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Eutrophication of Swedish Seas

REPORT 5509 • MARS 2006

EUTROPHICATION OF SWEDISH SEAS

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FINAL REPORT
Stockholm 13 March 2006

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ISBN 91-620-5509-7
ISSN 0282-7298

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FOREWORD

In recent years new information has been obtained concerning nitrogen fluxes to and from the sea as well as internal fluxes of phosphorus between the sediments and the water mass. In the in-depth evaluation of the environmental quality objective "Zero Eutrophication" it was concluded that there were strong reasons to make an extended evaluation of the nutrient problems in the seas surrounding Sweden. This may provide a scientific platform for the right measures to be taken in order to achieve the environmental quality objective.

An international panel of highly qualified eutrophication scientists, with background in limnological and marine research, was asked to scrutinise the scientific basis for the present strategy, and, if required, suggest alternative measures.

The expert group, which was appointed by the Swedish Environmental Protection Agency in co-operation with Swedish eutrophication scientists, consisted of the distinguished eutrophication experts Prof. Donald F. Boesch, USA, Prof. Robert E. Hecky, Canada, Prof. Charles R. O'Melia, USA, (chairman), Prof. David W. Schindler, Canada and Prof. Sybil Seitzinger, USA. Prof. Per Jonsson, Swedish Environmental Protection Agency, was the project coordinator for the evaluation.

The evaluation was financed and produced by the Swedish Environmental Protection Agency. Opinions expressed in this report are those of the authors, and do not necessarily reflect the official view of the Swedish Environmental Protection Agency.

Stockholm 13 March 2006

Martin Eriksson
Director Environmental Assessment Department
Swedish Environmental Protection Agency

EXECUTIVE SUMMARY

Concerns about eutrophication in the seas around Sweden initially arose in the 1960s when long-term trends in declining oxygen concentrations were reported in the deep basins of the Baltic Sea, raising concerns about loss of fish habitat and the production of demersal fishes. Eutrophication is caused in large part by excessive inputs of nitrogen and phosphorus to coastal fjords and archipelagos around Sweden, to the open waters of the Baltic Sea, and to the Öresund, Kattegat, and Skagerrak. Nitrogen inputs to the Baltic Sea, for example, have increased four-fold and phosphorus inputs eight-fold since the mid-19th century. Objectionable symptoms of eutrophication considered herein are massive algal blooms including Cyanobacteria and other toxin producers, anoxic "dead" zones in bottom waters in deep basins, lower transparency, and, in shallower near shore areas, the development of littoral mats of filamentous green algae and the disappearance of *Fucus* and eelgrass beds.

In the spring of 2005 this committee was formed by invitation of the Swedish Environmental Protection Agency to examine publications and data for Swedish coastal seas and to make recommendations for efficiently reducing eutrophication. The committee was specifically requested to address whether reduced nitrogen discharges lead to increasing problems with Cyanobacteria blooms as a part of its study. To do this we analyzed scores of publications and recent manuscripts, heard presentations by prominent Swedish scientists with differing viewpoints, and explored a number of databases for long-term trends.

It was concluded that different measures would be needed in different parts of the Baltic to reduce eutrophication most effectively. As a result, we have divided this report into three major sections: (1) the Swedish east coast, (2) the open Baltic Proper, and (3) the Swedish west coast. We chose not to evaluate the Bothnian Bay and the Bothnian Sea because these appear to be less affected by eutrophication at this time.

Recommendations

As the examples for Swedish seas illustrate, alleviating eutrophication should not be addressed as a single choice among controlling phosphorous only, nitrogen only, or nitrogen and phosphorus in combination. Limiting nutrients may differ from one environment to another, along spatial gradients, and over time. Furthermore, Swedish seas and coastal systems are bidirectionally interconnected and measures taken to reduce nutrient inputs into one can have spillover consequences to another. Reliance on simple decision metrics such as nitrogen:phosphorus ratios may lead to the wrong conclusions. With these considerations in mind, the committee makes the following recommendations.

1. *Reduce phosphorus inputs to the open Baltic Proper.*

Views among Baltic scientists and, indeed, among the members of this panel, differ regarding the benefits or risks of reducing nitrogen inputs to the Baltic Proper; however there is broad agreement that phosphorus inputs should be reduced to alleviate eutrophication, particularly the extensive Cyanobacteria blooms currently plaguing the sea. Efforts throughout the basin should begin with removing phosphorus from detergents and from point sources as the quickest way to decrease P loading. However, diffuse sources account for 60% of anthropogenic P inputs; therefore, controls on diffuse sources of P should also be implemented. Preserving and, where possible, restoring nutrient-retentive features of the landscape should be an important part of a longer term nutrient control strategy. Additional point source phosphorus removal by Sweden alone is not likely to have a significant impact on the open Baltic Proper because the most important point sources of phosphorus loading are along the eastern and southern coasts of the Baltic.

2. *Reduce atmospheric nitrogen deposition.*

Atmospheric deposition is the main external source of nitrogen to the Baltic Proper and the western seas of Sweden. So far, attempts to reduce atmospheric sources of nitrogen have had little effect on this loading. Reducing atmospheric deposition has benefits for terrestrial and freshwater ecosystems as well as the western seas. Efforts to reduce atmospheric deposition of nitrogen should be pursued, although without accompanying removal of phosphorus from land-based sources there is a risk of enhancing growth of bloom forming nitrogen-fixing Cyanobacteria in the Baltic Proper as reduced atmospheric inputs of nitrogen may give the Cyanobacteria an increasing advantage over other algal groups.

3. *Reduce nitrogen inputs to the waters of the Swedish west coast.*

Reduction of eutrophication problems in the West Sea and associated coastal waters will require significant reductions in inputs of nitrogen. In contrast to the eastern coasts and the Baltic Proper, there do not appear to be risks of Cyanobacteria blooms. Reductions of phosphorus inputs would also have positive results because of the presently high levels of anthropogenic loading of both nutrients, but only if accompanied by nitrogen reductions. While reductions in point sources of nitrogen would contribute to achieving eutrophication reduction goals, these goals cannot be approached without significant reductions in diffuse sources and atmospheric deposition. Achieving these goals will require a focus on diffuse sources and atmospheric deposition at local and regional scales.

4. *Appropriately reduce nutrient inputs in enrichment-sensitive areas of the Swedish east coast.*

Phosphorus is now removed at most sewage treatment plants in Sweden, but diffuse sources are still important in some areas. Further reduction of external P loading will require addressing anthropogenic non-point sources of P. While P removal from the Stockholm STPs by 1970 led to significant reductions in algal biomass and blooms of Cyanobacteria, internal loading of P from bottom sediments, although not fully quantified, is currently a substantial source of P. Increased oxygen concentrations reduce the rate of release of P from sediments and thereby affect the longer-term recovery from eutrophication, because P inputs from STPs are now small. The Committee is divided about the benefits of nitrogen removal to the fjords and coastal waters of the Swedish east coast. Some conclude that where eutrophication effects exist removal of nitrogen is warranted and consider that its effects have been clearly demonstrated. At the same time they recognize that extensive nitrogen removal may stimulate nitrogen-fixing Cyanobacteria if not otherwise limited by phosphorus. Other members consider that the available data do not demonstrate benefits of nitrogen reduction in these waters and that emphasis should continue to be directed at phosphorus removal only until there is a more convincing case for the benefits of nitrogen removal.

1 Introduction

Much of Sweden borders on semi-enclosed seas that are shared by other riparian states. These seas vary from the nearly marine Skagerrak to nearly lacustrine Bothnian Bay. In between lies the Baltic Sea, the world's largest brackish water ecosystem. For centuries, these seas have been an important resource for humans living along their shores and in their catchments. Since the mid-19th century, growth in human population, land use and industry has changed Swedish seas and the fjords and archipelagos that border them. These changes have accelerated in the latter half of the 20th century.

At present, sixteen million people live in nine countries along the coast of the Baltic Sea. A total of 85 million people live in the 14 countries in its catchment (Fig. 1.1). The distribution of population varies widely, and is generally much higher in the southern part of the drainage basin.

Figure 1.1 Map of the Baltic Sea and much of its surrounding watershed (courtesy of Mats Blomqvist).

While changes to ecosystems of Swedish seas have been caused by a variety of insults, one of the most important stressors has been eutrophication (Elmgren, 2001), the result of the overfertilization with phosphorus (P) and nitrogen (N). For example, nitrogen inputs to the Baltic Sea have increased four-fold and phosphorus inputs eight-fold since the mid-19th century (Larsson et al. 1985). The objectionable symptoms of eutrophication vary widely in different parts of the Baltic and West seas. They include massive algal blooms, including Cyanobacteria (Figure 1.2) and other toxin producers, anoxic "dead zones" in bottom waters, including the large, deep basins of the Baltic, and alterations of food chains on which fishery resources depend. In the shallower nearshore protected by fjords and archipelagos, development of littoral mats of filamentous green algae, disappearance of *Fucus* and eelgrass beds, and lower transparency are frequent objections.


Cyanobacterial blooms in the Baltic Sea
MODIS TERRA 2005-07-13, data from NASA
processed by SMHI

Figure 1.2. Cyanobacterial bloom in the Baltic Sea, July 13, 2005.

The human population of Sweden increased from 3.9 million in 1860 to 9 million in 2004. Use of P and N fertilizers in Baltic catchments also increased markedly starting in the middle of the 20th century. For example, use of P mineral fertilizers increased from less than 5 kg P/ha in 1930 to approximately 20 kg P/ha in the late 1970s, and decreased to less than 10 kg P/ha since 1990 (Löfgren et al. 1999). Use of N mineral fertilizers increased from less than 5 kg/ha in 1930 to almost 80 kg/ha in 1980 and has remained relatively constant since then. Discharges of both N and P from sewage treatment plants (STPs) are also significant contributors to eutrophication (Naturvårdsverket 2003).

Atmospheric deposition of N that originates both within and outside Sweden from fossil fuel combustion and from agricultural sources makes further addition to the nutrient loading to Swedish seas. Atmospheric N deposition increased until about 1980, leveling off in most countries and declining in some after that time (Tarranson and Schaug 2000). It continues to represent a large input of the element to the Baltic and West seas with values in the Baltic Proper exceeding 14 kg N $ha^{-1}y^{-1}$ (Granat 2001). Such high deposition in terrestrial parts of catchments unquestionably contributes to the riverine loading as well. Wright et al. (2001) found that 10 kg N $ha^{-1}y^{-1}$ was a deposition threshold above which nitrate could be expected to increase above background levels in stream runoff. While there have been some attempts to control emissions of nitrogen in Europe, Skjelkvåle et al. (2005) found no evidence of declining concentrations of nitrate in surface waters, including those in the Baltic region. Deposition of nitrogen has caused detrimental changes to freshwaters and forests of many regions (Dise and Wright 1995), adding weight to the arguments that it should be controlled to protect coastal ecosystems.

In response to growing concerns about eutrophication, some countries began to reduce point sources of phosphorus in the early 1970s. This was driven largely by evidence from freshwater systems, and partly by the relative ease of removing phosphorus from domestic sewage. Accumulation of evidence for nitrogen limitation in marine waters during the 1980s and 1990s caused some countries to start reducing point sources of nitrogen.

Aggressive efforts have been undertaken in Sweden to reduce both point and diffuse inputs of phosphorus and nitrogen to both fresh waters and coastal seas. Figure 1.3 summarizes estimates of land-based loadings of TN and TP to Swedish coastal waters in 1995 and 2000 made by the Swedish EPA (Naturvårdsverket 2003). These estimates are based on direct measurements of emissions from sewage treatment works and calculations of diffuse loadings. For phosphorus the diffuse loadings are to lakes and watercourses and these estimates are not viewed as reliable indicators of loadings to the sea.

Despite significant reductions over the past 35 years in nutrient inputs from point sources, eutrophication in the Baltic Sea Proper has continued to worsen and has shown limited signs of improvement elsewhere. In less saline parts of the Baltic Proper, nitrogen fixation by Cyanobacteria adds significantly to nitrogen inputs in midsummer. Fixation does not appear to enhance nitrogen inputs to the coastal waters of the west coast and Kattegat, possibly because salinity is too high for Cyanobacteria blooms to develop (>10 to 12 psu; Howarth and Marino in press).

