MARINE ENVIRONMENT QUALITY ASSESSMENT OF THE SKAGERRAK - KATTEGAT

RUTGER ROSENBERG¹, INGEMAR CATO², LARS FÖRLIN³, KJELL GRIP⁴ and JOHAN RODHE⁵

¹Göteborg University, Kristineberg Marine Research Station, S-450 34 Fiskebäckskil, Sweden

²Geological Survey of Sweden, Box 670, S-751 28 Uppsala, Sweden

³Göteborg University, Department of Zoophysiology, Medicinargatan 18, S-413 90 Göteborg, Sweden

⁴Swedish Environment Protection Agency, S-106 48 Stockholm, Sweden

⁵Göteborg University, Department of Oceanography, Earth Science Centre, S-413 81 Göteborg, Sweden

ABSTRACT

This quality assessment of the Skagerrak-Kattegat is mainly based on recent results obtained within the framework of the Swedish multidisciplinary research projekt 'Large-scale environmental effects and ecological processes in the Skagerrak-Kattegat' completed with relevant data from other research publications. The results show that the North Sea has a significant impact on the marine ecosystem in the Skagerrak and the northern Kattegat. Among environmental changes recently documented for some of these areas are: increased nutrient concentrations, increased occurrence of fast-growing filamentous algae in coastal areas affecting nursery and feeding conditions for fish, declining bottom water oxygen concentrations with negative effects on benthic fauna, and sediment toxicity to invertebrates also causing physiological responses in fish. It is concluded that, due to eutrophication and toxic substances, large-scale environmental changes and effects occur in the Skagerrak-Kattegat area.

Key words: eutrophication, contaminants, nutrients, oxygen concentrations, toxicity, benthos, fish

1. INTRODUCTION

The Kattegat and the Skagerrak (Fig. 1), with surface areas of about 22000 and 32000 km² and mean depths of 23 and 210 m, respectively, connect the brackish Baltic Sea with the North Sea, where the salinity is almost oceanic (Svansson, 1975). Water of Baltic origin forms a surface layer in the Kattegat with a salinity increasing from 15 psu in the southeast to 25 psu in the northwest. Water originating from the North Sea is found below a pronounced halocline at a depth of about 15 m. The salinity in the deep water ranges from 32 to 34 psu. The Kattegat surface water is bounded to the north by a sharp surface front, on average directed from Skagen towards the northeast. From here on the low-saline water of Baltic origin follows the Swedish and Norwegian coasts in the Skagerrak as a low-saline coastal current.

The hydrographic conditions in the Skagerrak are dominated by a deep-reaching flow of water from the central and northern North Sea with a salinity close to 35 psu. The core of this flow follows the slopes of the Norwegian Trench around the Skagerrak in a cyclonic

direction. This water constitutes the bulk of the water in the Skagerrak. A weaker inflow from the southern North Sea occurs close to the Danish coast, which is influenced by river discharge to the North Sea and has a salinity in the range of 31 to 34 psu. The entire surface of the Skagerrak is to some extent influenced by low-saline water from the coastal current along the Swedish and Norwegian coasts, due to frequently occurring upwelling events (North Sea Task Force, 1993; Rodhe, 1996).

In some areas, with strong stratification and low water renewal, as in the southern parts of the Kattegat and in some fjords along the Swedish and the Norwegian coasts in the Skagerrak, seasonal oxygen deficiency may develop in combination with eutrophication (Aure & Danielssen, 1995; Baden *et al.*, 1990; Magnusson & Johnsen, 1994; Rosenberg, 1990). The oxygen concentration in the deeper parts of the Skagerrak is stable, 5.5 to 7.3 cm³·dm⁻³ (Aure & Dahl, 1994; Dahl & Danielssen, 1992).

A few studies have dealt with ecological aspects of the pelagic system in the open Skagerrak. Pingree *et al.* (1982), Kiørboe *et al.* (1990) and Bjørnsen *et al.*

Fig. 1. Drainage areas (border lines indicated by ---) and main rivers discharging into the Skagerrak-Kattegat. Lightly shaded sea areas have been identified as eutrophicated problem areas by the Oslo and Paris Commissions (1992).

