from the Permian *ca.* 275 ma ago. At that time the principal basins forming the North Sea came into existence at the same time as the original continent combining present-day Europe, Greenland and North America started to break up (Pegrum *et al.* 1975). The subsequent geological history has shaped the present North Sea and also, during the last stages, has determined its bottom sediment characteristics to a large extent. During most of this history the North Sea was land or a shallow sea with the sea floor slowly subsiding. At present the sedimentary infill reaches a maximum thickness of *ca.* 7 km. The last time the North Sea fell dry was during the Pleistocene period, which altogether lasted approximately two million years (Oele *et al.* 1979). Cold periods with a sea level approximately 100 m below present level (at least during the last three periods) alternated with warmer periods like the present one with a higher sea level. During the cold periods the North Sea floor was partly covered by ice. After the last glacial period (the Weichsel or Würm period) ended (roughly 11000 years ago), the North Sea was flooded again, reaching the present level *ca.* 6000 years ago. Since then the sea level has continued to rise relative to the land in the southern parts of the North Sea because of subsidence of the sea floor, relative sea level now being 5–6 m higher than 6000 years ago. In Scandinavia and Scotland, however, relative sea level began to fall because of uplift of the land after the heavy ice cover had disappeared. Here, the old coastline is found inland at a maximum height of *ca.* 220 m above present level. The hinge lines between subsidence and uplift are located in northern Denmark and southern Scotland. During the period the North Sea had approximately its present extension, i.e. during most of the past 6000 years, only minor changes occurred; at the beginning the climate was slightly warmer than now, in the shallow areas the tidal currents were probably stronger at first, but the main changes occurred along the eastern side of the southern North Sea, where coastal land was built up (tidal flats, beachridges, beaches, dunes) which is still going on.

The present North Sea shows an intricate relation between physical conditions (waves, tides, currents, seafloor topography), water chemistry, sediments (in suspension and on the bottom), living organisms and human activities. It is the object of this paper to point out some of these relations, how they function and what we know about their historical background. This is done, however, in the realization that many of these relations are not clear and that relations may exist that we are as yet unaware of. As to the geographical limits of the North Sea I follow here the conventional ones, i.e. the Straits of Dover in the south, the gaps between Scotland, Orkney and Shetland and the 62° N parallel in the north, but including the Skagerrak, which forms an essential part of the natural system of the North Sea. The limit there is a line from Cape Skagen due east to the Swedish coast, separating the Skagerrak from the Kattegat (figure 1).

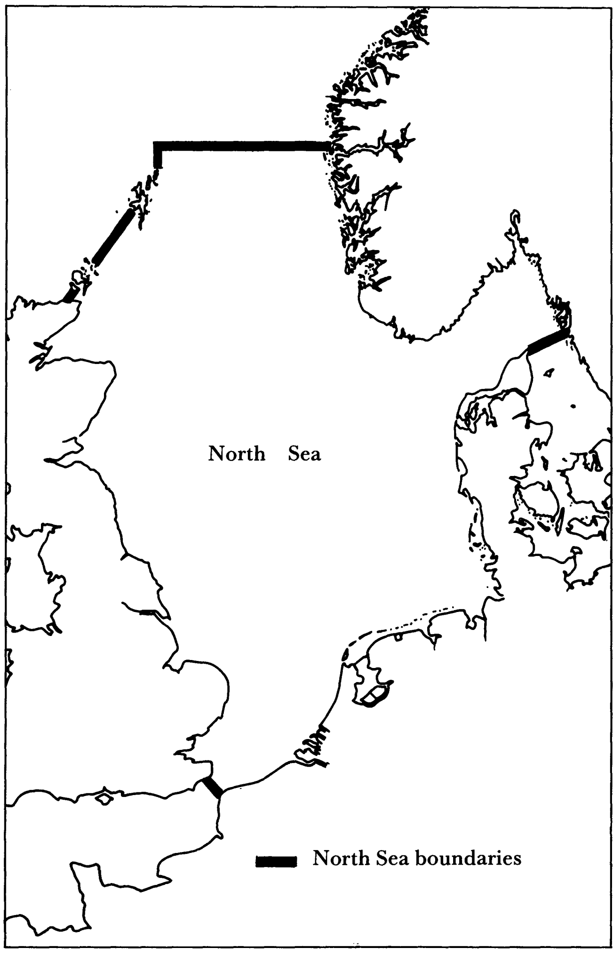

Figure 1. Limits of the North Sea as determined by the International Hydrographic Bureau, except between the Skagerrak and the Kattegat.

2. The physical environment

(a) *The sea floor*

The general shape of the North Sea basin is determined by the NW–SE direction of the geological fault structures which partly reflect structural trends that are much older than the Permian. The topography of the present sea floor, however, is of much younger age and was formed primarily during the last part of the Pleistocene (roughly during the past 300000 years). Huge glaciers excavated the Norwegian Trough and the Skagerrak where an older river valley

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probably existed before. Here the greatest water depths are reached: 700 m in the centre of the Skagerrak with a minimum depth of 225 m in the Norwegian Trough (figure 2). The remainder of the North Sea is less than 200 m deep, except for a few holes in the central North Sea that were also excavated by ice. The glaciers that came from Scandinavia and Scotland brought large quantities of sand and gravel to the North Sea floor. Huge deposits like Dogger

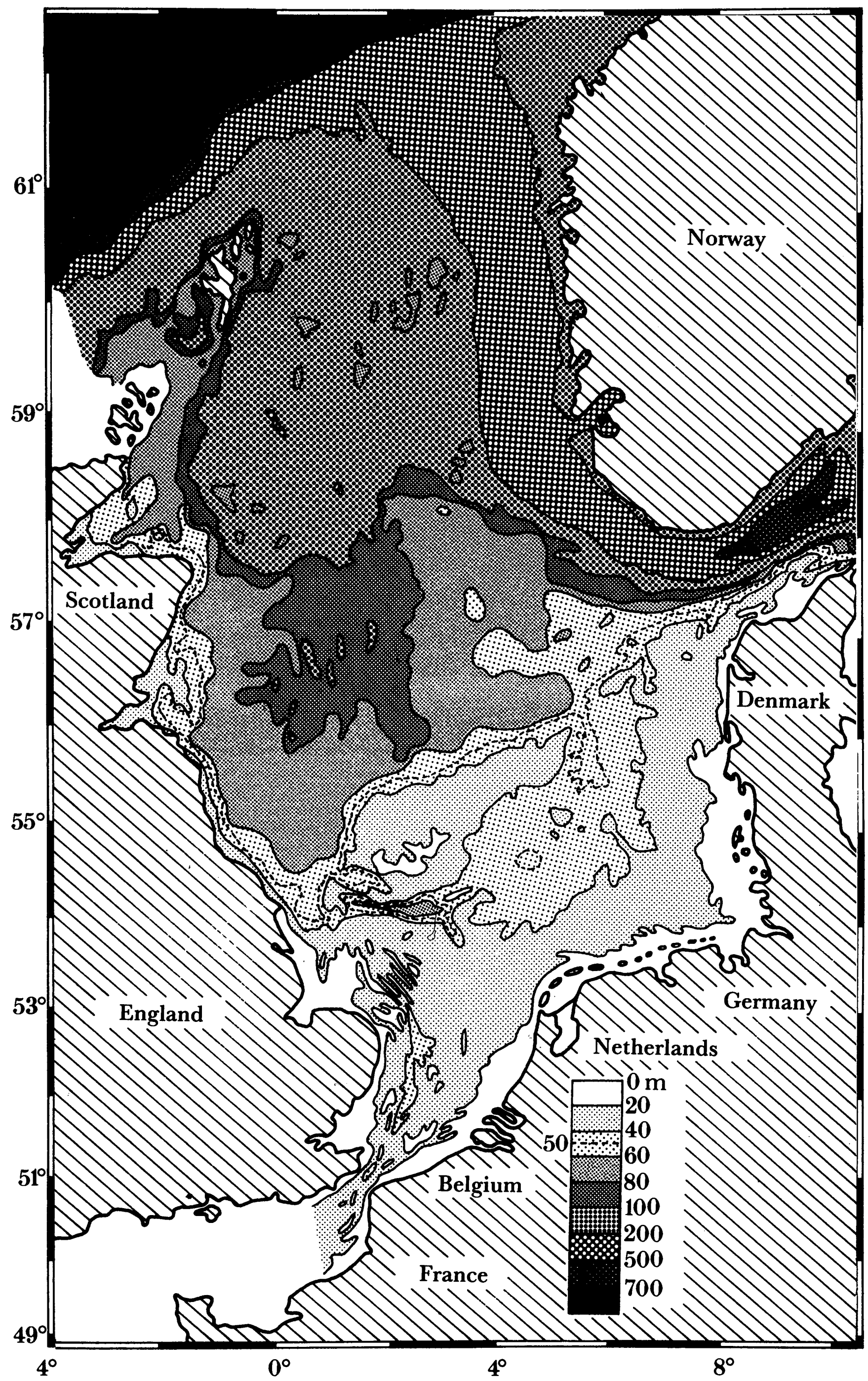

FIGURE 2. Water depth in the North Sea, in metres (after Eisma 1973).

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Bank were built up, and many smaller ones which were subsequently modified somewhat when the area was flooded again by the sea. This took place mainly during the last glacial period but one (the Saale or Riss glaciation). During the last glaciation the North Sea was land again but at that time large parts were not covered by ice. On the ice-free parts large outwash plains and river valleys were formed. Their remnants can still be seen in the present bottom topography in some cases (the Deep Channel and the Elbe Rinne in the southern North Sea) or can be traced in the sub-bottom where they have been filled up with younger sediment. When the area was flooded about 7000 years ago, other sand banks such as the Norfolk Banks, the Flemish, North Hinder and Zeeland Banks were formed, possibly during an early stage when (relative) sea level was lower, water depth was less and tidal currents were stronger. The most recent sedimentary formations are found near shore or along the coast: shallow sandbanks and beaches where surface waves have a strong effect, ripple systems up to a few metres high where tidal currents are strong, and mud deposits in sheltered or deeper areas (Waddensea, German Bight, Skagerrak/Kattegat/Norwegian Trough; Oele *et al.* (1979); Eisma & Kalf (1987)). Because of this varied history the distribution of gravel, sand and mud on the North Sea floor shows a mosaic of sediment types (figure 3).

