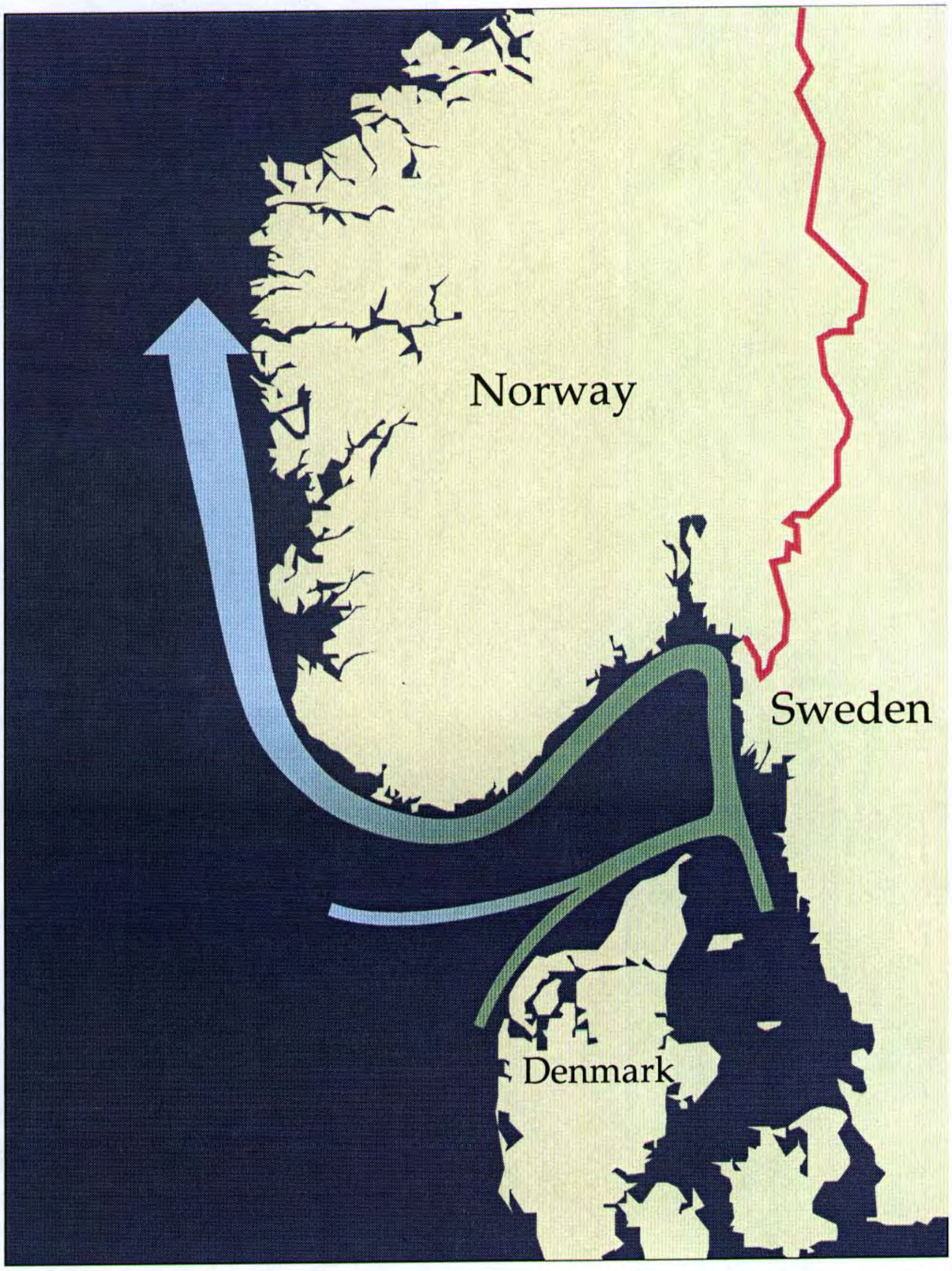
The Norwegian North Sea Coastal Water

# Eutrophication

## Status and trends



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# Preface

*In early 1995 the Norwegian State Pollution Control Authority decided to establish a group of marine scientists to investigate eutrophication in Norwegian coastal waters. In January 1996 the group presented its first report, a study of the state of eutrophication in the Outer Oslofjord and the expected effects from changed local nutrient discharges.*

*In April 1996 the group was asked to give an evaluation of the state of eutrophication of the Norwegian North Sea coastline from Jomfruland at the western border of the Outer Oslofjord to Stad at 62°N. The report was delivered in March 1997.*

*This report summarises these two reports. The data are in general organised according to the principles in "Common Procedure for the Identification of the Eutrophication Status of the Maritime Area of the Oslo and Paris Conventions". This work may therefore provide a basis for later application of the Common Procedure in Norwegian coastal waters.*

*Oslo, December 12, 1997*

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# Contents

# Conclusions

- The water mass of the Norwegian Coastal Current (NCC) along Skagerrak at Arendal is a mixture of water from the central and southern North Sea and water from Kattegat. This coastal water is diluted by admixture of Atlantic water as it flows westwards from Arendal and turns northwards around the southern tip of Norway.

- The coastal water mass in the Outer Oslofjord and along the Norwegian Skagerrak coast is influenced by nutrient enrichment from the large nutrient inputs to the coastal waters of the southern North Sea and the Kattegat. The degree of this regional nutrient enrichment is similar along the Norwegian Skagerrak coast to about Arendal, but decreases west of Arendal due to admixture of Atlantic water. There is no sharp western delimitation of the regional nutrient enrichment, but rather a transition zone. Lindesnes is located in this transition zone and can be considered as a western limitation for practical purposes. West of Lindesnes there is a weaker and more sporadic enrichment which is reduced to an insignificant influence in the coastal water mass in western Norway.

- The nutrient enrichment of the coastal water mass in Skagerrak is evidenced by elevated levels of inorganic nutrients in winter and spring and elevated levels of organic nutrients in summer. The concentration of nitrate in winter and spring off Arendal has shown an approximate doubling since the 1970s, when the concentration was considered to be close to the natural background level. The increase in nitrate off Arendal reflects mainly the increase in the concentration in the coastal water of the southern North Sea and the German Bight. The increase in inorganic phosphate over the recent decades has been less, resulting in a marked increase in the N/P-ratio based on nitrate and inorganic phosphate.

- The nutrient enrichment is associated with increased organic loading and oxygen consumption. There has been a significant decrease in the oxygen content of the coastal water in Skagerrak in autumn since about 1970. The average decrease has been about 0.4-0.8 ml $O_2$/l between 1970 and 1995 as a general trend against a background of large interannual variability. There has also been an increased oxygen consumption and a decrease in the oxygen content in fjord basins along the Skagerrak coast after about 1980. This increase in oxygen consumption corresponds to an increase in organic loading of about 50 % to basins east of Arendal and of about 25 % to basins between Arendal and Lindesnes. Depending on the basin topography and their sensitivity, this has caused the oxygen concentration in some basins to decrease to levels below that which causes negative effects on benthic organisms and fish.

- There is a regional pattern in the occurrence and development of algal blooms which often originate in Kattegat and Skagerrak and are transported westwards with the NCC along Skagerrak to western Norway. Such blooms appear to have become more common since the 1970s. The stratified waters of the NCC provide favourable conditions for flagellates with groups which contain harmful algae. Nutrient enrichment may have caused an increase in the occurrence and risk of blooms of harmful algal species.

- Macroalgal vegetation and benthic animal communities show changes along the Skagerrak coast from east to west. These changes are difficult to relate directly to eutrophication as they could also reflect a natural gradient, but some of them are consistent with an expected eutrophication gradient. The maximum depth of growth of red algae increases from east to west corresponding to an increase in visibility and light transparency. For three benthic animal species there are higher abundance and individual size in east than in west. The benthic foraminiferal fauna in the sediments in the Skagerrak deep have shown changes after about 1970, indicative of increased supply of organic material to the sediments.

- The total annual Norwegian input of nutrients to the Skagerrak and to the waters of western Norway are about 3.000 tonnes of phosphorus and 70.000 tonnes of nitrogen. Of these amounts are about 80 % of phosphorus and 50 % of nitrogen of anthropogenic origin, the remainder being natural runoff. Most of the Norwegian anthropogenic input to Skagerrak comes in the Oslofjord region where agriculture and human population are the main sources. On the west coast the input is scattered from many small sources where population, aquaculture and background sources (especially for nitrogen) are the dominant ones.

- The contribution of the Norwegian anthropogenic nutrient input to the nutrient budgets of the coastal water mass is generally very low. An exception is the inner (northern) part of the Outer Oslofjord where much of the nutrient input to Skagerrak is concentrated to a relatively small area and where it has a moderate effect on the nutrient budget of the upper brackish water layer. Stimulated phytoplankton production may have resulted in an approximate doubling in plankton biomass and a 20 % reduction in water transparency (visibility) in this area. This stimulated production is transported out of the fjord and is being diluted to a low contribution in the coastal current. The total Norwegian anthropogenic nutrient input to Skagerrak and the west coast contributes on the order of 1 % to the budgets of total nitrogen and phosphorus in the Norwegian Coastal Current.

# Summary

In this report we have compiled information and made an assessment of the situation with regard to nutrients and eutrophication in the water mass along the Norwegian coast in Skagerrak and north to the northern border of the North Sea (62°N) on the west coast. In the assessment we have considered the coastal watermass which covers the open coastal waters, skerries and open fjords. We have not considered in detail the specific local conditions in the many separate fjords along this coastal stretch.

The water circulation of the North Sea is generally counter-clockwise. Most of the currents which enter the North Sea flows into and converges in the Skagerrak before turning and exiting along the Norwegian coast. The Norwegian Coastal Current (NCC) flows westwards along the Skagerrak coast and turns northwards along the Norwegian west coast. While this is the persistent average flow pattern, the NCC is characterised by high temporal and spatial variability.

It has been demonstrated that the upper layer (0-30 m) of the NCC at Arendal is to a high degree a physical mixture of two water masses, respectively flowing into the Skagerrak north of Hirtshals in Denmark and flowing northwards through Kattegat. These two water masses comprises on average about 80 % and 20 % of the NCC at Arendal. The watermass outside Hirtshals is again composed of two main components, coastal water from the southern North Sea and the German Bight flowing northwards as the Jutland Coastal Current (about 20 %) and water flowing in from the more offshore areas of the southern and central North Sea (about 60 %).

The composition of the NCC at Arendal is assumed to be representative for the situation in the coastal watermass along the Skagerrak coast east of Arendal. The Outer Oslofjord is closely connected to the circulation in Skagerrak and communicates openly with the watermass of the NCC. In addition the upper water layer is influenced by fresh water from the Glomma and Drammen river. This freshwater may cause a distinct and shallow brackish surface layer in the parts of the Outer Oslofjord influenced by the rivers. A freshwater budget for the Outer Oslofjord has been calculated with a nested hydrodynamic model with 0.8 km spatial resolution in the fjord. Over the whole area of the Outer Oslofjord, the content of freshwater from the Baltic, including Swedish rivers on the west coast, is 5-10 times higher than the content of freshwater from the Norwegian rivers or from the freshwater discharge to the southern North Sea. Glomma and Drammen river have their maximum discharge due to snow melt from May to August. In this period the freshwater from local discharges can exceed the freshwater from the Baltic in the upper brackish layer.

From Arendal and westwards there is a substantial dilution of the freshwater content and an increase of the salinity of the NCC due to horizontal and vertical admixture of Atlantic water of higher salinity. Around Lista the NCC is often advected offshore in periods of northerly and westerly winds, resulting in upwelling of colder and saltier deep water at the coast. Prevailing southerly to westerly winds may periodically block the NCC in Skagerrak, followed by outbreaks with strong currents when the winds change. While the NCC is further diluted by admixture of Atlantic water as it flows northwards along the west coast, the salinity does not increase from Utsira north of Jæren due to freshwater input from rivers discharging to the fjords in western Norway.

The total annual Norwegian input of nutrients to the Skagerrak and to the waters of western Norway are about 3000 tonnes of phosphorus (P) and 70000 tonnes of nitrogen (N). Of these amounts about 80 % of P and 50 % of are of anthropogenic origin, the remainder being natural runoff. The annual anthropogenic inputs to Skagerrak are about 750 tonnes of P and 22000 tonnes of N. Most of this comes in the Oslofjord region where agriculture and human population are the main sources. The annual anthropogenic inputs to western Norway are about 1400 tonnes of P and 14000 tonnes of N.

Here the input is scattered from many small sources with population and aquaculture as the dominant ones.

Much higher inputs occur to the upstream areas of the NCC in the coastal area of the southern North Sea and in the Kattegat. The inputs of nitrogen have shown considerable increase over the last decades, whereas the inputs of phosphorus have levelled off after the 1970s. Due to the different patterns of N and P, there is now a substantial surplus of N over P relative to the N/P-ratio in natural seawater and in plankton.

The nutrient concentrations in the NCC at Arendal are to a large extent determined by the conditions in the parent water masses off Hirtshals and in the Kattegat. This is particularly the case in winter when there is low biological activity. There is evidence for a marked nutrient enrichment of the coastal water in Skagerrak. The concentration of nitrate in winter and spring in the coastal water at Arendal has shown an approximate doubling since the 1970s. This is revealed by comparing data from 1990-95 with a measurement series from 1975-80. A similar result is obtained by calculating the expected concentration at Arendal from concentrations in the parent water masses before the 1970s. The close agreement between these two independent methods suggests that the increase in nitrate at Arendal mainly reflects the increase in the concentration in the coastal water of the southern North Sea and the German Bight. Close similarity between the nitrate concentrations at Arendal in 1975-80 with present levels in Raunefjorden in western Norway suggests that the concentrations at Arendal in 1975-80 can be considered to be close to the natural background levels.

The increase in inorganic phosphate at Arendal between the 1970s and the 1990s has been slight, resulting in a marked increase in the N/P-ratio based on nitrate and inorganic phosphate in winter and spring. The slight increase in inorganic phosphate probably reflects the increase in phosphate prior to the 1970s and its subsequent levelling off in the parent water masses. Thus calculations suggest an increase of about 30 % at Arendal for the winter and spring period between the 1960s and the 1990s. The consequence of the surplus nitrate and the elevated N/P-ratio is that the general conditions for phytoplankton growth h as been shifted from a more balanced situation, perhaps on the side of N limitation, to a situation with indicated P limitation in the late spring and early summer period.

Total N and total P at Arendal have shown increases by 35 % and 20 %, respectively, as annual averages. The increases in total N and total P during summer reveal an increase in organic nutrients after the period of increase in inorganic nutrients in winter and spring.

The regional nutrient enrichment of the coastal water mass in Skagerrak has about the same magnitude west to Arendal. Beyond Arendal the dilution of the NCC by admixture of Atlantic water reduces the signal of elevated nutrient concentrations. The signal is still clear at Lista where the nitrate concentrations in winter and spring have increased by an average of 60 % compared to the 1970s. Model calculations suggest that the contribution from the regional nutrient enrichment is reduced to less than 20 % increase above the natural background north of Jæren at the south-western coast of Norway.

The contribution of local Norwegian nutrient input to the nutrient budgets of the Outer Oslofjord has been calculated based on a water budget calculated by a hydrodynamic model and data on nutrient inputs and concentrations. In the inner (northern) part of the Outer Oslofjord the total Norwegian nutrient input (including the natural runoff) causes an increase by 20-40 % for total N and 10-30 % for total P in the upper 15-20 m of the fjord water. Locally in the upper brackish layer the increase can be higher, representing about a doubling for N. In the southern and more open part of the Outer Oslofjord the contributions from the local nutrient input are about 5-10 % for total N and about 2-5 % for total P.

There is a regional pattern in the occurrence and development of algal blooms which often originate in Kattegat and Skagerrak and are transported westwards with the NCC along Skagerrak to western Norway. Such blooms appear to have become more common since the 1970s. The stratified waters of the NCC provide favourable conditions for flagellates, among which there are groups containing harmful algae. Nutrient enrichment may have caused an increase in the occurrence and risk of blooms of harmful algal species in this area.

The mean water transparency in spring and summer, measured as Secchi-depth readings, of the NCC increases from about 8-9 m in the Outer Oslofjord to about 12 m at the coast of south-western Norway. This could reflect a gradient due the nutrient enrichment of the NCC. In the Outer Oslofjord there has been a reduction in mean Secchi-depth reading of 0.7 m between 1936-40 and 1975-78.

The nutrient enrichment of the NCC in Skagerrak is associated with increased organic loading and oxygen consumption. There has been a significant decrease in the oxygen content of the coastal water in Skagerrak in the autumn since about 1970. The average decrease has been about 0.4-0.8 ml $O_2$/l between 1970 and 1995 as a general trend against a background of large interannual variability. There has also been an increased oxygen consumption and a decrease in the oxygen content in fjord basins along the Skagerrak coast after about 1980. This increase in oxygen consumption corresponds to an increase in organic loading of about 50 % to basins east of Arendal and of about 25 % to basins between Arendal and Lindesnes. Depending on the basin topography and their sensitivity, this has caused the oxygen concentration in some basins to decrease to levels below that which causes negative effects on benthic organisms and fish.

The main cause of the increased organic loading and oxygen consumption is the regional nutrient enrichment of the upstream parent water masses in the coastal part of the southern North Sea and the Kattegat. The nutrient and organic enrichment of the NCC influences the conditions in adjacent fjord basins by sedimentation of organic material into trapped water below sill depth. The Norwegian anthropogenic nutrient input contributes little to the organic loading of the coastal water mass. The local nutrient input may have an additional impact in some fjords, particularly those with low shallow sill depth and restricted water exchange with the outside coastal water.

Macroalgal vegetation and benthic animal communities show changes along the Skagerrak coast from east to west. Some species have their eastern limit of distribution along the Skagerrak coast. The individual size and abundance of kelp increases from east to west, as do species richness and composition of the softbottom benthic animal communities. These changes are difficult to relate directly to eutrophication as they could also reflect a natural gradient, but some changes are consistent with an expected eutrophication gradient. The maximum depth of growth of red algae increases from east to west corresponding to an increase in visibility and light transparency. For three benthic animal species there are higher abundance and individual size in east than in west. The benthic forameniferal fauna in the sediments in the Skagerrak deep have shown changes after about 1970, indicative of increased supply of organic material to the sediments.

In this assessment we have distinguished between three areas: the Outer Oslofjord, the Norwegian Skagerrak coast from the Outer Oslofjord to Lindesnes, and the West Norwegian coast from Lindesnes to Stad at 62°N. In the following the state of eutrophication of these areas is summarized.

## Outer Oslofjord

In Outer Oslofjord there are evidence of eutrophicaton from both transboundary and local nutrient load. The transboundary load is caused by large inputs of nutrients to the coastal waters in the southern North Sea and the Kattegat, contributing to regional eutrophication in the eastern Skagerrak. Effects of this regional eutrophication are seen in the Outer Oslofjord as increased nutrient concentrations with high N/P-ratios in spring and early summer, reduced oxygen concentrations in the intermediate fjord water in autumn, high organic load and high oxygen consumption in the deep basin water, and high biomass of softbottom benthic animals.

The local Norwegian nutrient load is mainly affecting the upper water layer in the northern part, and inshore areas in the eastern and western part of the Outer Oslofjord. Here the load contributes significantly to the nutrient budgets and causes stimulated primary production, increased phytoplankton biomass, and reduced water transparency. The maximum depth of occurrence of macroalgae has become shallower since the 1950s. The increased plankton production is mainly transported out of the fjord and into the NCC, with little sedimentation into deeper water layers in the Outer Oslofjord due to short residence time of the surface layer.

## The Norwegian Skagerrak coast

The effects of a regional eutrophication of eastern Skagerrak are clearly seen in the water mass of the NCC along the Skagerrak coast. The degree of this regional nutrient enrichment is relatively constant along the Norwegian Skagerrak coast west to about Arendal, but decreases west of Arendal due to admixture of Atlantic water. There is no sharp western delimitation of the regional nutrient enrichment but rather a transition zone. Lindesnes is located in this transition zone and can for practical purposes be considered as a western limitation.

The nutrient enrichment of the coastal water mass in Skagerrak is evidenced by elevated levels of nutrients, increased organic enrichment and oxygen consumption, and decreased oxygen concentrations. The concentration of nitrate in winter and spring in the coastal water off Arendal has shown an approximate doubling since the 1970s, and there has been a marked increase in the N/P-ratio. The oxygen consumption in fjord basins along the Skagerrak coast had increased after about 1980, corresponding to an increase in the organic load of about 50% to basins east of Arendal and of about 25% to basins between Arendal and Lindesnes. This has caused the oxygen concentration in some basins to decrease to levels which cause negative effects on benthic organisms and fish.

Macroalgal vegetation and benthic animal communities show changes along the Skagerrak coast from east to west. These changes are difficult to relate directly to eutrophication as they could also reflect a natural gradient. However, some of them are consistent with an expected eutrophication gradient. Blooms of harmful algae appear to have become more common in the Skagerrak coastal water as well as in the Outer Oslofjord since the 1970s. The stratified conditions in these water masses provide favourable conditions for flagellates, including harmful species. Nutrient enrichment may have caused increase in the occurrence and risk of blooms of harmful algae.

The Norwegian nutrient load to the Skagerrak comes mainly from the Oslofjord region. The input is high in N relative to P, and surplus N is exported from the Outer Oslofjord into the NCC. While this can potentially increase the imbalance between N and P in the surface layer after the spring bloom, such an effect is likely to be slight. The total Norwegian anthropogenic nutrient input to Skagerrak contributes on the order of 1% to the transport of total N and P in the NCC.

## The west coast

The coastal water from Lindesnes to Utsira north-west of Stavanger is a transition zone where the regional influence from Skagerrak is rapidly decreasing from dilution and biological consumption of nutrients. Algal blooms in Skagerrak are often transported by the NCC past Lindesnes and north to Utsira but seldom much further.

The environmental data available for this assessment have been less comprehensive for the Norwegian west coast than for the Skagerrak coast. There are no indications, however, that the coastal water is affected by eutrophication. The local Norwegian input of nutrients is relatively low and comes from a number of small sources scattered over a large area. The fjords in general communicate openly with the water of the NCC and there is extensive exchange of surface and intermediate water layers. The water from the fjords mixes into the NCC which has a typical transport time along the west coast of 2-3 weeks. The local nutrients input to the west coast comprises less than 1% compared to the natural flux of nutrients in the NCC.

Fjords and polls with shallow sills and restricted water exchange are special cases and exceptions to the general situation. These are sensitive environments with regard to nutrients and organic load, where even limited local nutrients input may cause eutrophication effects.

# 1. Introduction

According to the terms of the Ministerial Declaration on the Protection of the North Sea, anthropogenic inputs of the nutrients phosphorus and nitrogen to the coast from the Norwegian-Swedish border to Lindesnes should be reduced by about 50% between 1985 and 1995. At the Fourth International Conference on the Protection of the North Sea, Esbjerg 1995, the ministers of the North Sea countries agreed to apply in the North Sea and its catchment the measures for sensitive areas under the Urban Waste Water Directive, and to apply the measures for vulnerable zones under the conditions of Directive 91/676 (the Nitrate Directive). These measures are implemented for the whole North Sea except for those parts where comprehensive scientific studies demonstrate that nutrient inputs do not cause eutrophication effects or contribute to such effects in other parts of the North Sea.

In the beginning of 1995 the Norwegian State Pollution Control Authority established a group of marine scientists to carry out work regarding eutrophication in Norwegian coastal waters. This group has delivered two reports, a study of the Outer Oslofjord (ANON 1996) and an evaluation of the Norwegian coastal water from the western border of the Oslofjord to Stad at 62° N (ANON 1997).

These studies were based on information on local and transboundary nutrient loads, hydrodynamic conditions, and observed and calculated effects from nutrient enrichment. A number of special studies were initiated to assemble and evaluate the data, along with extensive use of modelling.

The present report summarises the two reports, with an overall evaluation of status of eutrophication and trends. There is a special focus on the importance of transboundary nutrient loads versus the local loads.

# 2. General description of the physical and environmental conditions along the Norwegian North Sea coast

***The water masses along the Norwegian North Sea coast are basically a mixture of water of Atlantic origin, freshwater from local runoff, brackish water of Baltic Sea origin and from large rivers draining the southern part of the North Sea. Circulationwise these waters combine to form the Norwegian Coastal Current, which roughly flows along the Norwegian coastline from east to west. Its average transport off the Skagerrak coast is about 230.000 $m^3/s$, but is characterized by large temporal (week to years) variations. It also exhibits large spatial variations due to meandering and instabilities on the mesoscale (10-50 km).***

## 2.1 Topography

Figure 2.1 shows the southern part of Norway, including the Norwegian North Sea coast. The coastline may be divided into two topographically different parts at Stavanger, where the coast of West Norway is characterized by a wider belt of islands and far larger and deeper fjords than the Skagerrak-coast. The area draining to the North Sea is 137 300 $km^2$, with a population of ca. 3 millions (1990-number).

The marine part of the area is dominated by the Norwegian Trench, running parallel to the coast. The water depth has its maximum of about 700 m in the north-eastern Skagerrak east of Arendal, decreasing to 250-400 m off the west coast (Figure 2.1).

The Outer Oslofjord is the area between Drøbak-Svelvik in the north and the Koster Island - Jomfruland line to the south (Figure 2.2). Nutrient budgets were derived for the area north of a line eastward from Jomfruland to Sweden (see also Figure 3.10). This area is characterised by:

- Surface area: 1400 $km^2$
- Volume: 103 $km^3$
- Average depth: 70 m

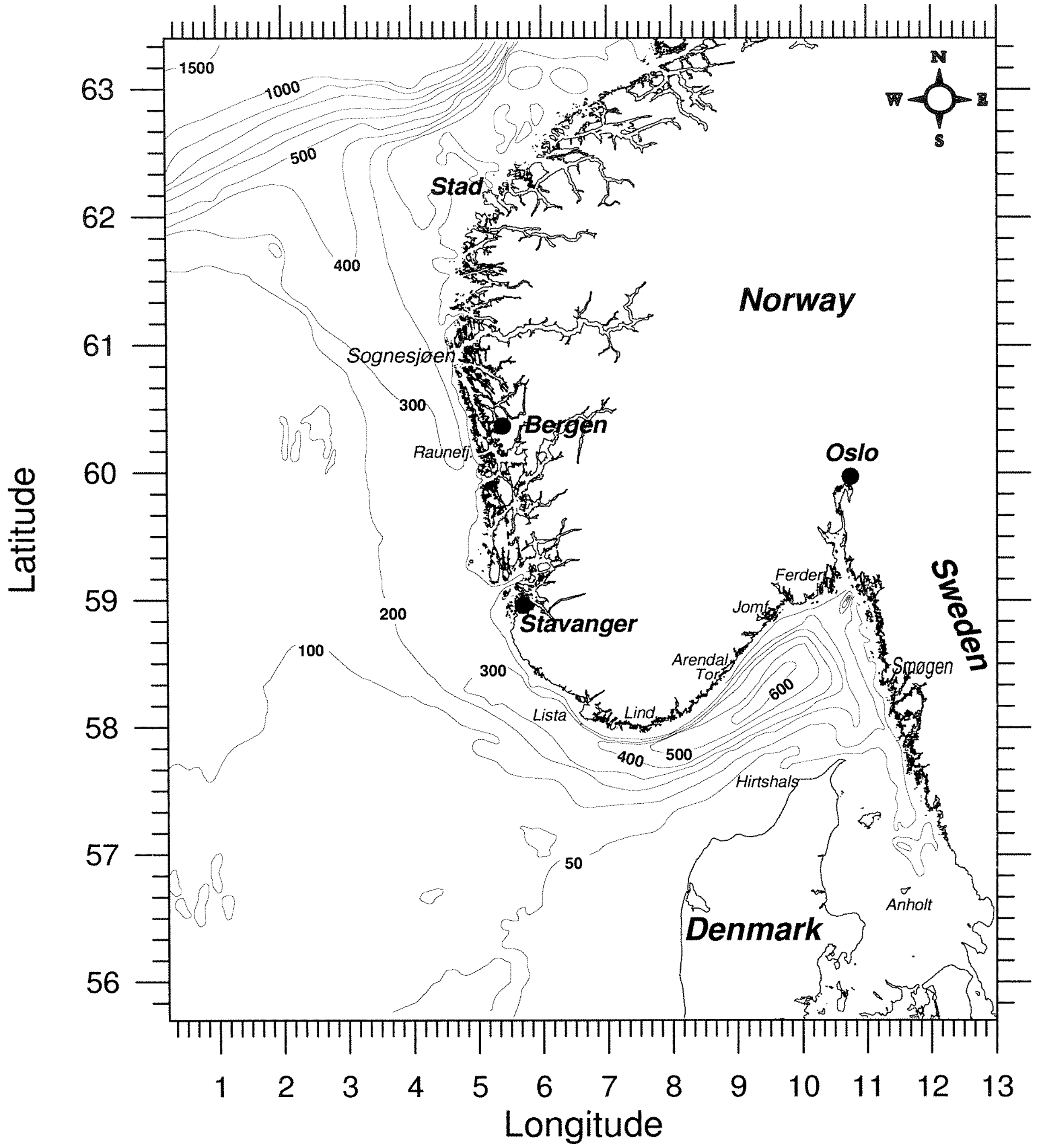


**Figure 2.1.** Southern Norway with bottom topography of Skagerrak, Kattegat and off the Norwegian west coast. Abbreviations: Raunefj. =Raunefjord, Lind=Lindesnes, Tor=Torungen, Jomf=Jomfruland. See Figure 2.2 for more details about the Outer Oslofjord.