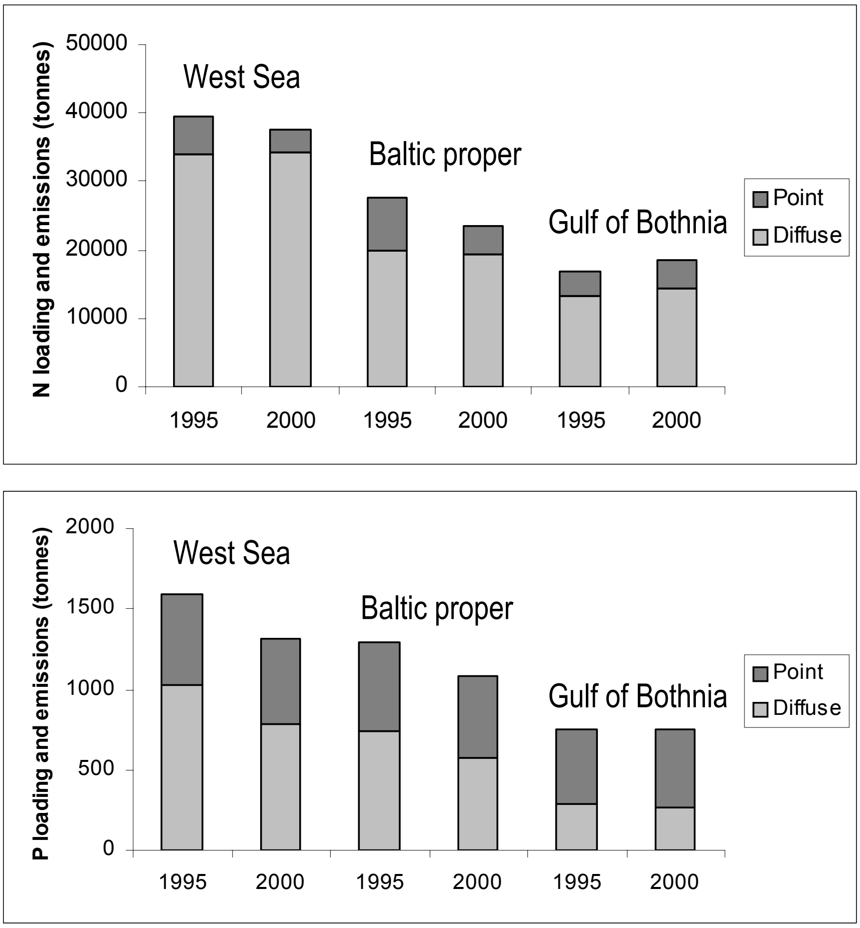


Figure 1.3. Estimated land-based loadings of nitrogen and phosphorus from Sweden in 1995 and 2000 (Naturvårdsverket 2003).

There are other complicating environmental factors that affect trends in eutrophication. Increasing temperatures in the Baltic (Fonselius and Valderrama 2003), possibly as a result of climate warming, have probably caused decomposition rates to increase, compounding the effects of nutrient loading. Also, periodic and unpredictable incursions of saline water from the Kattegat and North Sea have changed the rates of exchange between deep and surface waters of the Baltic Proper.

Different results from different regions, different interpretations of results and the relative roles of the above factors, and a shortage of definitive data have caused lively and at times acrimonious debate among scientists. Some believe that reversal of eutrophication will be more rapid if both nitrogen and phosphorus are controlled, while others believe that controlling nitrogen is a waste of money and that the focus of reductions should be on phosphorus alone.

In the spring of 2005, our committee was formed by invitation of the Swedish Environmental Protection Agency to examine publications and data for the Baltic and make recommendations for efficiently reducing eutrophication. The committee was specifically requested to address whether reduced nitrogen discharges lead to increasing problems with Cyanobacteria blooms among other questions. To do this, we analyzed scores of publications and recent manuscripts, heard presentations by prominent Swedish scientists with differing viewpoints, and explored a number of databases to look for long-term trends and relationships.

It quickly became obvious that different measures would be needed in different parts of the Baltic to reduce eutrophication most rapidly. As a result, we have divided this report into three major sections: (1) the Swedish east coast, (2) the Baltic Proper, and (3) the Kattegat, Skagerrak and the coastal waters of western Sweden (Figure 1.1). We chose not to evaluate the Gulf of Bothnia because it appears to be less affected by eutrophication at this time. However, we recognize that the Gulf is openly connected to the Baltic Proper such that nutrient loads there have consequences to the Baltic Proper (Hagström et al. 2001).

2 Swedish East Coast

Nutrient (N and P) inputs from land-based sources (both diffuse and point sources) to many of Sweden's coastal bays and estuaries have increased substantially above background levels. One indication of this is the higher phytoplankton biomass (summer chlorophyll *a*) in coastal waters observed in a number of Sweden's east coast systems, relative to many other east coast waters. Two regions where anthropogenic nutrient sources have caused phytoplankton chlorophyll to rise above background concentrations are the inner Stockholm Archipelago waters and the Himmerfjärden (Figure. 2.1).

While nutrient inputs to many of eastern Sweden's coastal systems have undoubtedly increased since the beginning the nineteenth century, beginning in the 1970s there were substantial decreases in P emissions from point sources due to P removal in sewage treatment plants (STPs) and also likely from diffuse sources due to a reduction in mineral P fertilizer use (Naturvårdsverket 2003). In the 1990s, N removal was added to many STPs, especially those serving >100,000 people. Substantial efforts to reduce non-point source N inputs from agricultural sources have also been made, including a slight reduction in mineral N fertilizer use.

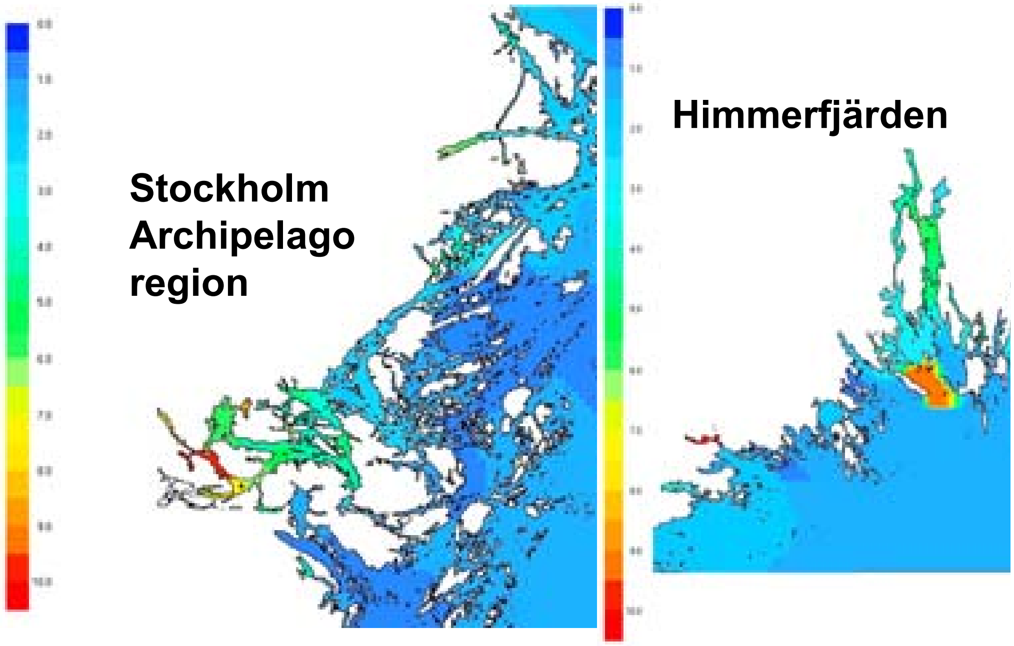


Figure 2.1. Summer chlorophyll levels (µg/L) in the Stockholm Archipelago and Himmerfjärden (Ulf Larsson, unpublished data).

Two case studies are reviewed here in an attempt to provide insight into the response of eastern Sweden's coastal waters to P and N inputs and to reductions in those inputs: the Stockholm Archipelago and the Himmerfjärden.

2.1 Stockholm Archipelago

The Stockholm Archipelago (Fig. 2.2) is comprised of at least 20,000 islands and is one of the most important recreational areas for Sweden. Land use in the drainage basin is a mixture of agriculture, urban, and forest. The surface waters are brackish; except in the outermost archipelago salinities are generally less than 6 psu with higher salinities in bottom waters (Figures 12 and 13 in Lännergren and Eriksson 2005). The dominant freshwater input is from Lake Mälaren with a mean outflow of approximately 165 m^3/s. Water residence times in the archipelago range from a few days in the outer region to over 100 days in the inner archipelago (Engqvist and Andrejev 2003). The inner region receives nutrient inputs from sewage treatment plants serving the Stockholm metropolitan area, with even larger inputs of nutrients from the surrounding watershed through the outlet of Lake Mälaren, the Norrström outflow. However, STPs provide most of the DIN entering the inner archipelago and most of the DIP during the low-flow summer months (June through August). Discharges are made to the inner archipelago from three large STPs, Henriksdal, Käppala and Bromma at depths ranging from 30 to 45 m. Numerous permanent and seasonal homes on the shores and islands of the archipelago are also potential sources of nutrients. Most are served by septic tanks. Detailed assessments of their nutrient contributions are not presently available and should be done to assess their possible effects on localized basins within the archipelago.

Figure 2.2. Stockholm Archipelago showing Stockholm Vatten sampling stations.

Hydrologically, the waters of the Stockholm Archipelago and other regions of the east coast are characterized by straits and basins and function essentially as estuaries (Engqvist and Andrejev 2003). Fresh water enters from the landward side and mixes with the saline waters of the Baltic Sea. This sets up estuarine circulation, with net seaward flowing waters near the surface and landward flowing waters below, which results in vertical mixing and water exchange with the Baltic many times the volume of the freshwater inputs (Dyer 1997). Because of the large discharges of fresh water in the form of treated sewage at mid-depth in the vicinity of Stockholm, the inner-most part of the archipelago actually develops four-layer circulation, with strong landward compensation flows both above and below the discharge plume (Fig. 2.3). In addition, other baroclinic (Ekman pumping) and barotropic processes at the Baltic boundary drive active, bidirectional exchange with the sea.

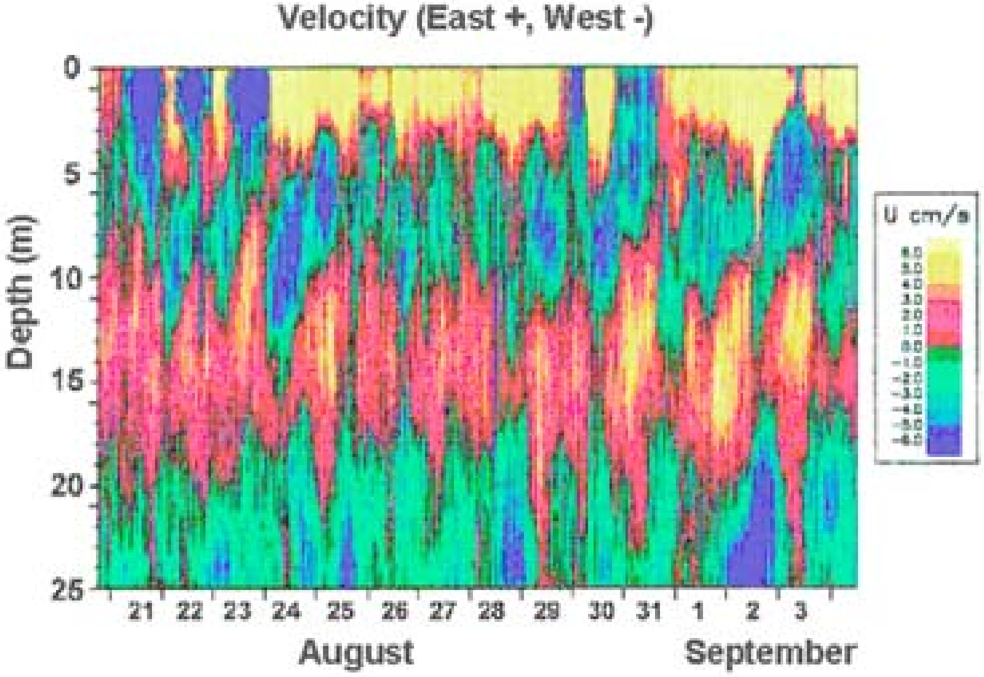


Figure 2.3. Acoustic Doppler current profiler record of flow at Blockhusudden in the inner archipelago. Surface waters are generally flowing seaward (east), with a landward flowing compensation current below it. At mid-depth, another seaward flowing current represents the STP discharge, below which is another landward flowing compensation current. (source: Christer Lännergren, Stockholm Vatten)

2.1.1 Nutrient sources and trends

Nutrient inputs to the sea from the whole of Sweden increased dramatically between 1860 and the late 1960s (Naturvårdsverket 2003). As early as 1900, the wastewater from approximately 200,000 people discharged into the Stockholm Archipelago (Brattberg 1986; Johansson and Wallström 2001). In 1941, the largest treatment plant in Stockholm (the Henriksdal) began operation, with wastewater discharges into the archipelago increasing markedly until about 1970. At that time about 70% of the annual total phosphorus (TP) inputs from land-based sources were from direct discharges to the archipelago by STPs and about 30% from the Lake Mälaren outflow (Figure. 2.4). In contrast, only about 40% of total nitrogen (TN) inputs were from STPs and about 60% from the Lake Mälaren outflow as of the early 1940s. (Note that TN and TP in the Lake Mälaren outflow consist of both diffuse sources from the watershed and STPs in the watershed.).