(1993) have found that, e.g. the doming of the pycnocline in the central eastern Skagerrak makes nutrients available to phytoplankton, and also that subsurface chlorophyll maxima frequently occur in the Skagerrak (see also Karlsson *et al.*, 1996). Dense phytoplankton concentrations have also been observed in frontal zone waters at the Skagerrak-Kattegat border (Richardson, 1985). Another study in the open Skagerrak showed that most of the nitrogen used by phytoplankton in May was regenerated nitrogen, and that most of the carbon was channelled through the pelagic microbial system (Rosenberg *et al.*, 1990a). Several experimental studies have shown that nitrogen stimulates algal growth in natural seawater, which suggests that nitrogen is generally the limiting nutrient for primary production (Granéli *et al.*,

1990). Exceptions to this can be local coastal areas with significant nitrogen run-off, or the later phase of the spring bloom when silica deficiency hampers growth of diatoms.

The sediment structure of shallow areas of the Kattegat and the northwestern Skagerrak off Jutland is rather coarse, predominantly sand and coarse silt. Deeper (>75 m) parts of the Skagerrak and the Deep Trench (≈ 100 m) intersecting the Kattegat from the north to the south are dominated by postglacial clayey sediments with an organic content of about 2% dry matter (Cato *et al.*, 1992; Kuijpers *et al.*, 1992). These areas are the main accumulation areas dominated by suspension deposition (Stevens *et al.*, 1996), not only of the Skagerrak and the Kattegat, but also of the North Sea as a whole (Eisma & Kalf, 1987; Van Weering & Qvale, 1983). Other important sedimentation areas are found along the Norwegian and Swedish coasts of the Skagerrak, with their rugged coastline, rich in islands, skerries and fjords, and consequently sheltered bottom areas dominated by organic postglacial clays and fine silt. The highest sedimentation rate in the Skagerrak is found in the northeastern part, $>4 \text{ mm} \cdot \text{y}^{-1}$, with means of $\approx 2 \text{ mm} \cdot \text{y}^{-1}$ at the slopes of the Norwegian Trench (van Weering *et al.*, 1987).

In early 1990, the Swedish Environment Protection Agency launched the research project 'Large-Scale Environmental Effects and Ecological Processes in the Skagerrak-Kattegat' (Rosenberg *et al.*, 1991) with the objectives to intensify marine research in the Skagerrak and the northern Kattegat, and to increase the knowledge on the environmental effects in these sea areas. It was suggested to put research emphasis on the influence of the North Sea on the open Skagerrak and the northern Kattegat and to investigate, for example, whether the accumulation bottoms in these areas are the dustbins for the North Sea. About 40 scientists and doctoral students have taken part in this multi-disciplinary project during 1990 to 1995, and a substantial part of the results are presented in this issue of the Journal of Sea Research (vol. 35, no.(1-3), 1996).

Preceding this project, the southern Kattegat was studied by Swedish scientists in a similar research project, the 'Eutrophication Project'. That project showed that strong seasonal environmental effects occur in that area due to eutrophication. Since the mid-1970s, excessive growth of filamentous algae occurs in spring and summer, and since 1980 bottom-water hypoxia occurs annually in late summer through autumn. The hypoxia is reducing benthic fauna and commercial catches of Norway lobster (*Nephrops norvegicus*) and demersal fish (Baden *et al.*, 1990; Josefson & Jensen, 1992a; Rosenberg *et al.*, 1992). The suggested goals and measures to be taken to improve the environmental conditions in the southern Kattegat is discussed in Rosenberg *et al.* (1990b) and Fleischer *et al.* (1994).

2. INPUT OF NUTRIENTS AND CONTAMINANTS TO THE SKAGERRAK - KATTEGAT

Input data of nitrogen and phosphorus from land and atmosphere are given in Table 1. Larger rivers and their drainage areas discharging into the Skagerrak-Kattegat are shown in Fig. 1. Approximately equal amounts of nitrogen enter the Kattegat from Denmark, Sweden and from the atmosphere. However, the largest Swedish contributor, the Göta River at Göteborg with a discharge of $\approx 17 \cdot 10^6$ kg N $\cdot$ y $^{-1}$ is at the border of the Skagerrak. The largest riverine input to the Skagerrak comes from Norway and mainly from Glomma River.