(*b*) *Hydrography*

Water flows into the North Sea through the connections with the Channel and with the North Atlantic ocean, whereas the outflow of North Sea water is concentrated along the eastern side of the gap between Norway and Shetland. Ocean water is forced into the North Sea by the predominantly westerly winds pushing the water in the North Atlantic towards NW Europe, by the tidal wave that enters the North Sea from the north and the south, moving through the North Sea in an anticlockwise direction, and by density differences that are chiefly caused by the inflow of fresh water from the coasts and low-salinity water from the Baltic. Most of the fresh water comes from rivers that flow into the southern North Sea, forming low-salinity coastal water that moves towards the Skagerrak. There the Norwegian coastal current originates. It is a mixture of coastal water, saline water from the central and northern North Sea, Baltic outflow, and Atlantic water flowing southwards along the western side of the Norwegian Trough. The Norwegian Coastal Current follows the Norwegian coast from the Skagerrak to the Norwegian Sea and there continues to flow northwards along the coast (figure 4) (Lee 1970; Hill & Dickson 1978).

The tidal currents are strongest and the tidal range is highest in the shallow parts of the North Sea, off capes and in straits and bights, where the tidal flow is obstructed. The highest ranges (up to 6 m) and the strongest tidal currents (more than 1 m s^{-1}) occur in the Straits of Dover, in the Southern Bight, along the coasts of the southern North Sea and between the islands in the north, decreasing towards the Skagerrak where the water is deepest and tidal current velocities are less than 10 cm s^{-1}. Where tidal currents are weak, the influence of the wind is more pronounced and flow tends to be more variable. In some areas, as off the northern coast of Denmark, wind-induced flow can be quite strong (in the order of 30–40 cm s^{-1}). Wind-waves, generated at the sea surface, may disturb bottom sediment at more than 100 m water depth during heavy storms. Where the tidal currents are strong too, the combination of waves and tidal currents can rework the bottom sediment intensively.

The general circulation pattern as indicated in figure 4 is influenced by more regional phenomena, as listed next.

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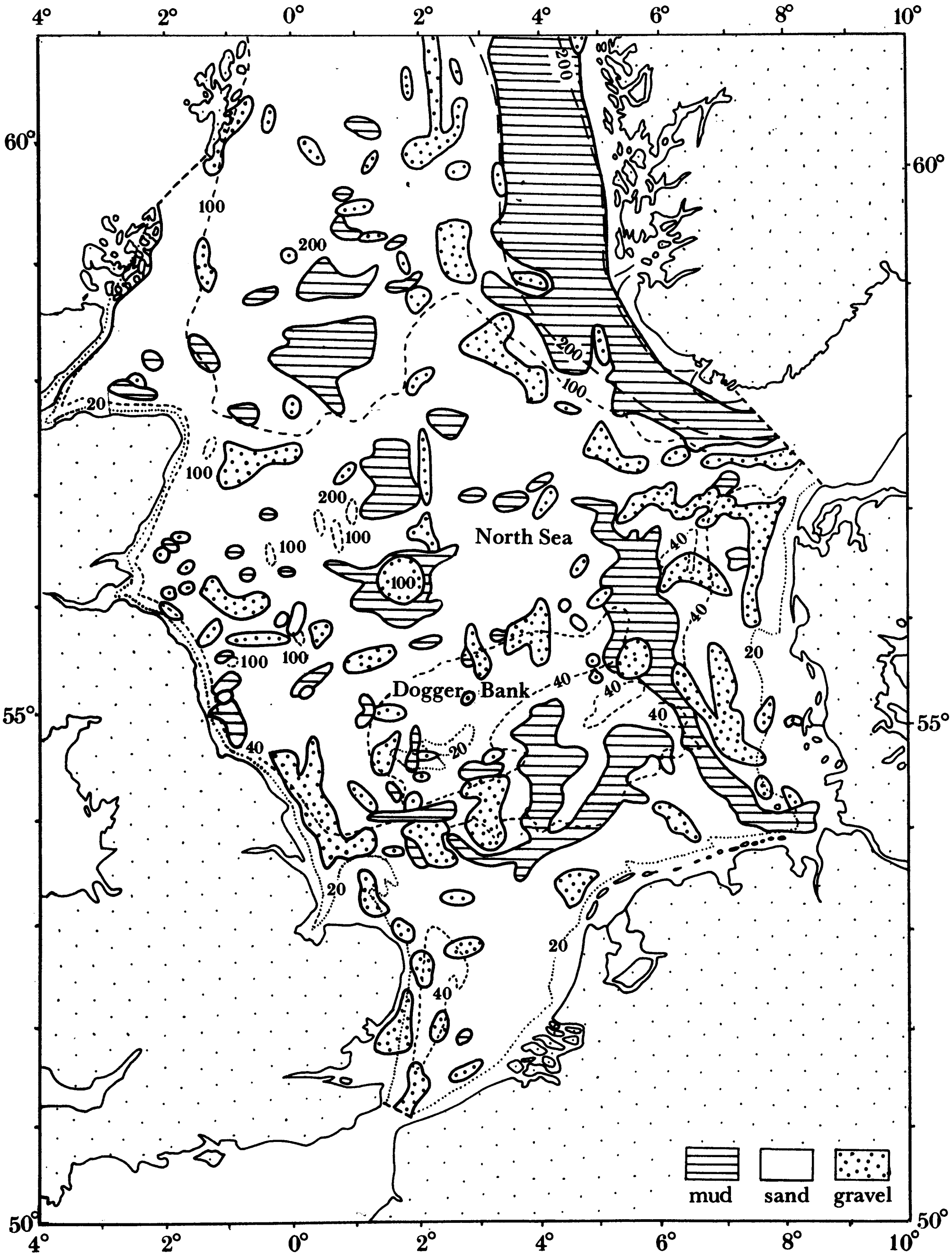

FIGURE 3. Distribution of bottom sediment in the North Sea (after Veenstra 1970).

(1) Wind-forcing can completely reverse the normal flow pattern for a few days, particularly in the shallower areas and where tidal currents are weak (Riepma 1980), but also, for example, in the Straits of Dover. In the Skagerrak strong westerly winds force the water eastwards, reducing the outflow, whereas easterly winds strongly enhance the outflow, an effect that can be felt even at the bottom (Aure & Saetre 1981).

(2) Heating of the surface water during spring and summer results in the formation of

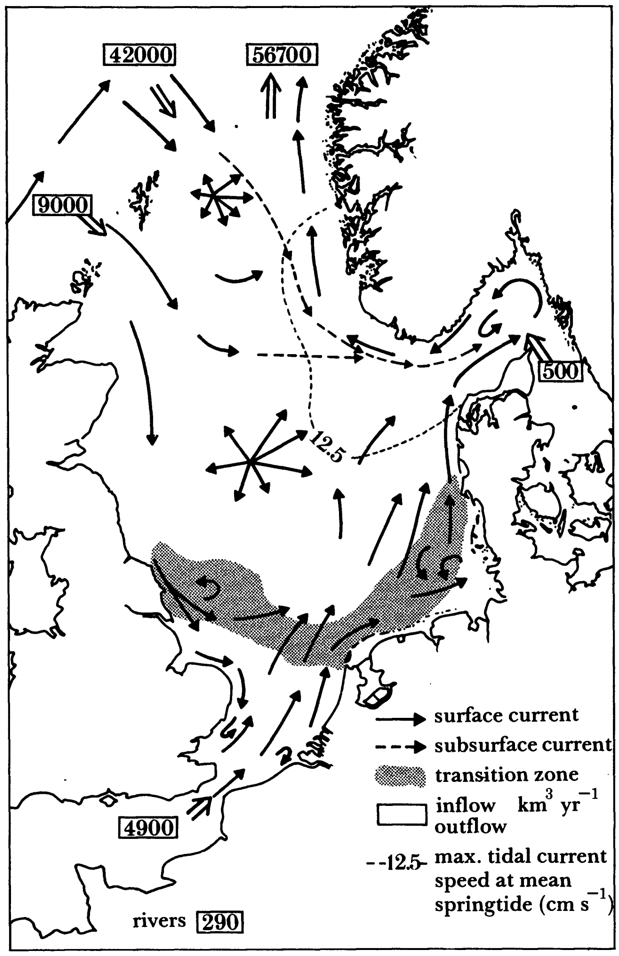

FIGURE 4. General water circulation in the North Sea (from Eisma and Kalf 1987).

relatively warm surface water (up to 18 °C), which in the deeper parts of the North Sea is separated from the cooler deeper water (of *ca.* 6 °C) by a sharp change in temperature (thermocline; Dietrich (1950)). This stratification does not occur in the shallower areas along the coast and in most of the southern North Sea, where tidal currents are strong and the entire water column is regularly mixed (figure 5). The thermocline disappears in autumn when turbulent mixing increases because of stormy weather and cooling of the surface water.

(3) Differences in water density caused by temperature and/or salinity differences result in fronts between water masses of different density (Pingree & Griffiths 1978). Such fronts are common (*a*) in the southern North Sea in a broad zone separating the main mass of North Sea water from the lower salinity water in the south, (*b*) along the Norwegian coast from the Skagerrak to the Norwegian Sea separating the Norwegian Coastal Current water from the more saline North Sea water, and (*c*) on a smaller scale off river mouths and in coastal waters.