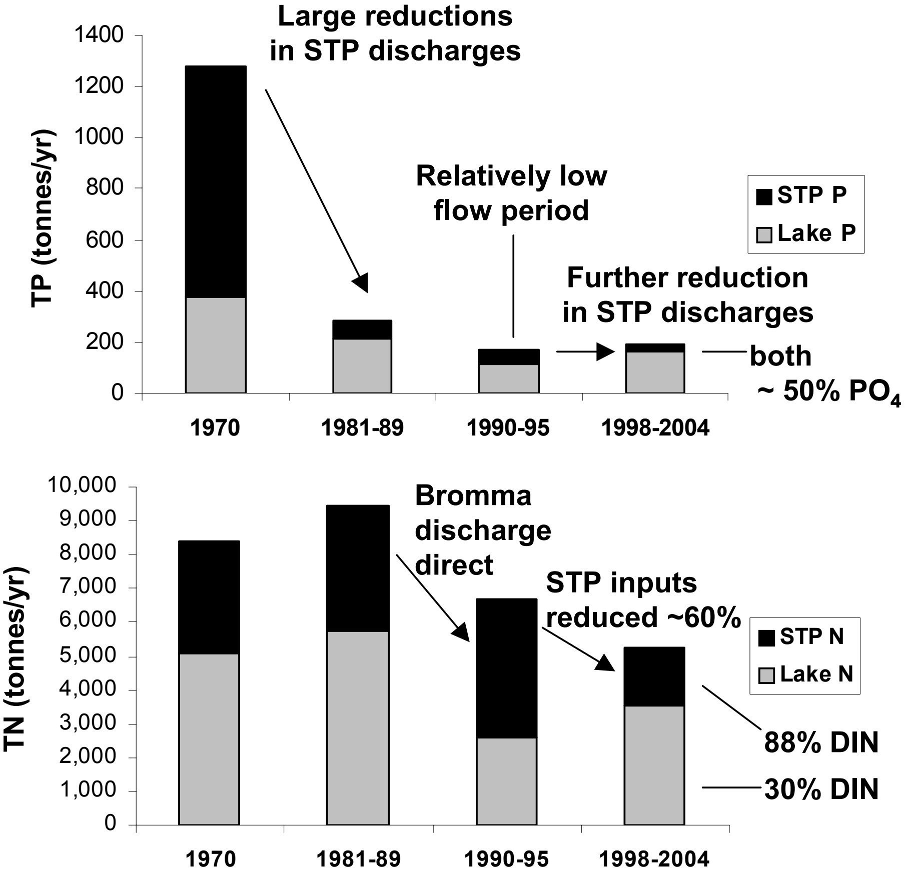


Figure 2.4. Summary of annual nutrient loadings to the Stockholm Archipelago from Lake Mälaren and sewage treatment plants from 1970 to present. Compiled from Brattberg (1986) and Lännergren and Eriksson (2005).

While TN and TP inputs increased from the 1940s to the late 1960s, TP inputs increased more rapidly than TN (Brattberg 1986). Between 1968 and 1973, sewage treatment plants (STPs) in the area began P removal and biological treatment. As a result, by 1980 TP inputs from point sources to the archipelago had decreased by approximately a factor of ten—from over 800 tonnes/y in 1970 to about 75 tonnes/y by 1980 (Brattberg 1986). During the 1980s about 25 % of the annual TP inputs were from STPs discharging directly into the archipelago; the vast majority of TP from land-based sources entered the archipelago from the Lake Mälaren outflow. Since 1980 there have been substantial year-to-year variations in TP inputs, primarily due to differences in outflow from Lake Mälaren (Figure 2.5), with a period of years of mostly below average outflows from 1989 through 1997 (see Figure 3 in Lännergren and Eriksson, 2005). There also was a further decrease in P from STPs in the mid-1990s, coincident with upgrades to enhanced tertiary treatment for N removal. Currently, on an annual basis only about 15-20% of both the TP and dissolved inorganic phosphorus (DIP) inputs to the inner archipelago are from STPs (Lännergren and Eriksson 2005).

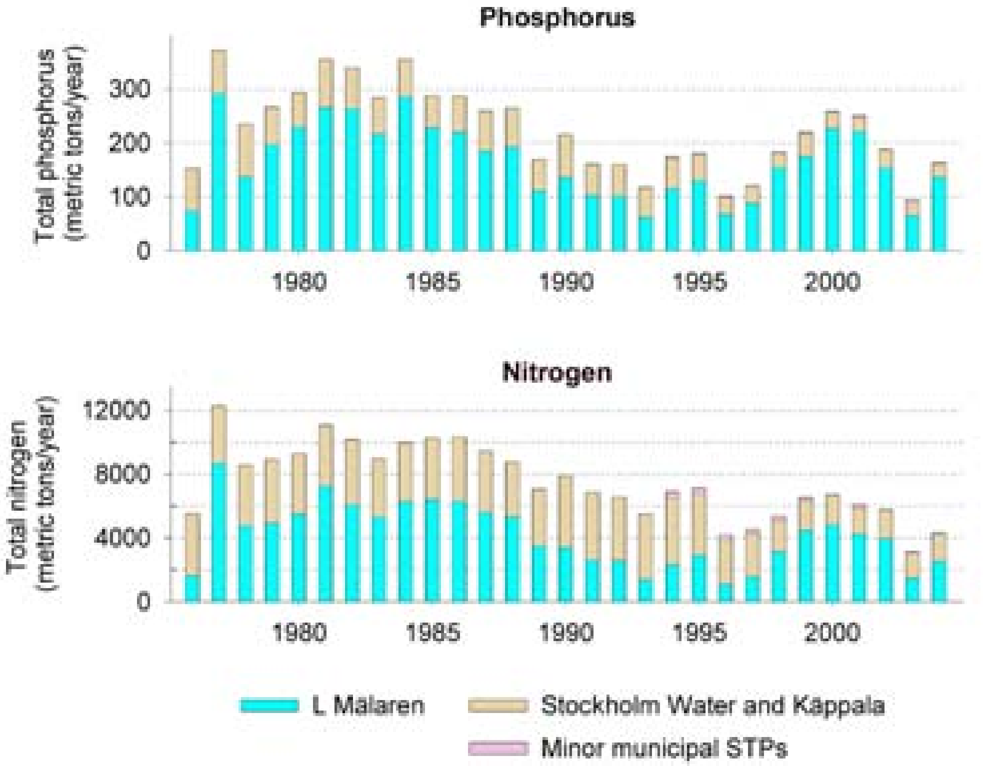
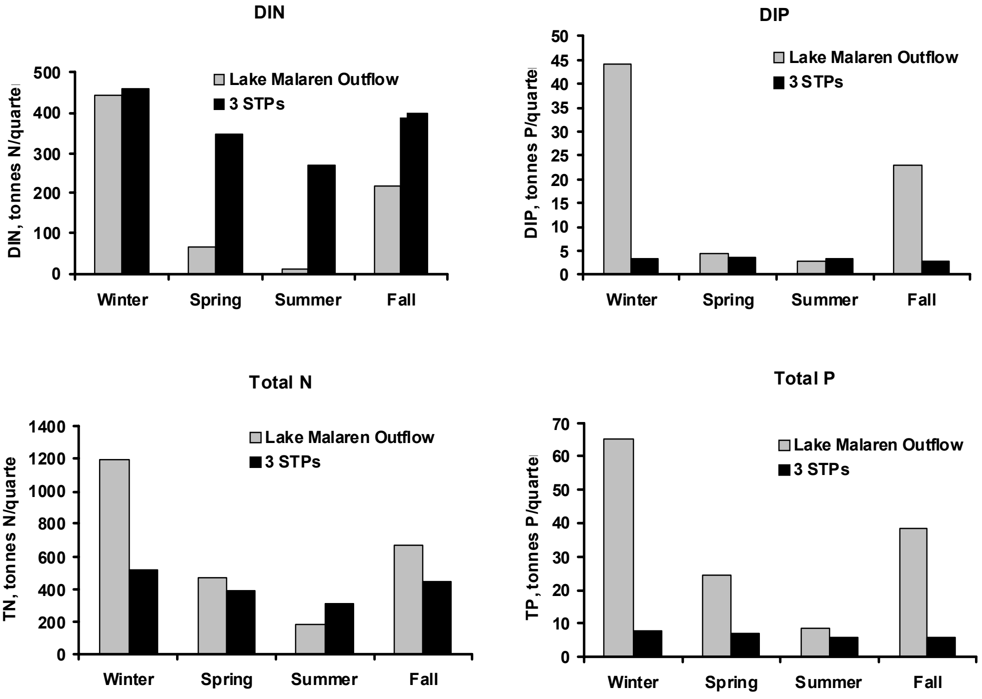


Figure 2.5. Phosphorus and nitrogen inputs to the Stockholm Archipelago beginning in 1976 (well after P removal from STPs began) through 2004. Inputs from STPs directly to the archipelago are in brown and inputs from Lake Mälaren in blue. (Lännergren and Eriksson 2005).

TN inputs from STPs and from Lake Mälaren continued to increase from the 1930s onward (Brattberg 1986). N removal in STPs was begun at Henriksdal in 1990 and fully implemented at all of the plants by 1996. This reduced TN inputs from STPs discharging directly into the archipelago by more than 50 % by 1998 (Figure 2.5). Between 1998 and 2004, TN inputs from Lake Mälaren plus the STPs were approximately 5,300 tonnes/year (down from about 9,600 tonnes/year in the 1980s). Except during dry years, Lake Mälaren supplies a majority of TN inputs to the inner archipelago; however STP loads are largely (88%) dissolved inorganic nitrogen (DIN) (Lännergren and Eriksson 2005), while only 30% of lake-outflow N load is in the form of DIN (Stockholm Vatten data courtesy of C. Lännergren) (Figure 2.6). Furthermore, during summer the STP inputs of

TN are greater than from Lake Mälaren, and DIN inputs from STPs are generally more than 10 times greater than from Lake Mälaren.

TP inputs from the STPs and Lake Mälaren declined precipitously in the 1970s from over 1,200 tonnes per year to about 300 tonnes per year by the 1980s (Figure 2.4) after which they have fluctuated, mainly as influenced by Lake Mälaren loads (Figure 2.5). STP loads of TP decline by about half as a result of additional phosphorus removal attained with the implementation of nitrogen treatment in the mid 1990s. This additional increment was, however, only about 5% of the STP load reductions that have been achieved to date (Figure 8 in Lännergren and Eriksson 2005). Even during dry years, Lake Mälaren still supplies a majority of annual TP inputs to the inner archipelago (Figure 2.5). In contrast to nitrogen, the proportion of the STP phosphorus in the form of DIP is essentially the same (55%) as for the Lake Mälaren outflow.


DIN

DIP

Total N

Total P

Figure 2.6. Quarterly loadings of DIN, TN, DIP and TP to the inner archipelago in 2004, apportioned into source (Lake Mälaren and STPs) (Data source: Stockholm Vatten).