The North Sea Task Force (1993) has estimated the transport of anthropogenic nitrogen and phosphorus from the Baltic to the Kattegat surface water at $13 \cdot 10^7$ and $1.1 \cdot 10^7$ kg $\cdot$ y $^{-1}$, respectively, and from the southern North Sea to the Skagerrak at $40 \cdot 10^7$ and $3.5 \cdot 10^7$ kg $\cdot$ y $^{-1}$. Recent measurements over the years 1990 to 1994 suggest that currents from the southern North Sea will transport $35 \cdot 10^7$ kg $\cdot$ y $^{-1}$ of inorganic nitrogen and $60 \cdot 10^7$ kg $\cdot$ y $^{-1}$ of total nitrogen into the Skagerrak (Rydberg *et al.*, 1996). The annual variation is great. Eventually, some of this nitrogen will be transported to the Kattegat. In the southeastern Kattegat surface water the largest contribution of nitrogen comes from the Swedish rivers (Fleischer & Jonsson, 1992).

According to the North Sea Task Force (1993) the input of heavy metals to the Skagerrak and the Kattegat is generally low. However, elevated concentrations, often up to ten times the background and occasionally up to 50 times, have been found for several elements (Hg, Cd, Pb, Cu, Mo) in some fjords (Cato, 1977, 1983, 1990, 1992) and urbanized estuaries, particularly the Göta River estuary (Olausson, 1975; Cato, 1986, 1992; Kuijpers *et al.*, 1993). Detailed studies have shown a close relationship between heavy metals and organic matter of the sediments (e.g. Cato, 1977). The results indicate that most metals discharged by river runoff are trapped in sediments within the coastal zone. Off the coast elevated concentrations of mercury have been found in the northeastern part of the Skagerrak (Cato, pers. comm.; O. Longva, pers. comm.), where the sedimentation rate was found to be high.

According to Kuijpers *et al.* (1993) lead and Chernobyl ^{137}Cs seem to be transported along the north Jutland coast to the Skagerrak. A considerable contribution of ^{137}Cs is also entering the region with the river run-off from Sweden and with the Baltic current along the Swedish coast.

Input data of organic contaminants to the Skagerrak-Kattegat are scarce, and it is known that most of these substances are generally transported in the atmosphere over long distances (Preston, 1992), which has also been shown for the Skagerrak-Kattegat (Brorström-Lundén, 1996). The highest concen-

TABLE 1

Annual input (10^3 kg per year) of nitrogen and phosphorus to the Kattegat and Skagerrak from land run-off (1990) and via atmospheric dry deposition (1986-1990) (Lindahl *et al.*, 1993).

	Total-N	%	Total-P	%
Kattegat				
Sweden	33900	35	1310	44
Denmark	35300	36	1570	52
Atmosphere	29000	30	130	4
Total	98200		3010	
Skagerrak				
Sweden	3800	5	150	8
Denmark	3300	5	300	17
Norway	33900	46	1160	64
Atmosphere	32000	44	190	11
Total	73000		1800	

trations of polyaromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), hexachlorbenzene (HCB), pesticides such as lindane (HCH), sum DDT and chlordane have been found in the sediments of the Göta River estuary, off Falkenberg, and for HCB off Stenungsund at the Swedish west coast (Cato, 1992). The surface sediments were up to >100 times more contaminated than the reference sediments off the Faroe Islands. According to Cato (1992) this indicates a strong input of contaminants by rivers and industrial discharges from the urbanized areas to the Skagerrak-Kattegat. The amount of PCB introduced by e.g. Göta River has been estimated at 10 to 15 kg $\cdot$ y $^{-1}$ (Ahnoff & Josefsson, 1975). However, as in the case of the heavy metals the organic micropollutants also seem to be trapped in the sediments rich in organic matter within the coastal zone. In Norwegian coastal waters elevated concentrations of e.g. Hg, PCB, PAH and dioxins were found in a gradient from the inner Friefjord (west of the Oslofjord) and out from the coast (Næs & Oug, 1991). In the open Skagerrak-Kattegat the highest concentrations of DDT were found together with somewhat elevated concentrations of PAHs and PCBs. This is partly in accordance with Lohse (1988), who found that in general several organic pollutants were higher in the Skagerrak than in the North Sea sediments.