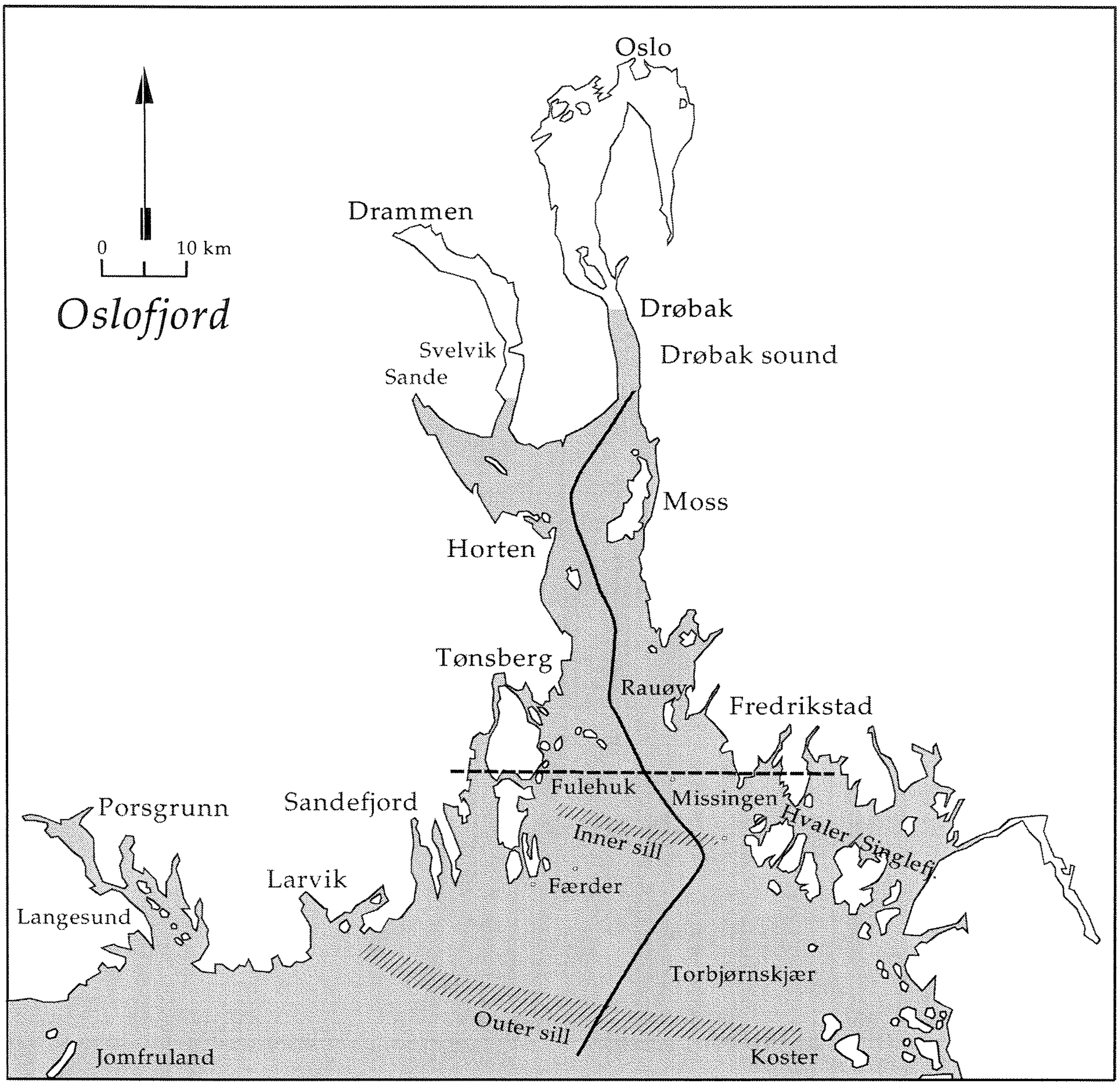


**Figure 2.2.** The Oslofjord area as defined in this report is marked with light grey. The border between the northern and southern halves is marked with a dotted line north of Fulehuk, the inner and outer sills are shown as hatched areas. The longitudinal bottom profile presented in Fig. 2.3 is indicated with a line from the Drøbak sound through the outer sill. This line traverses several deep basins. The inner sill shown in Figure 2.3 is 125 m deep. The outer sill is not well defined, but has a depth of 125-150 m.

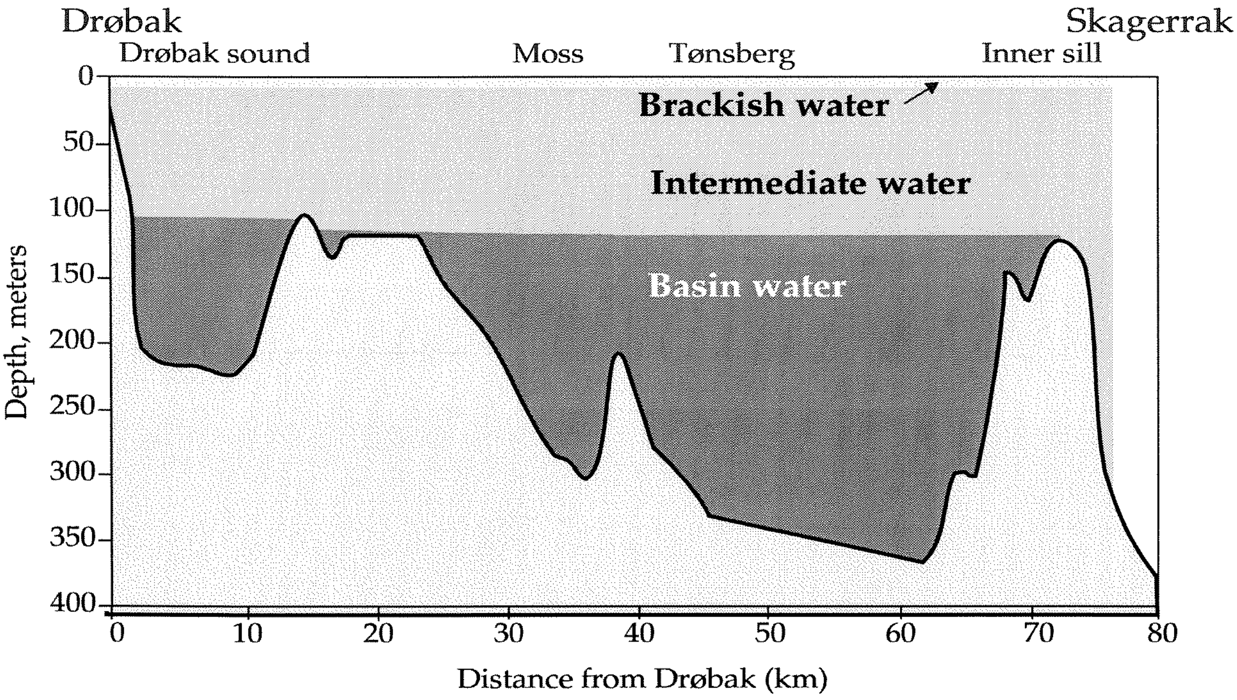


**Figure 2.3.** Bottom profile and main water masses in the Outer Oslofjord.

## 2.2 Meteorological conditions

The following description of the meteorological conditions along the Norwegian Skagerrak coast and the west coast is based on a report by Hackett and Røed (1997), based on the 30-year period 1961-90.

The predominant direction of the annual average wind is along the coast (Figure 2.4). In winter a high pressure area builds up in the cold interior of southern Norway and the wind blows mainly from land toward the sea. Due to the rotation of the earth, the wind turns to the right and on average the direction is thus parallel to the coast with the land to the right looking downwind. In summer a low pressure builds up over the relatively warm interior, and the wind starts to blow from the sea towards the land. Again the wind is turned to the right and parallel to the coast, but now with the land to the left.

Regarding temperature the annual variation is greater along the Skagerrak coast than at the west coast of Norway, with a maximum at Jomfruland and a minimum at Stad. However, the average annual temperature does not change much from station to station, and the differences are probably caused by local topographic effects.

Both the annual precipitation and its seasonal variations are greater on the west coast than on the Norwegian Skagerrak coast.

It is, however, important to emphasize that there is a large year-to-year variations in the meteorological conditions. For instance, while some winters have predominantly northern or easterly winds and corresponding high precipitation and relatively low temperature, other winters have wind from the south, high precipitation and relatively warm weather.

Many of the nutrient budgets and models used for this assessment of eutrophication in the coastal water were based on data from 1993. This year deviated from the 30-year normal, with southerly, relatively warm wind in January-February, and an autumn that was relatively cold and wet.

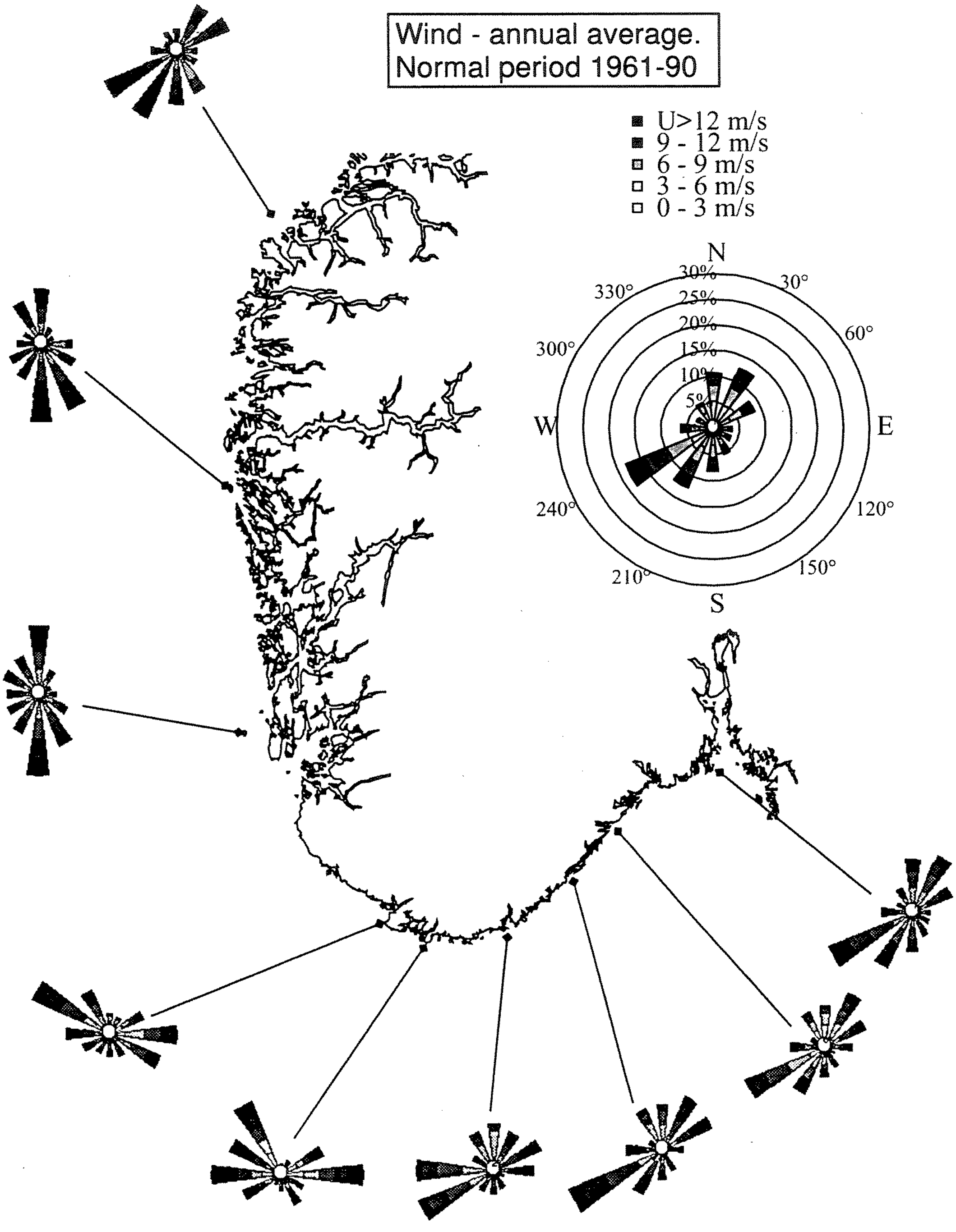


**Figure 2.4.** Annual average of wind direction and speed for some meteorological stations along the coast, for the normal period 1961-90 (after Hackett and Røed 1997).

## 2.3 Freshwater runoff

The coastal water on the Norwegian North Sea coast contains freshwater from the Baltic, from the southeastern part of the North Sea and from Norwegian and Swedish rivers draining to the Kattegat and directly to the North Sea. The average freshwater supply to the Skagerrak from the Baltic Sea and the Kattegat is approximately 15 000 $m^3/s$. The average total freshwater runoff to the southern North Sea is 4500 $m^3/s$, and the total freshwater supply to the Skagerrak have been estimated to be about 21 000 $m^3/s$, where direct river runoff is 10% (Gustafsson, 1997).

The Norwegian freshwater runoff to the North Sea was 5500 $m^3/s$ as an average for 1990-94. Figure 2.5 shows monthly means of freshwater runoff east (Skagerrak coast) and west of Lindesnes, based on data for 1993. The runoff to the west-coast is generally higher than to the Skagerrak coast.

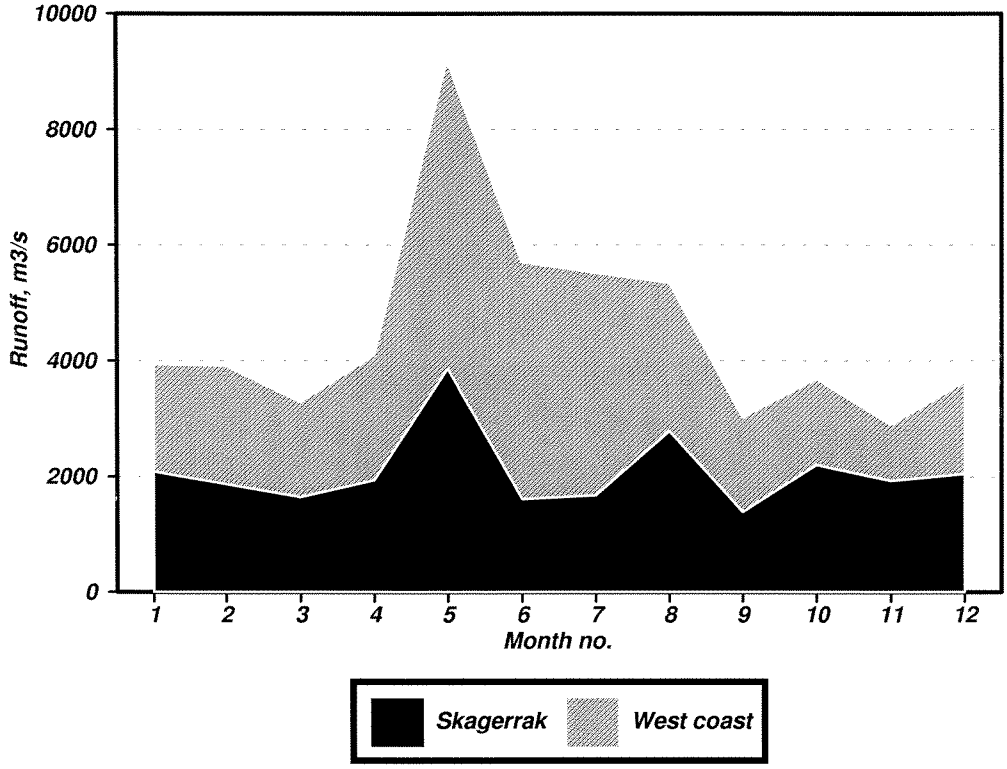


**Figure 2.5.** Monthly average of freshwater runoff to the Norwegian Skagerrak coast and the west coast (Lindesnes-Stad) in 1993. In May - August the runoff to the west coast is at its maximum.

Nearly half the freshwater runoff to the Norwegian Skagerrak coast comes from the Glomma and Drammen rivers in the Oslofjord area, with an average runoff of 685 $m^3/s$ and 290 $m^3/s$, respectively, over the period 1964-94. The interannual variations are significant, and in 1988 the Glomma spring flood was ca. 3000 $m^3/s$, or twice the 1993-flood.

## 2.4 Water masses

The coastal water along the Norwegian North Sea coast is basically a mixture of two water masses: Atlantic water (salinity >35) and freshwater. Most of the Atlantic water enters the North Sea through the passages between the Faroe Islands and Scotland, and between the Faroe Islands and Norway (Figure 2.6). Most of the freshwater comes from three sources: local runoff to the coast, from the Baltic Sea and from the large rivers draining to the southern part of the North Sea. Based on their origin and salinity, one may distinguish between the main water masses in the Skagerrak and in the North Sea (Table 2.1).

**Table 2.1.** Main water masses in the Skagerrak and the North Sea, and their salinity ranges. Water masses with index $^{1)}$ are defined in ANON (1993).

| Water mass | Code | Salinity |
|---|---|---|
| Baltic Water$^{1)}$ | BAW | 8.5-15 |
| Kattegat Surface Water$^{1)}$ | KSW | 15-25 |
| Kattegat Deep Water$^{1)}$ | KDW | 32-35 |
| Skagerrak Coastal Water$^{1)}$ | SCW | 25 - 32 |
| Continental Coastal Water$^{1)}$ | CCW | 31-34 |
| Norwegian Coastal Water$^{1)}$ | NCW | 32-34.5 |
| Southern North Sea Water$^{1)}$ | SNSW | 34.75 - 35.0 |
| Central North Sea Water$^{1)}$ | CNSW | 34.75 - 35.0 |
| Atlantic water$^{1)}$ | AW | > 35.0 |
| Brackish Water | BW | < 25 |
| German Bight Water | GB | 30.0 - 34.0 |
| Jylland Coastal Water | JCW | 31.0 - 34.0 |
| Skagerrak Water Upper | SWU | 32 - 34.5 |
| Skagerrak Water Lower | SWL | 34.5 - 35 |

These water masses combines to form the water masses typically associated with the Norwegian Coastal Current (NCC). The water mass in the NCC experiences large seasonal and interannual variations (Figures 2.7 and 2.8). Spatially there is (on average) a monotonic increase in salinity from Kattegat to Stad, with a particularly pronounced increase between Torungen and Lindesnes (Figure 2.9). This is probably due to horisontal and vertical mixing of water of Atlantic origin. Moreover, (horizontal) instabilities typically forms on the front between the NCC and the adjacent Skagerrak water creating mesoscale features such as jets, meanders and eddies, which on the larger scale mexes water of Atlantic origin into the NCC.

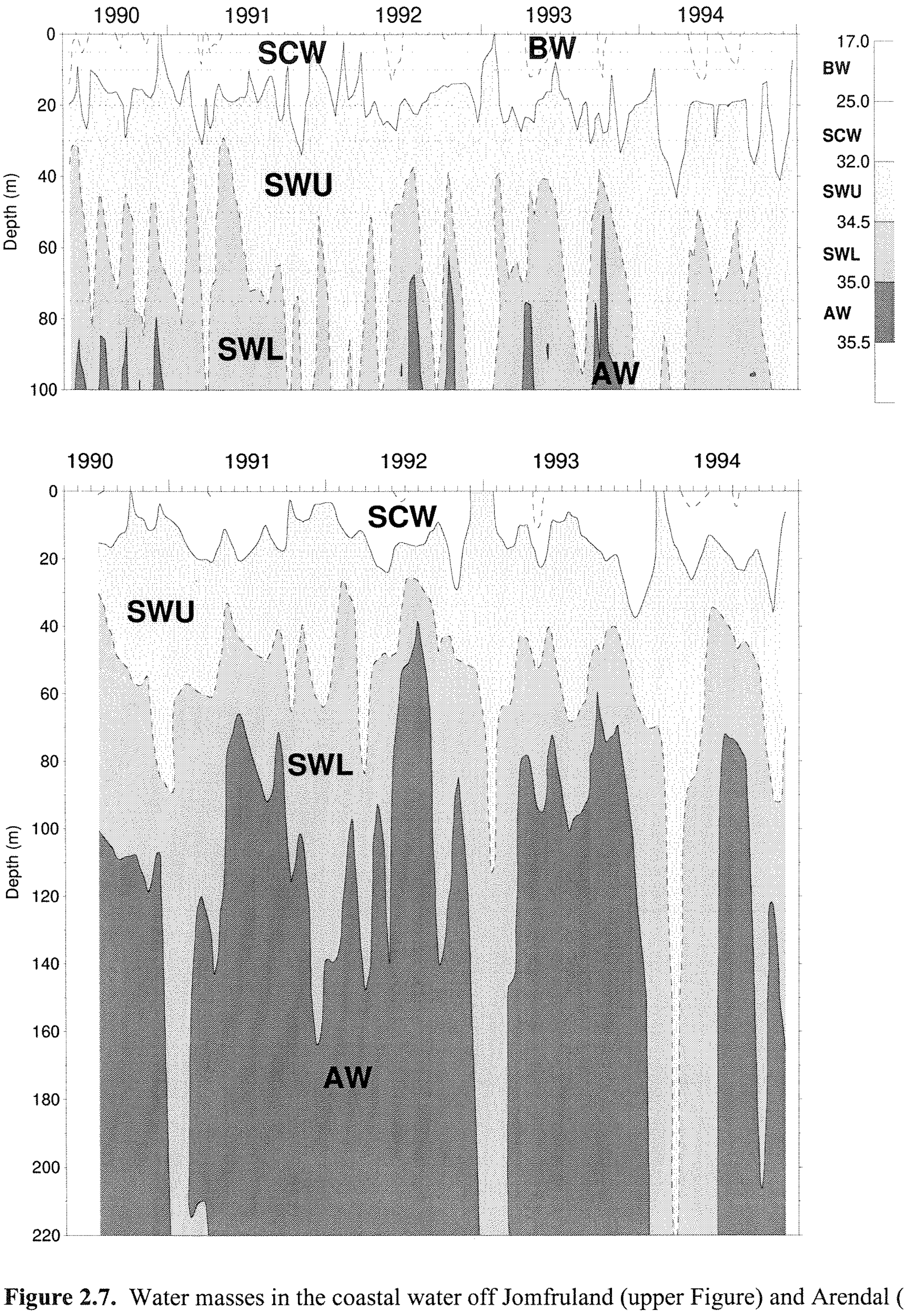


**Figure 2.7.** Water masses in the coastal water off Jomfruland (upper Figure) and Arendal (lower Figure) from May 1990 to September 1994. See Table 2.1 for codes and corresponding salinities.

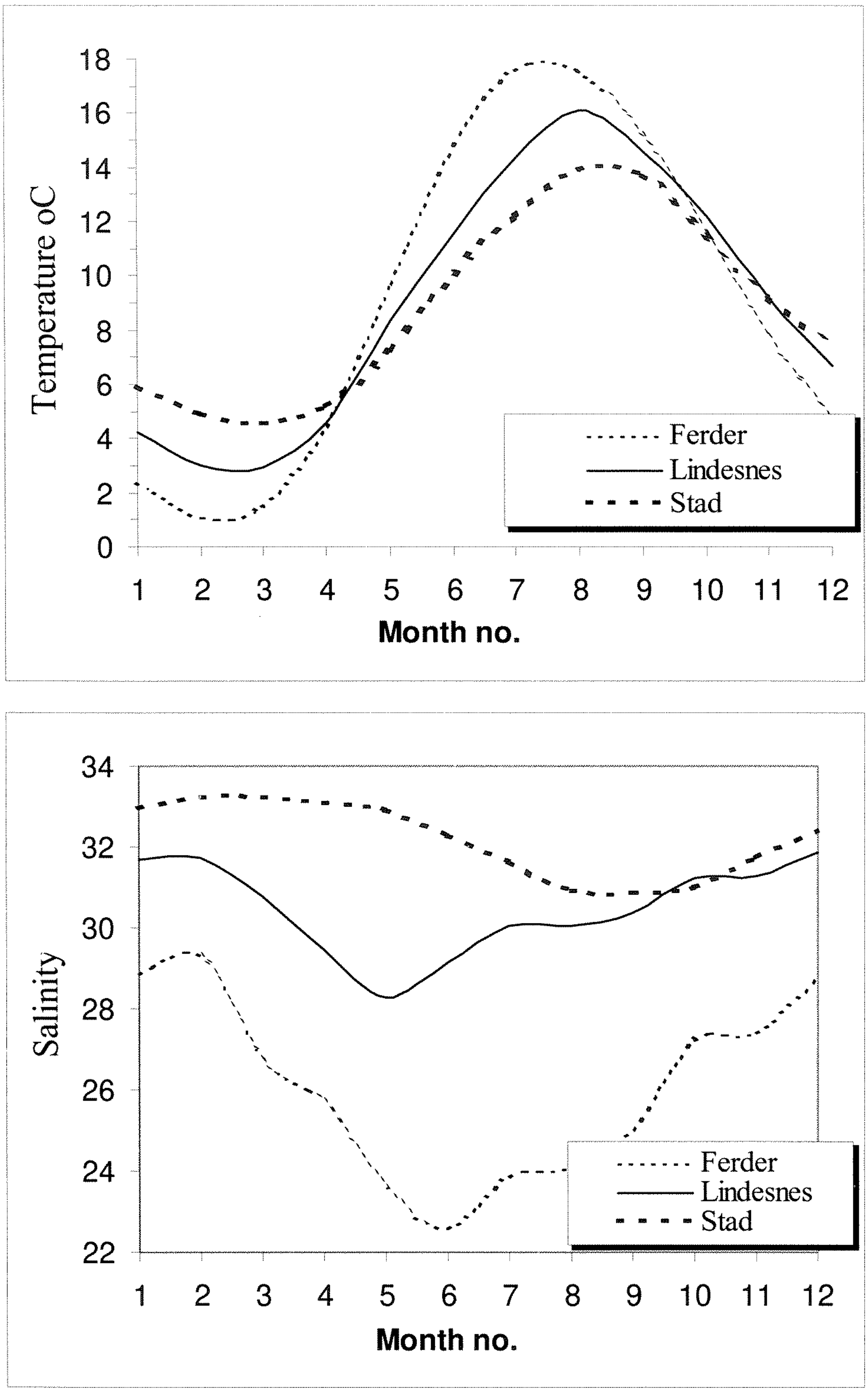


**Figure 2.8.** Average monthly temperature and salinity at 4 m depth at Ferder, Lindesnes and Stad. Data from 1936 - 1970. There is a considerable variation during the year, and a significant salinity gradient along the coast from Skagerrak to Stad.

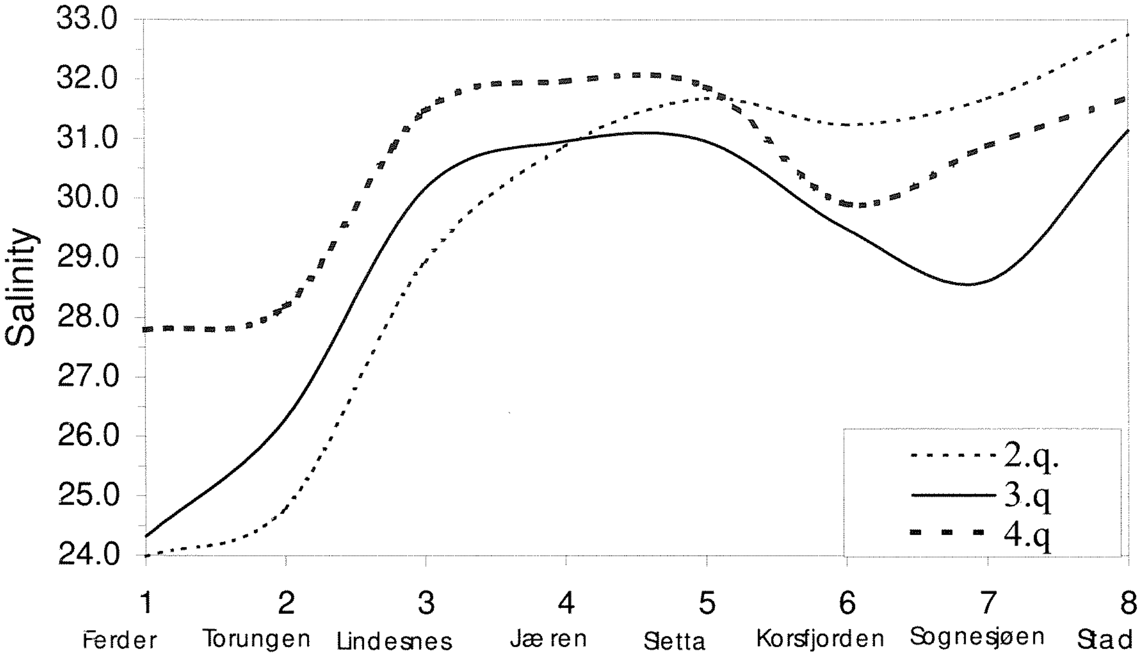


**Figure 2.9.** Salinity at 4 m depth in the coastal water for stations along the coast of Southern Norway. Averages for 2, 3 and 4 quarter. The largest increase takes place between Torungen and Lindesnes. Data from 1936 - 70. The station Sognesjøen is shown on figure 2.1, the stations Jæren, Sletta and Korsfjorden are situated south of Stavanger, north-west of Stavanger and south of Raunefjorden respectively.

Regarding the Outer Oslofjord its topography and hydrography suggests a distinction between three layers in the vertical (Figure 2.3). The local brackish layer (typically 4-6 m deep) is formed by a mixture of local freshwater and Skagerrak Coastal Water, but may also contain some Skagerrak Water Upper. Below the brackish layer there is an intermediate layer of Skagerrak Coastal Water. The basin water constitute Skagerrak Water Upper, Skagerrak Water Deep and Atlantic Water. Due to local and regional meteorological conditions, the situation is highly variable. The residence time for the brackish layer varies correspondingly, but is often less than one week (Røed et al. 1990).

The freshwater contribution from the Baltic and Swedish west-coast rivers to the Outer Oslofjord is generally 5-10 times higher than from other sources. However, during flood in May-August freshwater from Glomma (≤3000 $m^3/s$) and Drammen rivers (≤1000 $m^3/s$) will dominate the brackish layer in the southern and northern parts of the Outer Oslofjord, respectively (Hackett et al. 1995).

## 2.5 Circulation

Generally the NCC flows along the Norwegian Skagerrak coast turning northwards along the west coast of Norway (Figure 2.6). It is characterized by high variability in time and space, and a wedge-like appearance (Figure 2.10). Usually the NCC on the west coast is relatively deep and narrow during winter, and wider and more shallow in summer and autumn. In the Skagerrak prevailing winds from south and west may hold it back, resulting in sudden outbreaks and strong currents when the wind changes (Aure and Sætre, 1981).

Due to the Coriolis effect the NCC will follow the coastline, but the abrupt turn of the coastline off Lista, combined with periods of northern and western winds, creates an area where the current moves away from the coast, and with upwelling near the shore. The result is strong mixing and further dilution, and off Egersund the NCC is diluted to 30% of that off Arendal. Off Utsira and further along the west coast models show further dilution to 10% or less compared to the coastal water off Arendal.