Both TN and TP inputs have varied substantially since 1996 (but also previously), primarily due to differences in outflow from Lake Mälaren (Figure 2.5). On an annual basis, while currently 85% of the TP and 60% of the TN inputs to the inner archipelago are from the outflow from Lake Mälaren, this outflow supplies only 34% of the readily available DIN, the remainder coming from the STP discharges. Most of the nitrogen (88%) and somewhat over half (56%) of the phosphorus supplied by the STPs during the extended growing season (April-October) are in dissolved inorganic forms (NO_3 and NH_4 and PO_4, respectively, Figure 2.6). The STPs provide 84% and 56% of the externally supplied DIN and DIP, respectively, during this period (Stockholm Vatten data courtesy of C. Lännergren). In 2004 the nutrient ratios of external loads were approximately 25 for both TP:TN and DIN:DIP for the year as a whole, but 29 for TN:TP and 42 for DIN:DIP during the growing season (all ratios by weight).

Changes in nutrient removal within STPs have markedly changed the N:P ratio of nutrients entering the Stockholm Archipelago over time. The N:P ratio of inputs from land-based sources increased substantially from about 7:1 (by weight) as of the late 1960s, to about 30:1 since the 1980s (Table 2.1). The low N:P ratio in inputs in the late 1960s is consistent with the N-limited conditions in the archipelago at that time and with the occurrence of N_2-fixing Cyanobacteria (Brattberg 1986). High N:P ratios in inputs following P removal by STPs shifted the inner archipelago from an N-limited to a P-limited system, consistent with the decrease in Cyanobacteria (Brattberg 1986).

Table 2.1. Total N:P ratio (by weight) of inputs to the Stockholm Archipelago based on data in Figures. 2.4. and 2.5.

Period	N:P
Late 1960's	~7:1
1980-85	32:1
1990-95	38:1
1999-2004	26:1

With regard to N and P exported from coastal waters to the Baltic Proper, it is important to note that some portion of the N and P inputs are buried in the coastal sediments and, in the case of N, denitrified and returned to the atmosphere as nitrogen gases (N_2 or N_2O) (e.g., Voss et al. 2005). For N there exists a reasonably good relationship between water residence time and the proportions of N inputs that are retained within a system across a wide range of lakes, estuaries, coastal and continental shelf systems (Seitzinger 2000; Seitzinger et al. in press). The approximate water residence time in the inner, mid and outer archipelago is 110, 25 and 10 days, respectively (Engqvist and Andrejev 2003) (cumulative residence time 145 days). Applying the relationship between N retention and water residence time (% retained = 23.4 * (residence time in months $^{0.204}$) from Seitzinger et al. (in press) suggests that about 45% of the N inputs to the Stockholm Archipelago are removed by denitrification or burial within the system (measured to be approximately 20 % for the inner archipelago alone by Lännergren and Eriksson 2005) with the remainder exported to the Baltic Proper. The selective removal of nitrogen due to denitrification, coupled with mixing with return flow waters from the N-poor Baltic, act to decrease the N:P of surface water as one moves out of the Archipelago into the Baltic Sea.

2.1.2 Nutrient concentrations and dynamics

Surface-water total P concentrations, as measured at Solöfjärden in the inner archipelago, rapidly decreased from approximately 80-100 µg/L in 1968-1971 to 25-30 µg/L by 1974 (Figure 2.7), coincident with the large decrease in P loading to the archipelago from STPs (see section 2.1.1). The TP concentrations then remained consistently low through at least 1994 (Figure 2.7) but appear to have declined somewhat since the mid-1990s (Figure 30 in Lännergren and Eriksson 2005). At the same time that TP concentrations rapidly decreased in the early 1970s, total N concentrations, measured in the Trälhavet basin, also decreased from about 600 to 400 µg/L between 1970 and 1975, although DIN concentrations increased from near 2 µg/L to approximately 40 µg/l (Brattberg 1986), indicating a surplus of inorganic N that would be expected in a P limited ecosystem.

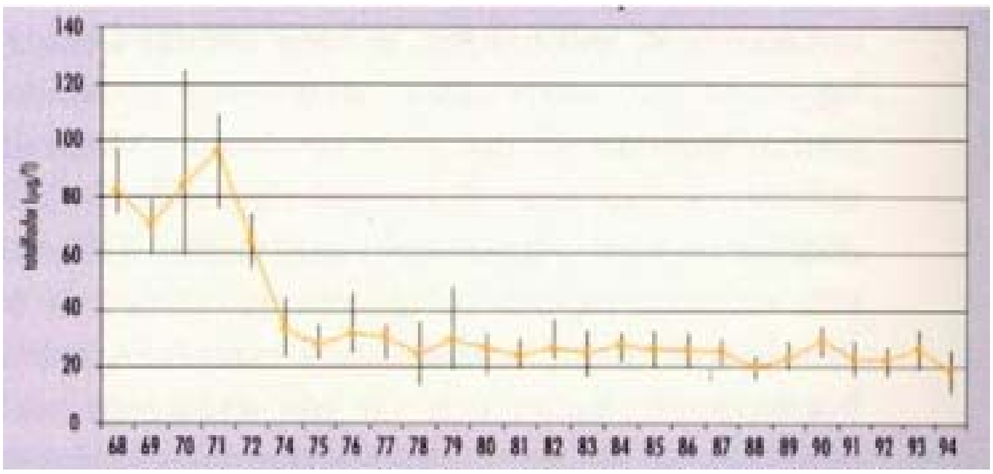


Figure 2.7. Total P concentrations (µg/L) at Solöfjärden in the Stockholm Archipelago between 1968 and 1994. Figure from Lännergren 1994. Slow additional declines are also evident since the mid-1990s (Figure 30 in Lännergren and Eriksson 2005)

Between 1970 and 1985 the total N to total P ratio (TN:TP) in surface waters increased from 10:1 to 20:1, and the inorganic N:P ratio increased from 1:1 to 20-40:1 as inorganic N concentrations increased markedly (Brattberg 1986). DIP concentrations were generally below the level of detection during summer (data from C. Lännergren). This change in N:P ratios from relatively low to high values following the large decrease in P loading from STPs in the late 1960s is consistent with a change toward greater P limitation.

Large reductions in N loading as well as accompanying reductions in remaining P loading from STPs occurred in the mid 1990s. The TN:TP concentration ratios by weight are currently approximately 20:1 in the inner archipelago and 17:1 in the mid-outer archipelago (2000-2004) (Lännergren and Eriksson 2005), well above those observed prior to P removal in the 1970s (Brattberg 1986). In summer, surface water DIN concentrations are now generally below the level of detection and DIP concentrations continue to be below detection in the mid-archipelago (data from Lännergren). While computing DIN:DIP ratios when both fall below detection is impossible, DIN:DIP during the spring and fall transitional periods when both can be measured is now typically below the Redfield ratio in this region. Furthermore, the DIN:DIP ratios within the pycnocline (where concentrations can be more readily measured and provide a source of resupply to surface waters) are also below the Redfield ratio. This suggests N limitation or co-limitation of production.

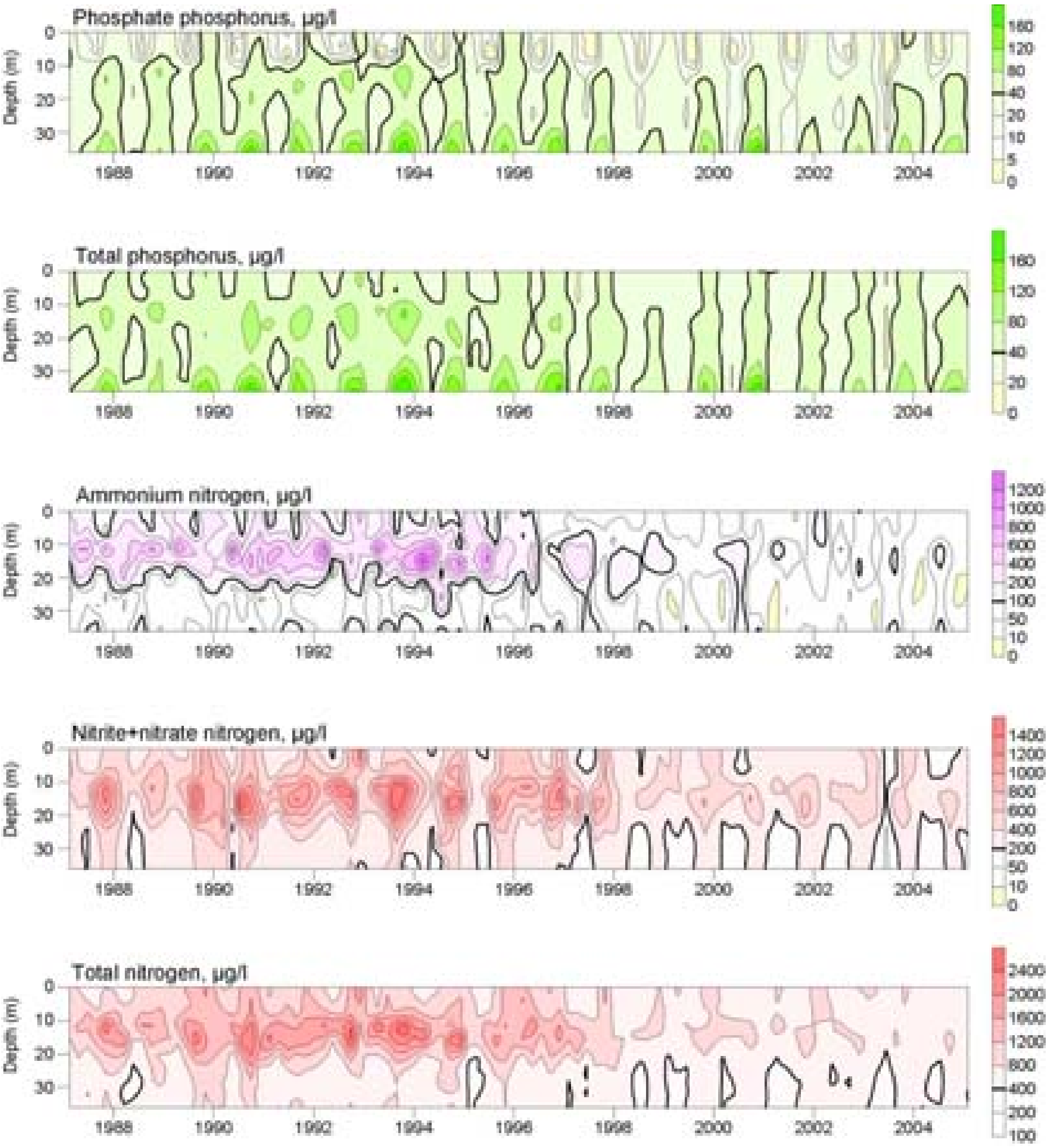


Figure 2.8. Variation in nutrient concentrations over depth and time at Blockhusudden (from Figure 24 A in Lännergren and Eriksson 2005).

Surface concentrations of nutrients, although important to understanding phytoplankton nutritional requirements, do not tell the full story. Plots of nutrient concentrations with depth and time (Fig. 2.8) present a more complete picture of the complex nutrient dynamics in the inner and mid archipelago (Lännergren and Eriksson 2005). These plots indicate that internal loading in the form of release of P from the bottom plays an important role in the dynamics of P, while the mid-depth injection of N (particularly DIN) from the STPs dominates the N dynamics. Furthermore, there was a striking reduction in TN and DIN throughout the water column following the implementation of N removal at the STPs in the mid 1990s that extends into the mid-archipelago region at least to Trälhavet (Figures 24 A-C in Lännergren and Eriksson 2005).

At the inner archipelago station (Blockhusudden) shown in Fig. 2.8, there was also a clear, but less dramatic reduction in P concentrations throughout the water column at that time. This reduction is more limited to the innermost archipelago stations (Slussen and Blockhusudden). The depth-time plot (Fig. 2.8) at this inner archipelago station also graphically illustrates differences in the relative importance of STP versus internal-loading sources of P and N. The highest concentrations of TP and DIP result from seasonal benthic release of P and its landward advection in bottom currents, while the seaward-flowing STP plume at mid depth is the primary source of N.

A comparison of the dissolved inorganic nutrient concentrations in surface waters before and after the implementation of N removal from STP discharges (Fig. 2.9) reveals the extent of these temporal patterns. DIN (ammonium, nitrite, and nitrate) concentrations were reduced through the mid-archipelago (at least to Sollenkroka), while observable reductions in DIP (phosphate) were confined to the inner archipelago (see Fig. 2.2 for locations). Throughout much of the summer, however, both DIN and DIP concentrations were below the level of detection in the middle to outer archipelago after N reduction (Lännergren and Eriksson 2005).