3. ECOLOGICAL EFFECTS IN THE SKAGERRAK AND THE NORTHERN KATTEGAT

3.1. COASTAL AREAS

Studies of pollution-induced ecological effects were initiated in the 1960s in the inner part of the Gullmarsfjord in Sweden. There, the benthic fauna was killed and reduced along a gradient from a river discharging effluent from a pulp mill (Leppäkoski, 1968). Later, benthic fauna in Swedish fjordic areas has undergone large-scale reductions due to eutrophication-induced

hypoxia (Josefson & Rosenberg, 1988; Josefson & Widbom, 1988). These reductions are associated with low and significantly declining oxygen concentrations recorded in the bottom water at many fjord sites over the period from the 1950s to 1984 (Rosenberg, 1990).

In the same region the macroalgal vegetation has changed drastically over the last 10 years. Many shallow bays (30-40%) are now covered by fast-growing filamentous green algae in spring to summer. This reduces important nursery and feeding grounds for coastal fish populations. Epiphytes on eelgrass (*Zostera marina*) have also been shown to reduce the number of fish species associated to these beds (Pihl *et al.*, 1996; Pihl *et al.*, 1995).

Disturbances in the Skagerrak coastal pelagic system have been reported by Lindahl & Hernroth (1983). Occurrences of toxic algae with harmful biological effects seem to have increased over the last decades (Granéli, 1987). Some of these toxic algae have lately poisoned mussels (*Mytilus edulis*) for extended periods and affected their marketing (Haamer *et al.*, 1990). Others, like *Gyrodinium aureolum*, have caused fish mortality (Dahl & Tangen, 1993).

In 1977 to 1981 hypoxia caused mortality and behavioural changes of the benthic fauna in the enclosed Limfjord in Denmark (Jørgensen, 1980). Also in the Oslofjord in Norway (Mirza & Gray, 1981) and in the Frierfjord (Gray *et al.*, 1988) the benthic fauna has undergone negative changes due to enrichment and pollution over the last decades. Since around 1960-1970, oxygen concentration has declined at Drøbak in the Oslofjord (Magnusson & Johnsen, 1994). In 1988/89 it was found that the macroalgal vertical distribution was reduced compared to 40 years earlier in the central and outer Oslofjord (Rueness & Fredriksen, 1991). In another study it was shown that several species of *Fucus* had increased their abundance from the period 1974-1980 to 1988-1990 in the inner Oslofjord. This was suggested to relate to improvements in sewage treatment and discharge practices (Bokn *et al.*, 1992).

3.2. OPEN SEA AREAS

In May 1988, the extremely toxic flagellate *Chrysochromulina polylepis* spread rapidly in the surface water almost all over the Skagerrak-Kattegat and killed and reduced both pelagic and benthic fauna down to 15 to 20 m (Lindahl & Dahl, 1990; Lindahl & Rosenberg, 1989; Rosenberg *et al.*, 1988). In one Norwegian coastal area, benthic fauna down to 180 m depth seems to have been affected by these sedimenting algae (Olsgard, 1993).

In offshore areas, temporal trends in macrobenthic fauna have been assessed in a number of investigations. In the 1980s, 25 stations were sampled in the Kattegat (Pearson *et al.*, 1985) and 23 in the eastern

Skagerrak including the mouth of the Oslofjord (Rosenberg *et al.*, 1987). The same sites were investigated already at the beginning of this century. The overall results suggest that the benthic fauna in the well-ventilated bottom areas of the northern Kattegat and the open Skagerrak had gained in biomass in the 1980s, but that the fauna in the stratified southern Kattegat had been reduced in biomass during the same period. Similar temporal trends were found during the 1970-1980s with declining biomasses in the southern Kattegat (Josefson & Jensen, 1992a; Rosenberg *et al.*, 1992) and increasing biomass in the northern Kattegat and the eastern Skagerrak (Josefson, 1990; Josefson & Jensen, 1992b). All these authors strongly suggest that the increased eutrophication over the last decades has caused a large-scale enrichment of the bottoms in the open Kattegat and the open eastern Skagerrak. In stagnant areas, however, the result has been seasonally (summer-autumn) occurring hypoxic bottom water.