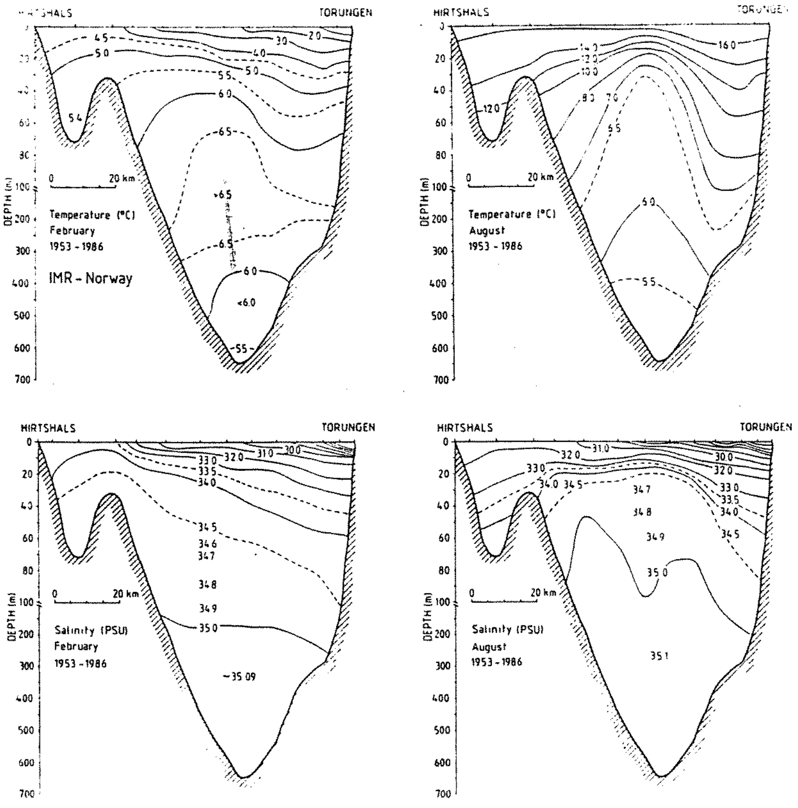


**Figure 2.10.** Mean temperature (°C) and salinity in the Torungen-Hirtshals section during winter (February) and summer (August), 1953 - 1986 (ANON, 1993).

The volume of water transport in the NCC off Arendal in 1993 have been estimated by means of a model (Stigebrandt 1983), and shown below on a monthly basis (Figure 2.11).

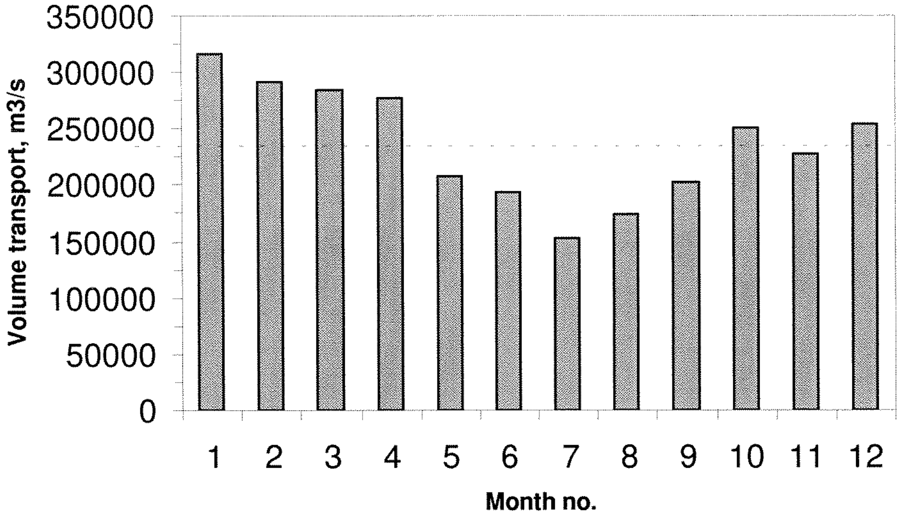


**Figure 2.11.** Calculated monthly average of volume transport in the NCC off Arendal for 1988 - 95. Dotted line shows average for the 8 years period (ANON, 1997).

Regarding the Outer Oslofjord, knowledge of its circulation has mainly been gathered from model simulations (Røed et al. 1989, Hackett et al. 1995) and field studies (Baalsrud and Magnusson 1990). The circulation is predominantly driven by local wind and freshwater runoff from local rivers such as Glomma and Drammen river, but also tides and the NCC makes its impact. Even though the NCC most of the time flows well south of the Oslofjord, model simulations show that NCC water masses may be found well into the fjord in the lower layers. The local freshwater discharge contributes to an estuarine circulation which is most pronounced in the vicinity of the river outlets. The estuarine circulation is, however, weak and not believed to be important for the water exchange in the main fjord.

The water exchange between the brackish layer and sill depth is mainly driven by variations in the density field in Skagerrak, and for 1993 numerical models show an average exchange of 150 000 $m^3/s$ between the Outer Oslofjord and the Skagerrak. Water from the German Bight, Baltic and Central North Sea contributes about 1/3 each. Modelling show that most of this water exchange takes part in the southern part of Outer Oslofjord, and only 10% of this water enters the northern half of the fjord (Hackett et al., 1995).

# 3. Nutrient enrichment of the coastal water

***The total nutrient transport in the Norwegian Coastal Current is far larger (>10-50x) than the anthropogenic load from Norwegian sources. There is evidence for a doubling of nitrate concentrations in the coastal water off Arendal during winter-spring, and a less increase for phosphate during the last 20-25 years. This has led to a shift towards higher N/P -ratios during the spring. Calculations strongly suggest that this is mainly caused by increased transboundary transport of nutrients from the southern North Sea, the German Bight, and to a lesser degree from the Kattegat.***
***Around Lindesnes this regional influence gradually disappears, and hydrochemical data from the coastal water off the west coast show normal concentrations.***

***In Outer Oslofjord an increased transboundary load has lead to increased nutrient concentrations with high N/P-ratios in spring and early summer. The local Norwegian load is mainly affecting the upper water layer in the northern part, and inshore areas in the eastern and western part of the fjord. Here the local load leads to increased nutrient concentrations - especially for nitrogen - and contributes significantly to the nutrient budgets.***

## 3.1 Nutrient load

### 3.1.1 The Norwegian load

The anthropogenic nutrient load of the coastal water from Norwegian land-based sources is reported annually as part of the Norwegian PARCOM programme for river monitoring (i.e. Holtan et al. 1994). Using the Teotil-model including PARCOM-data, freshwater runoff, data on population, industry, wastewater treatment plants, farming activities and aquaculture, Tjomsland and Braaten (1996) calculated the nutrient load for 16 coastal areas between the Swedish border and Stad for 1993. Figure 3.1 summarizes the results for the Skagerrak coast and the coast west of Lindesnes.

The total annual Norwegian input of nutrients to the Skagerrak and to the waters of western Norway are about 3000 tonnes of phosphorus (P) and 70000 tonnes of nitrogen (N). Of these amounts about 80 % of P and 50 % of N are of anthropogenic origin, the remainder being natural runoff.

The anthropogenic inputs to Skagerrak are about 750 tonnes of P and 22000 tonnes of N. Most of this comes in the Oslofjord region where agriculture and human population are the main sources. The anthropogenic inputs to western Norway are about 1400 tonnes of P and 14000 tonnes of N. Here the input is scattered from many small sources with population and aquaculture as the dominant ones. The annual anthropogenic nitrogen load to the Norwegian Skagerrak coast is therefore higher than to the west coast, while phosphorus shows the opposite pattern as a result of the discharges from the aquaculture industry, with its maximum in August - October.

The total nutrient load to the Outer Oslofjord for 1993 was 25000 tonnes of nitrogen and 860 tonnes of phosphorus (Figure 3.2), of which the anthropogenic load was approximately 16000 tonnes of nitrogen and 580 tonnes of phosphorus. This includes the load from the Inner Oslofjord and the Drammensfjord (Bjerkeng, 1997).

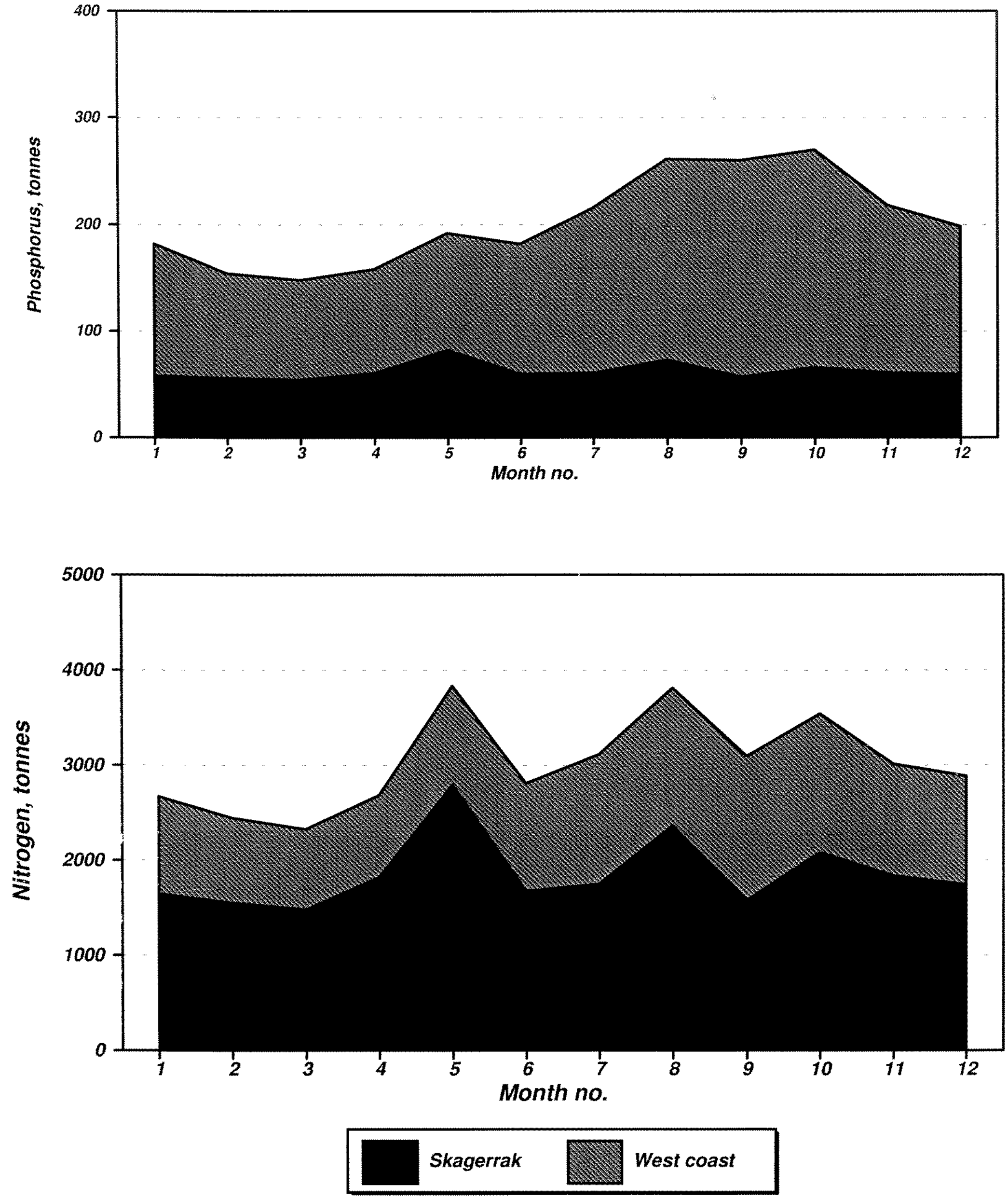


**Figure 3.1.** Calculated Norwegian anthropogenic nutrient load (total phosphorus, total nitrogen) to the Skagerrak and the west coast (Lindesnes - Stad) in 1993. The increase in phosphorus discharge to the west coast in June - December comes mainly from the aquaculture industry (Tjomsland and Braaten, 1996).

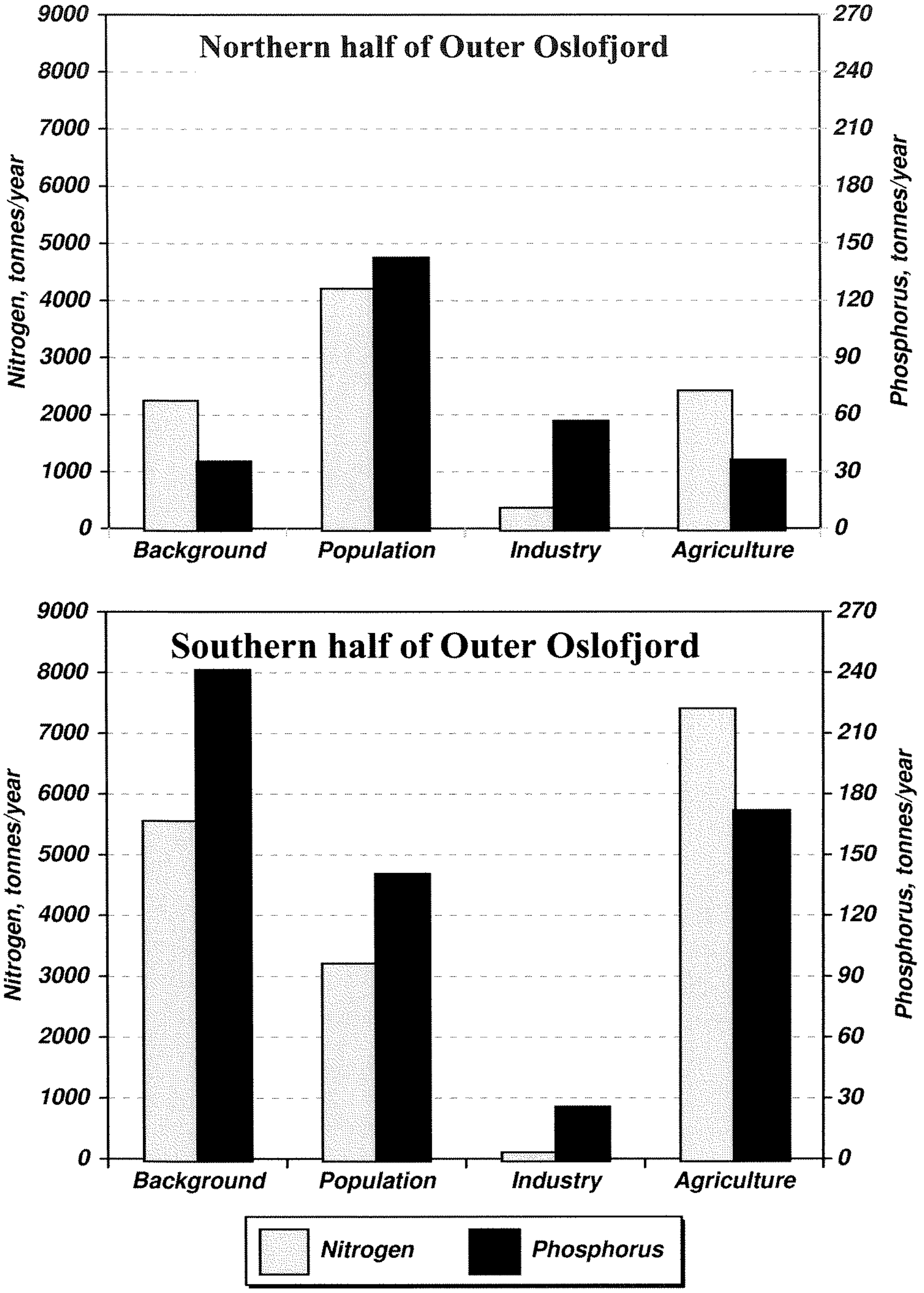


**Figure 3.2.** Discharges of nitrogen and total phosphorus to the northern and southern half of Outer Oslofjord in 1993. The relative high load to the southern half was dominated by Background and Agricultural sources through Glomma river (from ANON, 1996).

### 3.1.2 Transboundary load

The nutrient concentrations in the areas "upstream" of the Norwegian North Sea coast has increased significantly during the last 20 years, as documented by measurements in the Helgoland Bight (Hickel et al., 1995). However, the concentrations of nitrogen and phosphorus have developed differently since the late 70-ies, creating a significant distortion of the N/P-ratios towards a large surplus of nitrogen during winter and spring. During the autumn the nutrient load is significantly lower and there will be a surplus of phosphorus relative to N (Hickel et al., 1995). In the Kattegat, both the direct nutrient input and the indirect load via the Baltic have increased, and the Kattegat now experiences a marked surplus of nitrogen relative to phosphorus in the nutrient input.

The water masses flowing through Skagerrak thus transport large amounts of nutrients from the southern North Sea and Kattegat. The total input of anthropogenic nutrients from these areas in 1990 was approximately 630 000 tonnes of total nitrogen, and 55 000 tonnes of total phosphorus (ANON 1993).

The volume transport in the NCC off Arendal on the Norwegian Skagerrak coast is on average about 230.000 $m^3/s$, with a maximum during winter and a minimum during summer (ANON, 1997 and Figure 2.11). This includes water masses of salinity less than 34.5, a value which in this area is typically found at 80-100 m depth but at more shallow depths further offshore (Figure 2.9). The Norwegian Coastal Monitoring Program has provided corresponding nutrient concentrations, and the average monthly transport of nitrogen and phosphorus in the NCC off Arendal for 1990 - 94 is shown in Figure 3.3. The variations are large, because of varying concentrations and volume transport. A relatively low transport of nitrate and phosphate in July-September was mainly caused by low nutrient concentrations in the coastal current. As a whole the nutrient transport in the NCC is far larger (>10-50x) than the anthropogenic load from Norwegian sources.

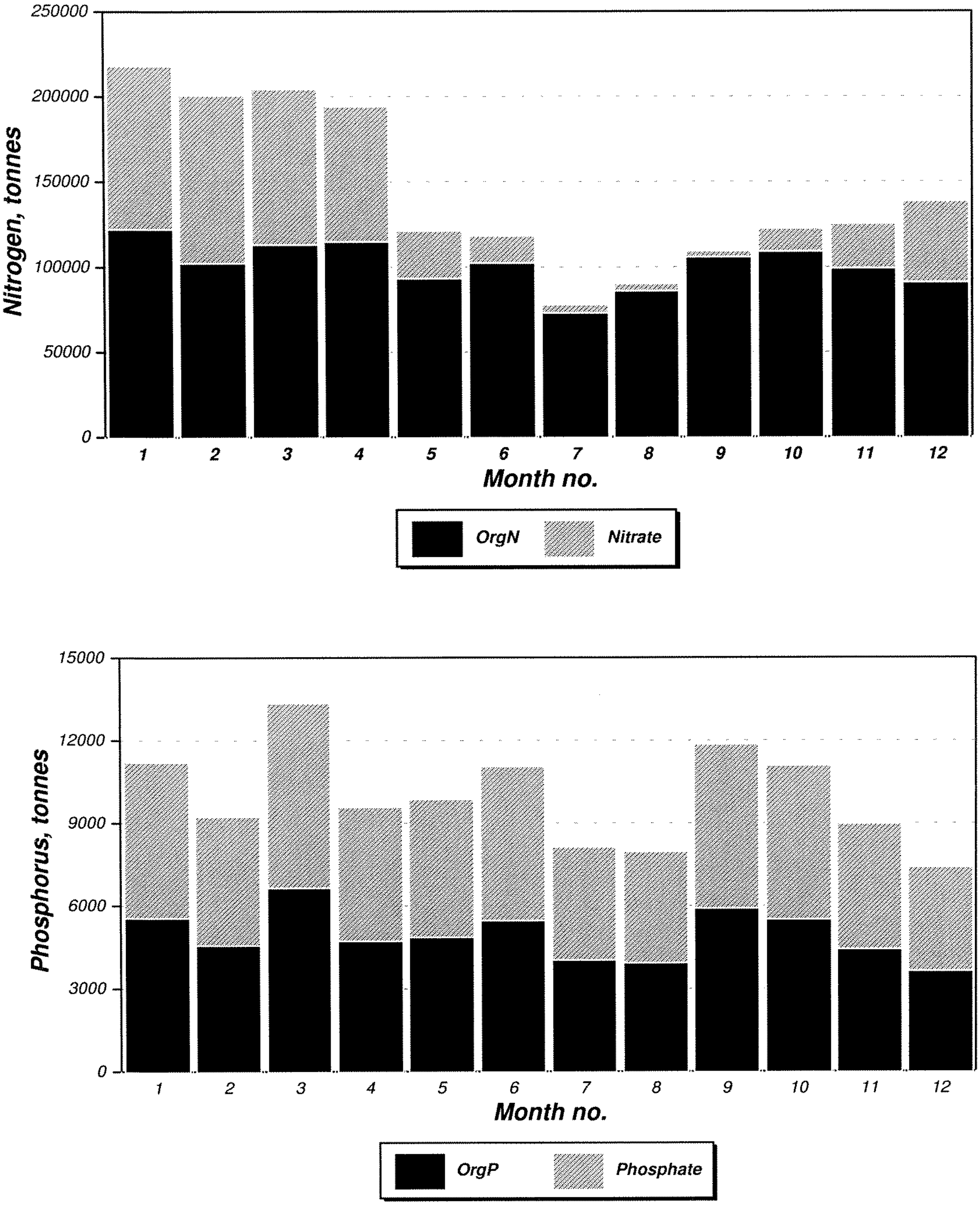


**Figure 3.3** Calculated monthly transport of organic nitrogen (OrgN), nitrate, and organic phosphorus (OrgP) have been calculated as the difference between total nitrogen and nitrate and total phosphorus and phosphate, respectively. Nitrate is the sum of nitrate+nitrite.

## 3.2 Effects of anthropogenic nutrient input on nutrient concentrations

### 3.2.1 Nutrient concentrations in the Norwegian Coastal Current

Data on nutrient concentrations have been assembled from several sources, mainly from monitoring activities. This includes data from the National Coastal Monitoring Programme with biweekly sampling since 1990 at the stations Jomfruland, Arendal, and Lista, data from monthly monitoring since 1980 at the Torungen-Hirtshals transect, Swedish and Danish data from monitoring at Anholt and Smøgen since the 1980s, and data from Raunefjorden at the Norwegian west coast for the period 1980-1994. Further description of the data is given by Aure and Johannessen (1997).

Time series of mean nutrient concentrations in the upper 30 m at Arendal are shown in Figure 3.4.

There is considerable interannual variability, particularly in the nitrate concentration and in the N/P- and N/Si-ratios based on nitrate. The nitrate concentrations in winter and spring were much higher in 1994 and 1995 with winter floods in the continental rivers, than in 1996 which was a dry and cold winter. This reflects the variable nutrient transport into Skagerrak from the southern North Sea and the Kattegat.

The consumption patterns of phosphate and nitrate in spring may differ as illustrated in Figure 3.5 where phosphate was depleted by the beginning of April while nitrate was still high and not decreasing until May-June. Phosphate started to increase in September or October. In 1992-94 the period of nutrient depletion in the surface layer off Jomfruland therefore lasted from April to September, which was the period when the growth of phytoplankton can be expected to be nutrient limited.

Figure 3.6 shows monthly mean values of nutrient concentrations, nutrient ratios, salinity and chlorophyll for the period 1990-95 for the coastal monitoring stations at Jomfruland, Arendal, Lista and from the Raunefjord at the Norwegian west coast.

The salinity generally increased in the main current direction along the Skagerrak coast from Jomfruland to Lista. The concentrations of nutrients during the winter were higher at the stations in Skagerrak than in Raunefjorden. Jomfruland and Arendal had similar nutrient concentrations, whereas Lista exhibited somewhat lower concentrations in particular for nitrate and silicate. The N/P- ratio based on nitrate and inorganic phosphate, was markedly higher than at the other stations at Jomfruland and Arendal during spring and at Jomfruland also during the summer. The concentration of total nitrogen showed a consistent decrease in the current direction from Jomfruland to Lista. Total phosphorus on the other hand showed no clear difference at the Skagerrak stations. The N/P-ratio based on total N and total P reflects the trend in total N with a decrease from Jomfruland to Lista. Total N was not measured in Raunefjorden, whereas the concentration of total P in winter was less than for the stations in Skagerrak.

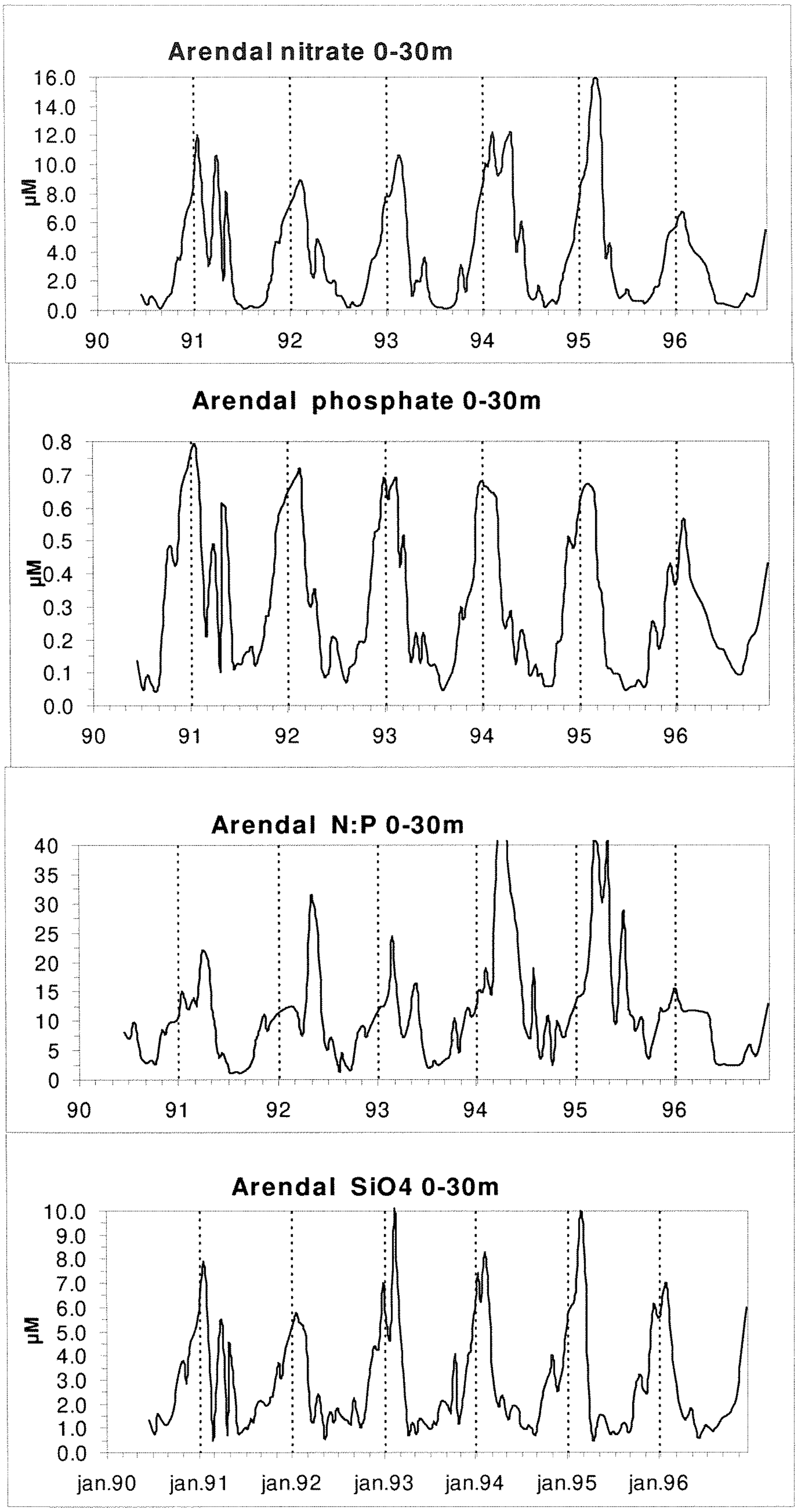


**Figure 3.4.** Nitrate, phosphate, silicate and N/P-ratios as averages for 0 - 30 m depth in the coastal water off Arendal for 1990 - 96 (Aure and Johannessen, 1997). There is a considerable interannual variability in addition to seasonal variations.

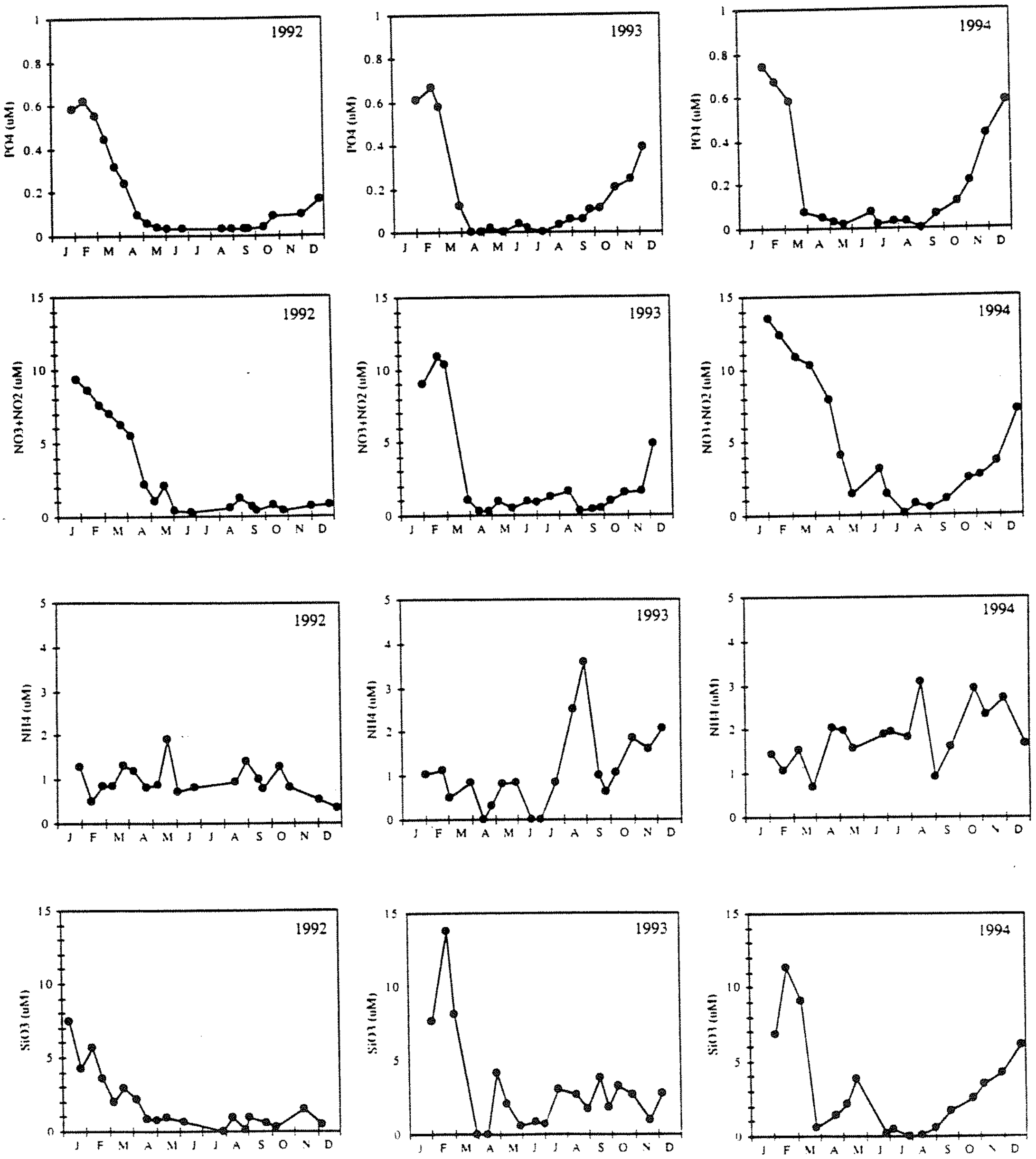


**Figure 3.5.** Average concentrations of phosphate, nitrate+nitrite, ammonium and silicate (0 - 10 m depth) in the coastal water off Jomfruland for 1992 - 94 (Bødtker et al., 1995).