(4) Local gyres and other secondary circulations are induced by the bottom topography, the configuration of the coast and, in coastal waters, by differences in density between nearshore and offshore waters. The latter results in a quasi-estuarine coastal circulation whereby the nearshore water moves away from the coast along the surface and offshore water moves shoreward along the bottom (Dietrich 1955; Mittelstaedt *et al.* 1983).

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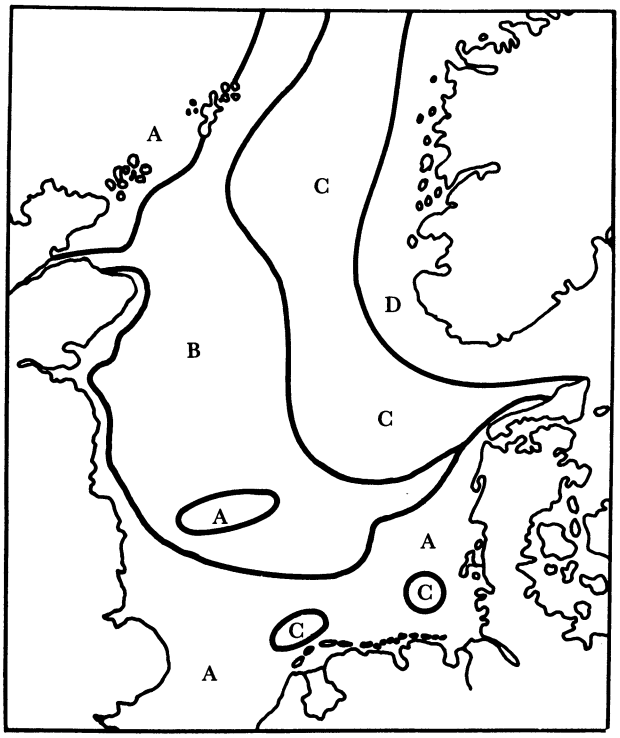

FIGURE 5. Stratification of the water in the North Sea. (A) No stratification all year round; (B) seasonal or permanent temperature stratification (thermocline), no vertical differences in salinity (homohaline); (C) seasonal or permanent salinity stratification (halocline), small seasonal variations; (D) seasonal or permanent salinity stratification (halocline) with strong seasonal variations (from Umweltprobleme der Nordsee 1980).

The effect of wind-induced currents is to enhance mixing, reducing fronts and thermoclines, whereas the formation of fronts and thermoclines indicates reduced mixing. Fronts show a complicated flow structure, usually including downwelling, upwelling, flow parallel to the front, and the formation of large eddies. The water masses separated by fronts often not only show differences in salinity or temperature or both, but also show differences in suspended matter concentration, colour, concentration of dissolved materials, flora and fauna. Fronts are often marked by streaks of foam on the surface. On the whole the North Sea water is renewed every 1–2 years but the renewal time varies in the different parts from more than three years in the German Bight and the western part of the central North Sea to less than six months at the eastern side north of Stavanger (Maier-Reimer 1977).

3. Sediment transport

At present, hardly any sand and no gravel is being supplied by rivers to the North Sea and only a very small amount comes from erosion of cliffs (Eisma *et al.* 1979). Virtually all sand and gravel is being reworked from older deposits by bottom currents and waves. Many sands and gravels contain a more recent admixture of organic matter and carbonate (shell) fragments left over (mainly) from benthic organisms, and probably to a lesser extent, from plankton. Suspended matter (less than *ca.* 125 μm diameter) is supplied to the North Sea to a total of, roughly, 40 million tonnes per year (dry mass), coming from the Channel, from the North Atlantic Ocean, from the Baltic, from rivers, from erosion of cliffs and the sea floor, from the atmosphere and from primary production (organic matter, diatom frustules, carbonate particles; Eisma & Kalf, 1987). Organic matter is produced in the North Sea in large quantities (in the order of 70 million tonnes per year) but almost all is mineralized and consumed so that only a very small fraction (in the order of 1% or less) is incorporated in bottom sediments (chiefly in mud deposits). During periods of plankton growth a very large amount of organic particles, living or dead, can be present comprising up to more than 90% of the total amount of suspended material.

Gravel is not transported under present conditions in the North Sea except in very shallow areas or on the beach where waves have a large impact. In any case, gravel is being transported only over relatively short distances. Sand transport is usually limited to those areas where tidal currents and wave action are relatively strong, i.e. the beaches and offshore in most parts of the southern North Sea, the southern Skagerrak and between the islands in the north, but during heavy storms (fine) sand may be temporarily moved at more than 100 m water depth. Sand goes in suspension only in the surf along beaches or on shallow sand banks, but is usually transported over or just above the bottom. During transport, sand is temporarily stored in ripples of varying size so that sand transport is slow compared with suspended matter transport. Resultant sand transport in a certain direction is usually small, except near to the coast, although tidal currents are able to move large amounts of sand (e.g. in the Southern Bight); almost all of this returns, however, during the next tidal phase when the current goes in the opposite direction.

Suspended matter is moved through the entire North Sea, roughly following the direction of water transport. Most suspended matter is concentrated nearshore, concentrations reaching 100 mg l^{-1} or more, because most of the sources are located nearshore (rivermouths, cliffs, the shallow sea floor) and because the nearshore water circulation concentrates suspended matter near to the coast, at the same time reducing the dispersal of suspended matter from the nearshore sources in an offshore direction. About one third of the suspended matter in the North Sea, which is approximately the same amount as that which comes in from the North Atlantic, flows out into the Norwegian Sea, which is not necessarily the same material that came in from the ocean. The remainder is deposited in a number of isolated areas as indicated opposite (figure 6). In these areas the suspended matter is concentrated by tidal mechanisms or in large tidally or topographically induced eddies. Wave activity near to the bottom is small, either because of the water depth or because the area is sheltered against the wind. Mud deposited in these areas is therefore not easily stirred up again. A balance of the supply and the outflow plus deposition of suspended matter in the North Sea is given in table 1. The figures in this table are approximate; because of the large variability in transport conditions and the limited number of data, budget calculations can only approximately give the amounts of suspended matter that are involved.

Bottom sediment and suspended matter:

(*a*) form a habitat for organisms that live in or on the bottom or attach themselves to suspended particles (bottom fauna, micro-organisms);

(*b*) contain food (in the form of organic matter) for pelagic or benthic organisms that filter suspended matter from the water or consume bottom sediment;

(*c*) provide the right conditions for higher organisms that feed on benthic fauna, use certain types of bottom sediment for spawning grounds, etc.;

(*d*) provide a carrier for substances that are adsorbed on to the particle surfaces, that are transported that way through the North Sea and become concentrated in bottom deposits.

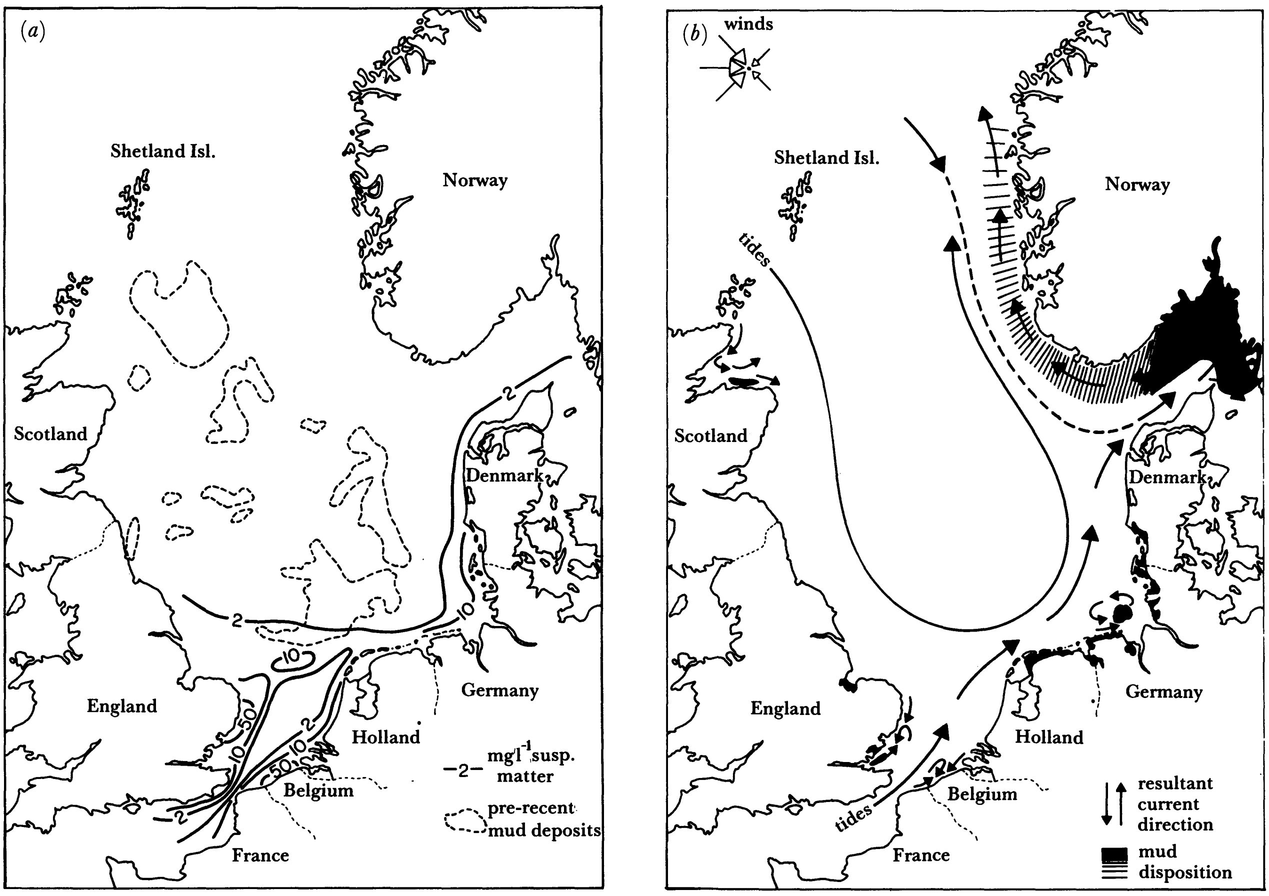

FIGURE 6. (*a*) Distribution of suspended matter (in mg l^{-1}) and (*b*) resultant transport directions, location of recent mud deposits (black) and older mud deposits (from Eisma & Kalf 1987).