In the Norwegian Trench, both the benthic meio- and macrofauna seem to be structured by sediment characteristics, transport and accumulation (Bergsten *et al.*, 1996; Boveé *et al.*, 1996; Rosenberg *et al.*, 1996). There is no obvious indication of a disturbance of these benthic communities due to pollution or hypoxia.

The sediment in the Norwegian Trench is, however, contaminated by organic pollutants such as DDT, PAH and PCB. Mussels (*Mytilus edulis*) caged in the area accumulated PAHs and had higher detoxification enzyme activities than mussels caged in pristine areas outside the Faroe Islands. The roundnose grenadier (*Coryphaenoides rupestris*) had enhanced levels of detoxification enzymes and showed histopathological changes compared with fish populations of the same species from the Faroe Islands (Förlin *et al.*, 1996). Overall, these biomarker responses in Roundnose grenadier and caged mussels indicate impact of PAH (Förlin *et al.*, 1995). Experimental studies of sediments from the Norwegian Trench, the eastern Skagerrak and the northern Kattegat have shown toxic effects on the crustaceans *Nitocra spinipes* and *Daphnia magna* (whole sediment), on mussel (*Mytilus edulis*) larvae (pore water), on rainbow trout (*Oncorhynchus mykiss*) (solvent extracts), and on the denitrification rate (Dave & Nilsson, 1994; Magnusson *et al.*, 1996). Sites at the Göta River estuary, eastern Skagerrak and the Norwegian Trench were considered most polluted. This is the first time ecological and physiological effects due to sediment toxicity have been reported from the open Skagerrak.

In 1980s the body burden of sDDT and PCB in juvenile harbour seals (*Phoca vitulina*) was about 1/4 to 1/2 in the Kattegat-Skagerrak compared with in the Baltic. Concentrations did not differ significantly between seals found dead during the mass mortality in 1988, caused by the virus epizootic, and animals

collected in unaffected areas (Blomkvist *et al.*, 1992). There is a possibility that the seals were suffering from immuno-suppression due to pollution prior to the virus outbreak, but such a relationship has not been established.

Regarding commercial fish species, no clear environmental effects have been established in the northern Kattegat and the Skagerrak, except from the effects of the fisheries themselves. However, in the seasonally hypoxic southern Kattegat a clear decline was shown in the catches of cod (*Gadus morhua*) and Norway lobster (*Nephrops norvegicus*) in the 1980s. During late summer-autumn the demersal fish species disappear from the hypoxic bottoms, which in some years encompassed 2000 to 4000 km² (Baden *et al.*, 1990). During hypoxic periods the demersal fish catches have been reduced by 75 to 95% of the biomass. From 1980 onwards the landings of plaice (*Pleuronectes platessa*) have declined in the Kattegat (Modin, 1994). The reason for this reduction may partly be eutrophication induced growth of filamentous algae in the shallow nursery areas in the Kattegat (Bagge & Nielsen, 1988).

4. FUTURE PERSPECTIVES

The marine ecosystem in the southern Kattegat and the coastal areas of the Skagerrak is in disorder due to the effects of eutrophication. Affected areas have been identified by the Oslo and Paris Commission (1992; Fig. 1), and the member states have decided to reduce the input of nutrients by 50% by the year 1995 in comparison with input data ten years earlier. This goal has not been achieved by any country concerning nitrogen, but measures are in progress. At present, however, no tendency can be observed that the large-scale environmental effects are diminishing and that the ecosystem is returning towards a healthier state. In the heavily affected areas of the south-eastern Kattegat a detailed temporal analysis of the Swedish riverine nitrogen input shows an increase from 1972 to 1992. Over the last decade, the nitrogen input from farm-land has been rather stable, whereas it has increased from forest-land (Fleischer *et al.*, 1994). Detailed measures have been implemented in the farm-land operations, but so far without results to reduce the nitrogen discharges. Over the last decades, the atmospheric deposition of nitrogen to the forest has increased and at present the soil seems to approach a stage where it may reach nitrogen saturation (Jacks *et al.*, 1994). As a consequence, saturated soils seem to be an additional source of large nitrogen input that contributes to the marine eutrophication in that area.