Spring TP concentrations at Trälhavet in the inner part of the middle archipelago did not initially respond to P reduction in the 1970s (Brattberg 1986), but summer concentrations showed a decline in the 1990s (Figure 30 in Lännergren and Eriksson 2005). While this suggests a long lag time for the dissipation of internal loads of P in sediments which has been found to be as much as 10-20 years in freshwater lakes (Soendergaard et al. 2001, 2002), one might have expected this effect to be gradual over the more than 20 years since the dramatic reduction of P loading (Figure 2.4). One alternate explanation is that the decline during the 1990s was a response to reduced outflows from Lake Mälaren (Figure 3 in Lännergren and Eriksson 2005); however spring TP concentrations did not increase when flows became more normal after 1997. Another possible explanation is that the reduction in TP concentrations at Trälhavet was a response to additional P removal from STP effluents accomplished with the implementation of N control in the early 1990s. However, that reduction was extremely small in comparison both to the previous STP load reductions that did not elicit a response and to the Lake Mälaren TP loads, which actually increased post-1997. A final explanation is that this reduction was a consequence of the reduction of N loading, either

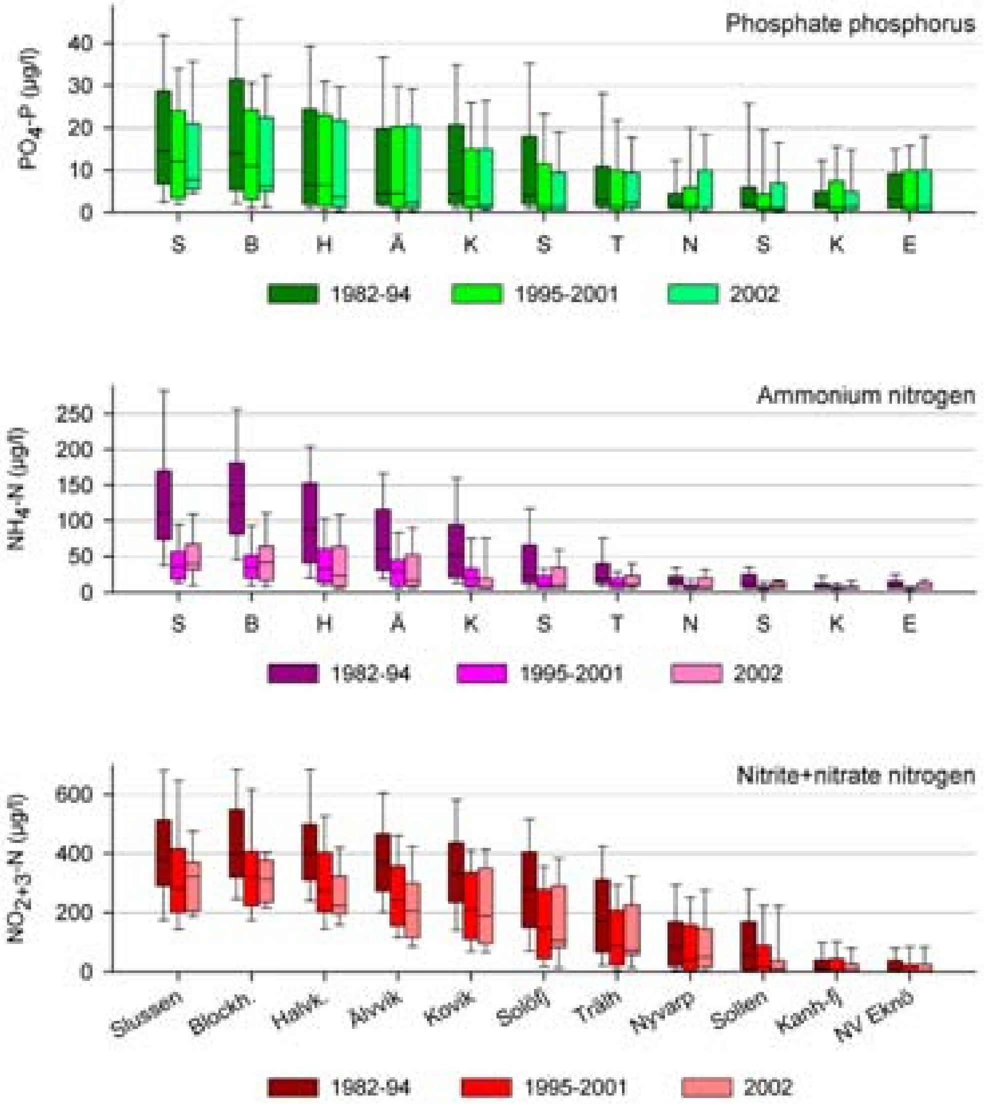


Figure 2.9. Changes in surface concentrations of phosphate, ammonium, and nitrite+nitrate during the summer between the period before (1990-1996) and after (1997-2004) extensive nitrogen removal from STP discharges along a gradient from Stockholm (Lake Mälaren outflow) to the Baltic Sea (Lännergren and Eriksson 2005). Bottom panel shows the low-range detail for nitrite+nitrate.

through reducing phytoplankton organic production (see next section) or lowered discharges of oxygen-demanding ammonia, or reduced biological oxygen demand (BOD) of effluents. Either might have alleviated bottom-water hypoxia that is responsible for remobilization of sediment P reservoirs (Blomqvist, et al. 2004). This is discussed in more detail below.

2.1. 3 Phytoplankton chlorophyll and production

Since the early 1900s the Cyanobacteria *Oscillatoria agardhii* was a characteristic species in the Stockholm Archipelago (Brattberg 1986). It is noteworthy that this genus has been recorded as a first symptom of eutrophication in lakes since the early 19th century (Hutchinson 1969). (The genus *Oscillatoria* subsequently has been changed to *Planktothrix*. Here we use *Oscillatoria* for consistency with the original report.) Until about 1970, the summer biomass of phytoplankton, mainly *O. agardhii* (not a N fixer) but also *Anabaena* spp., increased markedly throughout the archipelago (Brattberg 1986). *O. agardhii* largely occurred in areas with excessive phosphate, but with deficiencies of N. Laboratory nutrient enrichment experiments with *O. agardhii* indicated N limitation between May-September in 1970 (inorganic N:P ratios were less than 5:1). Towards the end of the spring bloom inorganic N concentrations decreased to very low concentrations; while phosphate concentrations also decreased they remained in surplus, thus favoring N-fixing cyanobacteria. Brattberg (1986) reported nitrogen fixation of 2.25 $gN/m^2/y$ in 1972. It declined in subsequent years as P concentrations declined. She reported, “the increased nitrogen load during 1950-1970 was of subordinate importance "[to N-fixation? evaluators´ addition] for the occurrence of massive blooms of cyanobacteria in the archipelago.”

Following P removal in STPs during the early 1970s, the N:P ratio increased and nitrogen fixation by Cyanobacteria and the biomass and temporal occurrence of *O. agardhii* decreased in the Stockholm Archipelago (Brattberg 1977). Overall, chlorophyll *a* concentrations decreased by about 50%, from a high of over 30 μg/L (1969-1972) to about 16 μg/L (1972-1985) in the inner archipelago, with decreases in the middle archipelago in summer as well. Thus, while the inner archipelago was apparently N-limited in the late 1960s, chlorophyll *a* levels declined rapidly and dramatically following the large reductions in point-source loading of only P. After P-reduction the inner archipelago was P limited (Brattberg 1986), but still characterized by relatively high chlorophyll *a* levels.

More recent changes in chlorophyll *a* concentrations are summarized in Figure 2.10 for spring and summer during three periods: 1982-1989 (well after the earlier reductions following P removal from STPs), 1990-1995 (a period during which annual average outflows from Lake Mälaren were 20% lower and further STP nutrient controls were beginning (Figure 2.5 and Figures 3A and 8 in Lännergren and Eriksson 2005), and 1999-2004 (when lake outflows returned to average or above and STP controls were fully implemented). Concentrations during the summer (June-September), a critical time for the manifestation of nutrient limitation, in the inner and mid-archipelago were similar during the 1982-89 and 1990-1995 time periods (Figure 2.10). However, chlorophyll *a* concentrations were lower during the 1999-2004 period relative to the two previous periods. The decrease was greater in inner and mid-archipelago stations (at least out to Trälhavet) than towards the outer region. In contrast, during the spring the average chlorophyll *a* concentrations were higher during the 1990-1995 period in parts of the inner archipelago (Blockhusudden and Halvkakssundet) than during either 1982-1989 or 1999-2004. However, in the mid-archipelago (past Solöfjärden), spring chlorophyll *a*

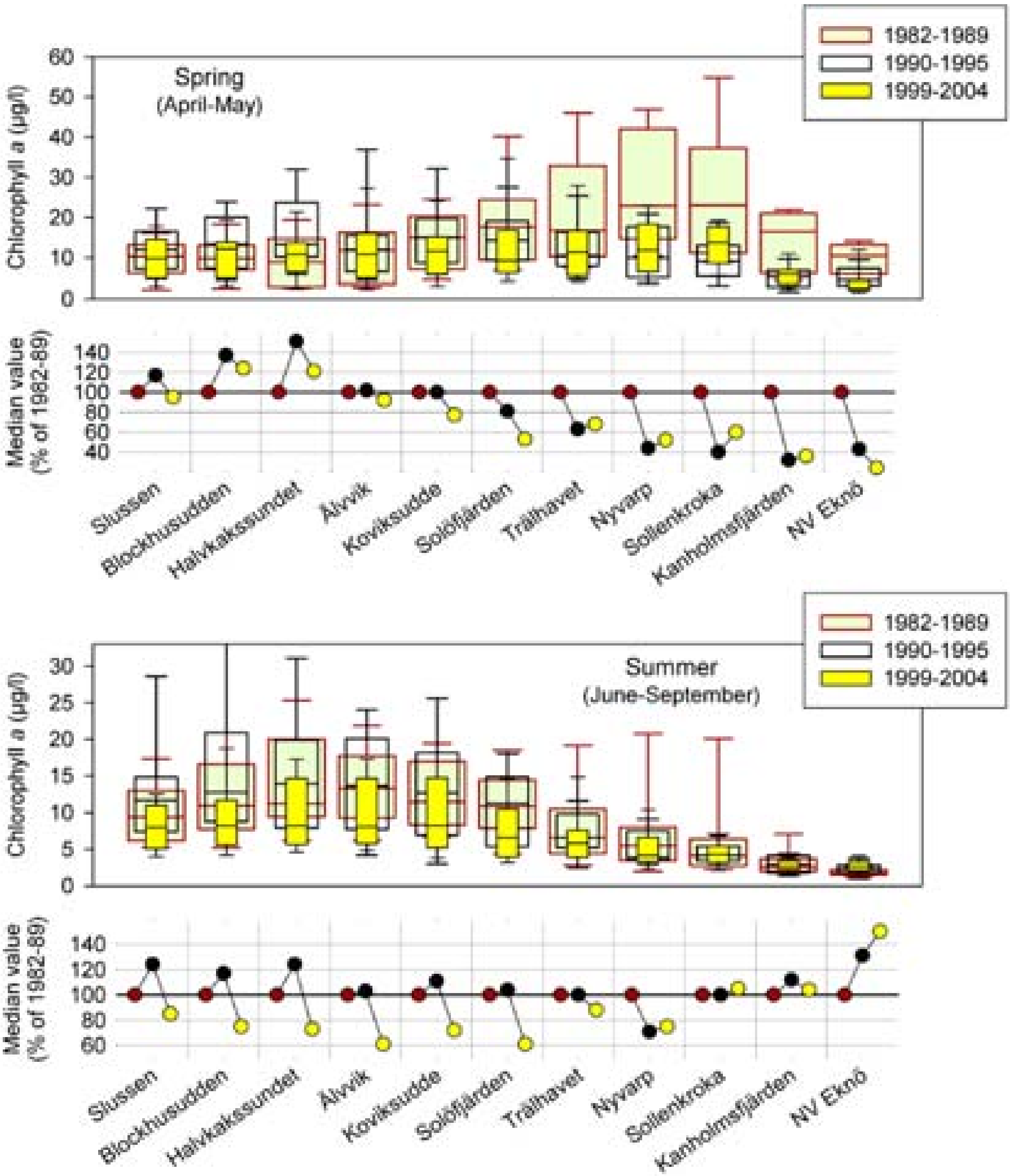


Figure 2.10. Surface chlorophyll *a* concentrations in the Stockholm Archipelago (inner to outer regions) during the spring (April-May) and summer (June-September) for various time periods (Lännergren and Eriksson 2005).

concentrations were substantially lower in the 1990-2004 period relative to the 1982-1989 period. This was apparent already in the 1990-1995 (low flow) time frame. The increases in spring chlorophyll *a* concentrations after 1982-89 at the inner stations at Blockhusudden and Halvkakssundet are somewhat of an enigma, as the loadings of both N and P were reduced (Figure 2.4). A possible explanation is the relocation of the ammonia-rich discharge of the Bromma plant into waters of the inner archipelago. The summer decrease in chlorophyll *a* was most evident only following implementation of more advanced nutrient reduction at the STPs.