TABLE 1. ANNUAL SUPPLY, OUTFLOW AND DEPOSITION (MEGATONNES)

supply	
North Atlantic Ocean	10
Channel	10
Baltic	0.5
rivers	4.8
seafloor erosion	9–13.5 (+?)
coastal erosion	0.7
atmosphere	1.6
primary production	1
total	37.6–42.1
outflow + deposition	
outflow	11.4 + < 3
deposition	
estuaries	2.5
Waddensea + The Wash	3.5
Outer Silver Pit	1–4 (?)
German Bight	3–7
Elbe Rinne	?
Oyster Grounds	?
Kattegat	8
Skagerrak	4–7 (+?)
total	33.4–46.4

Generally, the finer-grained sediments contain more organic matter and can support a denser population of organisms, but high or low organic matter content of the sediment is not necessarily an indicator of productivity. Where the supply of organic matter is high, a dense population can be maintained that has a high consumption, so that the concentrations of organic matter left over in the bottom sediment can be quite low (provided the organic matter has a high nutritional value). To understand such relations it is necessary to know the fluxes of supply, consumption and eventual storage.

Whether a bottom sediment is the right habitat for a benthic species is often related to the particle size of the sediment (Umweltprobleme der Nordsee 1980). It is not necessarily the particle size itself, however, that is important, but other factors related to it: water movement, water characteristics (e.g. turbidity), and also organic-matter content of the sediment, pore space, sediment structure, mud content, clay content, chemical composition, or a combination of these (figure 7). Intricate relationships, which still defy explanation, exist between the

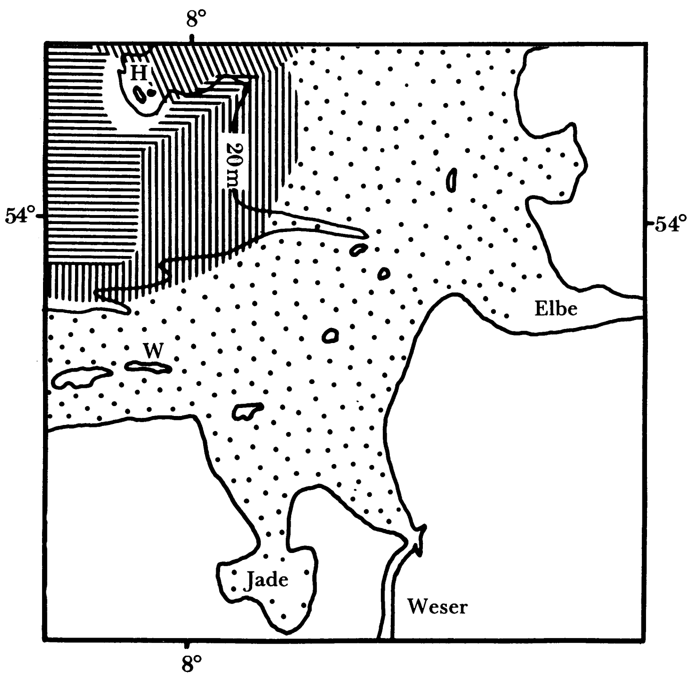

FIGURE 7. Distribution of bottom fauna communities in the German Bight (from Umweltprobleme der Nordsee 1980). Pointed area: *Macoma balthica* community, coastal sands; vertical lines: *Abra alba* community, mud; horizontal lines; *Echinocardium cordatum–Amphiura filiformis* community, fine muddy sand; oblique lines: *Venus striatula* community, coarse sand and gravel.

presence, absence or the abundance of benthic organisms on the one hand, and sediment characteristics as median diameter and sorting on the other. This can be related to the fact that most benthic organisms have pelagic larvae that must settle within a few weeks. If the right type of bottom sediment is not encountered within that period, they will settle in an area that is not optimum but may be still good enough for a large number of individuals to survive. Also, factors quite unrelated to sediment characteristics may determine whether benthic animals will be present or not; coastal sands in the southern North Sea are very poor in species

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as well as in specimens not because of the sand or the surf – elsewhere beach sands can be much more inhabited – but because the water becomes very cold during the winter, or because it has a lower salinity, or because of its high turbidity.

4. Nutrients

Phytoplankton, to be able to grow, need water, carbon dioxide, light, and microamounts of nutrients (phosphate, nitrogen compounds, for diatoms also silica) and probably also small amounts of trace metals and some organic compounds such as vitamins. Water and carbon dioxide (as bicarbonate) are present in abundance in the North Sea but light and to some extent nutrients are restricted (little is known about the influence of trace-metal concentrations and organic compounds). The intensity of the sunlight shows seasonal variations and its penetration in the water is limited by reflection, scattering and absorption. Particles in suspension restrict the penetration of light and the growth of the plankton itself, when it becomes abundant, can reduce the light penetration. In the North Sea the low light intensity during the winter months strongly reduces photosynthesis by phytoplankton. Low winter temperatures are not a limiting factor since diatoms can live and grow on and between ice. When light is sufficiently available, the concentration of nutrients usually limits phytoplankton growth.

The nitrogen compounds – nitrate being the most important – come into the North Sea from the North Atlantic, from rivers and from the atmosphere in rainwater (Cushing 1973; Johnston 1973; Umweltprobleme der Nordsee 1980). High concentrations occur where the influx of river water is high (coastal waters along the English and the Belgian–Dutch–German coast; figure 8*a*), but are lower elsewhere in the North Sea. In most of the North Sea there is a delicate balance between the supply of nitrogen from the three sources mentioned, the degree of mixing of surface water and deeper water, the depletion by growing phytoplankton and the amount of nitrate brought back into solution by mineralization of organic matter (including the upward flux of nitrate and other nutrients from the bottom sediments).

The concentration of phosphate, which is not transported through the atmosphere except as aerosols which contribute only a minor quantity, shows a similar distribution as nitrate with high concentrations in the North Atlantic inflow and near river mouths (Firth of Forth, Thames estuary, Belgian–Dutch coast, German Bight; figure 8*b*). The distribution of dissolved silica, which is supplied from the same sources as phosphate, is very similar. Conditions for photosynthesis (phytoplankton growth) are therefore favourable in the coastal areas but growth tends to be limited there (*a*) because of the high suspended-matter concentrations (up to 100 mg l^{-1}) limiting light penetration into the water, and (*b*) dispersal by mixing with offshore water poorer in phytoplankton and nutrients, which is probably more important than the turbidity of the water as a limiting factor. Outside the coastal areas phytoplankton growth in most parts of the North Sea is limited during most of the year by the formation of a thermocline restricting the mixing of surface water and deeper water. In the surface water above the thermocline nutrients are used up but in the deeper water high nutrient concentrations develop because of mineralization and sinking down of organic matter produced in the surface water. In the surface water a kind of steady state develops whereby phytoplankton populations increase to their limits and nutrient concentrations become low, while nutrients that become available by mineralization of the organic matter that is produced are quickly used up again so that their concentration in solution remains low. Only part of the organic matter that is