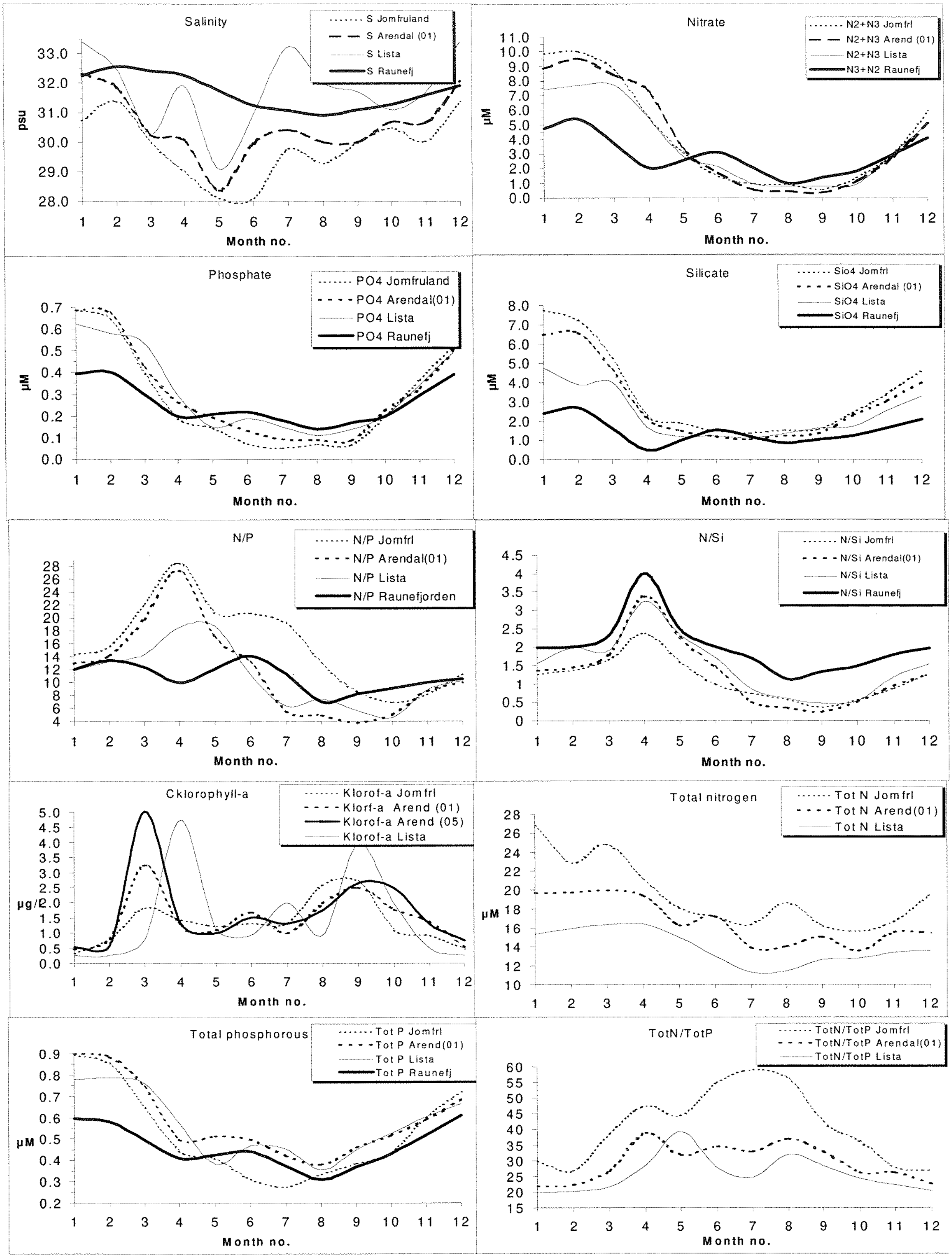


**Figure 3.6.** Monthly averages of salinity, nitrate, phosphate, silicate (unit: µM), N/P-, N/Si-ratio, chlorophyll a (unit: µg/l), total nitrogen, total phosphorus (unit: µM), and TotN:TotP for 0 - 30 m depth in the coastal water off Jomfruland, Arendal, Lista and Raunefjorden for 1990 - 1995.

### 3.2.2 Estimated increase in nutrient concentrations in the coastal water mass in Skagerrak

Two different approaches have been used to estimate the increase in nutrient concentrations in the coastal water due to increased nutrient input. The first approach uses reference nutrient concentrations from an earlier time period whereas the second approach uses calculations of the contribution from different water masses and temporal trends in nutrient concentrations in the sources of these water masses.

Nutrient concentrations and ratios at Arendal for the recent period 1990-95 have been compared with similar data from Arendal for the period 1975-80. For nitrate the Arendal 1975-80 data corresponds very closely with the present situation (1990-95) in the Raunefjord (Figure 3.7).

The Raunefjord receives little anthropogenic nutrient input and the nutrient concentrations there can be taken as being close to the natural background concentrations. The close correspondence with the Raunefjord 1990-95 suggests that the nitrate concentration at Arendal in 1975-80 can be assumed to have been close to the natural background concentration. For phosphate the situation was somewhat different. The present concentration of phosphate at Arendal is not so much higher than the concentration in 1975-80, while the latter was considerably higher during winter than the present level in the Raunefjord. This suggests that the 1975-80 level of phosphate cannot be considered to be a natural background level. This difference between nitrate and phosphate fits well with the different patterns in concentrations observed in the German Bight. Here the main increase in the phosphate concentration took place before the 1980s, while the concentration of nitrate in contrast has shown its main increase after about 1980 (Hickel et al. 1993, 1995).

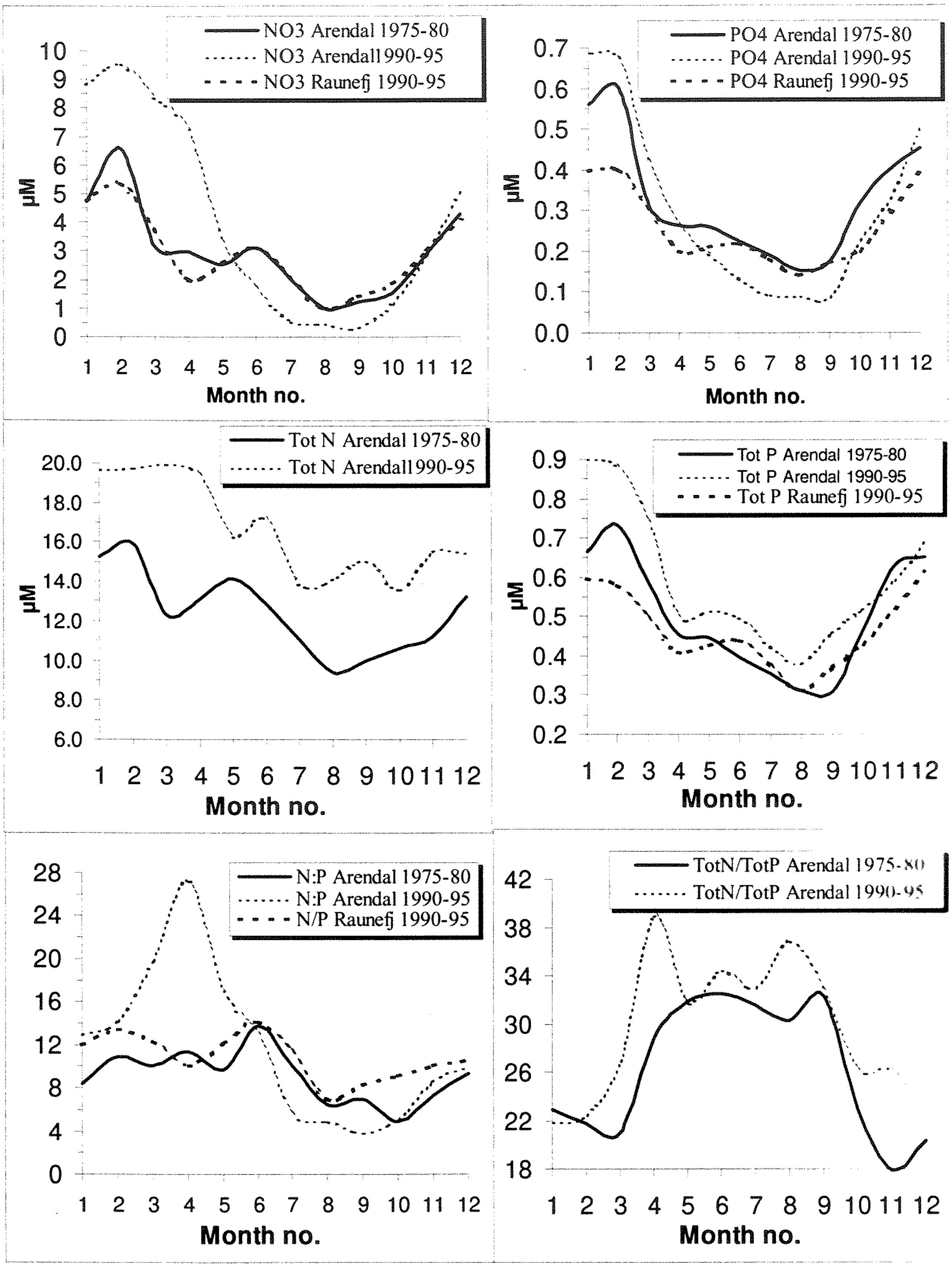


**Figure 3.7.** Monthly averages of nitrate, phosphate, N/P-ratio, total nitrogen, total phosphorus (unit: µM), and TOTN:TOTP for 0 - 30 m depth in the coastal water off Arendal 1975 - 80, 1990 - 95 and Raunefjorden for 1990 - 1995.

For nitrate there has been about a doubling in concentration for the winter and spring period at Arendal. The situation is different for the summer and autumn period for which the data indicate a decrease in the present concentrations. The explanation for this is not apparent. For inorganic phosphate the present winter concentrations are somewhat higher than the 1975-80 values at Arendal, but less markedly than for nitrate. As a result the N/P-ratio based on nitrate and phosphate shows a marked increase compared to the 1975-80 values at Arendal, particularly during the spring. The N/P-ratios for the period 1975-80 at Arendal are slightly lower than the ratios in the Raunefjord. This may reflect the already elevated concentrations of phosphate at Arendal in 1975-80. The increases in nitrate and N/P-ratio are generally less at Lista than at Arendal.

The concentration of total N has shown a consistent increase at Arendal between 1975 - 80 and 1990 - 95. As a mean over the year this increase has been about 35% with no clear seasonal pattern. There has also been an less pronounced increase in total phosphorus with an annual mean of 20%. Due to the more marked increase in total nitrogen there has been a general increase in the N/P-ratio based on total nitrogen and total phosphorus at Arendal between 1975 - 80 and 1990 - 95. The concentration of total phosphorus at Arendal in 1975 - 80 was somewhat higher than in the Raunefjord during winter. This suggests also that there was a contribution to elevated levels of phosphorus above natural background concentrations in 1975 - 80. The fractional increases in total nitrogen and total phosphorus were less pronounced at Lista than Arendal, particularly for total nitrogen.

The nutrient concentration in the coastal water mass has also been evaluated by an alternative approach. The water mass in the upper 30 m at Arendal is to a large extent a product from mixing of water which flows into the Skagerrak outside Hirtshals at the northern Danish coast (Jutland coastal water) and water which flows into Skagerrak from Kattegat (Kattegat surface water). Evidence for this is found in plots of concentrations of nitrate versus salinity for the three stations at Hirtshals, Anholt in Kattegat, and Arendal. If the data points of nitrate versus salinity for Hirtshals, Anholt and Arendal fall on a straight line, this can be taken as evidence for the fact that the water mass at Arendal is a product of physical mixing of water masses at Hirtshals and at Anholt (Figure 3.8). This method assumes conservative behaviour of nitrate. Deviation from linearity will occur if this assumption is not fulfilled or if water from other sources also has contributed to the water mass at Arendal.

There was in general a high degree of linearity in the relationship between salinity and nitrate for Hirtshals, Anholt, and Arendal, as revealed by high correlation coefficients (Table 3.1). This was particularly the case during winter (November-February) where 95 - 99% of the variance was explained by the linear relationship. The correlation was weaker in May and June when only 30 - 50% of the variance could be explained by the linear relationship. One reason for this could have been local input of nutrients to the coastal water mass in Skagerrak by spring flood of rivers due to snow melt (see also Figure 2.5).

Based on the assumption that the water masses at Arendal is a physical mixture of Jutland coastal water from off Hirtshals and water from Kattegat, it is possible to use the monthly mean values of salinity for the three water masses to calculate the proportions of water from respectively Hirtshals and Kattegat that have gone into producing the water mass at Arendal. 70 - 90% of the water at Arendal stems from off Hirtshals while 10 - 30% originates from the Kattegat (Table 3.1).

The calculation of fractions of water from Hirtshals and Kattegat in the coastal water mass at Arendal allows one also to calculate expected concentrations of nutrients based on the monthly mean nutrient concentrations in the source waters at Hirtshals and in Kattegat. This calculation is based on an assumption of conservative behaviour of the nutrients in the time between they are measured at

**Table 3.1.** Correlation between average concentration of nitrate+nitrite and salinity, and computed percentage of water mass off Hirtshals and Kattegat surface water in 0 - 30 m depth off Arendal. Data from 1980 - 95.

| Month no. | $r^2$ | % Hirtshals water | % Kattegat water |
|---|---|---|---|
| 1 | 0.98 | 83 | 17 |
| 2 | 0.99 | 77 | 23 |
| 3 | 0.79 | 77 | 23 |
| 4 | 0.96 | 75 | 25 |
| 5 | 0.52 | 72 | 28 |
| 6 | 0.33 | 83 | 17 |
| 7 | 0.98 | 91 | 9 |
| 8 | 0.62 | 88 | 12 |
| 9 | 0.94 | 86 | 14 |
| 10 | 0.75 | 83 | 17 |
| 11 | 0.99 | 82 | 18 |
| 12 | 0.95 | 80 | 20 |
| Year | 0.82 | 81 | 19 |

Hirtshals and Anholt and they appear off Arendal. The results of this calculation are shown in Figure 3.9).

There were reasonably good agreements between these calculated nutrient concentrations and those actually observed at Arendal. One deviation occurred in March when the observed concentrations of nitrate and silicate were lower than the calculated concentrations. This probably reflects high consumption rates of nitrate and silicate by the spring bloom of phytoplankton which develops at this time as seen from the peak in chlorophyll concentration at Arendal in March (Figure 3.6). Somewhat higher observed than calculated nutrient concentrations in May and June may reflect nutrient input by the spring flood in the riverine discharge to the Skagerrak. The estimated phosphate concentrations were higher than the observed concentrations from September to March. A possible explanation for this could be consumption of phosphate by phytoplankton and heterotrophic micro-organisms during this period.

The Jutland coastal water is itself a mixture of water from the German Bight and water from the southern North Sea. Based on mean salinities, the proportions of German Bight Water and Southern North Sea Water in the coastal water mass at Arendal have been calculated for the winter and spring periods (Table 3.2). This is the time of the year when the largest transports of water and nutrients from the Southern North Sea into Skagerrak occur. On average the coastal water at Arendal consists of 55 - 58% of water from the Southern North Sea, 19 - 20% from the German Bight, and 22 - 26% from Kattegat in the winter and spring periods.

The contributions of nutrients from these three sources of water have been calculated based on typical mean nutrient concentrations in these water masses from the time period after 1980 (see Table 3.3).

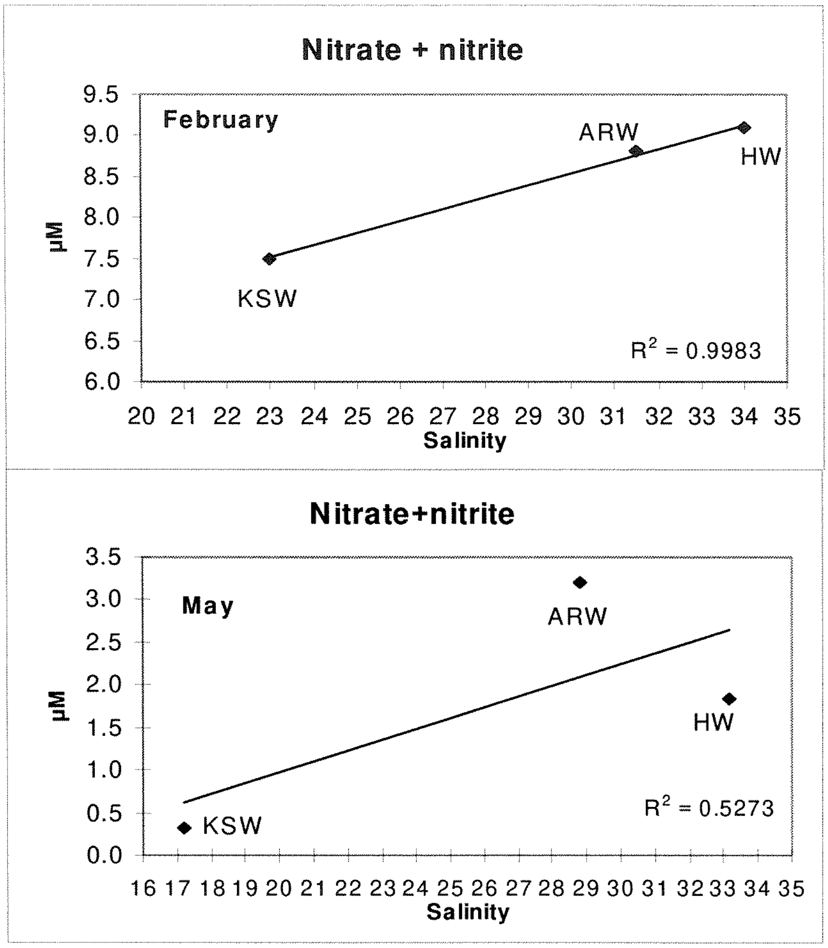


**Figure 3.8.** Concentrations of nitrate+nitrite versus salinity for Kattegat Surface Water (KSW), Hirtshals Water (HW) and calculated concentrations for Arendal Water (ARW, 0 - 30 m depth, data from 1980 - 95). The correlation-coefficient shows that the method for calculating ARW works will for a winter situation with low freshwater runoff to the Norwegian Skagerrak coast, but is less suited for spring - summer with higher runoff and non-conservative behaviour of nitrate.

**Table 3.2.** Typical percentages of Kattegat Water, German Bight Water and Southern North Sea Water (SN) and their percentage contribution to concentrations of nitrate, phosphate and silicate in winter-spring in the coastal water (0 - 30 m depth) off Arendal. Data from 1990- 95.

| Water mass | % Water | % Nitrate | % Phosphate | % Silicate |
|---|---|---|---|---|
| Kattegat - winter | 22 | 15 | 25 | 23 |
| Kattegat - spring | 26 | 6 | 18 | 27 |
| German Bight -winter | 20 | 74 | 40 | 57 |
| German Bight - spring | 19 | 81 | 45 | 33 |
| SN - winter | 58 | 11 | 35 | 20 |
| SN - spring | 55 | 13 | 37 | 40 |

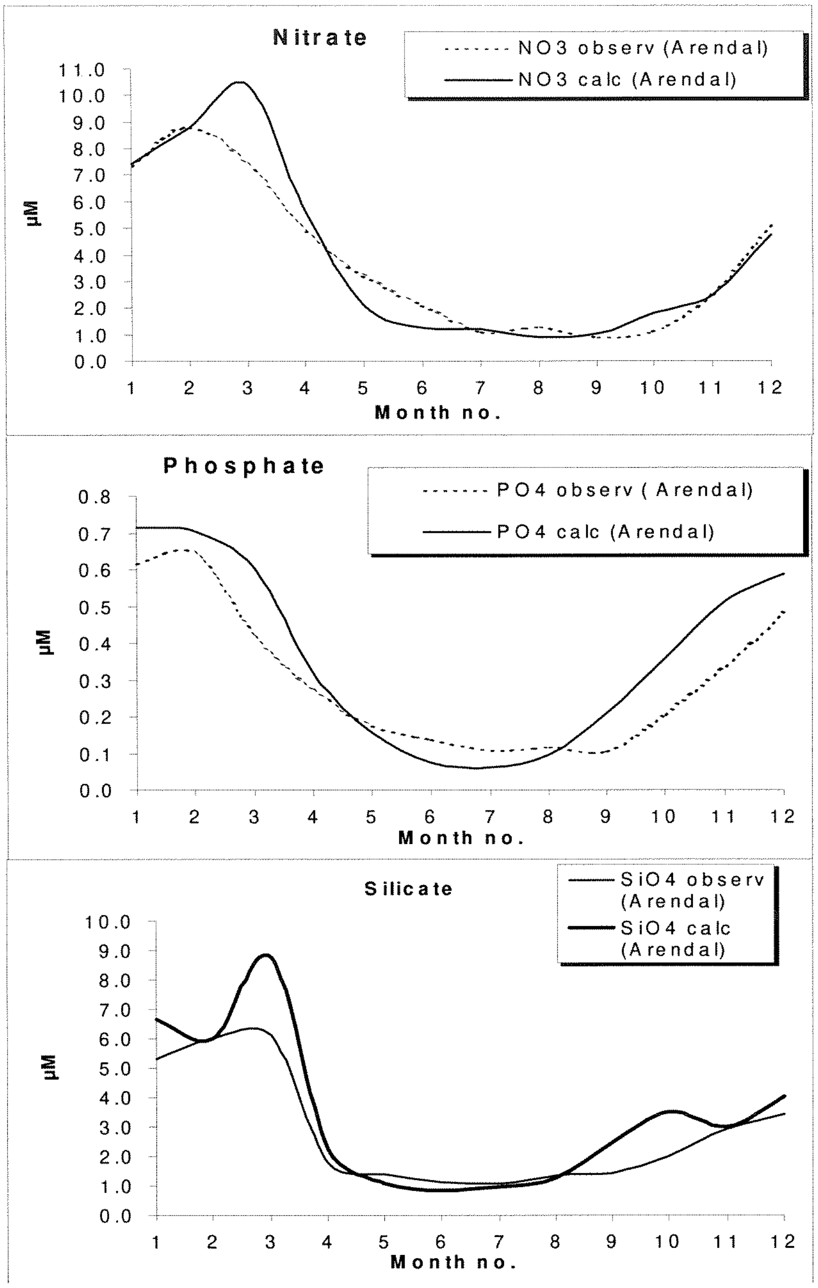


**Figure 3.9.** Monthly means of nitrate, phosphate and silicate based on observed and calculated values for 0 - 30 m depth in the coastal water off Arendal for 1980 - 95.

The relative contributions of nutrients have also been calculated based on typical nutrient concentrations in the three water masses for the period before 1970. The estimated nitrate concentrations during winter and spring at Arendal is about twice as high for the period after 1980 than for the period before 1970 (Table 3.3). For phosphate the increase is less marked, with about 50% increase in the estimates for the winter period. Due to the different patterns of increase in nitrate and phosphate, the calculations reveal a marked increase in the N/P-ratio particularly for the spring period. There are also increases in the calculated N/Si-ratio.

**Table 3.3.** Typical observed nutrient concentrations (µM) during winter-spring in German Bight Water, Southern North Sea Water and Kattegat Surface Water before 1970 and after ca. 1980, together with calculated concentrations of nutrients and ratios in the coastal water (0 - 30 m) off Arendal.

| **Winter before 1970** | **Nitrate** | **Phosphate** | **Silicate** | **N/P** | **N/Si** |
|---|---|---|---|---|---|
| German Bight Water | 16 | 0,8 | 20 | 20 | 0,8 |
| Southern North Sea Water | 2 | 0,2 | 2 | 10 | 1,0 |
| Kattegat Water | 5 | 0,6 | 7 | 8,3 | 0,7 |
| **Coastal water Arendal** (average) | **5,4** | **0,41** | **6,7** | **13,4** | **0,8** |
| **Spring before 1970** | **Nitrate** | **Phosphate** | **Silicate** | **N/P** | **N/Si** |
| German Bight Water | 10 | 0,5 | 3 | 20 | 3,3 |
| Southern North Sea Water | 2 | 0,2 | 2 | 10 | 1,0 |
| Kattegat Water | 2 | 0,2 | 3 | 10 | 0,7 |
| **Coastal water Arendal** (average) | **3,5** | **0,26** | **2,4** | **13,7** | **1,4** |
| **Winter after 1980** | **Nitrate** | **Phosphate** | **Silicate** | **N/P** | **N/Si** |
| German Bight Water | 37 | 1,2 | 25 | 30,8 | 1,5 |
| Southern North Sea Water | 3 | 0,35 | 3 | 8,6 | 1,0 |
| Kattegat Water | 7 | 0,7 | 9 | 10 | 0,8 |
| **Coastal water Arendal** (average) | **10,6** | **0,6** | **8,7** | **17,9** | **1,2** |
| **Spring after 1980** | **Nitrate** | **Phosphate** | **Silicate** | **N/P** | **N/Si** |
| German Bight Water | 37 | 0,7 | 5 | 53 | 7,4 |
| Southern North Sea Water | 2 | 0,2 | 2 | 10 | 1 |
| Kattegat Water | 2 | 0,2 | 3 | 10 | 0,7 |
| **Coastal water Arendal** (average) | **8,6** | **0,3** | **2,8** | **29,3** | **3,0** |

Reflecting the differences in nutrient concentrations, the three sources of water contributes to different fractions of the nutrient content in the coastal water mass at Arendal. For nitrate, 74 - 81% originates from the German Bight, 11 - 13% from the Southern North Sea, and 6 - 15% from the Kattegat (Table 2.2). For phosphate, the differences are less pronounced, with 40 - 45% from the German Bight, 35 - 37% from the Southern North Sea, and 18 - 25% from the Kattegat.

There is a reasonably good agreement between the calculated concentrations of nutrients in the coastal water mass at Arendal and the observed concentrations for the periods 1975-80 and 1990-95 (Figure 3.9). A comparison between the increase in observed nutrient concentrations for the winter and spring period between 1975-80 and 1990-95 and the increase in calculated nutrient concentrations from the period before 1970 to the period after 1980 is given in Table 3.4.

**Table 3.4.** Observed and calculated relative change in nitrate, phosphate and N/P-ratio in the coastal water (0 - 30 m) off Arendal based on winter-spring data from 1975 - 80 and 1990 - 95. Calculated relative change following a 50% reduction in concentrations of nitrate and phosphate in German Bight Water.

| Parameter | Observed relative change | Calculated relative change | Calculated (50% reduction) (before 1970) |
|---|---|---|---|
| Nitrate | 1,9 | 2,1 | 1,7 |
| Phosphate | 1,1 | 1,3 | 1,2 |
| N/P-ratio | 1,8 | 1,6 | 1,4 |

The two independent approaches both provide evidence for a substantial temporal increase in nutrient concentrations in the coastal water mass at Arendal. For nitrate this increase represents about a doubling in the concentrations during winter and spring. The increase has been less for phosphate, leading to a shift in the N/P-ratio to values much higher than the Redfield ratio during spring. The close agreement between the observed and calculated increases in nitrate is evidence that the major source of the increase in nitrate and N/P-ratio is the transboundary transport of nutrients from the coastal areas of the Southern North Sea and the German Bight and, to a lesser degree, from the Kattegat. The contribution from Norwegian sources is by comparison quite low due to the low inputs. This conclusion is treated in more detail in the next section.

With the method used to calculate the contribution from the upstream water masses to the nutrient content in the coastal water mass at Arendal, it is possible to calculate the effect of reductions in the nutrient input. With a 50% reduction in the concentrations in the German Bight there would still be a marked increase in nitrate and the N/P-ratio during winter and spring at Arendal compared to the situation before 1970 (Table 3.4).

The NCC is diluted by admixture of saltier Atlantic water during its flow westwards along the Skagerrak coast and northwards along the Norwegian west coast. This contributes also to dilute the nutrient content from the upstream sources in the southern North Sea and the Kattegat and to reduce the nutrient concentrations in the water masses of the NCC. This is seen in the results from the station at Lista where the mean increase in nitrate for the winter and spring period is about 60% compared to the approximate doubling at Arendal. The NCC is further diluted with Atlantic water west and north of Lista, and results from a numerical model (Søiland et al., 1996) suggest that the contribution of nutrients from the Southern North Sea and the Kattegat is reduced to less than 20% increase above natural background concentrations north of Jæren at the southwest coast of Norway.

### 3.2.3 Estimated increase in nutrient concentrations in the Outer Oslofjord

For nutrient budgets and modelling purposes the Outer Oslofjord has been divided into 16 areas (Figure 3.10). The increase in nutrient concentrations in the upper layer in these areas that originate from the Norwegian nutrient load has been calculated using three different methods (Bjerkeng, 1997).

**1. Contribution from local freshwater**

The relative proportions of local freshwater (Glomma and Drammen rivers), Baltic water and water from rivers discharging into the south-eastern North Sea in the Outer Oslofjord-water have been calculated for 1993 by Hackett et al. (1995) for four vertical layers:

| | |
|---|---|
| Layer 1: | density less than 1.022 ton/m$^3$. |
| Layer 2: | density between 1.022 ton/m$^3$ and 1.024 ton/m$^3$. |
| Layer 3: | density between 1.024 ton/m$^3$ and 1.026.9 ton/m$^3$. |
| Layer 4: | density higher than 1.026.9 ton/m$^{3.}$ |

The depth of layers 1-2 are shown in Figures 3.11 - 3.12.