Before the mid-1970s there was no awareness of eutrophication symptoms in the Skagerrak-Kattegat. Thus, this ecosystem has experienced significant environmental changes over a short period, and in the last 10 to 15 years the environmental impact has

worsened. It has been suggested that eutrophication may be a self-accelerating process (*e.g.* Duarte, 1995). Input of nitrogen will lead to increased algal biomass and a higher sedimentation of organic material which may reduce the oxygen concentration in stratified areas. This may reduce the benthic fauna and as a consequence the aerobic/anaerobic sites in the sediment, which results of both field studies and experiments suggest are essential for the nitrification/denitrification transformations (Baden *et al.*, 1990; Kristensen *et al.*, 1991). The effects of hypoxia have not only been spreading in the Skagerrak-Kattegat, but occur with increasing frequency in eutrophicated, stratified coastal areas in many places all over the world, with large-scale negative effects on the benthic system and demersal fisheries (Diaz & Rosenberg, 1995).

Elevated concentrations of nutrients have been recorded for the Kattegat and the eastern Skagerrak (Andersson & Rydberg, 1988; Andersson, 1996; Rydberg *et al.*, 1990). Part of these changes may be due to inflow of continental river water from the southern North Sea. Although the frequency of large inputs of this water may not be high, the amount of nutrients may at times be significant. This was manifested in recent floods in southern Germany and the Netherlands (Rydberg *et al.*, 1996). Other sources of nutrient input are the atmosphere, rivers and municipal sewers (Table 1).

The recent findings of both widespread toxicity in the Skagerrak-Kattegat sediments and indications of physiological responses in fish and caged mussels in the Skagerrak indicate that pollutants contribute to the stress in this marine ecosystem. The extent of this contribution is not known. Information on pollutant effects is scarce in open sea areas of the Skagerrak-Kattegat, and it is not known if the contamination by pollutants over the last decades has improved or worsened. Although significant concentrations of contaminants are found in the Skagerrak-Kattegat area there should be no immediate danger to humans who consume fish or invertebrates from this area. As the deeper parts of the Skagerrak and northern Kattegat are the main accumulation areas for suspended particles from the southern North Sea (Eisma & Kalf, 1987; Van Weering *et al.*, 1993), a significant proportion of the contaminants found in these sediments is likely to originate from the North Sea (Rodhe & Holt, 1996). Additional sources may be the atmosphere, Glomma and Göta Rivers, the Baltic, and local industries. The coastal zone seems, however, to trap a considerable amount of these pollutants. Finally, the apparent large-scale environmental distribution and transport of contaminants should lead to intensified efforts to reduce the flow of wastes into the sea.

5. CONCLUSIONS

- Input of nitrogen from the southern North Sea to the

Skagerrak varies between years but will contribute to the eutrophication of the Skagerrak-Kattegat.

- During the last 20 years, significant increases of both nitrogen and phosphorus have been recorded in the Kattegat and the eastern Skagerrak.
- Experimental studies suggest that nitrogen is the limiting nutrient for primary production during most seasons and in most areas of the Skagerrak-Kattegat.
- Fast growing filamentous green algae have increased in coastal areas in the Skagerrak-Kattegat and changed nursery and feeding grounds for fish.
- Bottom water oxygen concentrations have declined in many areas with strong negative effects on the benthic system.
- Substantial amounts of heavy metals and organic pollutants are discharged from urbanized areas into the Skagerrak-Kattegat, but significant amounts seem to be trapped in the fine-grained, organogenic coastal sediments.
- Large quantities of particles from the North Sea accumulate in the deeper parts of the Skagerrak-Kattegat; these particles are likely to contribute to the toxicity of these sediments as contaminants are mainly particle-bound.
- Substantial amounts of organic toxic substances are deposited in the Skagerrak-Kattegat via the atmosphere.
- Sediments from several areas of the Skagerrak-Kattegat are toxic to invertebrates and cause physiological responses in fish.
- In summary, this multi-disciplinary research project has shown large-scale environmental changes and effects on the ecosystem in the Skagerrak-Kattegat.

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