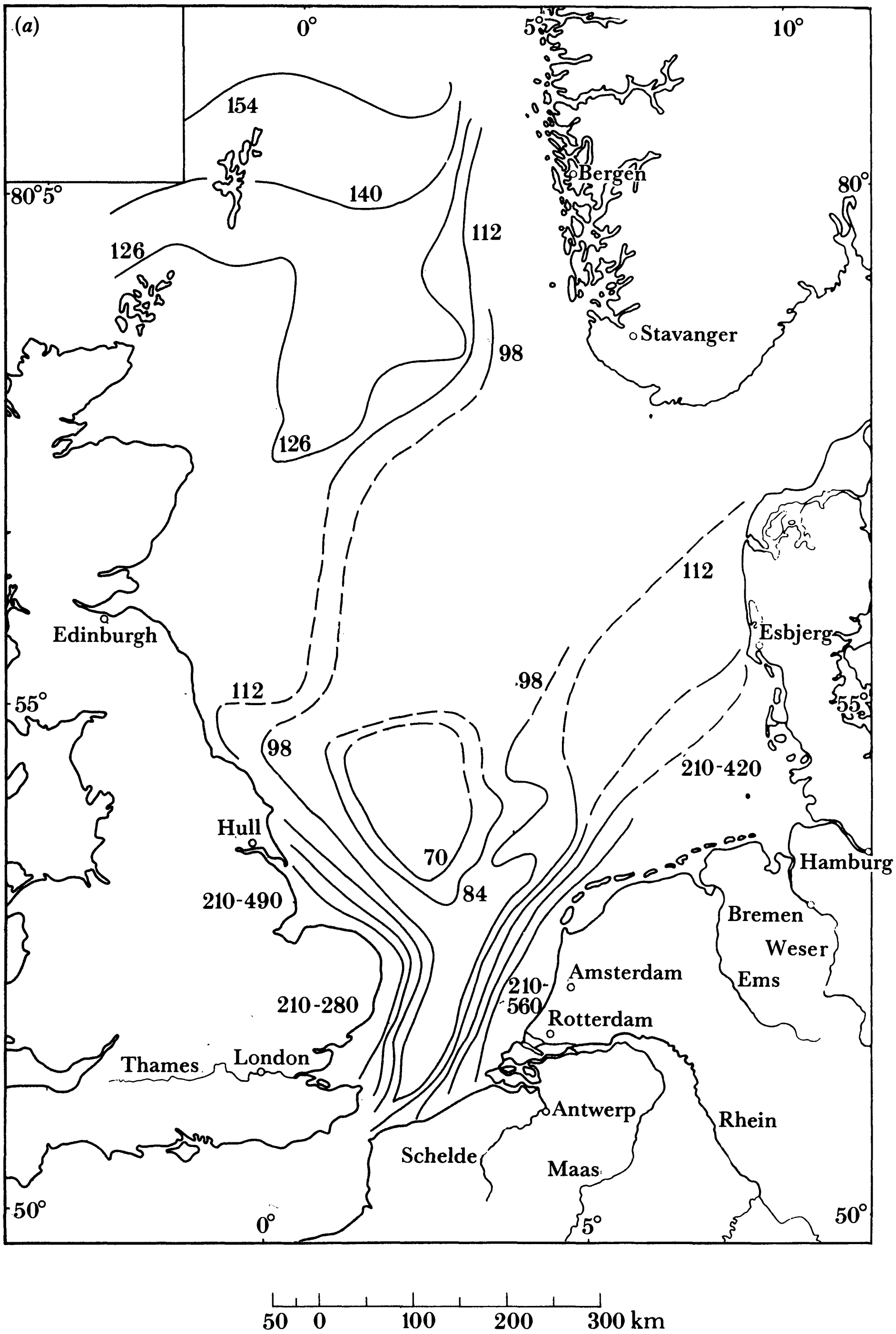

FIGURE 8a. For description see opposite.

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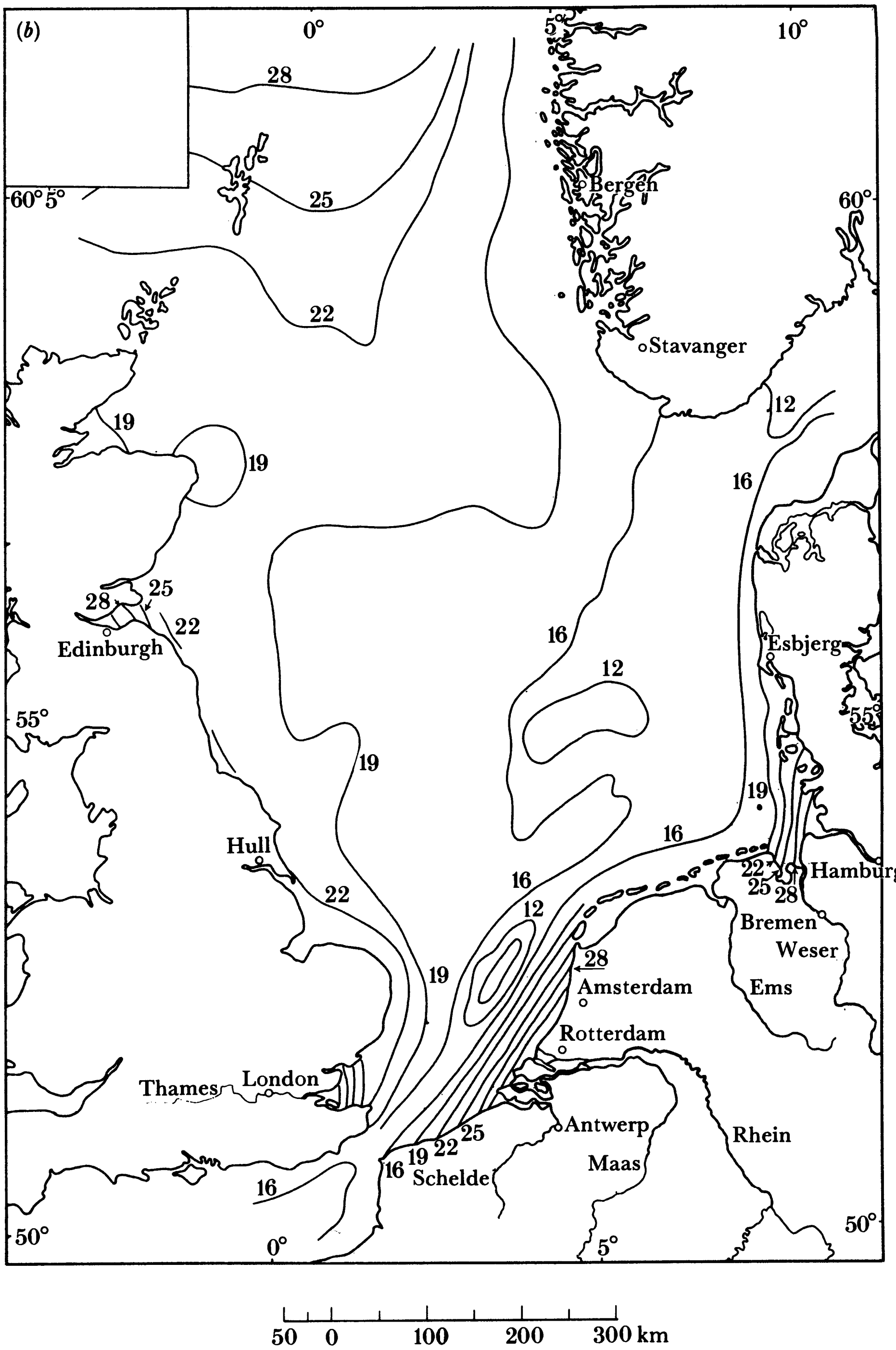

FIGURE 8. Distribution of NO_3-N (*a*), and PO_4-P (*b*), both in micrograms per litre in the North Sea surface water in winter (from Johnston 1973).

produced in the surface water (normally in the order of 1% but much higher after a period of plankton bloom and on the whole probably 30–50%) sinks through the thermocline into deeper water, where it is mineralized or incorporated in bottom sediments (where it forms a valuable source of food for benthic organisms; Smetacek (1984)), so that in the surface water a high productivity can be maintained.

The phytoplankton production in the central and northern North Sea tends to have two maxima during the year (figure 9; Colebrook & Robinson 1965): one in early spring when light becomes increasingly stronger and nutrient concentrations are high because of mixing and

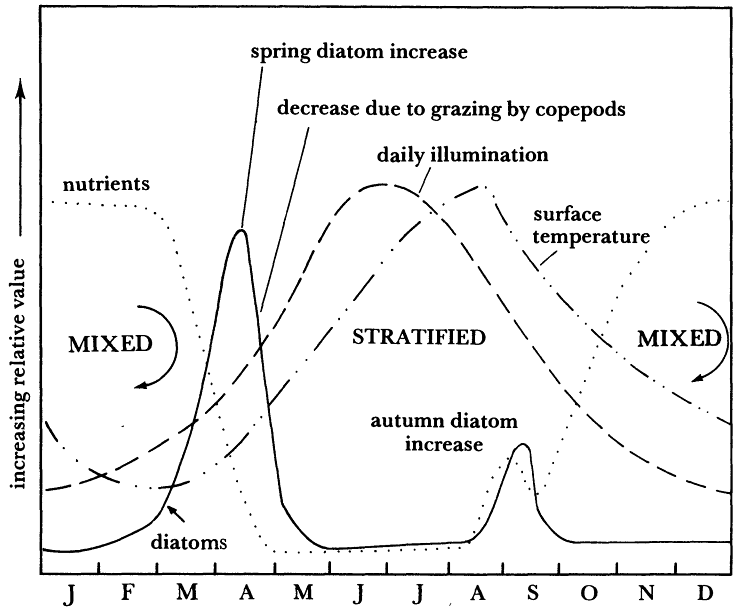

Figure 9. Seasonal variations in phytoplankton growth and nutrient concentrations in the (northern) North Sea (after *Waterkwaliteitsplan Noordzee* 1985).

advection during the winter, and one (usually a smaller one, which is often absent) in autumn when the thermocline is broken up. Mixing makes nutrients from deeper water available in the surface water while there is still sufficient light for photosynthesis. In the shallower coastal waters and in most of the southern North Sea where no thermocline is formed and haloclines have a limited distribution, phytoplankton growth is largely determined by the degree of advection of nutrients from rivers and the limiting factors indicated above. Diatoms are usually the dominant group as long as silica is sufficiently available. When that is depleted to very low levels and other nutrients are still there, other phytoplankton species, mainly flagellates, take over. Phytoplankton, living or dead, forms the basis of all other life in the sea. Diatoms are eaten by the larger zooplankton species (copepods), which in their turn are consumed by other pelagic organisms and by fish. The smaller flagellates are mostly eaten by smaller zooplankton species, which are primarily the food of jellyfish. The dead organic matter is consumed (*a*) by organisms like bacteria and copepods that live on organic matter in suspension, (*b*) by organisms that filter suspended matter from the water (consuming living and dead organic matter indiscriminately, the particle size determining whether a particle can be ingested or not), and (*c*) by benthic organisms that eat bottom sediment.

The supply of phosphate and nitrate (but not of silica) to the North Sea has increased considerably during the past decades, because of the human population increase and the increased use of detergents and fertilizers in the countries around the North Sea (van Bennekom *et al.* 1975; Gerlach 1984). The increased supply chiefly reaches the North Sea by way of the rivers and to a lesser extent from direct discharges of organic waste or through the air. The effect of this eutrophication up to now has not been easy to assess. The changes in the populations of phytoplankton and of other marine organisms that have occurred can be related to other factors such as hydrographical changes (e.g. changes in storm frequency, temperature anomalies) and changes in the zooplankton populations that graze on phytoplankton. Some shifts may be related to changes in nutrient supply: along the Dutch coast the silica supply has decreased somewhat during the past 50 years, whereas phosphates and nitrates increased so that diatoms, which were dominant 50 years ago, have been replaced by flagellates which are dominant now. Around 1930 phosphate supply to the coastal waters was a limiting factor for plankton growth, whereas at present mixing with nutrient-poorer offshore water is most likely to be the principal limiting factor. It is also possible that pollutants are (partly) responsible for the observed changes (Postma 1985).