The local freshwater contribution to Layer 1 was combined with winter nutrient concentrations in the Glomma and Drammen river for 1993 (Holtan et al., 1994), giving the contribution to the N- and P-concentrations in this layer (Table 3.5).

**Table 3.5.** Relative proportions of local freshwater and the corresponding contribution to concentration of nitrogen and phosphorus in Layer 1 (density less than 1.022 ton/m$^3$) in Outer Oslofjord in winter. See Figure 3.10 for position of the areas.

| Areas no. | Relative proportion of local freshwater (%) | Contribut. to N-concentration (μM) | Contribut. to P-concentration (μM) |
|---|---|---|---|
| 1+2+3 | 11 - 23 | 4.3 - 8.9 | 0.03 - 0.05 |
| 4+5+6+7 | 8 - 15 | 3.6 - 6.4 | 0.03 - 0.05 |
| 8+9 | 16 - 27 | 9.3 - 15 | 0.1 - 0.16 |
| 10+11+12+13 | 6 - 12 | 3.6 - 6.4 | 0.03 - 0.06 |
| 14+15+16 | 2 - 5 | 1.0 - 2.1 | 0.01 - 0.02 |

As the freshwater flow from Glomma and Drammen rivers is primarily to the upper 5-10 m, the calculated increase in nutrient concentrations for Layer 1 may normally underestimate the effect of the local nutrient load for this water mass. Table 3.6 shows the increase of N-concentrations in a 10 m deep layer for April-June assuming all local freshwater is concentrated in this layer.

**Table 3.6.** Estimated maximum increase in N-concentrations from local freshwater to the Outer Oslofjord in April-June 1993, assuming entry only to the upper 10 m of the water mass (Bjerkeng, 1997).

| Areas no. | Contribution to concentration of total nitrogen (μM) | |
|---|---|---|
| | Interval | Median for May |
| 1+2+3 | 3.6 - 14 | 10.0 |
| 4+5+6+7 | 1.4 - 10.7 | 7.1 |
| 8+9 | 5.7 - 28.6 | 16.1 |

This simple approach shows the potential for reducing the nutrient concentrations in layer 1, but does not give any information about the variations in time and space due to mixing of various water masses.

## 2. Scenarios for concentrations based on nutrient inputs, volumes and transports

Using data on volumes, residence time and water exchange for the various areas and layers in the Outer Oslofjord (Hackett et al.,1995), the effect on average nutrient concentrations in layer 1 from riverine input and from local sewage treatment plants have been calculated (Bjerkeng 1997). In addition to the 1993-situation, the calculations included the following three scenarios (Figure 3.11 - 3.12):

- With 70% nitrogen removal in sewage treatment plants around the Outer Oslofjord.
- With 80% nitrogen removal in main sewage treatment plant for Oslo.
- Without Norwegian discharges from densely populated areas.

As background concentration for Skagerrak-water concentrations of total phosphorus and nitrite, nitrate and ammonium (biologically active nitrogen) is used and like the previous method only the effect from dilution is included. Effects of biological processes and vertical transport of particulate nitrogen and phosphorus will tend to reduce the concentrations. The results indicate that the total Norwegian nitrogen input to the northern part of the Outer Oslofjord on the average may increase the total nitrogen concentrations in Layer 1 by 7.1 µM. Further south the average increase may be up to 2.1 µM.

The influence on the phosphorus concentrations from Norwegian nutrient input is smaller than for nitrogen, about 0.03 - 0.1 µM in the northern part of the Outer Oslofjord and 0.1 -0.02 µM in the southern part.

N-treatment at the main sewage treatment plant for Oslo may on the average reduce the N-concentrations of Layer 1 in the northern part of the Outer Oslofjord by 0.71 - 1.07 µM. Correspondingly, N-treatment of municipal wastewater discharged directly to the Outer Oslofjord may reduce the N-concentrations in Layer 1 by 0.36 - 0.57 µM. Thus the total predicted effect of N-removal in municipal sewage treatment plant around the Inner and Outer Oslofjord is a reduction of the order of 1.43 µM in Layer 1, or 15 - 20% of the concentrations relative to total Norwegian nutrient input. The obvious reason is that the N-input from municipal sewage is relatively small, and also to a large extent is trapped in Layer 2 since discharges are by deep water outfalls. On the other hand the amount of freshwater found in all specified layers, even the deepest, indicates that the vertical mixing of the model may be too strong (Hackett et al., 1995). In that case the influence from Norwegian nutrient input on the concentrations in Layer 1 may be underestimated.

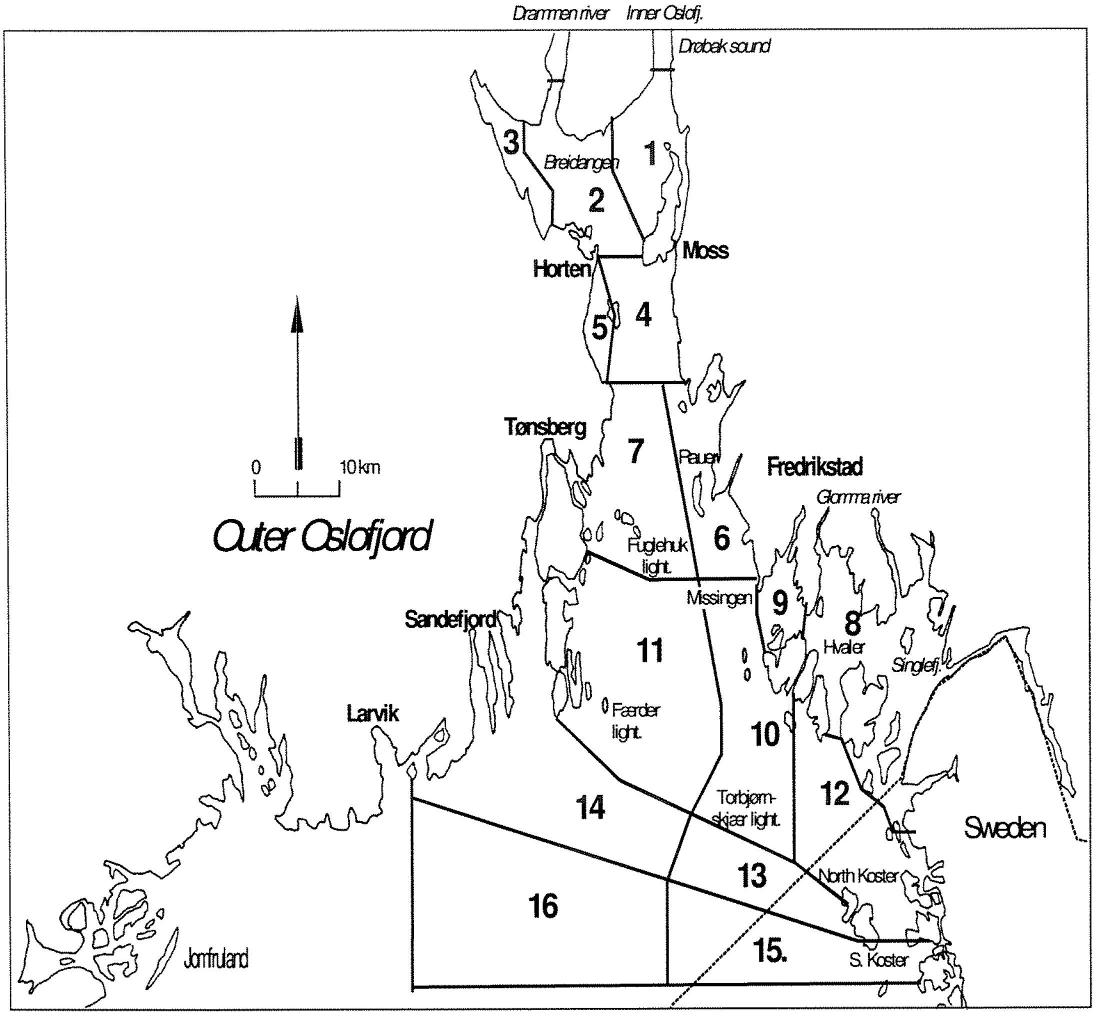


**Figure 3.10.** Map of the Outer Oslofjord showing areas for calculation of nutrient input, water exchange and nutrient concentrations.

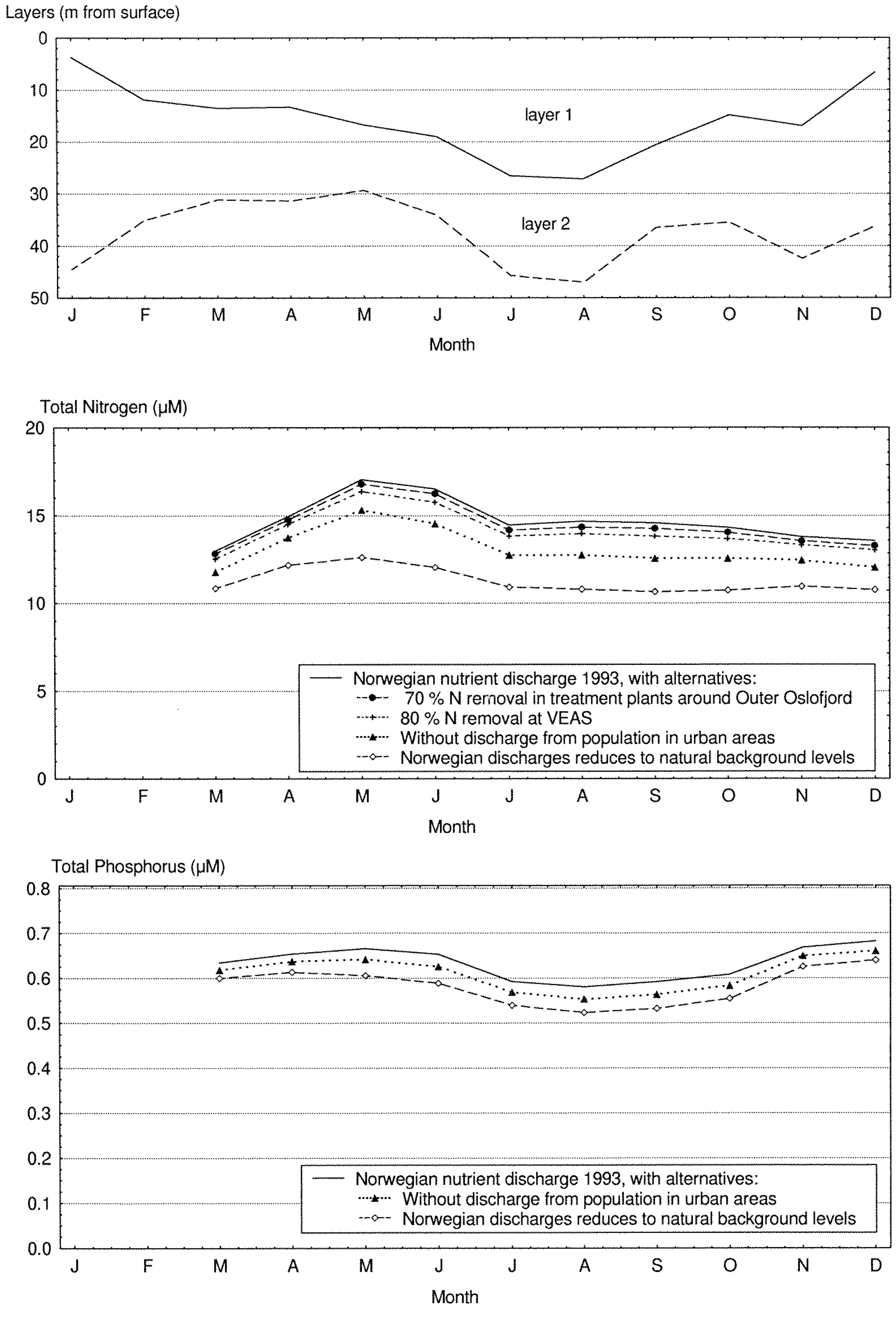


**Figure 3.11.** Model calculations of monthly mean depth of layers 1 and 2 in 1993, and corresponding concentrations of total nitrogen and total phosphorus in layer 1 in the northern part of the Outer Oslofjord (areas 1 - 3, se Figure 3.10) for various nutrient input scenarios.

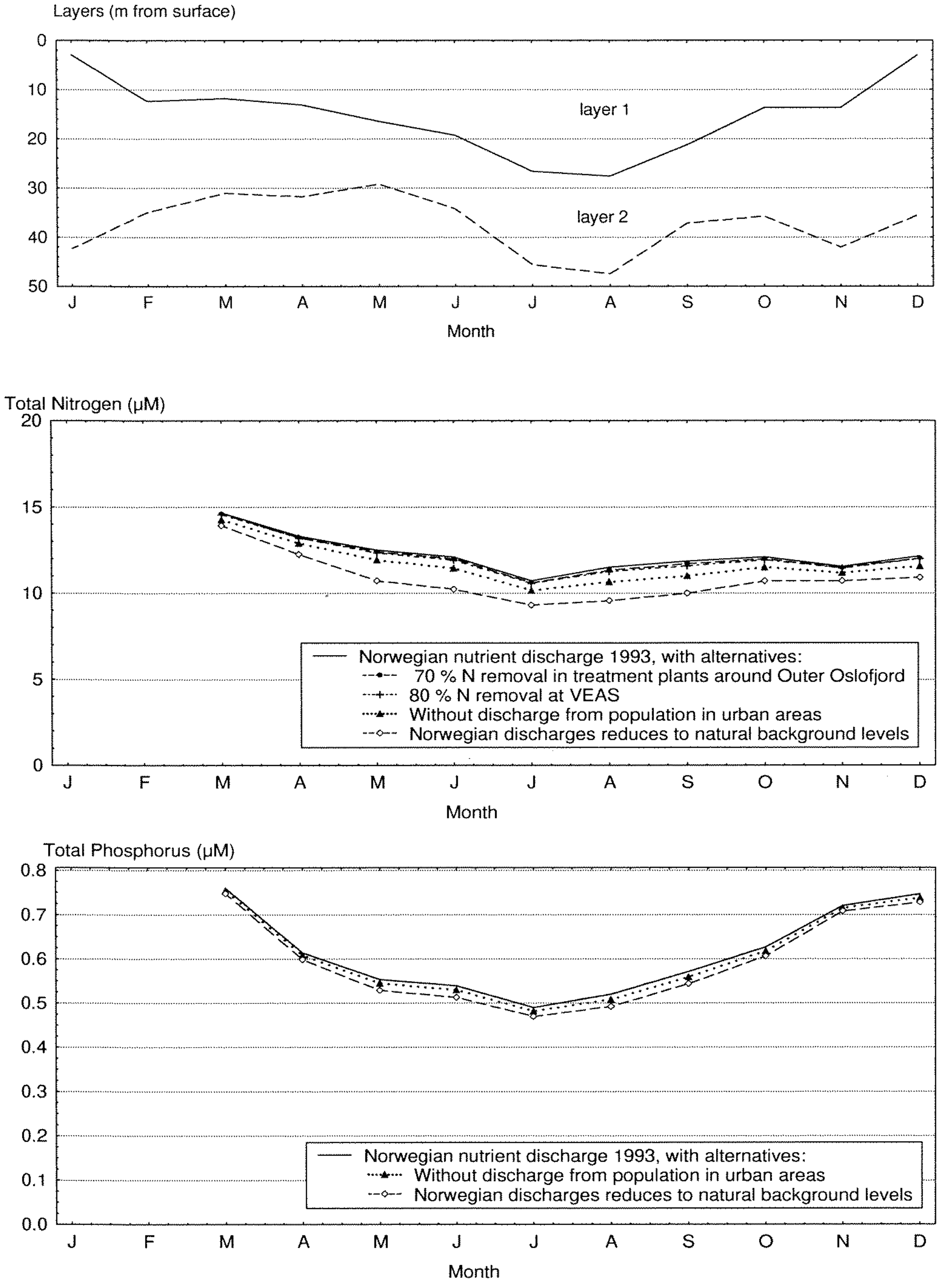


**Figure 3.12.** Model calculations of monthly mean depth of layers 1 and 2 in 1993, and corresponding concentrations of total nitrogen and total phosphorus in layer 1 in the southern part of Outer Oslofjord (areas 6 - 7, se Figure 3.10) for various nutrient input scenarios.

## 3. The model Fjordmiljø

From 1919 to 1989 there has been a marked increase in the nutrient load to the northern half of the Outer Oslofjord (Table 3.7). The N/P-ratio for the increase in bioavailable nutrient load is 41:1, which is far higher than the general Redfield ratio of N/P= 16:1. It therefore indicates a significant surplus of nitrogen relative to the average planktonic demand.

Using a simple fjord model (Aure and Stigebrandt, 1989) the average water exchange between the northern and southern half of the Outer Oslofjord have been calculated for the upper 5 m deep water mass. If all the bioavailable nitrogen is used for primary production in this layer in the northern half of the fjord, the Redfield ratio indicates an average carbon concentration of about 57 μM (see chap. 4.1). This is 2-3 times higher than concentrations ever observed, and may indicate that a significant part of the local nitrogen load is flushed out of the area without being used in the primary production.

**Table 3.7.** Nitrogen and phosphorus load (tons/year) to the northern half of Outer Oslofjord (areas 1-7) in 1910 and in 1989 (ANON 1996).

| | Total load (tons/year) | | | Bioavailable load (tons/year) |
|---|---|---|---|---|
| Year | 1910 | 1989 | Increase | Increase |
| Total nitrogen | 2700 | 14000 | 11300 | 6780 |
| Total phosphorus | 182 | 638 | 456 | 365 |

# 4. Effects of nutrient enrichment

***There is a moderate trend towards lower oxygen concentrations in the coastal water in the autumn, and this is explained as an effect from a regional organic load upstream of the Norwegian Skagerrak coast. Through the water exchange this load is imported into the fjord basins along the Skagerrak coast, and may seriously reduce the capacity of these basins to assimilate local loads of nutrients and organic matter. Coastal benthic communities (hard- and soft-bottom) do not show any clear effects from eutrophication, although effects cannot be excluded. The degree of eutrophication seems reasonably constant from Jomfruland to Arendal, decreasing westward towards Lindesnes. Algal blooms in Skagerrak are often transported past Lindesnes and north to Utsira, but seldom much further. Data from the coastal water off the west coast does not indicate any biological eutrophication effects.***

***In the Outer Oslofjord several eutrophication effects are documented, mainly increased planktonic biomass, reduced water transparency, reduced lower depth for growth of macroalgae and a trend towards lower oxygen concentrations in the intermediate and basin waters. A relatively frequent and changed appearance of harmful algae is observed, but cannot be attributed to eutrophication alone.***

## 4.1 Phytoplankton biomass and suspended organic material

The seasonal pattern of phytoplankton biomass in Skagerrak is characterized by a spring bloom typically in March, lower biomass with frequent blooms in summer, and often high biomass associated with blooms of dinoflagellates in the autumn (Tangen et al., 1997). The seasonal pattern based on monthly mean chlorophyll a concentration in the upper 30 m along the Torungen-Hirtshals transect is shown in Figure 4.1.

The spring bloom tends to occur slightly later at the Danish side compared to the Norwegian. The autumn bloom of dinoflagellates occurs mainly in coastal waters and is absent from the central part of the transect across Skagerrak. There is very large interannual variability, however, in the seasonal pattern and magnitude of chlorophyll concentration.

Measurements of total nitrogen and phosphorus provide integrated measures of the sum of dissolved inorganic and organic nutrients, biomasse of phytoplankton and small heterotrophic organisms, and dead particulate organic material. There is a general decrease in the concentration of total nitrogen in the current direction from Kattegat and further along the Norwegian Skagerrak coast from Jomfruland to Lista (Figure 3.6). This decreasing trend is clearly expressed also in the sum of dissolved and particulate organic nitrogen and phosphorus, estimated as the difference between total nitrogen or phosphorus and nitrate or inorganic phosphate, respectively (Figure 4.2).

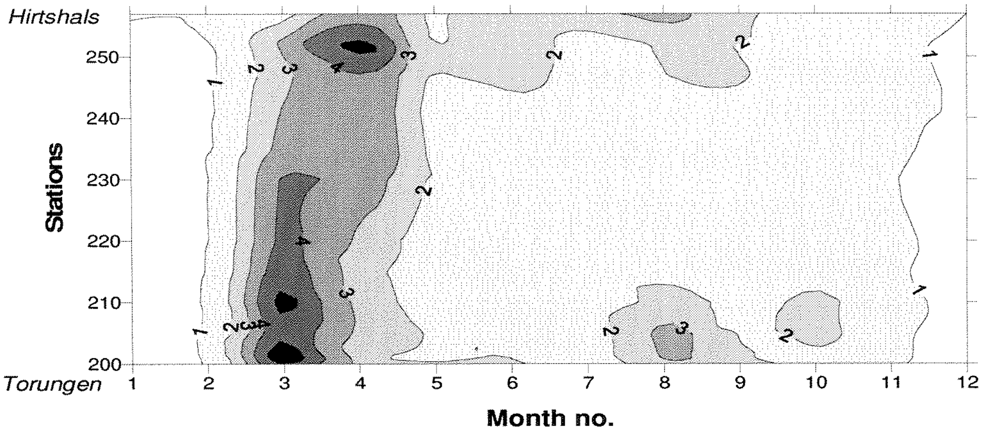


Figure 4.1. Average chlorophyll *a* concentrations (μg/l) in 0 - 30 m depth on the cross-section Torungen - Hirtshals.

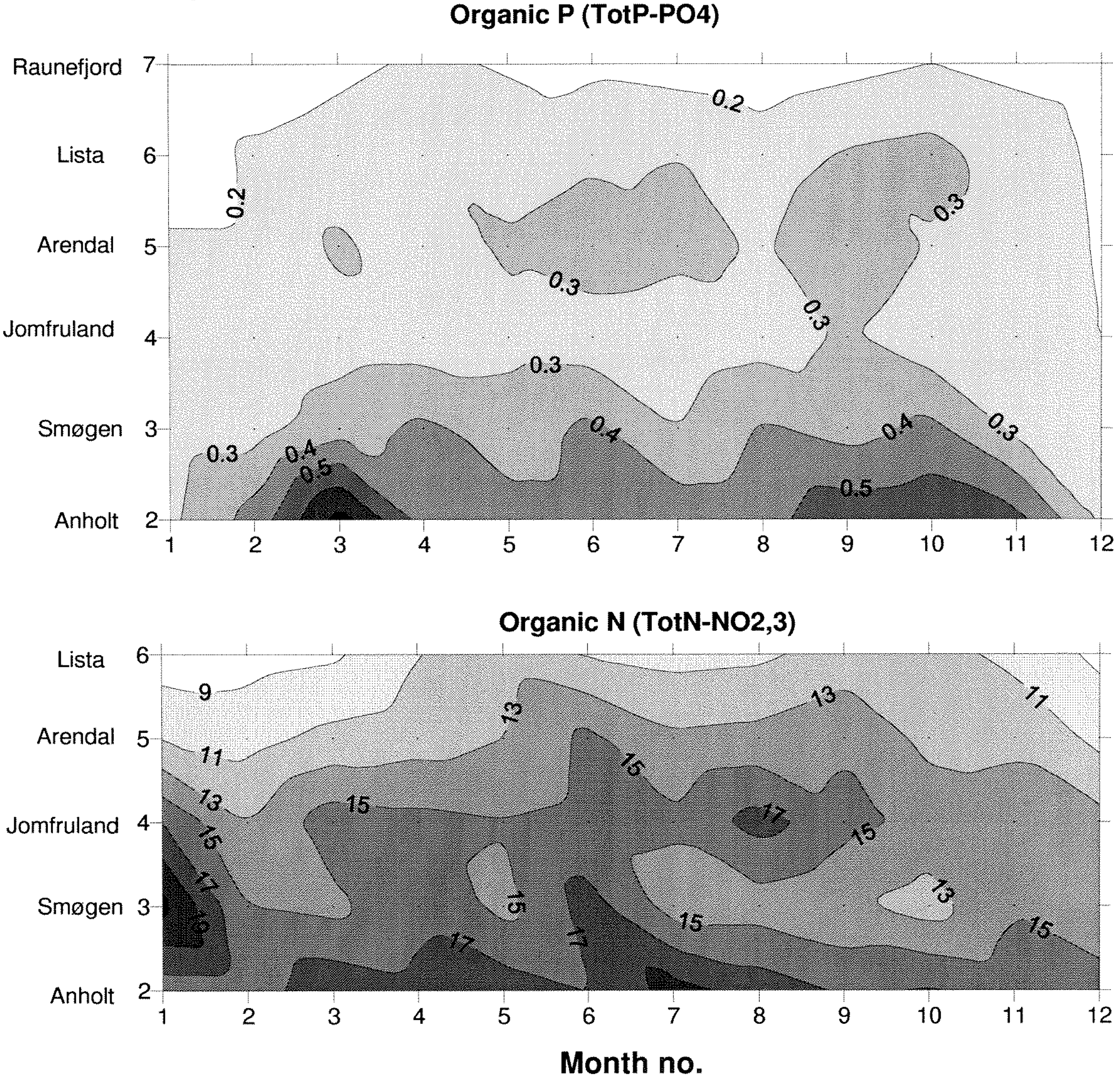


Figure 4.2. Average concentrations of organic phosphorus and organic nitrogen (μM) in 0 - 30 m depth in the coastal water from Anholt to Raunefjorden (Lista). Data for 1988 - 95.

Particulate organic carbon, nitrogen, and phosphorus (POC, PON, POP) have been measured regularly as part of the coastal monitoring programme at Jomfruland and Arendal since 1990. As means over the measurement period, the concentrations of POC, PON and POP were markedly and significantly higher at Jomfruland compared to the two stations at Arendal (Figure 4.3).

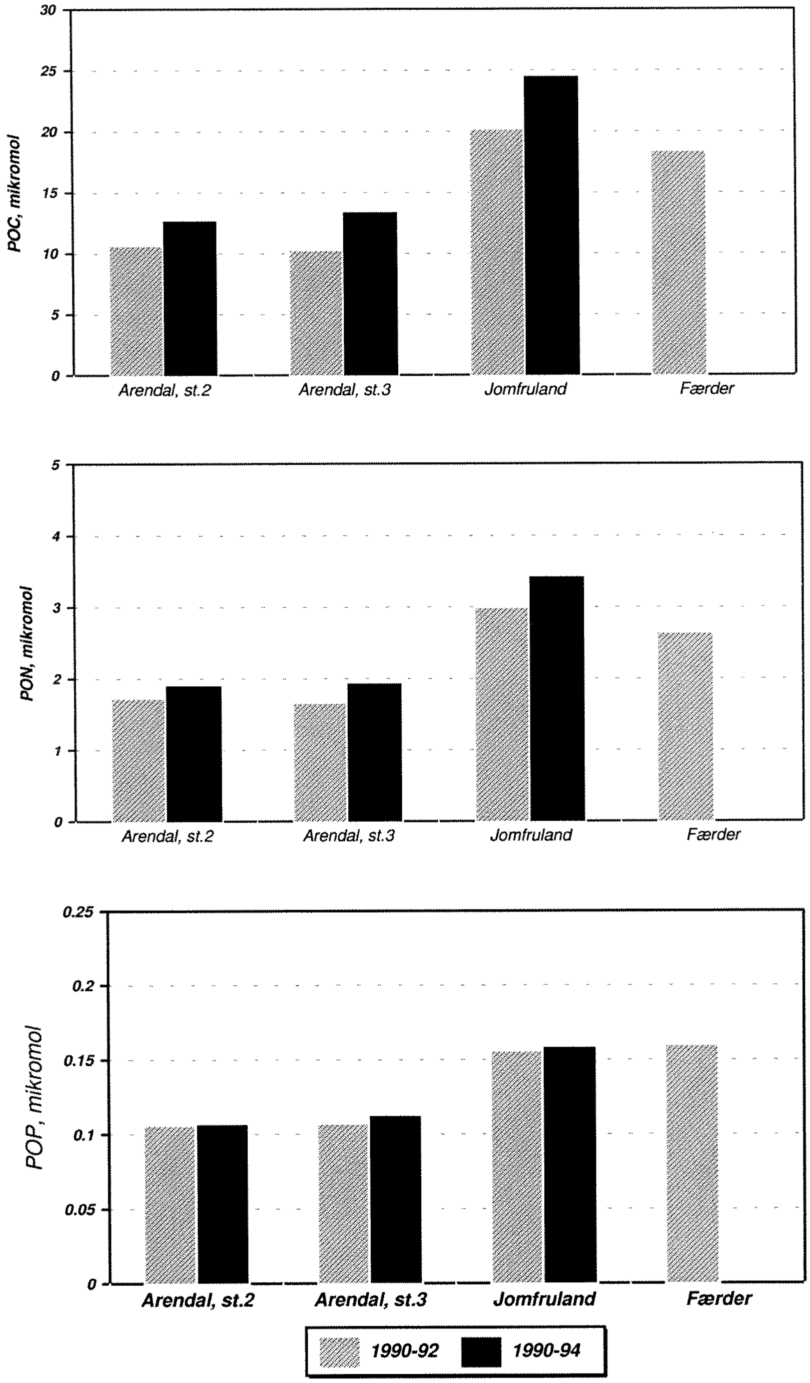


**Figure 4.3.** Average concentrations of particulate organic carbon, particulate organic nitrogen and particulate organic phosphorus in 0 - 30 m depth in the coastal water off Ferder, Jomfruland and Arendal. Data for 1990 - 92 and 1990 - 94 (Ferder only 1990 - 92).

There are no available data from the stations upstream off Hirtshals or at Anholt in the Kattegat to suggest if the higher concentrations at Jomfruland compared with Arendal are part of a more extensive gradient along the current system. The concentrations of POC at Jomfruland and Arendal have been compared with concentrations in two fjords in western Norway (Boknafjord and Lindåspollene) which receive little nutrient input, and the Inner Oslofjord and the poll Nordåsvannet in western Norway which receive considerable input of nutrients. The POC levels at Arendal were comparable to those at the non-eutrophied fjord localities, whereas the levels at Jomfruland were in the range of the more strongly eutrophied localities (ANON, 1997).