A seasonal shift in the period of peak phytoplankton biomass, as measured by chlorophyll *a* concentrations, in the mid-archipelago has also been noted (Figure 34B in Lännergren and Eriksson 2005). Peak blooms were observed in June in the mid-1980s but in May at Trälhavet or even in April farther out at Kanholmsfjärden during the last 10 years. Coupled with the declining summer DIN concentrations (Figure 2.9) and low DIN:DIP ratios, this suggests that peak phytoplankton production is now declining earlier as surface DIN supplies are depleted.

Secchi depth also increased following nutrient removal implemented in the 1990s (Figure 40A in Lännergren and Eriksson 2005). Since 1997 the average Secchi depth has been greater during each summer than the previous decade of record (including the low outflow years in the early 1990s) extending out at least as far as Sollenkroka. Spatial, seasonal and interannual patterns of Secchi depth are strongly related to surface chlorophyll *a* concentrations (Figure 36 in Lännergren and Eriksson 2005).

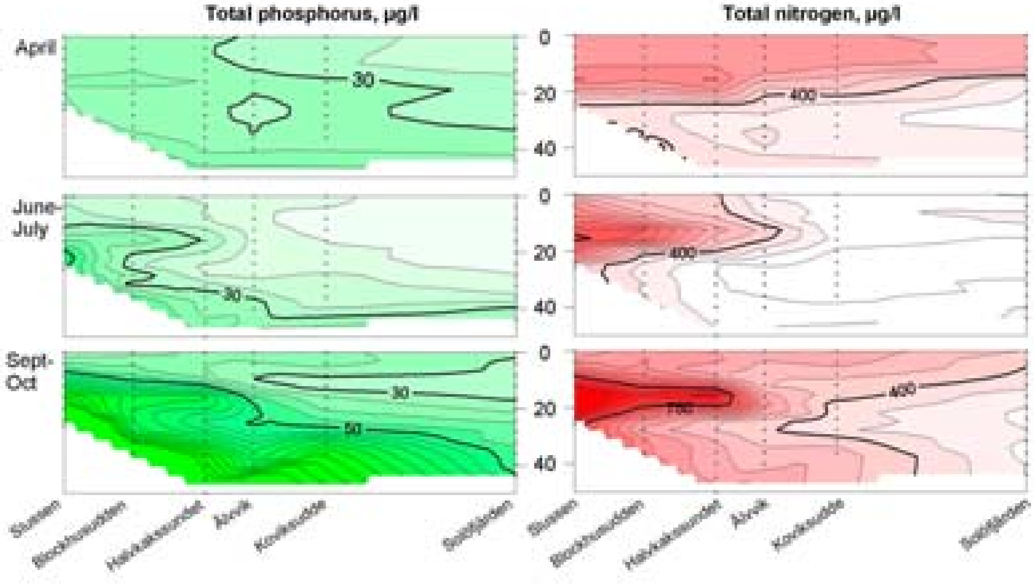


Figure 2.11. Vertical distribution of total phosphorus and total nitrogen concentrations along the waters of the inner archipelago. The STP inputs strongly influence the distribution of TN, but internal loads from benthic release dominate the seasonal and spatial dynamics of TP. (Lännergren and Eriksson 2005).

Based on consideration of the three-dimensional (distance-depth-time) patterns of nutrient concentrations, a reasonable explanation of these changes in chlorophyll *a* concentrations and water clarity is that they were responses to N loading from the STPs. While changes that were becoming evident in the early 1990s might have been due to low outflows from Lake Mälaren between 1989 and 1994, substantial improvements observed during 1999-2004 occurred during a period in which outflows were at or above the long-term average (Figure 2.4). Surface DIN concentrations declined over essentially the same spatial extent as and coincident with the decline in chlorophyll *a* concentrations, while reductions in surface DIP were confined to the inner archipelago where chlorophyll *a* also dropped. Although the advanced waste treatment implemented during the 1990s did reduce STP loadings of TP by about half (Lännergren and Eriksson 2005), these loadings were already relatively low. These further reductions constituted only about a 7% decrease in loadings of TP or DIP (including Lake Mälaren), while the N removal at the STPs reduced annual DIN loadings by about 40%. Furthermore, the vertical distribution of nutrients (Figures 24 A-C in Lännergren and Eriksson 2005) gives the strong impression that the dominant source of P for phytoplankton growth, except for the innermost archipelago, is currently benthic phosphate release (internal loading). This is supported by the presentations of Lännergren and Eriksson (2005) of: higher surface phosphate concentrations in the winter in the inner-mid-archipelago than in Lake Mälaren (Figure 26 in Lännergren and Eriksson 2005), the dominant land-based source of P; seasonal longitudinal sections of the vertical distribution of TP and TN along the inner archipelago (Figure 32 in Lännergren and Eriksson 2005, reproduced here as Figure 2-11); budgets that suggest that the inner archipelago exports more P than it receives from land-based inputs (Figure 33 B in Lännergren and Eriksson 2005); and the strong coupling of density stratification, oxygen deficiency, and bottom water phosphorus concentrations in basins at Kanholmsfjärden and NO Stora Möja in the outer archipelago (Figure 19 in Lännergren and Eriksson 2005). Consequently, the significant improvement in oxygen concentrations in the inner archipelago from Slussen to Koviksudde since 1995 (Lännergren and Eriksson 2005) may have contributed to reduced DIP in surface waters of the inner archipelago even more than the reductions in external loading. Although currently not fully quantified, the internal loading of P should decline over time especially where oxygen conditions are improving dramatically.

2.1.4 Littoral macroalgae

Currently, littoral filamentous algae occur in high biomass on the rocks surrounding many of the islands throughout the Stockholm Archipelago. There is anecdotal evidence that littoral filamentous algae have increased and that *Fucus vesiculosus* has decreased in recent years. However, it appears that there are few long-term studies documenting this change or addressing the causes of such a change in the Stockholm Archipelago. In the Öregrund archipelago, changes in the macroalgal vegetation between the late 1990s and the early 1940s and 1960s were recorded (Eriksson et al. 1998). They confirmed the decreased depth penetration of *Fucus vesiculosus* reported in the 1984 study of Kautsky et al. (1986). The weighted average depth of the *Fucus vesiculosus* belt in 1996 was about 1.7 m shallower than in the early 1940s, and the lower distribution limit of this species was about 2.5 m shallower. The results for *Spacelaria* and *Cladophora* were not always consistent with major changes between 1940s and the late 1990s. A number of factors, including eutrophication, could have contributed to the observed changes in macroalgal distribution, including increasing sedimentation. Further investigations addressing the specific causes are needed as the increase in littoral filamentous algae and decrease in *Fucus* are of considerable concern not only in the Stockholm Archipelago, but other regions as well (Stockholms marina forskningscentrum 2000).

2.1. 5 Bottom waters

The increasing area of regions with anoxic bottom water in the Stockholm Archipelago through at least the mid-1990s is indicated by an extensive analysis of sediments cores taken in the inner, mid and outer archipelago (Jonsson 2003). Laminated sediments, due to the absence of sediment mixing by infauna, are one indication of the occurrence of hypoxic bottom water. They do not necessarily indicate permanent hypoxia as a few short hypoxic events can kill the benthic fauna, which therefore drastically decreases sediment mixing.

As early as the 1930s, 40% of the soft bottom area of the inner archipelago exhibited laminated sediments indicative of hypoxic conditions (Figure 2.12). Laminated sediments occurred in only about 10% of the middle archipelago and essentially none of the outer archipelago at that time. By the 1950s the extent of laminated sediments had increased in all areas; almost 80% of the inner, 40% of the middle, and 10% of the outer soft bottom area are estimated to have had laminated sediments by the 1950s. Following the decrease in P loading in 1971, the laminated sediment area began to increase again in the inner archipelago, from 60-~80% by the mid 1980s. The middle and outer regions continued to increase as well until, by 1990, 80% of the inner and mid, and 65% of the outer archipelago had laminated soft bottom sediments (Jonsson 2003). From 1990-1996/7 (most recent year for which data are available), the extent of laminated sediments has remained relatively constant, with possibly a decrease in the outer region. Cores

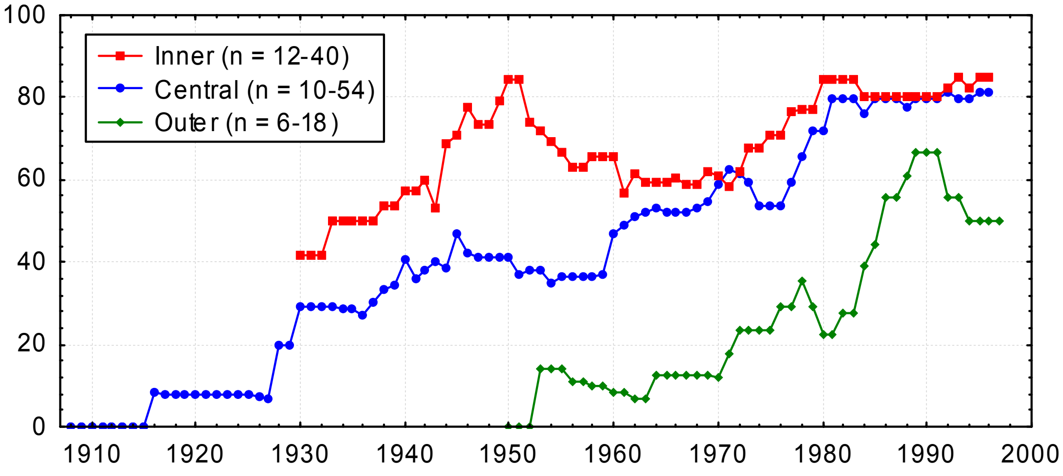


Figure 2.12. Percent of area of soft bottoms covered by laminated sediments in the Stockholm Archipelago (Jonsson 2003).

taken more recently from locations in the northern and southern parts of the outer archipelago show some signs of bioturbation activity (P. Jonsson, personal communication), but it is not possible to say if this is a definite or widespread trend.

There is no indication that a reduction in land-based P inputs has decreased the area of laminated sediments or anoxic bottom waters in the Stockholm Archipelago (Jonsson, 2003). This may have been due to the delays in equilibration of organic-rich sediment with reduced loadings, which is known to require 10-20 years in some freshwater lakes (Soendergaard et al. 2002). However, it has been 30 years since the ten-fold reduction of STP loadings of P; the lack of response could also be due to the continued inputs of organic matter in the inner and mid-archipelago even after reductions in P loading and to the greater export of N to the mid and outer archipelago particularly during the spring as the inner and mid-archipelago became P-limited (Figure 2.11). This has been observed in other estuarine systems where the imposition of P limitation through reduction of P point-source inputs at the head allowed more N to be advected down-estuary where it fueled production that worsened hypoxia (Paerl et al. 2004).

While the time course of development of laminated sediments, particularly prior to 1970, in the Stockholm Archipelago is consistent with the trend of nutrient loading from land-based sources, it must be noted that other areas outside the Stockholm Archipelago without significant nutrient inputs from land-based sources show a similar trend in area of laminated sediments (Jonsson 2003). The occurrence of bottom water hypoxia is a multifactorial problem involving both stratification strength and bottom water temperature (physical factors) and inputs of organic matter (eutrophication connection).