Another possible effect of eutrophication is the lowering of the concentrations of dissolved oxygen in the water (Gerlach 1984). Under aerobic conditions mineralization of organic matter involves uptake of oxygen that is dissolved in the water. In areas with high phytoplankton growth periodically both high and low dissolved oxygen concentrations can be expected; high because of the production of oxygen during photosynthesis so that even supersaturation may develop, and low because of oxygen being used up during the decomposition (mineralization) of organic matter produced by phytoplankton. The actual concentration of dissolved oxygen in the water is the result of the relation between supply (from the atmosphere and/or from photosynthesis) and consumption. In the North Sea, as in almost all other sea areas, the advection of dissolved oxygen through the water (by currents, waves and turbulence) has always been sufficient to maintain, even in the near-bottom waters, sufficiently high dissolved oxygen levels for most organisms to be able to live there (i.e. at least a 30% saturation). Very low oxygen concentrations have now occurred in the German Bight and along the Danish west coast, resulting in a high mortality of bottom fauna, which is probably mainly related to discharges of organic waste or to increased nutrient supply from the Elbe river. In bottom sediments that are little disturbed the decomposition of the organic matter in the sediment usually results in anaerobic conditions (with dark blue or black colouring because of the formation of iron sulphide) below an oxidized layer of variable thickness (ranging from 1 mm to more than 10 cm). The diffusion of dissolved oxygen from the overlying water through the pore-water into the sediment is too slow to compensate for the oxygen consumption at deeper levels. Where deep-burrowing organisms occur in the bottom sediment, their activities bring oxygen-rich water deep into the sediment.

5. Other trace constituents

The natural levels of many trace metals and organic compounds, present in concentrations of a few milligrams per litre or (much) less, are not known because the analytical techniques to determine them reliably in solution in seawater were developed when pollution had already been occurring for many decades. Natural levels of trace metals in sediments and suspended matter can be estimated from fine-grained sediments dating from before *ca.* 1850 (figure 10),

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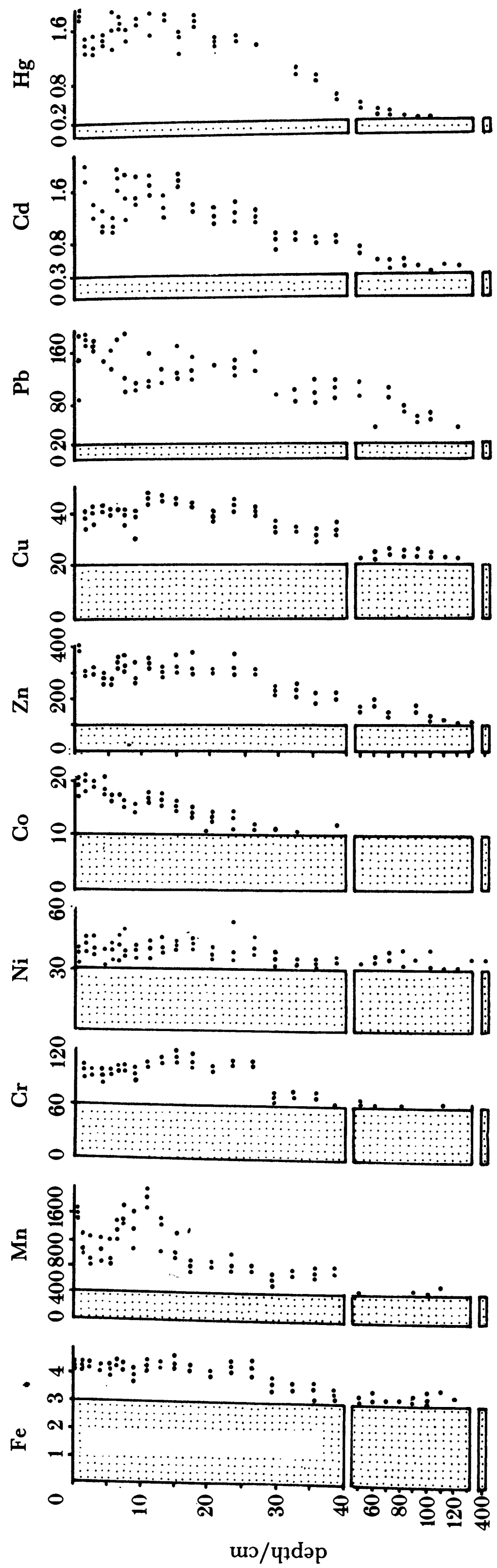

FIGURE 10. Distribution of trace elements in a sediment core from the German Bight (from Förstner & Reineck 1974). During the first part of the 19th century the concentrations were still the natural concentrations (geochemical background). Trace-element concentrations are shown in parts per million by mass of dry sediment.

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but the partitioning ratio between the amount in solution and the amount in particulate form is not well enough known to reconstruct natural concentrations in solution. For practical purposes the concentration in North Atlantic water can be taken as the natural concentration in seawater, whereas estimates of natural concentrations in river water are based on the present partitioning ratios. Compared with 1850 the concentrations of many trace metals in sediments have increased by 100–700 %. Other trace constituents, in particular many organic compounds, are purely artificial and only reached the North Sea during the last 100 years (many, much more recently).

For many trace constituents the interaction between the dissolved and the particulate phase and of both phases with organisms is strongly related to the form in which the constituent is present; in inert particles, as irreversibly adsorbed material that can only be desorbed through (partial) conversion of the particulate material, reversely adsorbed material that can be exchanged, and in solution as well as several types of chemical species (oxide, hydroxide, sulphide, ionic, molecular; Salomons & Förstner 1984). Concentration changes in the water, changes in pH, temperature, turbidity and in particle characteristics may result in mobilization of a trace constituent from particles into solution or removal from solution into particulate form. There are two important mechanisms whereby trace constituents are concentrated: one is by adsorption on to particulate matter and deposition of this on the sea floor, and the other is by uptake and concentration in organisms. In both ways the concentration can increase by several orders of magnitude (figure 11). Dead organic matter plays a large role in the adsorption of trace constituents on to particles; all surfaces in seawater are quickly covered by an organic coating and organic matter is very surface-active. The mechanisms involved, in particular those resulting in high concentrations in organisms, are badly known, and the toxic as well as the potentially toxic effects of the concentrated substances are usually difficult to assess. An example is the strong decline in the number of seals in the Dutch Wadden Sea. The study of dead seals indicated that the decline may be related to poisoning with mercury, to parasites, to oil-caused skin infections, to physical disturbance by ships, planes, target practising and tourists chasing the mothers from their young, and to poisoning with organic poisons, notably PCBs. Further research indicated that the effects of mercury were probably neutralized by the uptake of selenium and that the PCBs are the most likely cause (Reijnders & Wolff 1981; *Waterkwaliteitsplan Noordzee* 1985).

Laboratory tests are a logical way to estimate effects of trace constituents (*Waterkwaliteitsplan Noordzee* 1985) but in spite of many such tests, the toxic levels of trace constituents in water or sediments are difficult to estimate because:

(1) there are a great many toxic or potentially toxic substances and a large variety of marine organisms; for many substances and for many marine organisms no tests have been made, while the results of the tests that have been made are difficult to interpret considering the complexity of biological relations in the North Sea and the possibility of synergetic or antagonistic effects (laboratory tests are usually done with only one species and one trace constituent);

(2) for many trace constituents the dispersal patterns and the amounts supplied to the North Sea are not very well known;

(3) the relation between bottom sediment composition and bottom fauna is not well known;

(4) there is the possibility that marine organisms and marine ecosystems adapt to changing conditions, including higher levels of trace constituents.

These uncertainties directly affect decisions on what levels of pollutants can be regarded as

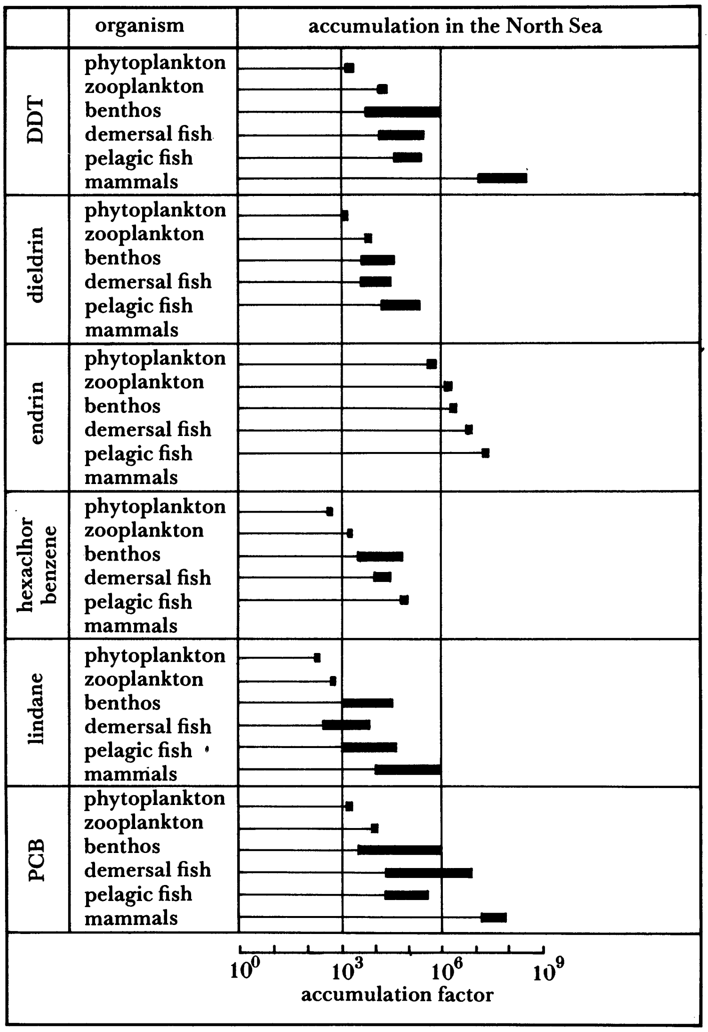

FIGURE 11. For description see opposite.

acceptable. There are only a few instances known from the North Sea where the effects of pollution are clear and where cause can be related directly to effect, such as oil affecting sea birds (but then, whose oil?), copper poisoning fish along the Dutch coast and pesticide poisoning in the Dutch Wadden Sea that could be traced directly to a factory in Rotterdam. In the latter case it took, as in Minamata Bay, a considerable amount of research to establish the link between effect and cause. Prevention of harmful effects caused by trace constituents in the North Sea can therefore only be done on the basis of rather general, and therefore rather vague and unsatisfactory criteria.