Theoretical calculations of the effect of the local input of nutrients to the Outer Oslofjord region have been done using the model "Fjordmiljø" (Aure and Stigebrandt 1990, Stigebrandt et al. 1992). The Outer Oslofjord consists of an inner, fjord-like part (inside Missingen) and an outer bay openly connected to the Skagerrak (Figure 3.10). The calculations have been done for the inner part which receives a mean freshwater discharge of about 500 $m^3/s$ and annual inputs of about 400 and 7000 tonnes per year of bioavailable phosphorus and nitrogen of anthropogenic origin. For an upper 5 m thick layer, these inputs correspond to increases in mean concentration of particulate organic carbon (POC) from an assumed natural background of 20 µM to about 38 µM based on phosphorus and 57 µM based on nitrogen. The local input of nutrients is therefore expected to have caused a doubling or more in the concentration of POC in the upper brackish water layer in the northern parts of the fjord.

The water flow through the outer part of the Outer Oslofjord is part of the general counter-clockwise circulation in Skagerrak and is about an order of magnitude higher than the water exchange between the inner and outer part of the Outer Oslofjord. The surface layer with elevated concentrations of phytoplankton and particulate organic material in the inner part will be rapidly diluted in the outer part and mixed into the westwards flowing coastal current.

### 4.1.1 Limiting nutrients and ratios

The period of nutrient limitation of phytoplankton growth occurs from about April to September, as indicated by nutrient depletion of the upper water layer. Outside this period nitrate and phosphate are generally available and the phytoplankton growth is mainly governed by light limitation. Within the period of nutrient limitation, there is a continuous supply of nutrients generated through nutrient recycling supporting regenerated primary production. This is illustrated by the relatively high concentrations of ammonium during this period (Figure 3.5). The degree to which the individual algal cells are experiencing nutrient limitation is dependent on the interaction between light limitation, grazing and nutrient recycling.

Phosphate is depleted more rapidly than nitrate in the coastal water masses in Skagerrak during the spring period (Figure 3.6). This causes a marked increase in the N/P-ratio and leaves a surplus of nitrate when inorganic phosphate is depleted from the upper layer. The increase in the N/P-ratio during spring is a recent phenomenon related to the stronger increase in nitrate than in inorganic phosphate (Figure 3.7). The consequence of the surplus nitrate and elevated N/P-ratio is that the general conditions for phytoplankton growth has been shifted from a more balanced situation, perhaps on the side of nitrogen limitation, to a situation with indicated P limitation in the late spring and early summer period.

The stronger increase in total N than in total P also resulted in an increased N/P-ratio based on total N and P during most of the year. This ratio is highest in the north-eastern Skagerrak, decreasing westwards from Jomfruland to Lista (Figure 4.4). The N/P-ratio based on total N and total P is generally considerably higher than the Redfield N/P-ratio of 16. This is also indicative of a shift towards potential P limitation due to the stronger increase in nitrogen than in phosphorus from human sources.

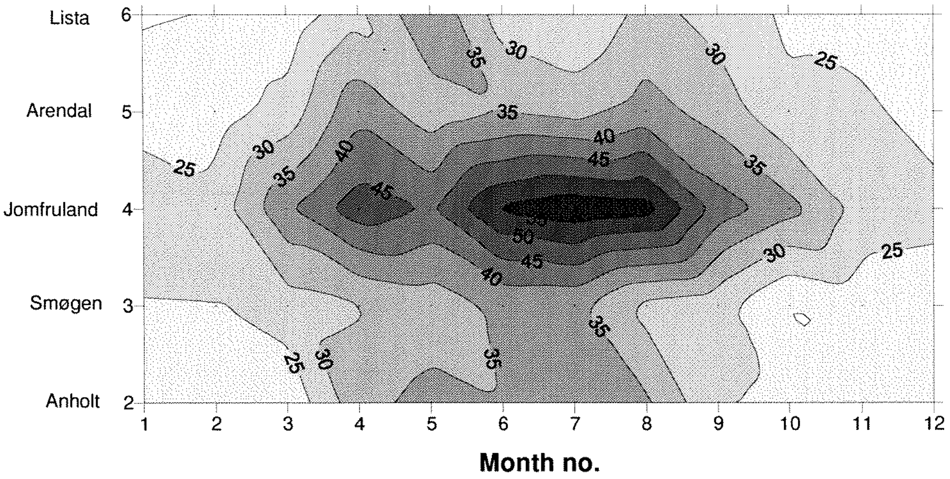


**Figure 4.4.** Average ratio between concentrations of total nitrogen and total phosphorus in 0 - 30 m depth in the coastal water from Hirtshals to Raunefjorden. Data for 1980 - 95.

The elemental composition of the suspended particulate organic material revealed decreases in the C/N, C/P and N/P-ratios during the spring bloom (Figure 4.5). This suggests potential N limitation of the spring bloom, and is therefore, contradictory to the data from the inorganic and total nutrient content. This apparent contradiction may, however, be due to changes in the relative proportions of phytoplankton and dead organic material (detritus). The decrease in the N/P- and C/P-ratios during the bloom could reflect a shift from a dominance of detritus with a low P content prior to the bloom, to dominance by phytoplankton biomass during the bloom.

## 4.1.2 Primary production

There are few measurements of primary production in the water masses in the Outer Oslofjord and along the Norwegian Skagerrak coast. We have therefore indirectly estimated primary production based on chlorophyll, nutrient budgets and through modelling.

Phytoplankton primary production has been calculated from the integrated content of chlorophyll a in the water column (0-30 m) and incoming light, using an algorithm developed by Prasad et al. (1994). The seasonal pattern of estimated primary production for 4 years is shown in Figure 4.6. The estimated production is generally low during the period of light limitation from October to February/March. The spring bloom is not clearly revealed as a peak in primary production in all years.

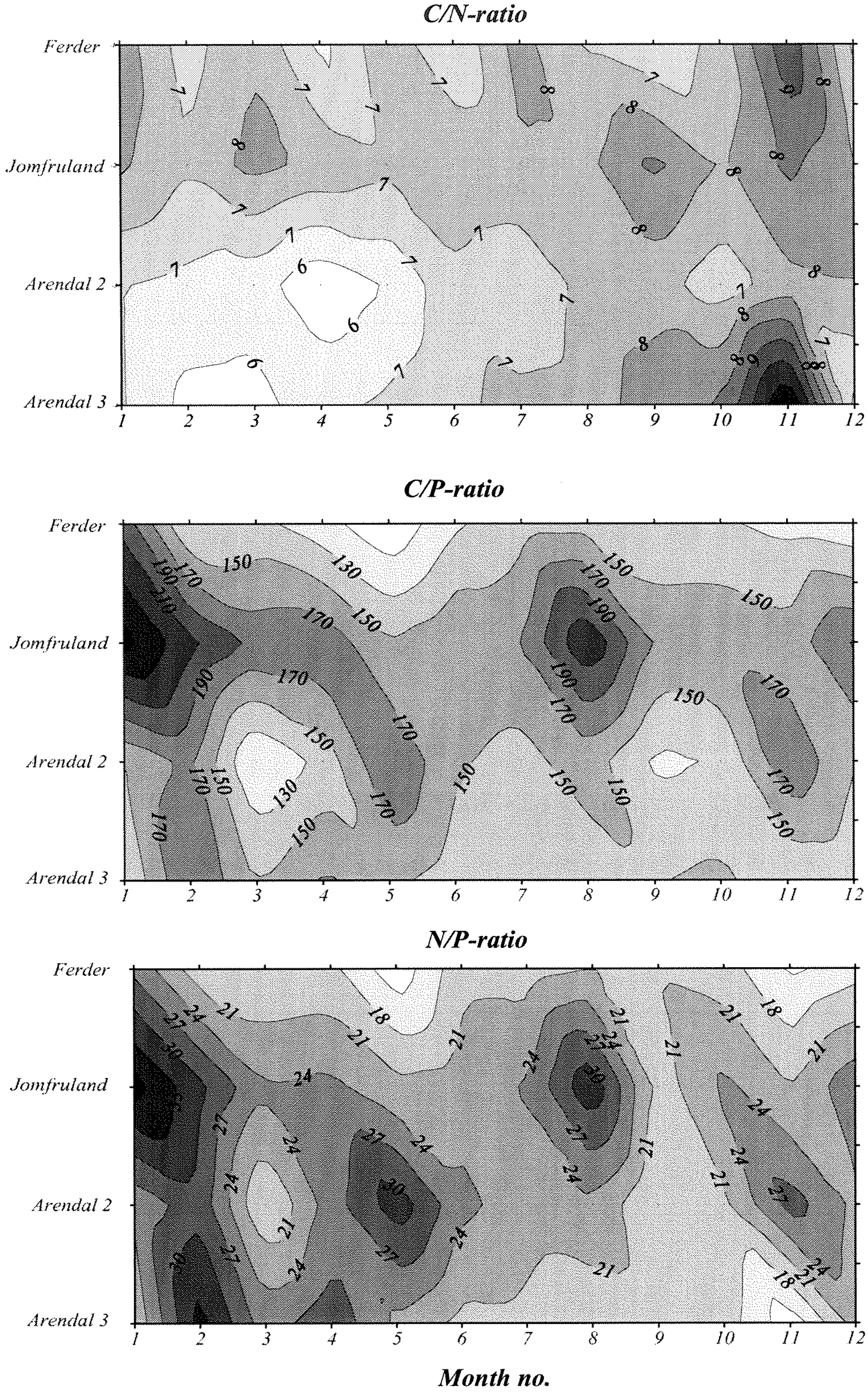


**Figure 4.5.** Average ratios between particulate carbon (C), particulate nitrogen (N) and particulate phosphorus (P) for 0 - 30 m depth in the coastal water off Ferder, Jomfruland and Arendal. Data from 1990 - 95.

Primary production estimated from chlorophyll is associated with considerably uncertainty. The method has been applied to areas for which there also exist data on direct measurements of primary production by the $C^{14}$ method. These comparisons revealed that in the Swedish Gullmarfjord, (Lindahl, 1995) and the Boknafjord in western Norway (Figure 4.7), the indirect estimates of primary production based on chlorophyll were within 15% of those measured. For the Fauskangerpoll the deviation was 35%, and even larger discrepancies were revealed for data sets from the Raunefjord in western Norway (Wassmann & Ådnesen, 1984). The indirectly estimated primary production was consistently lower than the measured production. Despite the uncertainty, the estimates suggest that the annual primary production in the water mass along the Norwegian Skagerrak coast is of the order of 100-150 g C/$m^2$.

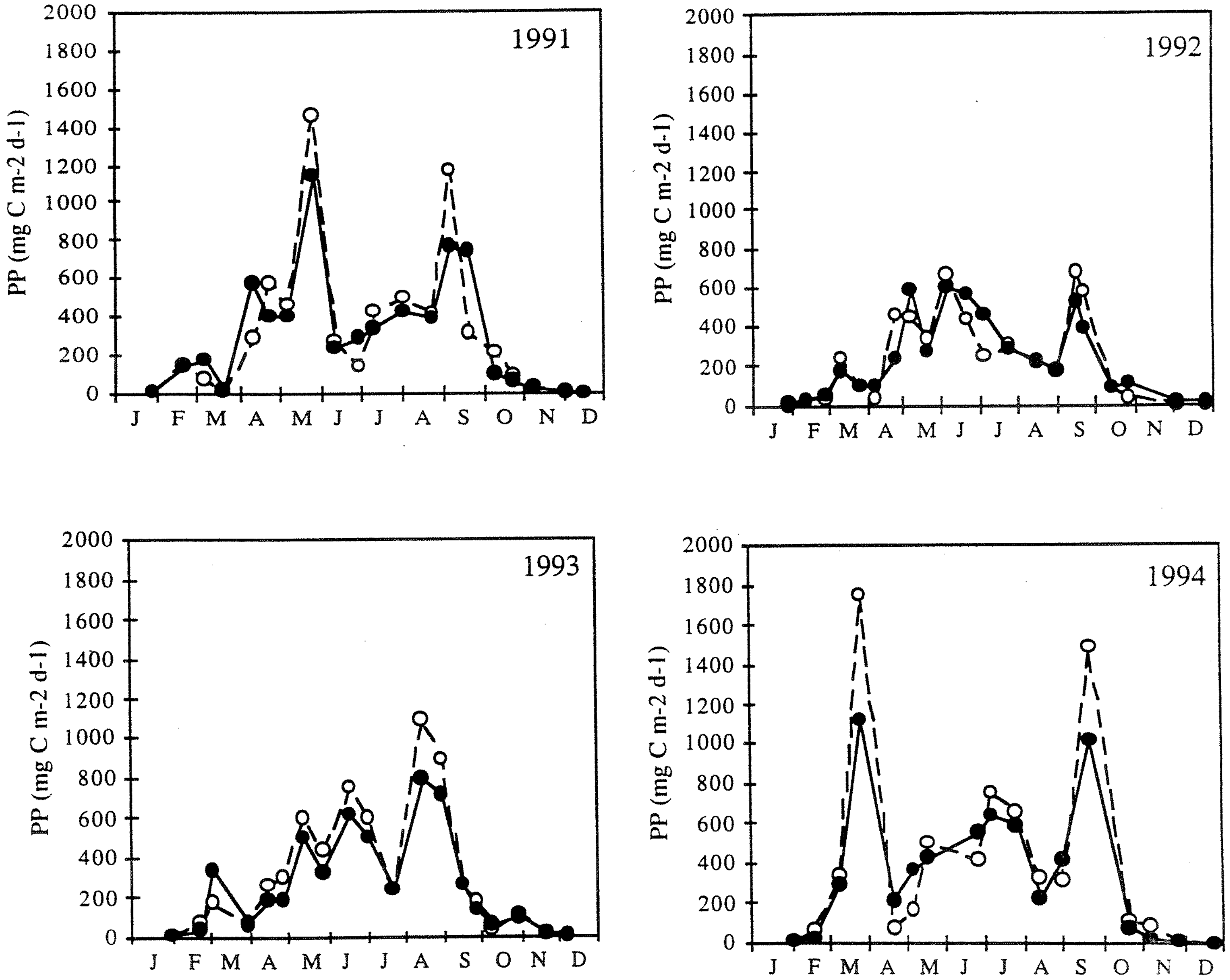


**Figure 4.6.** Calculated primary production in the coastal water off Jomfruland for 1991 - 94.

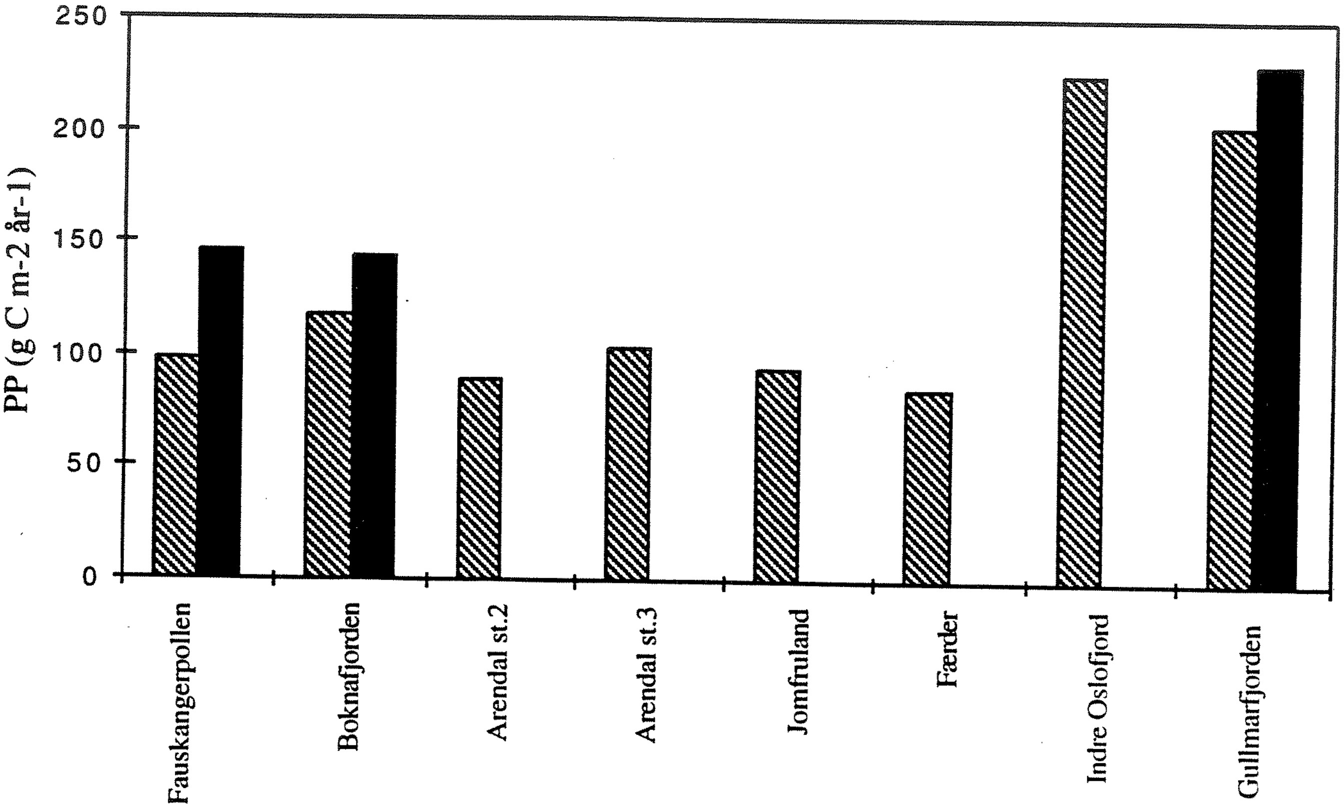
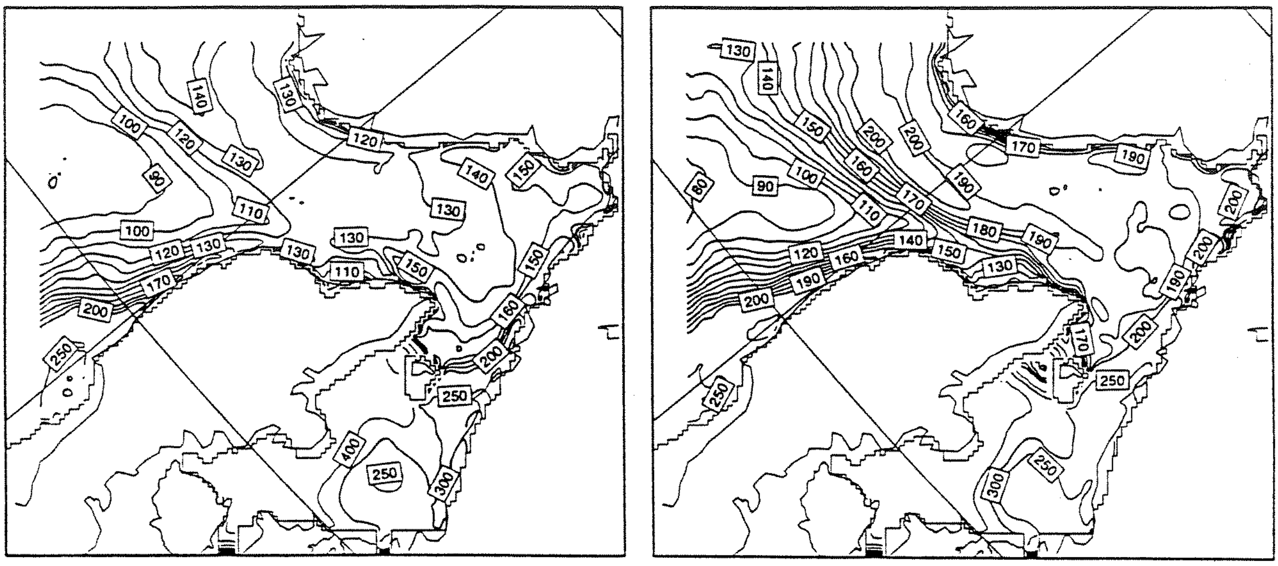


**Figure 4.7.** Measured (black) and estimated (hatched) annual primary production at locations in the coastal water and in fjords along the Norwegian and Swedish (Gullmaren) Skagerrak coast.

Phytoplankton primary production has also been estimated with a 3-D coupled physical-chemical-biological model system (NORWECOM) (Svendsen et al. 1995). The modelled total annual primary production for 1988 and 1993 are shown in Figure 4.8. These two years were chosen because of contrasting conditions of inflow of nutrient rich water from the southern North Sea into Skagerrak, with high transport in 1988 and low transport in 1993. The simulated production was lower in 1988 than in 1993, reflecting the stronger influence of nutrient rich Atlantic water in the year with reduced transport of coastal water from the southern North Sea.


TOTAL PRODUCTION (gCm⁻²year⁻¹) (1988)

TOTAL PRODUCTION (gCm⁻²year⁻¹) (1993)

**Figure 4.8.** Computed total production in Skagerrak and Kattegat in 1988 and 1993 (Svendsen et al., 1995).

The modelled annual primary production in the water mass of the NCC along Skagerrak is in the range of 100-200 g C $m^2$. This is in rough agreement with the estimates based on chlorophyll, although the model-estimates are also associated with considerable uncertainty. The spatial pattern in simulated production is, however, considered to be reliable, showing a decreasing trend in the main current direction from Kattegat and along the Norwegian Skagerrak coast.

Model simulations of scenarios with reduced anthropogenic nutrient input have been carried out to reveal effects on nutrient budgets and primary production. Reductions by 50 or 100% of the anthropogenic nutrient inputs led to reductions in the primary production by up to 30% in the coastal areas of the southern North Sea and in the Kattegat. The effect was reduced in the main current directions and was of the order of 5% or less in the Skagerrak. This effect was, however, calculated for a large area. It is possible that the model does not accurately maintain the sharp gradients in currents and in hydrographical conditions in this area, and that the effect of reduced nutrient input therefore is spread over a too large area and thereby diluted and dampened.

Removal of anthropogenic nutrient input from Norwegian sources resulted in a reduction of primary production by 10% or more in the inner part of the Outer Oslofjord. The effect rapidly diminished in the outer and more open part of the Outer Oslofjord and was not noticeable in the NCC (ANON, 1996).

Potential contributions of the Norwegian input of nutrients have also been inferred from their contributions to the nutrient budgets in the Oslofjord (Tables 3.5 and 3.6). Assuming that nutrients are used for primary production in the same proportion as they contribute to the nutrient budgets, the local input of P would contribute about 2 - 25% of the primary production in different regions of the Oslofjord. Similar estimates based on input of N indicate contributions from about 5 to 50%. The difference reflect the high N/P-ratio in the Norwegian nutrient input as is the case for most anthropogenic nutrient inputs to the North Sea. Since P is considered to be the main limiting nutrient, the real contribution is probably closest to the estimate based on P. This assumes that a surplus of N is exported unused from the Outer Oslofjord region. Locally if one considers a shallower upper layer (Table 3.6), the contribution of local inputs to primary production may be higher than indicated above.

The Norwegian nutrient input to the Oslofjord region during the 6 months from April to September would represent a production of 13 and 54 g C/m$^2$ based on P and N, respectively. This assumes that all the nutrients are utilised before the water leaves the Outer Oslofjord, and the estimates would represent new production. It is likely that all P is utilised. Some of the surplus N could also be utilised with concurrent use of recycled P. It is not known to what extent this occur, but it is suggested that the new production based on the Norwegian nutrient input to the Oslofjord region constitute about 20 g C/m$^2$ per year. The total annual primary production is suggested to be in the range 100-200 g C/m$^2$. New production is typically around 1/3 of the total annual production. The new production due to the Norwegian nutrient input would therefore constitute 10 - 20% of the total annual primary production and 30 - 60% of the new production in the Outer Oslofjord area (see map in Figure 3.10).

### 4.1.3 Water transparency

Secchi-depth reading is a measure of the water transparency. Phytoplankton, other planktonic organisms, detritus, and dissolved compounds contribute to make the water more turbid and the visibility less. A large data set on daily or near daily observations of Secchi-depth at a number of coastal stations has been assembled and assessed (Tangen et al., 1997). A common seasonal pattern is a reduction of visibility to less than 6 m during the spring bloom, followed by a post-bloom period with greater visibility. During June the visibility is frequently low, as it is during August-September when there are blooms of dinoflagellates. Generally there is large short-term variability in visibility related to shifting oceanographic conditions. There is also marked interannual variability related to different patterns of algal abundance between different years (Tangen et al., 1997).

The mean Secchi-depth readings for the growth period March-September over 6 years (1990-95) are shown in Figure 4.9 for different coastal stations. The visibility at the station in Singlefjord is low due to the influence of the river Glomma. The visibility generally increased from about 8.5 m at Torbjørnskjær in the open Outer Oslofjord westwards to Egersund and Espevær at south-western Norway where the mean visibility is close to 12 m. The visibility is again lower (8-10 m) at stations at Askøy, Svanøy and Aukra on the west coast of Norway. The lower visibility along the Skagerrak coast than at the coast of south-western Norway could reflect increased content of organic material due to eutrophication. The lower visibility on the west coast of Norway is not likely to be due to eutrophication. These stations are not located in the open coastal water but are influenced by outflowing water from fjords. Inorganic particles and humic substances from riverine inputs to the fjords as well as more concentrated plankton biomass in the upper surface layer is likely to have contributed to lower visibility.

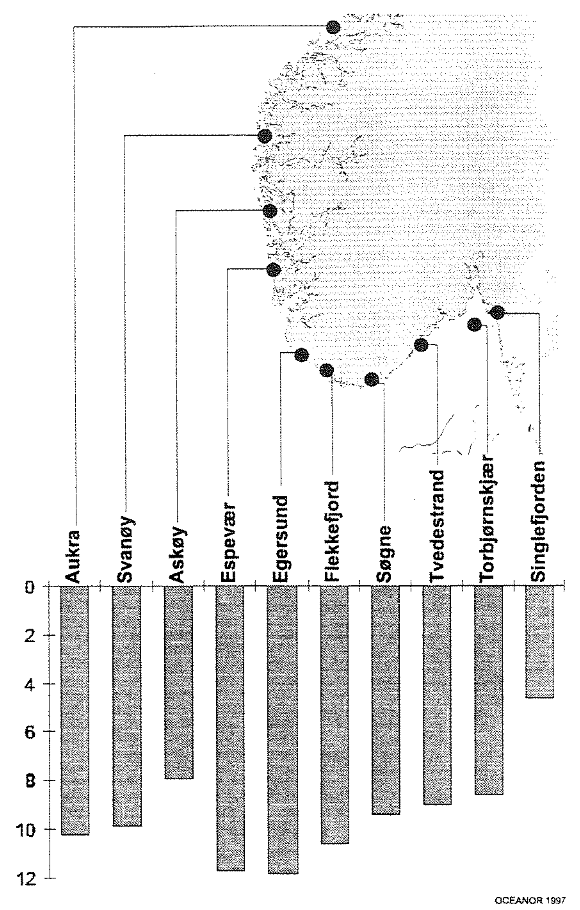


**Figure 4.9.** Average Secchi-depth on coastal stations in March - September for the period 1990 - 95.

A comparison of Secchi-depth readings at 20 stations in the Outer Oslofjord showed that the mean visibility was 0.7 m less in 1975-78 than in 1936-40 (Aas 1990). Calculations with the model "Fjordmiljø" (Stigebrandt and Aure 1990, Stigebrandt et al. 1992) based on increased input of P since 1910, indicate a reduction in water transparency of about 20% for the inner part of the Outer Oslofjord. During summer when the Secchi-depth is typically about 6 m, this corresponds to a shallowing of about 1 m in visibility.

However, visibility has also been recorded during annual investigations of sublittoral fish fauna in late September at a number of stations in the Outer Oslofjord since the 1960s by the research station at Flødevigen. This time series reveals no clear change in the Secchi depth over this period.

Indirect evidence for decreased visibility is found in the shallowing of the maximum depth of occurrence of macroalgae. Recent investigations have found the maximum depth of occurrence to be 5-10 m shallower now than during the early 1950s.

### 4.1.4 Effects on phytoplankton species composition and algal blooms

Data on phytoplankton species composition and abundance have been compiled and assessed by Tangen et al. (1997). Harmful algal species have been monitored in the coastal water mass at Arendal and at the section Torungen-Hirtshals since 1981. In the 1990s algae have been monitored at several coastal stations for the purposes of assessing risks for mussel toxicity and for the aquaculture industry. For the Outer Oslofjord region there are also data from investigations in previous years which have been used to assess the current situation (Tangen et al., 1995).

There is a general pattern in the seasonal occurrence of phytoplankton although there may be large interannual variations. The spring bloom of phytoplankton is typically dominated by diatoms. It may occur in February-March in the Oslofjord region and usually somewhat later in western Skagerrak and at the west coast of Norway. The spring bloom is commonly seen as a marked peak in chlorophyll concentration (Figure 4.1). After the spring bloom there is typically a period with little phytoplankton followed by one or more blooms of diatoms during early summer. These secondary diatom blooms are related to the maximum in river runoff at this time due to snow melt in mountain regions. During the summer period the algal biomass is generally moderate with a high diversity of species. Blooms of certain species can occur during this time. The coccolithophorid *Emiliania huxleyi* typically blooms in fjords and coastal waters in May-June.

The dinoflagellate *Prorocentrum minimum* often blooms during summer in the Outer Oslofjord. Massive blooms of dinoflagellates are a common feature in the autumn period. There has been a regional pattern of large and conspicuous algal blooms occurring in the Skagerrak over the last 20 years. From Skagerrak these blooms may be transported with the coastal current westwards and northwards to the coasts of south-western and western Norway. Lack of time series data make it difficult to ascertain how much of the apparent increase is due to increased awareness and monitoring effort. This area seems, however, to follow the general pattern of increased algal abundance and frequency of blooms associated with eutrophication of coastal waters as seen in many regions (Smayda 1989, Hallegraef 1993, Anderson 1994).

The dinoflagellate *Gyrodinium aureolum* has since its first occurrence in North-European waters in 1966, established itself as one of the most common dinoflagellates in our coastal waters in the autumn. After 1981 there have been frequent blooms of this species that has caused mortality of fish in fish farms. Many of the blooms seem to have started in open waters in Kattegat and Skagerrak and have spread with the coastal current (Figure 4.10). The highest frequency of blooms has been found in the area west of Lindesnes, but few blooms have extended north of Bergen on the west coast.

Large dinoflagellates *Ceratium* spp. have also bloomed in Skagerrak in autumn with a pattern resembling that shown by *Gyrodinium aureolum*. Time series data from the CPR program reveal that *Ceratium* spp. are common in Skagerrak and that there has been an increase in their abundance since the early 1980s in the eastern North Sea and Skagerrak (Reid et al. 1990). There has been a marked increase in *Ceratium furca* in the coastal water at Arendal during the 1990s.