Isolation of bottom waters from the sources of oxygen in surface waters due to increases in the strength and duration of stratification may be as important as eutrophication status. Nonetheless, there are encouraging signs of a trend toward higher summer oxygen concentrations in bottom waters at some stations in the inner archipelago region following the implementation of advanced nutrient removal in the 1990s (Figure 20 in Lännergren and Eriksson 2005). Further in-depth analysis of the causes of laminated sediments and bottom water hypoxia and their recovery in Sweden's coastal sediments are needed in order to more fully evaluate this trend. Alleviation of severe oxygen depletion of bottom waters is a very important factor in reducing phosphorus availability to phytoplankton and attached algae in the Stockholm Archipelago.

2.1.6 Actions taken and their effects

Between 1968 and 1973 sewage treatment plants (STPs) in the Stockholm Archipelago area (including those entering Lake Mälaren) implemented P removal and biological treatment. Following reductions in land-based P inputs, TP and DIP concentrations decreased dramatically in the inner-mid archipelago. Total N:P ratios in the recipient waters increased from about 10:1 (1970) to 20:1 (early 1990s) and inorganic N:P ratio increased from 1:1 to >20:1 as inorganic N concentrations increased markedly (June to September means up to 40 to 80 µg/L inorganic N). Chlorophyll *a* concentrations decreased by about 50% in the inner archipelago and the abundance of

Cyanobacteria (N-fixing and non-N-fixing) decreased considerably. Thus, the extensive reductions in P input moved the system from limitation of primary production by N toward limitation by P.

N removal in the STPs began in the early 1990s and was fully implemented in 1996, following which there was a further reduction of 15 to 40% in chlorophyll *a* concentrations during the summer (1999-2004 period compared with 1982-1989) in the inner and mid archipelago (from Slussen to Nyvarp, Figure 2.10). Although P loading from the STPs also decreased at the same time, this source of P was small compared to reductions that had been previously achieved, P inputs from Lake Mälaren and from internal loading from P release from sediments (although STP loads are an important source of P from June to August). Although rates of internal loading have not been fully quantified, seasonal dynamics of TP in the water column and estimated net export of TP from the inner archipelago (Figure 33B in Lännergren and Eriksson 2005) indicate that this is a major source of P in this system. Currently, both DIN and DIP concentrations in surface water in summer are below their respective detection limits from at least the outer portion of the inner archipelago (Figure 28 in Lännergren and Eriksson 2005). However, phytoplankton can still grow at significant rates at these low nutrient concentrations. The decrease in chlorophyll *a* and increase in Secchi depths with reduced STP N loadings support the view that reduction in N loading had positive effects on the archipelago waters. However, the complex factors that regulate internal loading of P, including gradual depletion of sediment reservoirs and dissolved oxygen conditions, are likely also important and merit further research.

There were large increases in the extent of laminated sediments, indicative of high organic matter inputs and anoxic bottom waters, from the early 1900s through at least the mid 1990s. The initial increase in areal extent corresponded to increases in nutrient inputs; however, reduction in P loadings from point sources in the early 1970s did not reverse this trend. While there is some sign of improving oxygen conditions in the inner archipelago following N removal, it is too early to conclude that there has been a direct effect on the extent of hypoxia. The interrelationships of N and P limitation, primary production and bottom water hypoxia are complex, involving nutrient uptake dynamics, stratification and mixing, and multi-layer estuarine circulation. Reduction in organic production in surface waters (as reflected by the observed decreases in chlorophyll *a* levels) is likely to result in decreased oxygen consumption in bottom waters, less severe hypoxia and reduced P-release from bottoms sediments. The trajectory of restoration of eutrophic coastal ecosystems is a nonlinear process with amelioration of hypoxia playing an important role and characterized by relatively dramatic thresholds of recovery (Boesch et al. 2001; Kemp et al. 2005).

The cause/effect relationship between the increase in littoral filamentous algae and the decrease in *Fucus* is not well documented for the Stockholm Archipelago and waits further assessment. With demonstrable improvements in light environment throughout the Stockholm Archipelago since the 1990s the conditions of benthic algal growth should improve.

2.1.7 Conclusions for the Stockholm Archipelago

- N appeared to be the nutrient most limiting to phytoplankton production in the late 1960s/early 1970s in the Stockholm Archipelago. At this time rates of N and P loading from anthropogenic sources were high; P concentrations were in surplus; the N:P ratios of land-based inputs and of waters in the archipelago were low (about 6:1); and summer chlorophyll concentrations were high. Cyanobacteria were abundant in summer.
- Large-scale P removal from STPs in the late 1960s/early 1970s imposed P limitation on the archipelago and resulted in substantial reductions in algal biomass and Cyanobacteria in the inner Stockholm Archipelago.
- N removal in the STPs was implemented in the 1990s. Monitoring results suggest that the decrease in N loading from the STPs and perhaps also a decline in P loading (mainly internal loading) contributed to the recently observed (1999-2004) decreases in DIN, DIP, chlorophyll *a*, and greater water clarity in the inner and mid-archipelago.
- Although N and P from STPs have been dramatically reduced, nutrient inputs to the Stockholm Archipelago from land-based sources are still substantial, internal sources of P in the sediments remain likely large and poorly quantified, and chlorophyll *a* concentrations are still relatively high compared to many other east coast waters. Reduced nitrogen and phosphorus inputs are likely to reduce algal production further. STP discharges remain an important source of reactive N, and the drainage basin of Lake Mälaren is an important source of both elements. Atmospheric sources of nitrogen may be important as well.
- Local inputs of N and P to the Stockholm Archipelago from the increasingly large year-round population on the islands, in addition to an increasing summer recreational use of the Archipelago, are of potential concern with regard to future localized increases in eutrophication.
- While working to further reduce eutrophication, attention must be paid to managing loadings so that the ratio of available N to available P in surface waters does not drop so low as to create the risk of inducing the growth of N-fixing and/or noxious Cyanobacteria.
- Continued monitoring and in-depth studies of the physical, chemical, and biological conditions in the Stockholm Archipelago are needed to understand the cause of degradation of the archipelago ecosystem and to track future changes in the ecosystem. Research on the factors regulating the internal loading of P is needed to resolve critical unknowns. Water quality objectives should be set against which future management actions can be evaluated. Modeling of the circulation and nutrient sources within the Stockholm Archipelago should be conducted to guide further nutrient abatement strategies.

2.2 Himmerfjärden

Himmerfjärden (Figure 2.13) is a 232 km^2 coastal fjord-like inlet of the Baltic Sea located 60 km south of Stockholm at 59^o 00' N, 17^o 45'E. The fjord has a mean depth of 17 m and a maximum depth of 52 m. The water is brackish (6 psu) with very little fluctuation (±2 psu). The fjord is connected to Lake Mälaren by a sluiceway near the northern end, which flows when water levels in the lake are high.

The drainage basin has an area of 1,282 km^2, covered by a mixture of forest and agricultural land. Until 1974, Himmerfjärden received only a small amount of sewage that received primary treatment. It also received water containing substantial amounts of nutrients from the Mälaren sluiceway and a number of smaller streams. The former is the most important source of diluting water, averaging 187 million m^3 per year (Elmgren and Larsson 1997). While comparison of the annual inflow and direct precipitation volume to the volume of the Himmerfjärden suggest a slow water renewal time of about 5 years, because of estuarine circulation and other baroclinic and barotropic processes at the Baltic boundary, the retention times in the four basins range from 1 to 5 months (Engqvist 1996).

Figure 2.13. Map of the Himmerfjärden, showing long-term monitoring stations.

2.2.1 Nutrient sources and trends

The discharge of sewage to Himmerfjärden began in response to attempts to recover Lake Mälaren, which was suffering badly from eutrophication in the mid-20th century (Ahl 1975; Willén 2001). Phosphorus inputs to the lake began to be reduced in the late 1960s, in order to recover the lake (Wilander and Persson 2001). One of the actions taken was to divert sewage that had once gone into the southern part of Lake Mälaren to Himmerfjärden, after treatment that included removal of phosphorus.

The tertiary-treated sewage (i.e., with substantial P removal) began to be discharged to Himmerfjärden in 1974. It is discharged at a depth of 25 m, at least initially remaining below the thermocline when the fjord is stratified, but eventually mixing throughout the water column. Initially, the sewage treatment plant (STP) served 90,000 people. The population served by the STP increased rapidly during the 1970s and 1980s, eventually reaching 240,000. Phosphorus removal from the sewage averaged 96 % and the total phosphorus discharged from the STP was 7 to 20 tonnes per year over the period from 1974 to 2004 (Figure. 2.14). An exception was 1983-84, when 31 tonnes of P were deliberately released, to test whether primary production in the bay was limited by P or N.

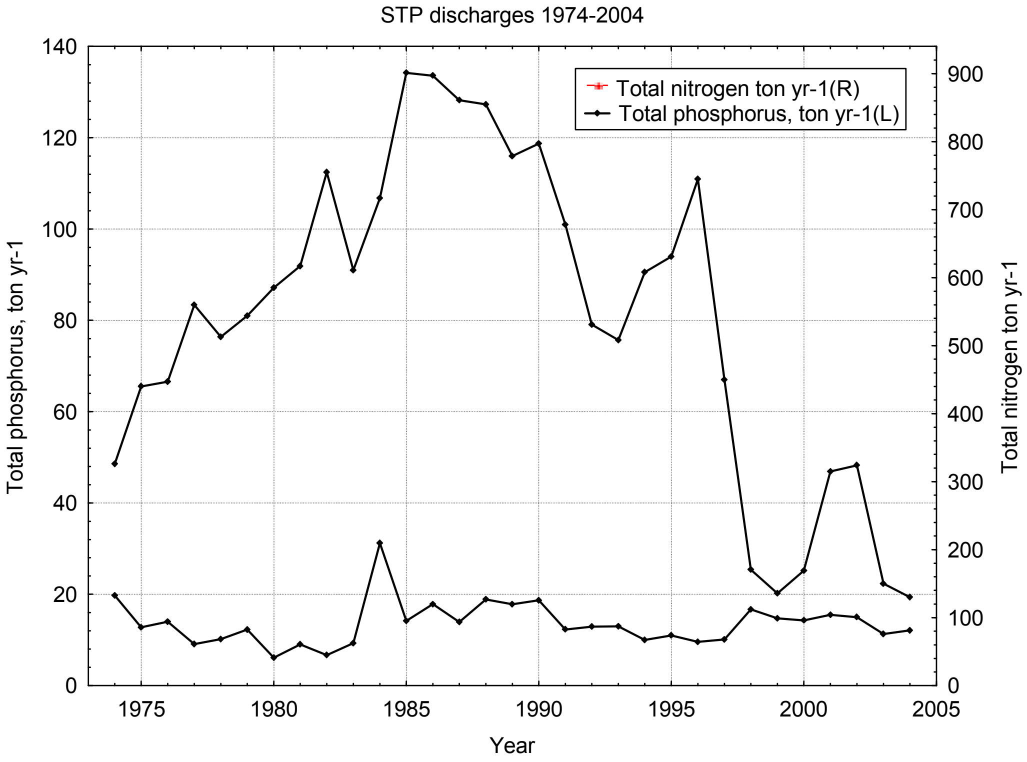


Figure 2.14. Nutrient inputs to Himmerfjärden from the sewage treatment plant. Discharge of tertiary-treated sewage (96% phosphorus removal) began in 1974. Partial nitrogen removal began in 1993 and increased until 1998, except in 2001 and 2002, when there was deliberate experimental increases in nitrogen discharge. Data from R. Elmgren and U. Larsson.

In contrast, nitrogen discharge in the sewage increased rapidly from about 280 tonnes per year to over 900 tonnes per year in the mid 1980s. Beginning in 1993, nitrogen was progressively removed from the effluent. From 1998 onward, discharge was about 140 tonnes per year except in 2001-2002, when N release was deliberately increased to slightly over 300 tonnes per year to test impacts on Cyanobacteria in the fjord. An efficiency of N removal of 85 % was attained after 1998 except in 2001-2002 when the deliberate increases in N discharge occurred.

Considerable amounts of nutrients also reach Himmerfjärden from other sources. During the period 1976-1994, from 400 to 800 tonnes per year of nitrogen and 17 to 40 tonnes per year of phosphorus passed through the sluiceway from the Lake Mälaren outflow or from other diffuse sources (Engqvist 1996; Savage et al. 2002). There is no apparent long-term trend in either element from these sources during this period (Savage et al. 2002). While data for diffuse sources are not available for the last several years, averages for inputs from Lake Mälaren and diffuse sources (Anonymous 1997; Savage et al. 2002) indicate that in recent years the STP supplied about 36 percent of the phosphorus and 54 percent of the nitrogen from land-based sources (Engqvist 1996; Savage et al. 2002). Because of bi-directional exchanges with the Baltic Sea, nutrients are also supplied to the Himmerfjarden from the sea as well as from the land. Because measured imports of P are nearly in balance with the measured exports (Engqvist 1996), the contribution of P from the sea must approach that from land-based sources. Nitrogen, on the other hand, is more strongly and consistently exported, especially from the inner basins (including the basin in which H4 is located). Especially when losses of denitrification are considered, this indicates that land-based inputs of N are considerably larger than inputs from the sea.