6. Biological relations

Phytoplankton and zooplankton populations in the North Sea are related to water characteristics like temperature, salinity, nutrient concentrations, turbidity, degree of stratification, to the water circulation, to the time of the year and to biotic factors. Within each

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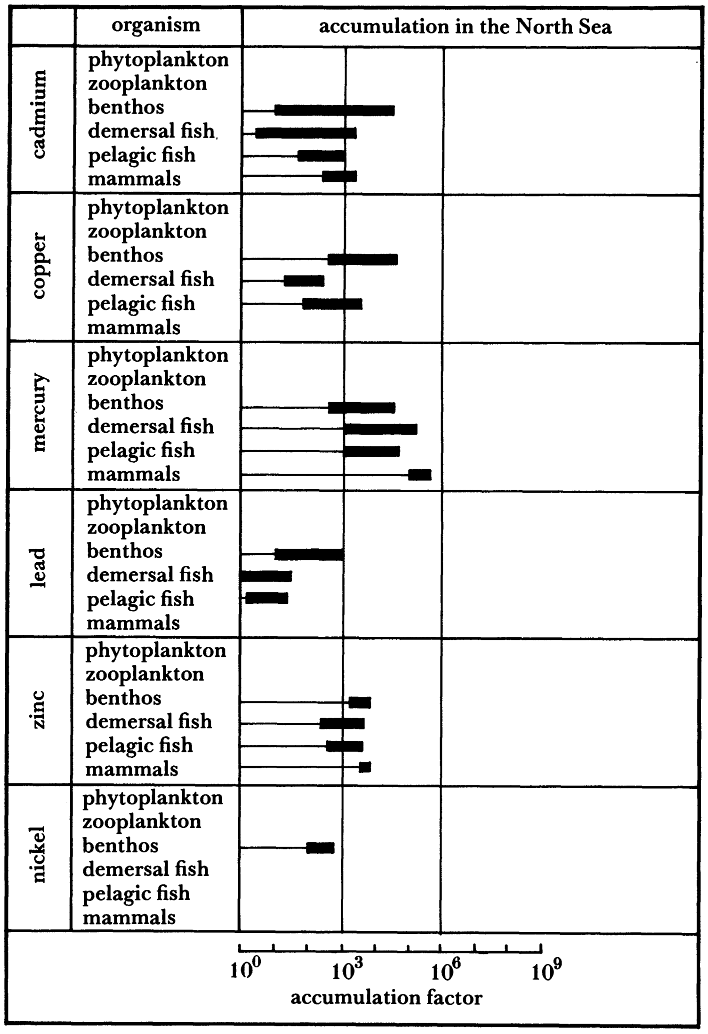
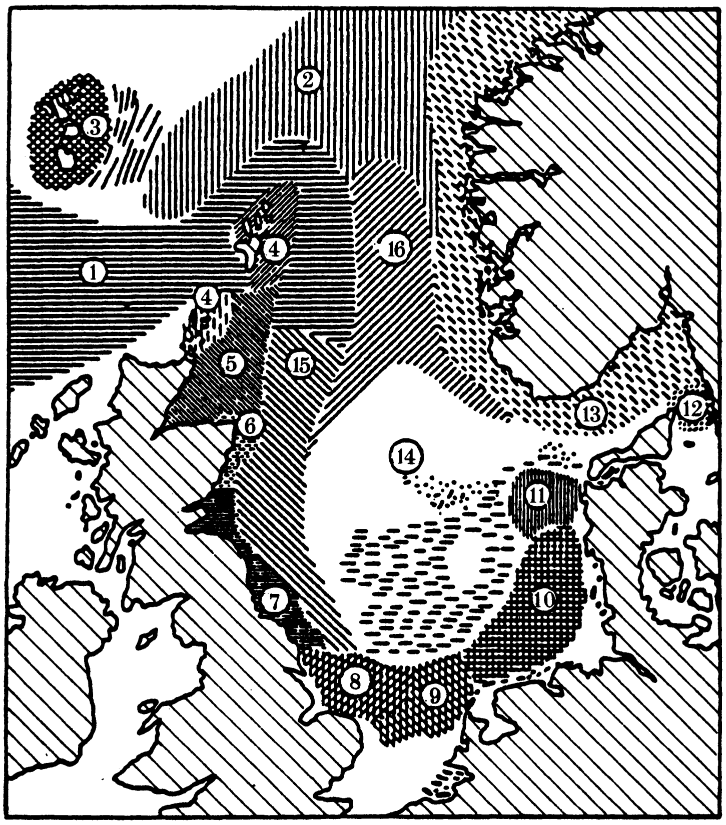


FIGURE 11. Accumulation of some trace metals and organic compounds in different groups of organisms in the North Sea (after *Waterkwaliteitsplan Noordzee* 1985). The accumulation factor is obtained by dividing the concentration in the organisms by the concentration in the seawater.

distributional area, which can only be loosely defined, the phytoplankton shows a patchy distribution (figure 12). The distribution of zooplankton is linked to the phytoplankton distribution (Cushing 1973) but there is usually some time-lag, the phytoplankton population developing first and the zooplankton population following, but the mechanisms leading to an increase or a decrease in zooplankton populations are badly understood. Zooplankton consists of species that are entirely planktonic and species that are only temporarily planktonic, like the larvae of many bottom-dwelling organisms and of fish. Therefore the distribution of bottom fauna and of fish is to some extent related to the same water characteristics as the planktonic populations. Fronts that separate water masses of different characteristics play a large role in these species distributions.

The distributions of the higher organisms at the end of the food chain (fish, mammals and birds) are far more varied and complex than the distribution of phyto- or zooplankton. The distribution of fish is related to the locations of good spawning areas, to areas where the young



tribution of different phytoplankton communities in the North Sea (after Braarud *et. al.* (1953), from *Waterkwaliteitsplan Noordzee* (1985)).

fish can grow up, and the distribution of food. Most fish species migrate during the year: from one area in the North Sea to another, from offshore to nearshore and inshore waters, and from salt water to fresh water and back. Herring and cod are examples of the first kind, plaice and sole of the second, and salmon and eel of the third. Shallow tidal areas like the Wadden Sea and a number of sandy beaches are very suitable for summer growth of young fish and shrimp (Zijlstra 1972) because of the relatively high temperature, the availability of food based on the local production of algae and other small organisms, and a lower predation. This leads to a seasonal migration: landward in spring, seaward in autumn. Migration to and from fresh water is at present very much reduced because of the destruction of suitable spawning grounds like the gravel beds along many rivers and water pollution.

The distribution of marine mammals is largely determined by their sensitivity to high or low temperatures, by the distribution of the fish that constitutes their food, by the need of some species for certain types of coastal areas to rear their young (e.g. sand flats for common harbour seals) and, at present, also by the degree of water pollution and disturbance. The distribution of bird species is also linked to the availability of food (fish and bottom fauna) as well as to their requirements for nesting (cliffs, dunes and trees). A large number of bird species in the North Sea are migratory; migration occurs to and from areas outside the North Sea and ranges from Greenland and Siberia north and central Africa (Evans 1973).

The general relations between organisms in the North Sea are given in figure 13. To

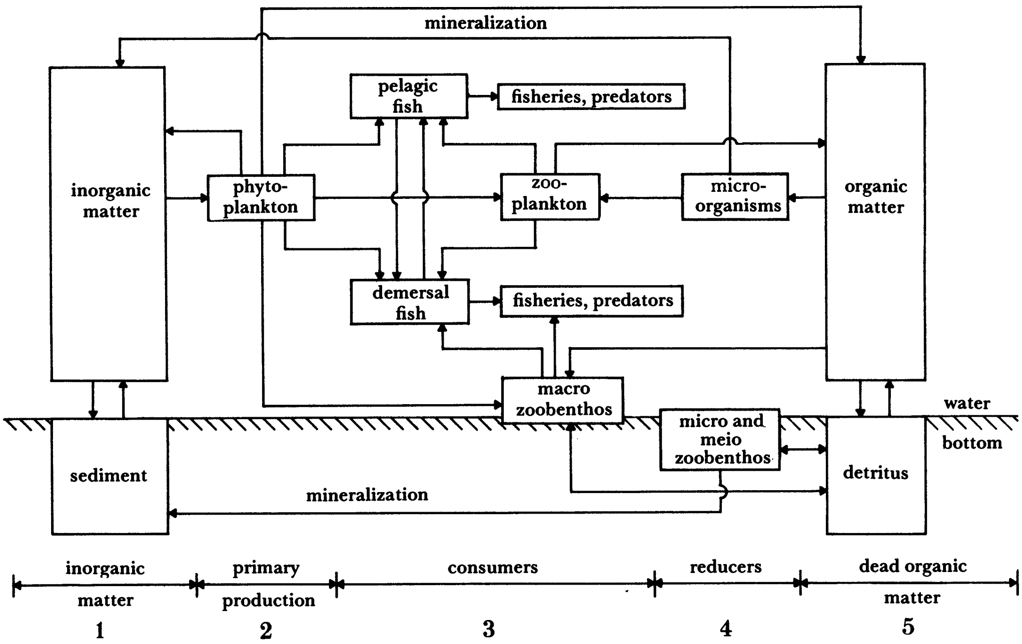


FIGURE 13. General scheme of the relations between the different groups of organisms in the North Sea (from *Waterkwaliteitsplan Noordzee* 1985).