The bloom of *Chrysochromulina polylepis* in May-June 1988 started in Kattegat and eastern Skagerrak and spread westwards with the coastal current before it culminated in south-western Norway. The bloom originated in water with elevated nutrient concentrations and altered nutrient ratios (high N/P- and N/Si-ratios), which made it likely that there was a connection between this bloom and eutrophication (Skjoldal and Dundas 1989). In subsequent years there have been several smaller and larger blooms of this species without any noticed toxic effects as seen in 1988.

Based on an assessment of the available data, the Oslofjord area has been divided into 7 regions with regard to phytoplankton species composition and abundance (Figure 4.11). The inner coastal areas of regions E and D are distinguished by relatively large abundance of phytoplankton throughout the growth season.

In general, occurrence and blooms of phytoplankton of both toxic and non-toxic species are determined by the combination of physical, chemical and biological environmental factors. Multifactorial explanations are therefore, usually required to explain specific bloom events. Without detailed investigations it is often difficult to link a single bloom event unequivocally to eutrophication, and is also the case for the coastal waters in Skagerrak. A particular difficulty is the increased awareness and observation frequency of harmful algae in recent years which may have contributed to the increase in reported harmful algae events. Nevertheless, there is a pattern here as in many other areas of increased reported occurrence of conspicuous bloom events often of «new» or unusual species, which indicates a relationship with eutrophication. Since the early 1980s blooms in the coastal water mass in the eastern Skagerrak or Kattegat have spread westwards and northwards with the coastal current from their area of origin. This parallels both partially and temporally the eutrophication of these waters as revealed by the increased nutrient content.

Stratified waters may be particularly sensitive to eutrophication with regard to growth of harmful algae. Most of the harmful algae species belong to groups of flagellates. These are generally favoured and dominant in stratified waters with low nutrient content and availability. In contrast diatoms are more common and dominant under conditions of stronger mixing and higher nutrient content and availability. Eutrophication of stratified water may therefore increase the occurrence of flagellates including harmful species. Enrichment with N and P but not Si would act to strengthen this trend.

The coastal water mass in Skagerrak is strongly stratified. Eutrophication would be expected to lend to unbalanced nutrient composition and an increased abundance and frequency of blooms of harmful algae even if one does not assume selective mechanisms. We therefore consider it likely that there is a connection between the observed nutrient environment and the apparent increase in occurrence of harmful species in Skagerrak.

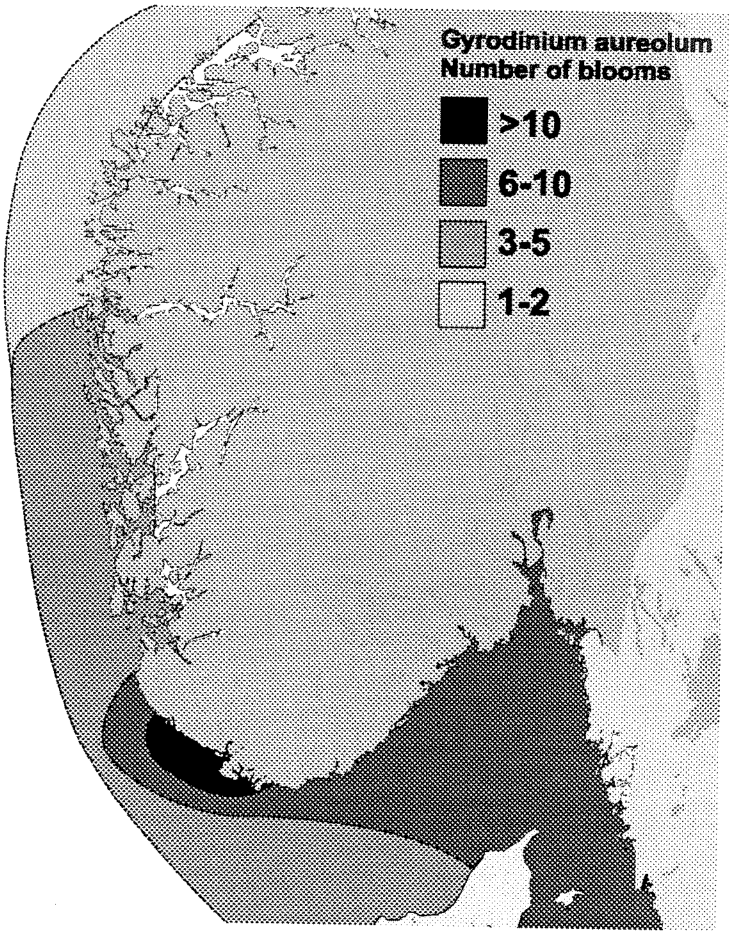


**Figure 4.10.** Geographic distribution of blooms of *Gyrodinium aureolum.*

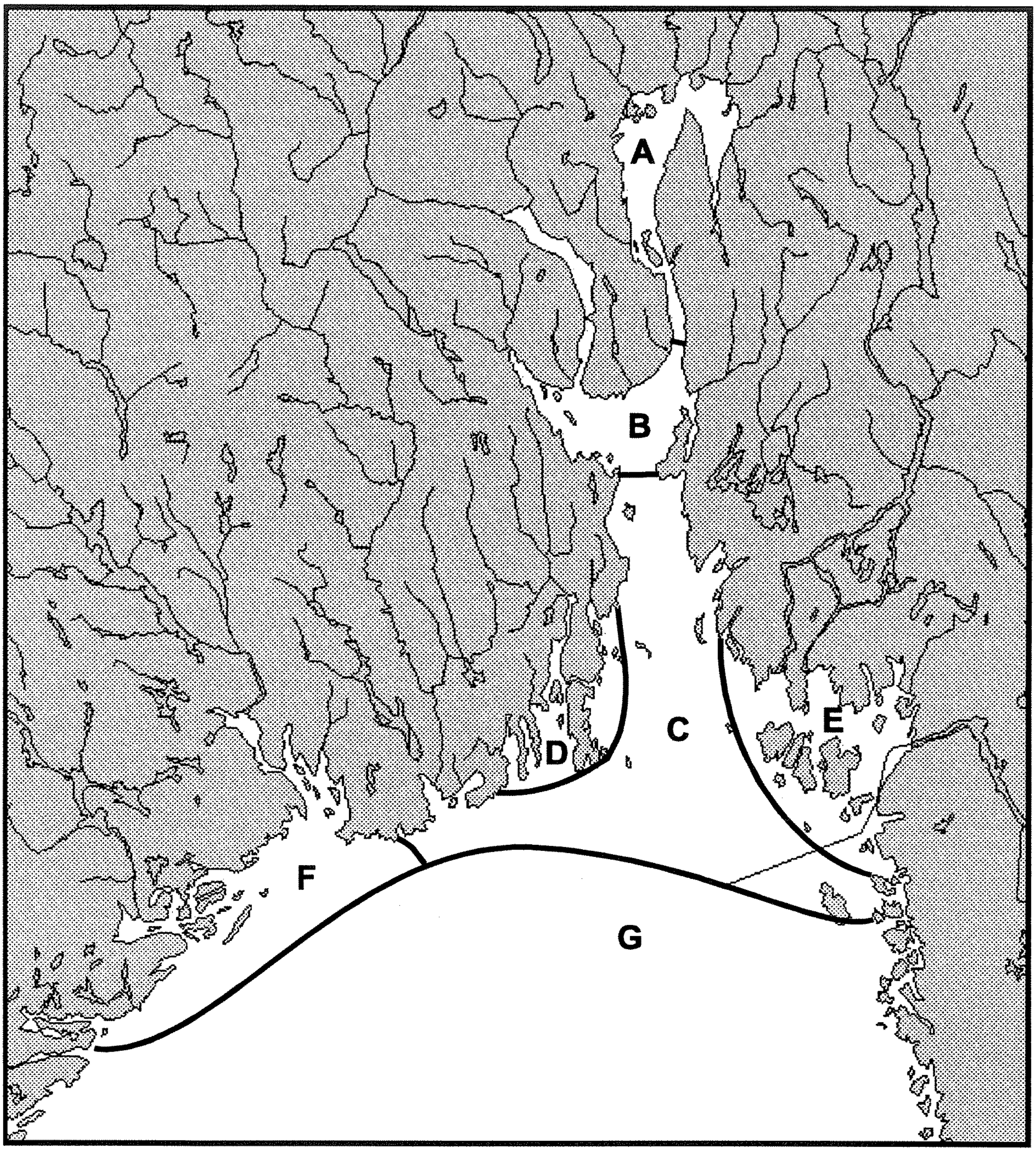


**Figure 4.11.** Oslofjord divided into areas with different growth conditions and occurrence of planktonic algae.

## 4.2 Effects on oxygen consumption and concentrations

From the general circulation in the North Sea and Skagerrak follows that the oxygen concentrations and organic load along the Norwegian North Sea coastline may be influenced by the conditions in water masses in eastern Skagerrak. The oxygen-development in the Skagerrak and Kattegat has been studied by Andersson (1996), who over the period 1971-90 found a moderate, but significant decline in the oxygen concentration for the period August-November (Table 4.1).

**Table 4.1.** Trend analysis of oxygen concentration in Skagerrak and Skagerrak coastal water. Mean values for 1971-90 ($mlO_2/l$), significance level (p-value) and slope dc/dt (extract from Andersson, 1996).

| Area | Parameter | Skagerrak water | Skagerrak coastal water |
|---|---|---|---|
| Northwest Skagerrak | O2<br>dc/dt<br>p | 5.97<br>-0.05<br><0.05 | 6.11<br>-0.01<br><0.05 |
| Eastern Skagerrak | O2<br>dc/dt<br>p | 5.92<br>-0.01<br><0.05 | 5.96<br>-0.03<br><0.005 |

For the Norwegian Skagerrak-coast most information is found in Johannesen and Dahl (1996), who analysed the oxygen trends in coastal water and fjords, based on measurements at the end of September every year since 1923. The data are thus collected in the middle of the period used for the analysis of Swedish data. The main stations in the Norwegian studies are shown in Figure 4.12. The Norwegian Coastal Monitoring Programme has provided monthly observations of oxygen at stations 998, 201 and 205 for the period 1990-94, confirming that September-data coincides with an annual minimum in the coastal water (Figure 4.13).

These studies shows a significant decline in oxygen concentrations in the coastal water along the Norwegian Skagerrak coast (Table 4.2 and Figure 4.1). This decline has been attributed to water masses with salinity less than 35 (Skagerrak water and Skagerrak coastal water), and mainly the last 20-25 years (Figure 4.14), but see Gray and Abdullah (1996) for an alternative explanation. Regression coefficients of 0.01-0.02 $mlO_2/l$/year are comparable to those found by the analysis of Swedish data, and it seems probable that this decline to a large extent is associated with an regional influence from water masses upstream of the Norwegian Skagerrak Coast. However, with regard to oxygen the average water quality is still "Very Good" (>4.5 ml $O_2/l$) according to the Norwegian marine water quality criteria (Molvær et al., 1997) and there is a margin of 0.5 - 1 ml $O_2/l$ to the next lower class ("Good"). Assuming an average yearly decline of 0.02 $mlO_2/l$, this may take 25 years with present trends of nutrient addition. However, it should be noted that there is a significant interannual variability.

Along the Norwegian North Sea coastline one finds a large number of fjords with sills. Above the sill depth these fjords have a free water exchange with the coastal water, and the organic load for the basin water thus comes from both imported organic matter from the coastal water and from local input and local primary production. In this context the coastal water represents a regional organic load.

**Table 4.2.** Trend analysis of oxygen concentration ($mlO_2/l$) for various depth on stations 4, 10, 100 and 121 for 1955 - 1995. The slope *b* for the regression line, significance *p* of *b* different from 0 (t-test) and estimated oxygen concentration in 1995 (from Aure et al., 1997).

| **Station** | **20 m** | | | **30 m** | | | **50 m** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **b** | **p** | **1995** | **b** | **p** | **1995** | **b** | **p** | **1995** |
| 4 | -0.008 | 0.325 | 5.50 | -0.006 | 0.299 | 5.35 | -0.018 | 0.002 | 4.96 |
| 10 | -0.019 | 0.008 | 5.38 | -0.008 | 0.176 | 5.43 | -0.016 | 0.006 | 5.12 |
| 100 | -0.010 | 0.147 | 5.50 | -0.008 | 0.208 | 5.37 | -0.018 | 0.007 | 5.27 |
| 121 | -0.029 | <0.001 | 5.34 | -0.026 | <0.001 | 5.22 | -0.014 | 0.041 | 5.15 |
| **Station** | **75 m** | | | **100 m** | | | **150 m** | | |
| | **b** | **p** | **1995** | **b** | **p** | **1995** | **b** | **p** | **1995** |
| 4 | -0.019 | 0.011 | 5.06 | -0.016 | 0.003 | 5.13 | -0.002 | 0.769 | 5.60 |
| 10 | -0.016 | 0.008 | 5.16 | 0.024 | 0.001 | 5.06 | | | |
| 100 | -0.011 | 0.053 | 5.22 | -0.015 | 0.011 | 5.10 | -0.015 | 0.001 | 5.35 |

Due to natural variations in water exchange, the oxygen concentrations in fjord basins will vary from one year to another. The lowest values are probably most representative for a situation with stagnant basin water, and best suited for a study of oxygen consumption and organic load. By comparing the median of the 25 percentile of oxygen concentrations in September for 8 fjord basins over the period before 1975 and the period after 1975, one find that the minimum oxygen concentrations are significantly lower for the latter period (Figure 4.15).

Based on oxygen measurements in fjord basins during stagnation periods, one may also compute the oxygen consumption and the corresponding organic load (Aure and Stigebrandt, 1989). This method takes into account the different topographic and hydrographic properties of the basins, and have been applied to a number of comparable fjord basins along the Skagerrak coast and on the West coast. Data from a previous study of 30 fjord basins north of Stad have been used for reference data. The results indicate that the organic load in fjord basin on the Norwegian Skagerrak coast is 25 - 50% higher than for corresponding basins north of Stad (Figure 4.16). For fjord basins east of Arendal, observations furthermore show a 50% increase in oxygen consumption during the 1970-ies (Aure et al., 1997).

The overall picture is a of an organic load decreasing from the Outer Oslofjord towards the south-east, mainly due to a regional eutrophication in the coastal water and to a lesser extent from local loads to some fjord basins.

In the Outer Oslofjord a decline in oxygen saturation over the last 25 years is found, most pronounced between 30 - 50 m depth (Table 4.3). This corresponds to the general decline in the coastal water which has been discussed above. For the main basin water of the Outer Oslofjord estimates of oxygen consumption indicates an organic load of 6 g $C/m^2$/month, which is about twice the load for a similar fjord basin on the west coast. The highest load is found in the southern basin. The typical residence time for the brackish layer in the Outer Oslofjord is in the order of one week, which indicates that the main part of the organic load from local primary production is flushed out of the system before it reaches the basin water. Apart from periods with exceptionally long residence time, rapid settling of aggregated marine organic material or flood in the local rivers, it is reasonable to assume that an organic load of regional origin dominates the oxygen consumption in the basins of the Outer Oslofjord.

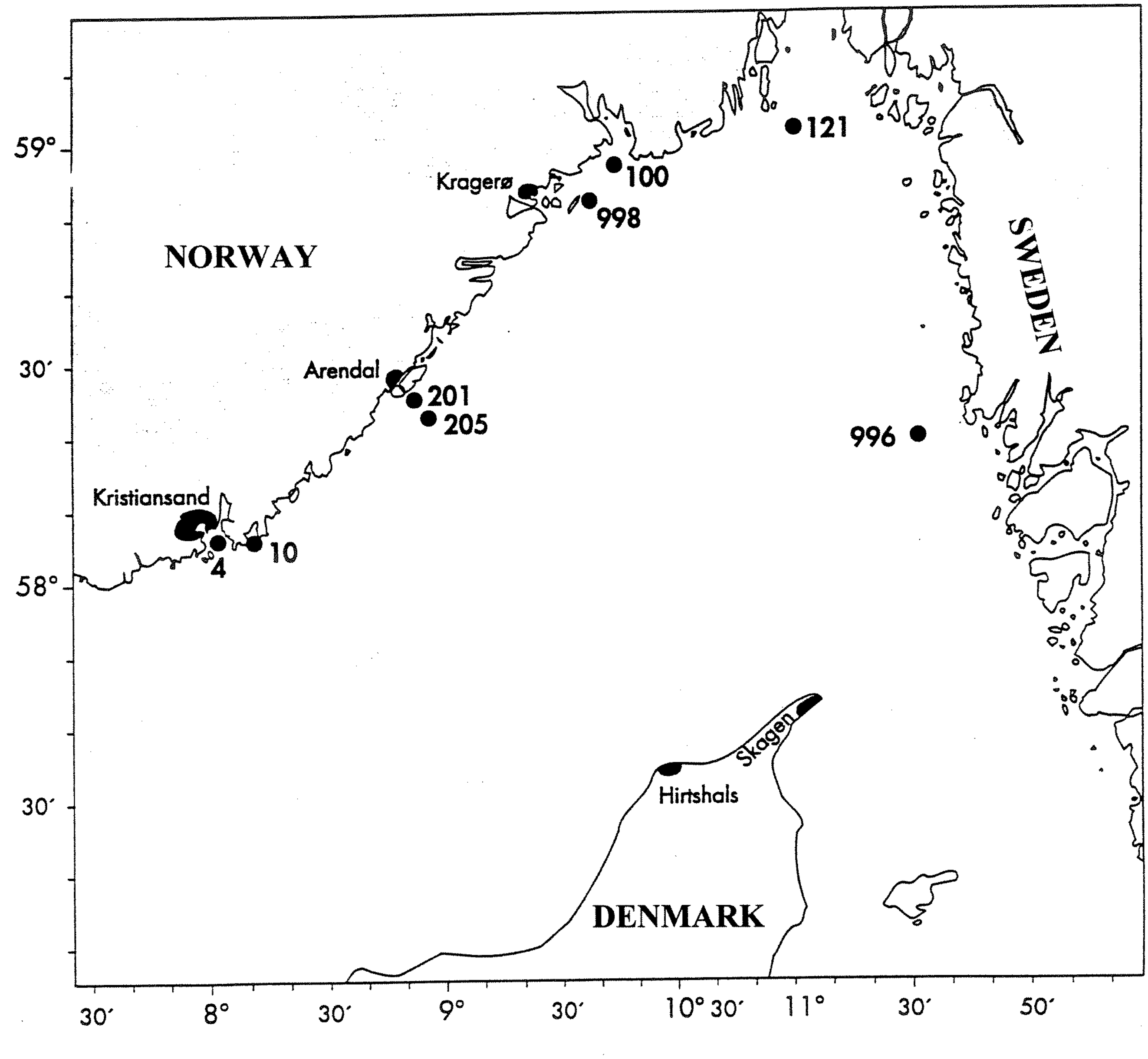


Figure 4.12. Open coastal stations.

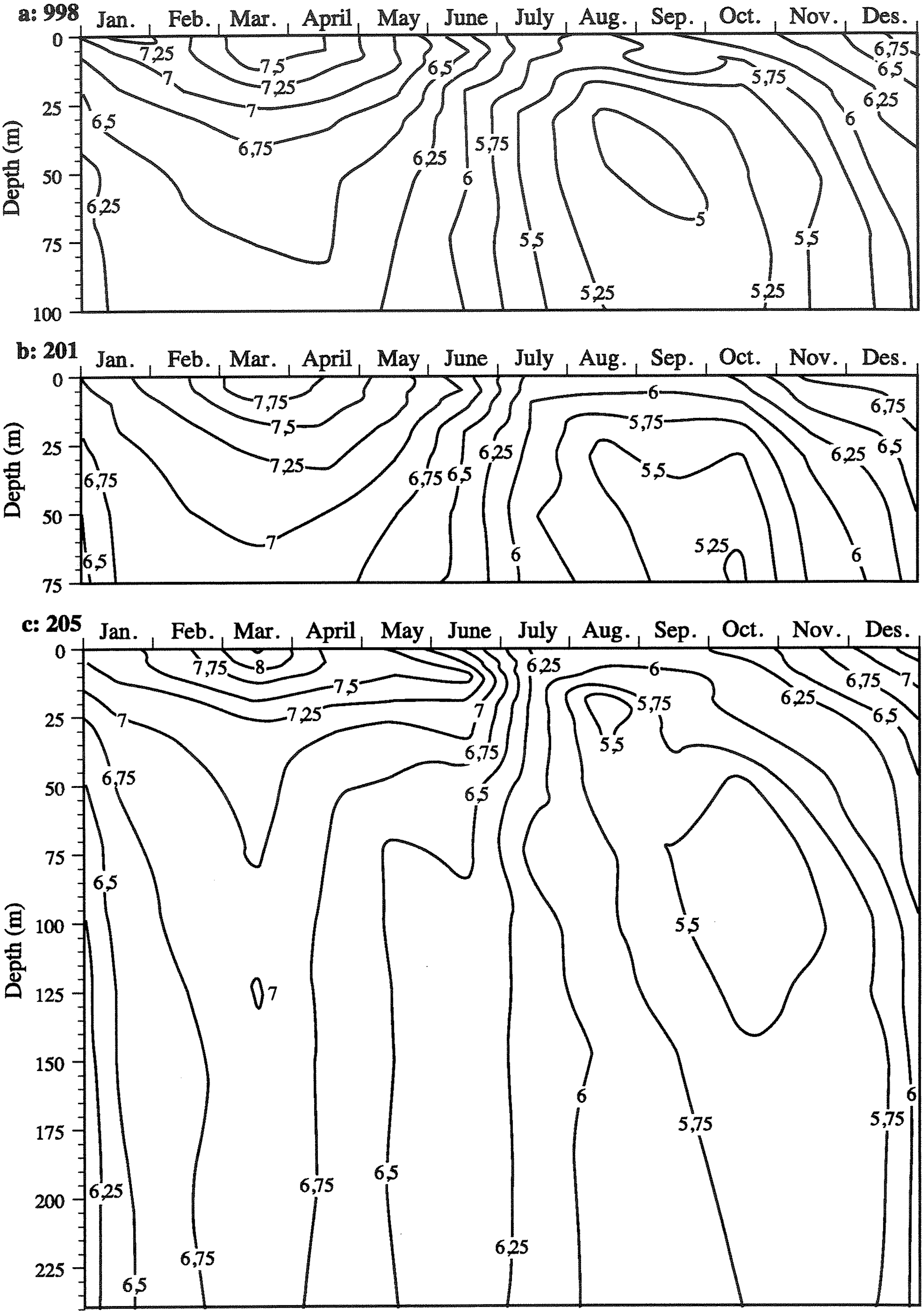


**Figure 4.13.** Average (1990-94) oxygen conditions ($mlO_2/l$) in the coastal water off Jomfruland and Torungen, based on fortnightly measurements. a: station 998, Jomfruland. b: station 201, Torungen Inner. c: station 205: Torungen Outer.

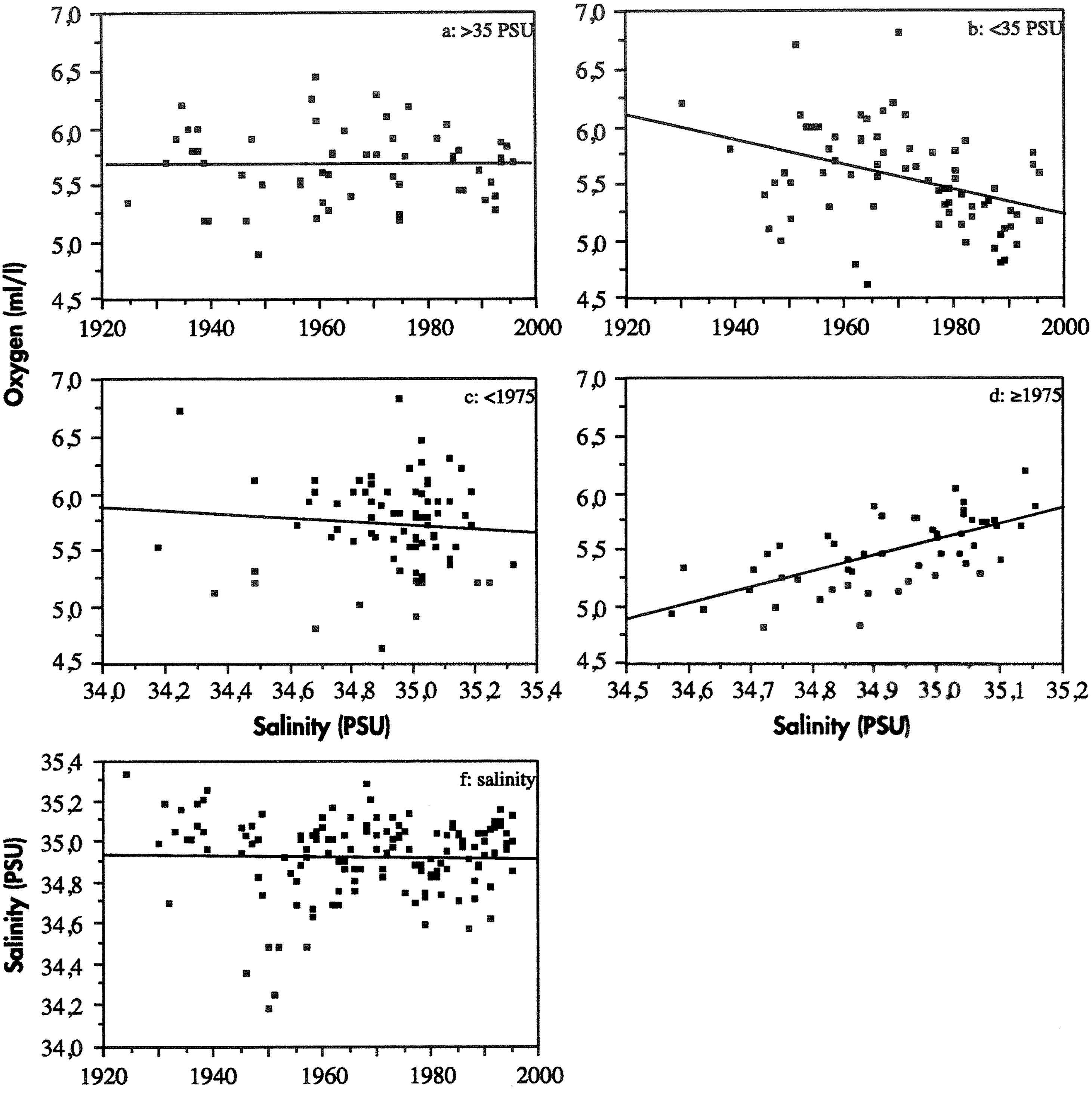


**Figure 4.14.** Oxygen relations in 150 m depth for stations 4, 10, 100 and 121 on the Skagerrak-coast. a) and b) show oxygen development in Atlantic water (salinity >35) and water with salinity <35. c) and d) show relations between salinity and oxygen concentration for period before 1975 and for 1975-95. f) shows salinity in 150 m depth.

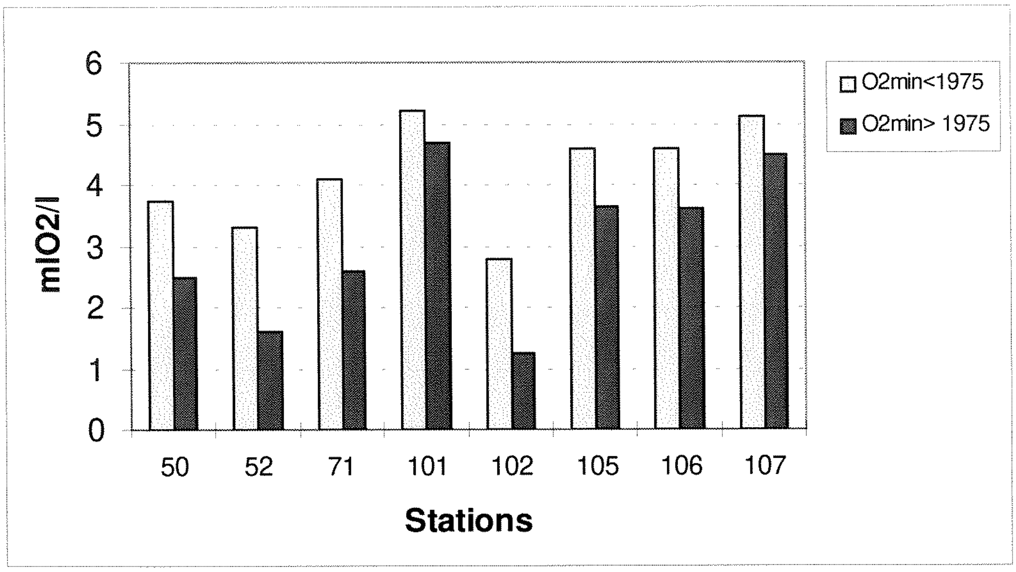


**Figure 4.15.** Calculated oxygen minimum before and after 1975, as the median of the lowest 25% of oxygen concentrations in the basin water in 8 fjords on the Norwegian Skagerrak coast. The oxygen minimum is significantly lower after 1975 (from Aure et al. 1997).

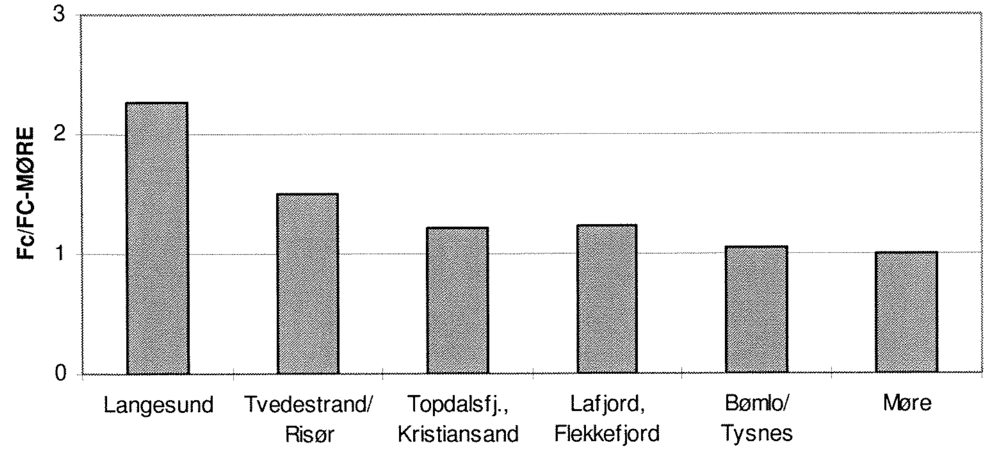


**Figure 4.16.** The ratio between the organic load ($F_c$) for fjord basins on the Skagerrak coast and the west coast (Langesund - Bømlo) and the organic load for fjord basins north of Stad ($F_{c\text{-Møre}}$). There is a gradient with decreasing load from east towards west (from Aure et al. 1997).