understand these relations better and to get some understanding of the quantities involved, the flux of carbon through this system is considered. An example for the Belgian coast is given in figure 14, which shows the complexity of even a small area (Joiris *et al.* 1982). Data for the North Sea as a whole, however, are not available, mainly because data for the central and northern North Sea and for species that are not of economic interest are lacking. Even the data for biomass production in the different groups, as shown in figure 14, are only rough estimates. Some general relationships, however, can be indicated. There is a short carbon cycle where a large part of the organic matter produced by algae (planktonic or benthic) is consumed by Protozoa and bacteria. For a number of these organisms the substrate is very important as they attach themselves to particles, and they themselves are probably an important food source for bottom fauna. There is also a longer cycle in which organic matter, living or dead, having been consumed by zooplankton, passes to fish and marine mammals (including man). Fisheries interfere in both cycles. In the shallow areas the benthic food chains are important besides the pelagic food chains. In the deeper parts of the North Sea the pelagic cycles dominate and the benthic cycles play a secondary role, although still *ca.* 30% of the available energy in the form of food is used by benthic organisms. At different levels within the food chains there are vast differences in actual biomass and a large variability, while there is not much of a relationship between biomass and trophic level. Also, the reproduction is very different at different levels: the total plankton biomass reproduces itself every 5–10 days (averaged over the year), the biomass of small benthic organisms (meiofauna) every 45 days, the large benthic organisms once or twice a year, and fish only once a year, but there are large variations from year to year. Much of the organic matter produced is 'lost' going from a lower trophic level to a higher one because of respiration and the excretion of organic material, so that only *ca.* 1% of the annually produced organic matter goes into the production of fish. It follows that the effects

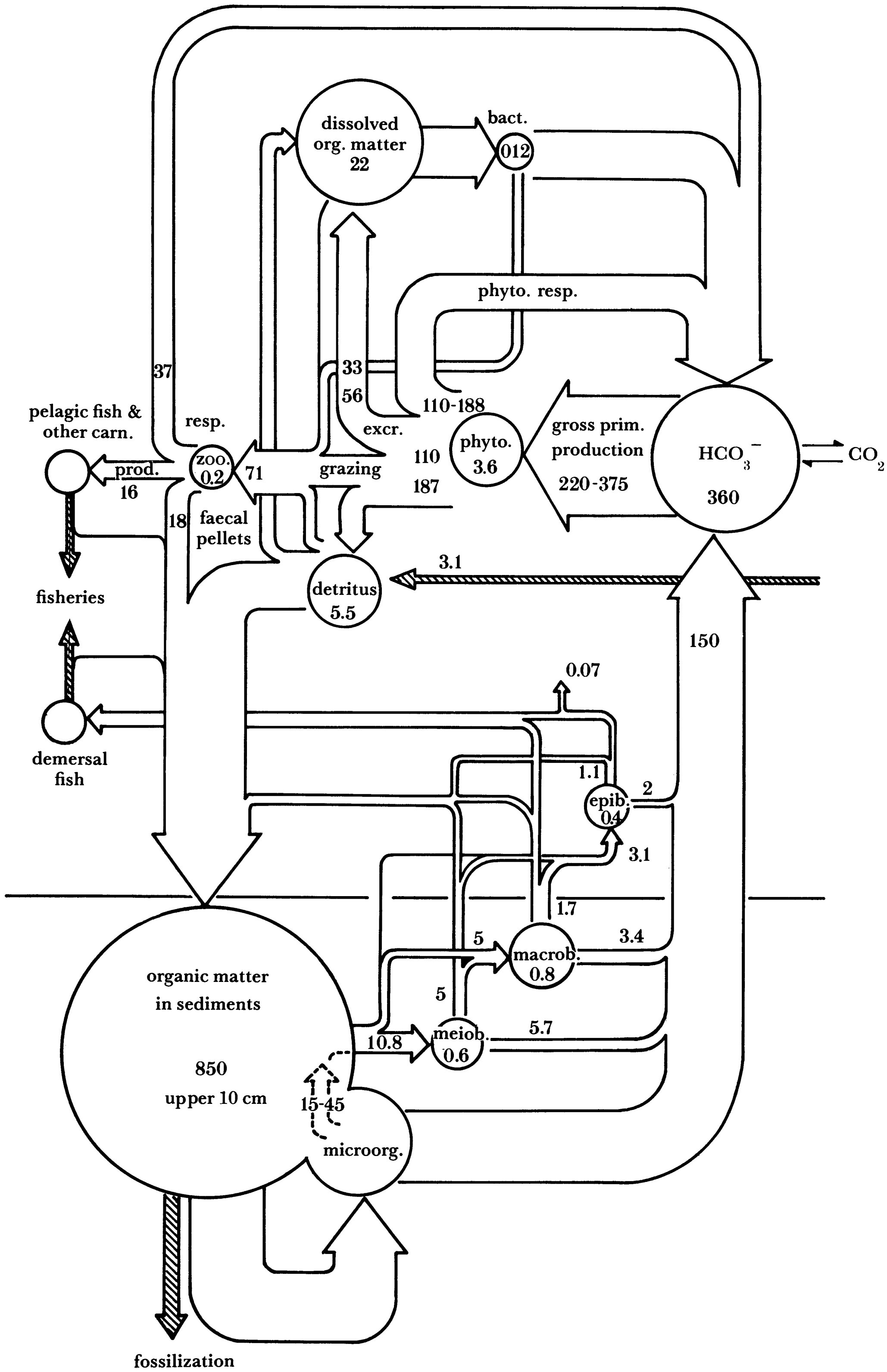


FIGURE 14. Budget of organic carbon off the Belgian coast (from Joiris *et al.* 1982). Numbers within the circles: grams of carbon per square metre present in the water column or in the upper 10 cm of the bottom. Numbers in the arrows; annual flux of carbon expressed in grams of carbon per square metre.

of natural variations or man-induced changes, affecting the phytoplankton production in the first place but also affecting the different trophic levels separately, are difficult to assess. That such changes take place is indicated by the occurrence of a higher biomass of microflagellates and dinoflagellates (more 'red tides' and fluorescing seas) during the past decades compared with the decades before, a lower biomass of diatoms and zooplankton, lower oxygen concentrations near to the bottom in some shallow areas, more demersal fish (living on bottom fauna) relative to pelagic fish, and an increase in the total biomass of fish and in the biomass of shrimp (at least along the Dutch coast). All these changes can be the effect of an increase in the phytoplankton biomass because of increased nutrient supply in combination with a shift in the relative amounts of the supplied nutrients, but such a conclusion can only be tentative because a combination of natural shifts (e.g. in the water temperature), of fisheries (selective removal of certain species), as well as unknown factors at other trophic levels may have caused these changes.

7. Summary

Summarizing, our knowledge on the North Sea is incomplete.

(1) There is a reasonably good idea of the general water circulation through the North Sea and of the composition and the topography of the sea floor, although more detailed knowledge is still inadequate.

(2) There is also a reasonably good idea of the general transport of sediment (bottom transport and in suspension) through the North Sea, but the mechanisms involved are poorly understood, the *in situ* particle characteristics are badly known and on the whole suspended matter transport is much less clear than water transport.

(3) Nutrients have been studied intensively, resulting in a reasonable insight into their origin, distribution and fate but for other microconstituents this knowledge is largely lacking, which is hardly surprising considering that the necessary analytical techniques were developed in the late sixties or even later. Fluxes of nutrients and other trace constituents in the benthic boundary layer need further investigation.

(4) The ecology of the North Sea remains largely obscure because of the complexity of biological relations and the fact that most studies have been limited to commercially important species

(5) Apart from some self-evident or well-studied effects, an assessment of the effects of pollution and other human activities in the North Sea is very difficult to make.

To Dr G. C. Cadee and Dr P. A. W. J. de Wilde I am much indebted for critically reading the manuscript and to H. Hobbelink and R. Nichols for the illustrations.

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Discussion

R. Johnston (24 *Hilton Drive*, *Aberdeen*, *U.K.*). There is no evidence of abnormal shortage of silicate in the open waters of the main part of the North Sea. How does Dr Eisma explain the development of the induced deficiency of silicate in coastal waters off Germany and The Netherlands?

D. Eisma. Although there has probably been a slight reduction in the silicate supply to the southern North Sea in the past decades, the relative deficiency of silicate in the coastal waters off Germany and The Netherlands is caused by the two- to fourfold increase in the supply of phosphate and nitrogen compounds. This has resulted in a shift from diatom predominance to a predominance of flagellates. The effect of this shift is reduced by the limitations on primary productivity imposed by the turbidity of the coastal waters and the mixing of coastal water with offshore water having a lower nutrient content.

J. I. G. Cadogan, F.R.S. (*British Petroleum International Co. plc, London, U.K.*). Dr Eisma said that the assessment of the effects of pollution versus normal changes is difficult to make. Nevertheless does he consider that fixed emission standards are appropriate or should the North Sea be zoned, with different standards being set for different areas?

D. Eisma. Different areas in the North Sea do not have the same sensitivity to pollution. So in a large accident in the North Sea involving oil, tidal flats like the Wadden Sea are more liable to be damaged and more difficult to tidy up than the open waters of the central North Sea, while continuous discharges of small amounts of oil will have similar effects in both areas. Some degree of zoning therefore seems logical, whereby the regulations are adapted to the characteristics of the zoned areas.

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