**Table 4.3.** Reduction of oxygen saturation (%) in 30 - 150 m depth in the Outer Oslofjord from 1970 to 1995. Average of four stations (from ANON 1996).

| Depth (m) | 1970 | 1995 | Reduction |
|---|---|---|---|
| 30 | 89.9 | 83.5 | 6.4 |
| 50 | 88.9 | 81.8 | 7.1 |
| 75 | 84.2 | 80.3 | 3.9 |
| 100 | 82.6 | 77.3 | 5.3 |
| 150 | 81.9 | 79.4 | 2.5 |
| | | **Average** | 5.0 |

## 4.3 Benthic community structure

The mobility of most benthic organisms is low and many species have long life-spans, so that benthic animals and algae accumulate information on the environment for many years. However, to separate weak or moderate effects on community structure and species composition caused by eutrophication from natural changes are often notoriously difficult. This difficulty is usually caused by the lack of good reference data, either such data sets are completely lacking or they are just merely qualitative. The expected effects on both soft and on hard bottom communities are reduced number of species and a shift towards more opportunistic groups that are able to utilize more effectively the increased amount nutrients during an eutrophication episode.

One should also be aware of the fact that the investigated area is characterized by large differences in hydrographical conditions, like tidal range and temperature and salinity fluctuations, details are found in this report. These are all factors that will influence the living biota, specially those plants and animals that lives on shallow depths (down to 50 m). This might be exemplified by the fact that many species of macroalgae do not grow into the Skagerrak area, but have their eastern limit around Lindesnes - Mandal in the southwest.

The Norwegian Coastal Monitoring Program (Pedersen et al., 1995) is the main data source on hard- and softbottom communities from the Outer Oslofjord to Bergen. In addition there are data from a number of local studies of environmental problems in fjords and coastal areas. The Norwegian west coast is also covered by a number of studies by the University of Bergen. Moy et al. (1996) have aggregated and evaluated these datasets (Figure 4.17).

The macroalgal vegetation in the littoral zone do not show any clear indications on effects from eutrophication neither for the Skagerrak coast nor the west coast. Number of species registered per station and the percentage of the three major algal groups, red algae, brown algae and green algae are the same in both the Skagerrak area and in western Norway (Table 4.4).

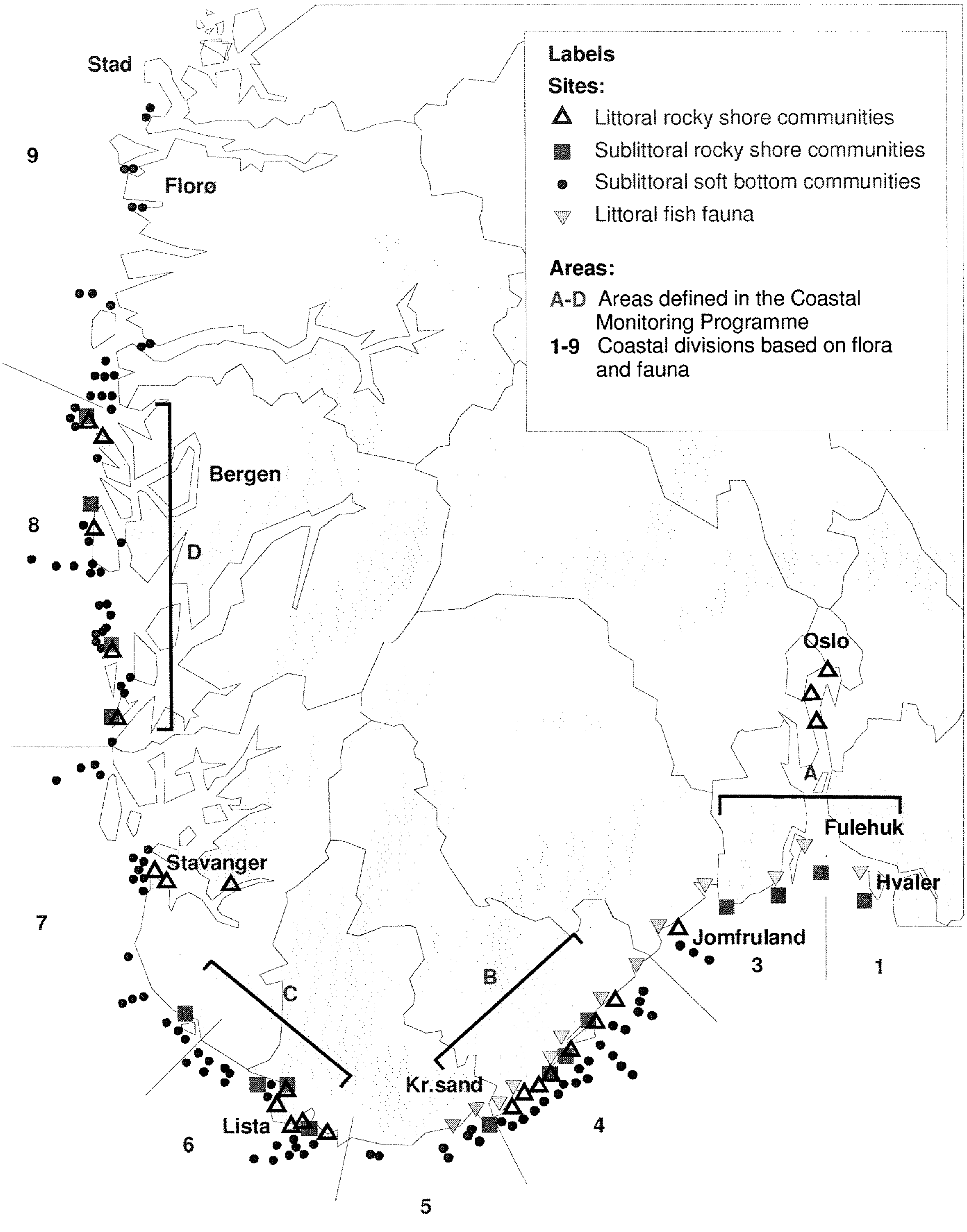


**Figure 4.17.** Benthic stations for studies of littoral and sublittoral rocky shore communities, sublittoral soft bottom fauna and littoral fish fauna. Areas A - D are the main areas in the Norwegian Coastal Monitoring Program (after ANON 1997).

**Table 4.4.** Total number of species in the different regions (Figure 4.16) through studies of semi-exposed and protected stations in the littoral zone during 1991-95 (from Moy et al., 1996).

| | **Regions 7-8** | | **Region 6** | | **Region 4** | |
|---|---|---|---|---|---|---|
| Number of stations | 4 | | 11 | | 8 | |
| Number of observations | 15 | | 17 | | 20 | |
| | No. of species | % | No. of species | % | No. of species | % |
| Red algae | 24 | 48 | 37 | 54 | 35 | 46 |
| Brown algae | 19 | 38 | 21 | 31 | 26 | 34 |
| Green algae | 7 | 14 | 10 | 15 | 15 | 20 |
| Sum algae | 50 | 100 | 68 | 100 | 76 | 100 |
| Animals | 37 | | 35 | | 37 | |
| SUM species | 87 | | 103 | | 113 | |

Studies of the sublittoral macroalgae has been included in the NCMP on the Skagerrak coast since 1990, but the series is too short to allow conclusions whether there have been any changes during this period. It is not possible to see any differences between the number of species in the Outer Oslofjord area and on the west coast. Neither could any differences in the percentage distribution between red, brown and green algae be spotted (Figure 4.18).

Comparisons with quantitative data from studies performed 100 years ago on stations near the mouth of Sognefjord at the west coast of Norway showed no significant change in the species composition. This indicates that there has not been any change in the water quality in that particular area during this period. However, lack of similar qualitative, and quantitative data from the Skagerrak coast significantly weakens the basis for the conclusions regarding this area.

However, in the Outer Oslofjord several investigations have shown that the depth penetration of benthic algae is reduced by 5-10 m from 1953 to 1989 due to increased turbidity from increased phytoplankton biomass and possibly increased flux of particles in the freshwater runoff (Figure 4.19). For some species of red algae NCMP has found a shallower maximum depth for growth on the Skagerrak coast east of Arendal, compared to the coastline further to the west. This corresponds to an increase in Secchi-depth from east to west along the Norwegian Skagerrak coast, and may be attributed to an increase in concentration of suspended particles due to a regional eutrophication (Figure 4.9).

Multivariate analysis of species composition and abundance in hardbottom fauna from Outer Oslofjord to Hordaland on the west coast have shown some differences in community structure, but it has not been possible to determine to what extent these are caused by differences in natural environmental factors or caused by eutrophication.

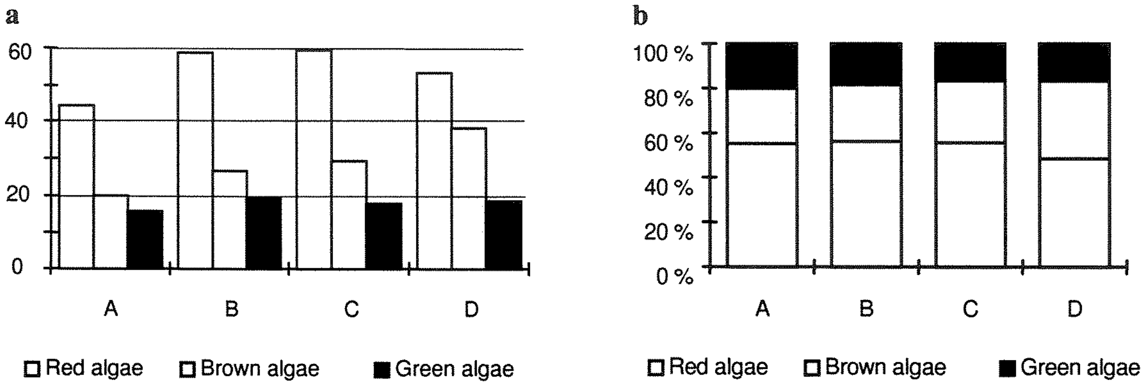


**Figure 4.18.** **a)** Average number of taxa of red-, brown- and green algae in area A, B, C and D, based on 4 stations in each area. **b)** Percentage proportions of average number of taxa of red-, brown- and green algae in area A, B, C and D.

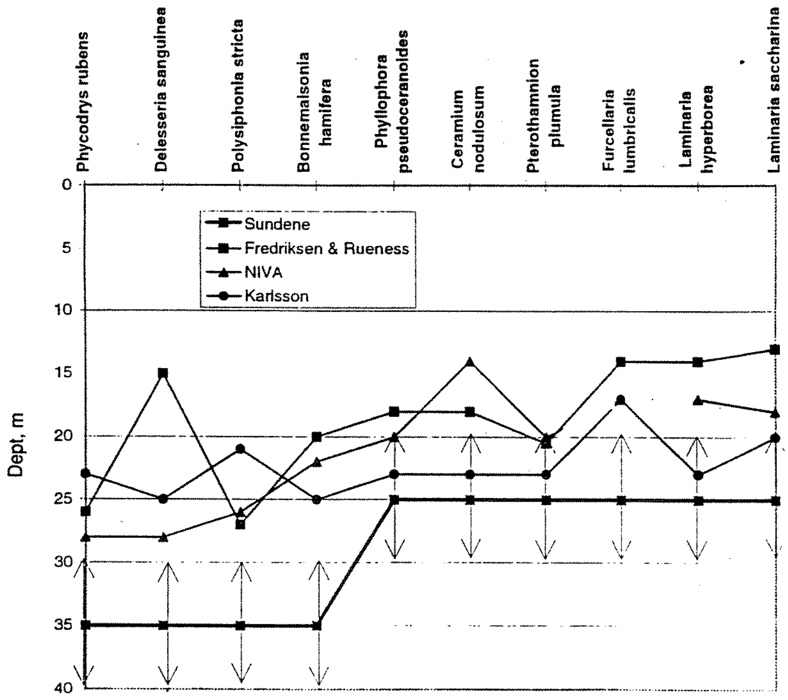


**Figure 4.19.** Lower depth for growth of benthic macroalgae in Outer Oslofjord. The observations of Sundene (1953) are shown with a variation of ±5 meters (After ANON 1996).

Quantitative studies of softbottom fauna at about 150 sites (cf. Figure 4.17) along the outer coast performed in the period 1973 to 1996 show in general high diversity, but also a significant increase in diversity from Outer Oslofjord to the southern part of the west-coast (Figure 4.20), with no change or possibly a minor decrease in diversity in areas farther north on the west coast (Figure 4.21). The increase in diversity seems mainly to be reflected in the deeper stations. Total individual densities of soft bottom fauna did not show any clear geographical trends.

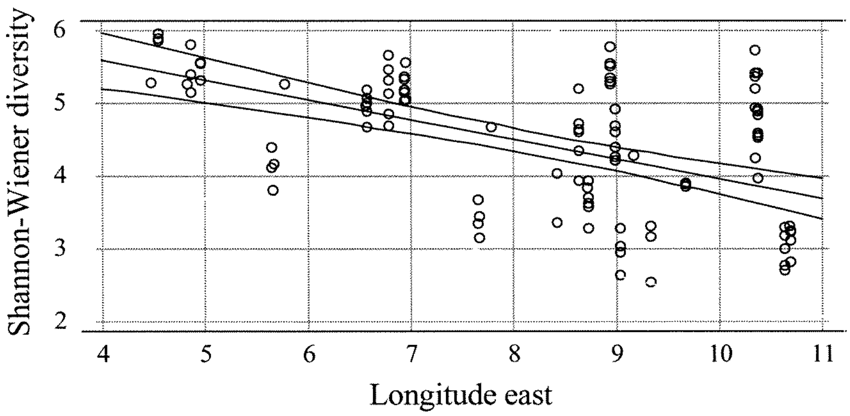


Figure 4.20. Change in Shannon-Wiener diversity with longitude among the soft bottom stations of the NCMP Program 1990-1995.

Studies of three dominating species of polychaetes in the NCMP Program in 1994 showed a decrease in average individual biomass and higher density along an east-to-west gradient. This indicates higher supply of organic material to the sediments in the Outer Oslofjord compared to areas further west.

In summary the softbottom macrofauna along the Skagerrak and the west coast shows the following trends:

- increasing species diversity in from east to west
- changed species composition from east to west for stations in deep areas
- decreasing individual biomass from east to west for three of the most common species of polychaetes.

These trends may be indications of an gradually increasing degree of eutrophication from west towards the east, but on basis of the available data on cannot distinguish between effects from a natural geographical change in the environment or from more recent anthropogenic nutrient load.

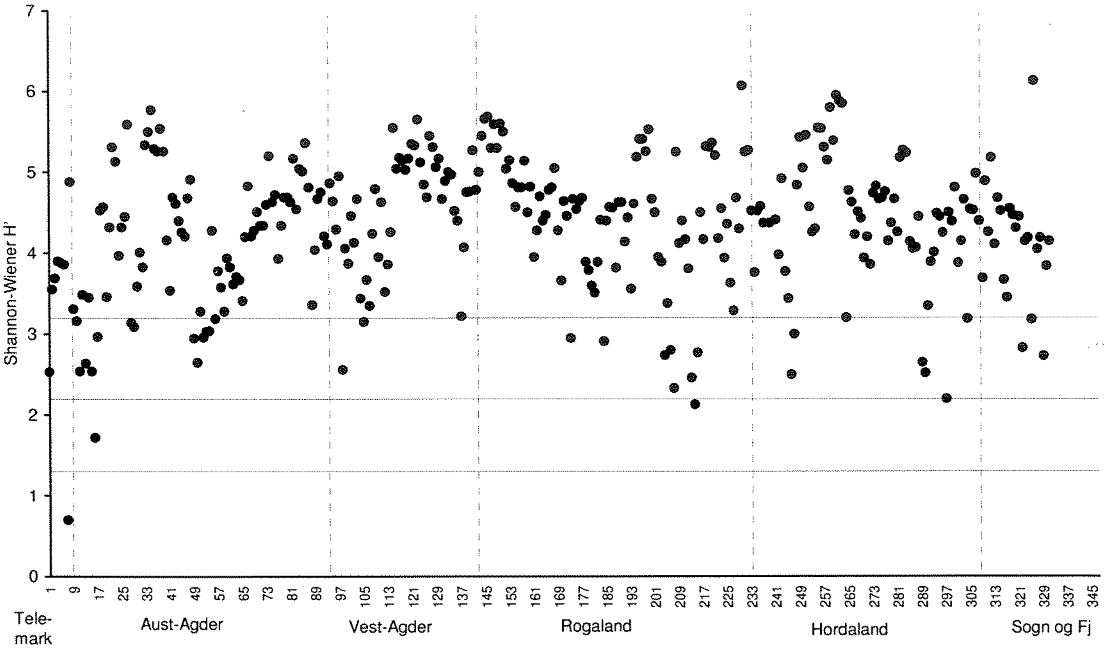


**Figure 4.21.** Shannon-Wiener diversity of 347 stations arranged along the coast from Jomfruland to Stad. Points indicate either individual geographical sites or the same site sampled several times. Total number of sites are 151. Sampling period 1973-1996.

A comparison of data for the foraminiferal fauna from 1937, 1949/51 and 1992/93 in the deep Skagerrak basin has shown changes in species composition and an increasing density of an opportunistic species (Alve and Murray, 1997). Taking analysis of vertical sediment cores into consideration, the authors conclude that the results indicate a change in sedimentation pattern in the deep areas in Skagerrak after approx. 1970, and that this change at least in part implies an increased sedimentation of particulate organic matter.

In Outer Oslofjord a comparison of data from studies of softbottom fauna in 1915 and 1985 shows an increase in biomass (Rosenberg et al. 1987). However, the composition of the softbottom fauna in this area is primarily determined by depth and later studies further show that annual fluctuations in biomass are large enough to explain the observed increase.

The overall picture from studies of the benthic communities is that there are no indications of eutrophication from the coastal stations on the west coast. For the Norwegian Skagerrak coast significant eutrophication effects are improbable, but the results indicate an east-to-west quantitative and/or qualitative gradient in sedimentation, as well as an increased input of organic material since about 1970 to the deeper soft bottoms.

## 4.4 Fish

Since 1919 the Institute of Marine Research, division Flødevigen, has conducted annual beach seine surveys at fixed stations along the Norwegian Skagerrak from Outer Oslofjord to Kristiansand, except for the years 1940 - 1944. The samples include fish and invertebrates inhabiting the littoral and upper sublittoral zone (depth < 15 m). These coastal populations consists of local stocks with a low age of maturity and a short life span. This data has been reported by Johannessen & Sollie (1994) and later by other authors (see below). The catches of 0-group cod, pollack and whiting show large variations both for the whole coastline and for the separate stations, with general decreasing abundance from the mid 70-ies (Figure 4.22). This decrease seems to be strongest in the western part of the Skagerrak coast.

Stenseth et al (1997) have recently analysed the data on Skagerrak populations of 'O' and '1' group Atlantic cod (*Gadus morhua* L.). A model has been derived which shows a 2-2.5 year cycle and illustrates how both regulatory (density-dependent) and disruptive (stochastic) forces are crucial in shaping the dynamics of the coastal cod populations. Such a cycle has also been documented by Fromentin *et al.* (1997a) for pollack (*Pollachius pollachius* L.) and whiting (*Merlangius merlangus).*

Recruitment of fish is generally characterised by large variations over time, and with possible exception for 2 - 3 fjords with a marked pollution load it is at present not possible to see any clear connections between the variations for 0-group abundance and eutrophication. It is likely that most of the trends observed in the Skagerrak cod are due to extrinsic factors, such as fluctuations in the sea grass coverage or human exploitation (Fromentin *et al.* 1997b).

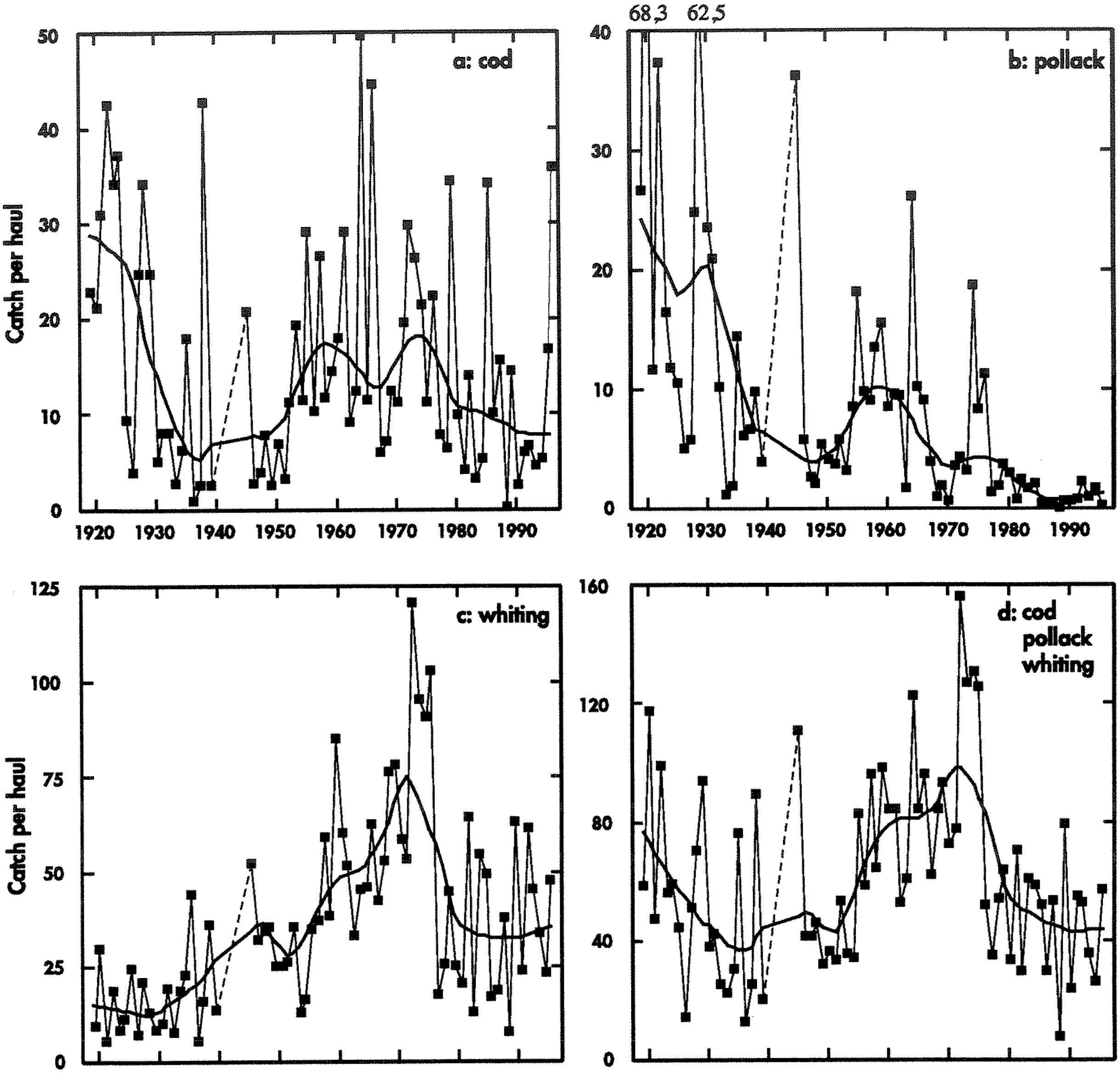


Figure 4.22. Average catch of 0-group of cod, pollack and whiting on the coast of Skagerrak on 37 beach seine stations, smoothed by LOWESS (after Johannessen and Sollie, 1994).

# 5. Overall assessment of the Norwegian North Sea coastal water

The available information on hydrodynamic conditions, local and transboundary nutrient load, degree nutrient enrichment and effects of the nutrient enrichment on phytoplankton, oxygen conditions and benthic communities, has been used as a basis for the following overall assessment of nutrients and eutrophication of the Norwegian North Sea coastal waters. The assessment covers mainly the open coastal waters and to some extent also skerries and open fjords.

It seems appropriate to distinguish between the Outer Oslofjord, the Norwegian Skagerrak coast from the Outer Oslofjord to Lindesnes and the coastline from Lindesnes to Stad (the west coast).

## 5.1 Outer Oslofjord

In the Outer Oslofjord there are weak to moderate eutrophication effects from nutrient sources outside the fjord area, and from the local nutrient load. The former load is part of an regional eutrophication of the coastal water of the eastern part of the Skagerrak, which to a large extent is caused by large inputs of nutrients to the coastal water in the southern parts of the North Sea, and to the Kattegat. In the Outer Oslofjord these regional effect in the main water body is indicated by:

- high concentrations of nutrients, with high concentrations of nitrate and high N/P-ratios in spring and early summer.
- reduced oxygen concentrations in the fjord intermediate water in autumn.
- high organic load and high oxygen consumption in the basin water of the Outer Oslofjord.
- higher individual biomass and lower species diversity in bottom fauna in the deep parts of the Outer Oslofjord compared to areas further west on the Norwegian Skagerrak coast.

The observed or calculated effects from the Norwegian nutrient load on the Outer Oslofjord are found both in the main water body and in the local, inshore areas:

- significant contributions to the nutrient budgets for the upper layer in the northern parts of the Outer Oslofjord and inshore areas in the eastern and western part of the fjord.
- stimulated primary productions and increased phytoplankton biomass in the brackish layer.
- an increase of planktonic algae, especially for the northern parts of the Outer Oslofjord and inshore areas in the eastern and western part of the fjord.
- reduced transparency of the brackish layer.

The effects from the local and the regional nutrient load have altered the planktonic biomass, led to reduced transparency in the brackish layer and reduced the lower depth for growth of macroalgae. Increased planktonic biomass and reduced transparency in the upper layer may change the species composition of both littoral and sublittoral flora and fauna. However, beyond a 5-10 m reduction in lower depth for growth of macro-algae since 1953, obvious changes have not been documented.

There are indications of increased organic load and oxygen consumption both in the intermediate and the bottom layer. We consider this to be a mainly regional effect, combined with a lesser effect from the local nutrient load. As the Outer Oslofjord is an open and deep fjord with high water exchange and with a corresponding high tolerance for organic load, critical oxygen conditions in the basin water has not been observed up to 1995. However, taking interannual variability into account, generally reduced oxygen concentrations will increase the risk for periods with serious oxygen problems. The fjord basins along the east and west coast of the Outer Oslofjord depend on the water exchange with the main water body for oxygen supply, and this negative trend will also reduce their capacity to tolerate local loads of nutrients and organic matter.

Harmful (or potentially harmful) algae have been observed more frequently in recent years, though this phenomena cannot be attributed to eutrophication alone. Toxic effects have occurred, for instance by the coastal blooms of *Gyrodinium aureolum* in 1981 and *Chrysochromulina polylepis* in 1988, where a regional eutrophication probably was an important co-operating cause. There is a risk that eutrophication may lead to increased blooms of harmful algae or to the establishment of new species in the Outer Oslofjord.

## 5.2 The Skagerrak coast

This report shows a relatively clear picture of how an increasing nutrient load to the upstream areas leads to increasing nutrient concentrations in the coastal water along the Norwegian Skagerrak coast. This is especially evident as increased concentrations of inorganic nutrients in winter-spring and organic nutrients in the summer, and in the coastal water off Arendal the concentrations of nitrate in winter and spring has shown an approximate doubling between 1975-80 and 1990-95. According to the Norwegian guidelines for environmental quality classification the increase corresponds to moderate to marked changes from the natural background levels.

Just as in the Outer Oslofjord, there has been a significant decrease in the oxygen content in the coastal water in autumn since about 1970. This decrease has been 0.4-0.8 ml$O_2$/l from about 1970 to 1995 as a general trend against a background of large interannual variability. The increased organic load and lower oxygen concentrations in the coastal water in autumn leads to a reduced capacity of the fjord basins for local loads of nutrients and organic matter. Combined with an local load, this have contributed to poor or critical oxygen levels in a number of basins along the Norwegian Skagerrak coast. Beyond this, clear effects on the benthic communities are not documented as the gradients from east to west can both reflect natural changing conditions and a possible eutrophication gradient. As the data material is limited the possibility of weak to moderate eutrophication effects cannot totally be excluded. The foraminiferal fauna in bottom sediments of the deep Skagerrak basin indicates an increase in the organic load after ca. 1970.

The environmental conditions along the Skagerrak coast are probably more favourable to the growth of toxic algae than the rest of the Norwegian North Sea coast. The brackish Skagerrak coastal water is characterised by a high N/P-ratio in spring, most pronounced in eastern Skagerrak. This will favour growth of algal groups containing harmful species. The Norwegian nutrient load to the Skagerrak comes mainly from the Oslofjord region, and with a marked nitrogen surplus relatively to phosphorus. Even though the Norwegian load is small compared to the natural nutrient transport in the NCC, it may still increase the imbalance between nitrogen and phosphorus in the surface layer of north-eastern Skagerrak after the spring bloom. However, Norwegian rivers also transport significant amounts of silicate to the coastal water, which stimulates the growth of diatoms and reduces the risk for growth of harmful flagellates.

The degree of nutrient enrichment in the coastal water is similar along the Norwegian Skagerrak coast to about Arendal. West of Arendal significant amounts of Atlantic water is entrained into the NCC, reducing the regional eutrophication effects. There is no well defined western limit to the regional influence, but rather a transition zone. In practical terms the area around Lindesnes may be the western border to regional eutrophication effects.

## 5.3 The coast of Western Norway

The coastal water from Lindesnes to Utsira north-west of Stavanger, is a transition zone where the regional influence from Skagerrak is rapidly decreasing from dilution and biological consumption of nutrients. Algal blooms in Skagerrak are often transported by the NCC past Lindesnes and north to Utsira but seldom much further.

The environmental data available for this assessment have been less comprehensive for the Norwegian west coast than for the Skagerrak coast. There are no indications, however, that the coastal water is affected by eutrophication. The local Norwegian input of nutrients is relatively low and comes from a number of small sources scattered over a large area. The fjords in general communicate openly with the water of the NCC and there is extensive exchange of surface and intermediate water layers. The water from the fjords mixes into the NCC which has a typical transport time along the west coast of 2-3 weeks. The local nutrients input to the west coast comprises less than 1% compared to the natural flux of nutrients in the NCC.

Fjords and polls with shallow sills and restricted water exchange are special cases and exceptions to the general situation. These are sensitive environments with regard to nutrients and organic load, where even limited local nutrients input may cause eutrophication effects.

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