Development of bioavailable nutrient budgets for the Himmerfjärden is difficult because of the various nutrient forms. It is not only the quantity but also the quality of nutrients that is important in determining their effects. Generally over 80% of the TN and 50% of TP in STP effluents are in dissolved inorganic form (based on data for the major STPs in Stockholm Archipelago discussed in the preceding section). In contrast, diffuse source nutrients may be largely organic and/or particulate, and thus less available to algae. For example, since 1990 53% of the TP but only 36% of the TN in the Lake Mälaren outflow into the Stockholm Archipelago has been dissolved inorganic (Stockholm Vatten data). Data on nutrient forms in STPs and diffuse sources to the Himmerfjärden were not available but are likely similar to those indicated above.

2.2.2 Phytoplankton chlorophyll

Himmerfjärden has not been highly eutrophic at any time. Its average chlorophyll concentration prior to nitrogen removal at the STPs was mesotrophic when compared to the trophic classification for lakes (Wetzel 2001). More recently it has been in the border region between mesotrophic and oligotrophic. Based on its phosphorus loading of 0.1 to 0.2 g P/m^2/yr from point and diffuse sources, it is comparable to oligotrophic Lake Huron or Lake Vänern (Wilander and Persson 2001). Throughout the period the Himmerfjärden would be classified as mesotrophic for estuarine and coastal waters based on organic carbon supply (Nixon 1995).

Phytoplankton chlorophyll *a* concentrations were measured with consistency from 1977 onward. At central station H4 (Figure 2.13) there was a variable but declining trend in annual average chlorophyll *a* concentration prior to 1998, followed by somewhat lower concentrations thereafter (Figure 2.15). In contrast, chlorophyll *a* levels at reference station B1, located outside of the Himmerfjarden (Figure 2.13), did not vary much and show no secular trend over the period of record. The generally higher chlorophyll *a* concentrations prior to 1989 appear to be associated with a climate pattern of cold winters, late springs and more storm mixing in contrast to the milder winters, warmer summers and prolonged stratification since then (Elmgren, personal communication).

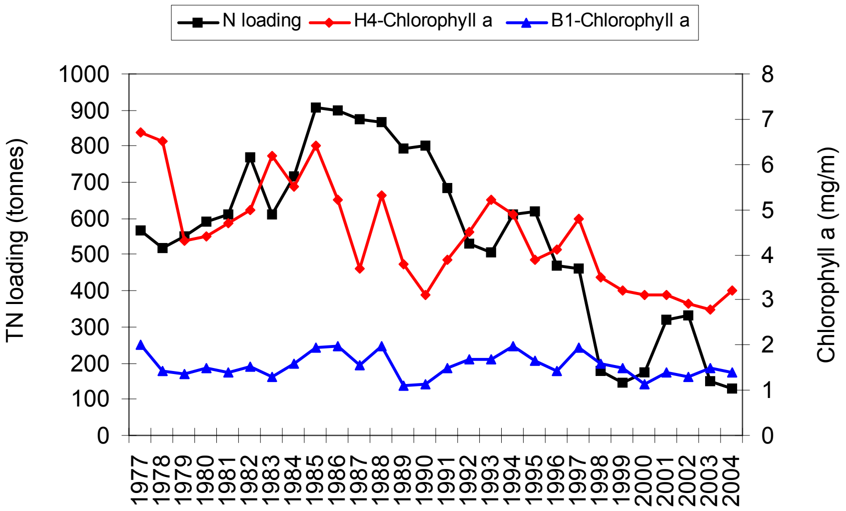


Figure 2.15. Trends in yearly mean chlorophyll a at station H4 in Himmerfjärden and at B1 (see Figure 2.13) in relation to changes in total nitrogen loading from the sewage treatment plant. Data from R. Elmgren and U. Larsson.

Some of the variability, for example lower annual mean concentrations for 1989 and 1990, due to anomalously early or modest spring blooms, is apparent at both H4 and B1. Chlorophyll *a* concentrations at H4 following full implementation of N removal (1998-2004, except for 2001-2002) averaged nearly one half of those in the preceding seven years and were significantly lower for both spring and summer (R. Elmgren, personal communication). While mean Secchi depth in spring increased slightly at H4 after N removal began, the differences were not statistically significant in summer (Figure 2.16).

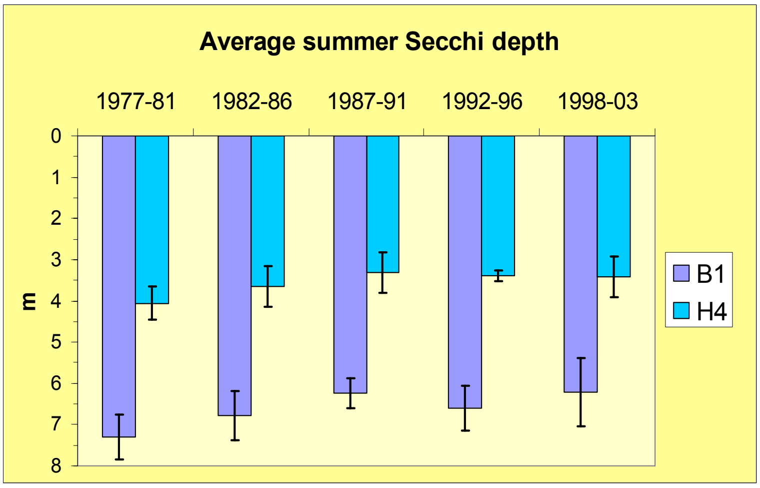


Figure 2.16. Summer Secchi depth at station H4 in Himmerfjärden and at reference station B1. There are no significant differences in Secchi depths during periods when nitrogen removal was in place. Figure from Elmgren and Larsson (unpublished).

2.2.3 Cyanobacteria

An increase in nitrogen-fixing Cyanobacteria (chiefly Aphanizomenon) followed within a year of full N removal at the STP (Figure 2.17), increasing to about 50 % of phytoplankton biomass on a very few occasions (R. Elmgren, personal communication). However, it is noteworthy that annual average chlorophyll *a* was only about 3 µg/L at the time. It is significant that the increase in Cyanobacteria occurs as the DIN/DIP ratio in water declines to below Redfield ratios.

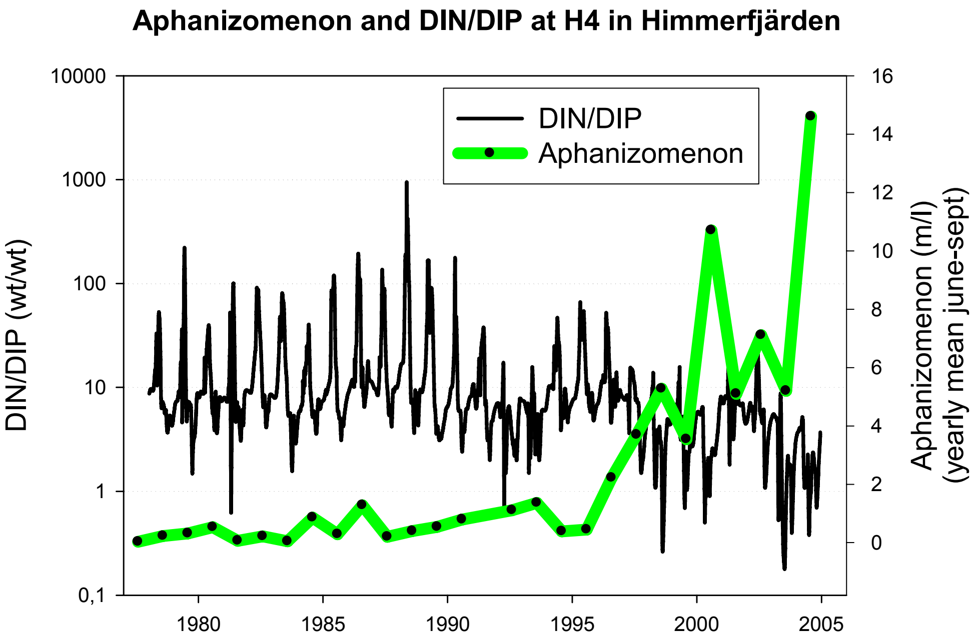


Figure 2.17. The trend in abundance of *Aphanizomenon* at station H4, Himmerfjärden. Units are meters of filament per liter of water. Note the increase in abundance during the period when nitrogen was removed from sewage entering the fjord and the DIN/DIP ratio decreased below Redfield ratios. Data from Ragnar Elmgren and Ulf Larsson (unpublished).

2.2.4 Other ecosystem components

There are no data available for time trends in phytoplankton production, attached filamentous algae, macroalgae, macrozoobenthos, or extent of anoxic zones that encompass the period of change in N removal from sewage effluent, although Savage et al. (2002) noted an increase in diversity of biomass of bivalves and amphipods from 1988-1994. These investigators analyzed a 23-year record (1972-1994) of macrobenthic communities in the Himmerfjärden. Both species abundance and biomass of common genera (*Macoma balthica*, bivalve; *Monoporeia*, amphipod) increased in the first several years and then declined as nutrients increased further. The period of record that they analyzed included only the first few years after N-removal so an accurate assessment of long-term recovery is not possible.

Excessive growth of filamentous macroalgae and impaired *Fucus* have also been observed in the Himmerfjärden. Filamentous algae are more luxuriant and greener closer to the STP discharge. Although there are anecdotal observations that the cover of filamentous algae has declined following removal of N from the sewage discharge, there are no published results from systematic monitoring that document such an improvement.

2.2.5 Discussion

The Himmerfjärden case study demonstrates the complexity of responses to anthropogenic nutrient enrichment in estuarine ecosystems in which both nitrogen and phosphorus can play roles in different times and places and where environmental processes and dynamics are critical factors. While there are uncertainties that could not be addressed because of the lack of information or insufficient time available to the committee, the following presents a plausible explanation of the responses of the ecosystem to inputs and abatement of anthropogenic nutrient inputs that is consistent with the observations and general knowledge of processes involved.

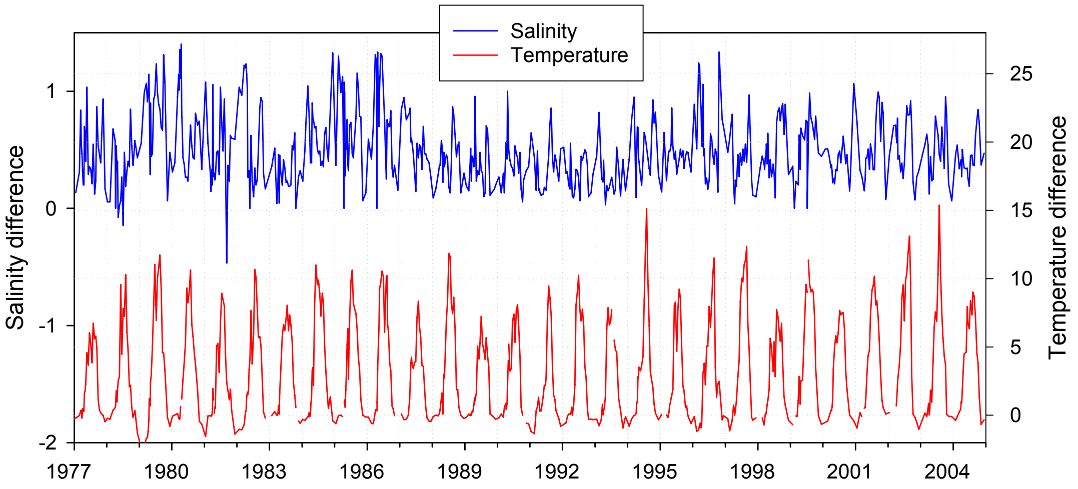


Figure 2.18. Temperature and salinity differences between surface and deep waters at station H4.

In contrast to the Stockholm Archipelago, the Himmerfjärden never received large inputs of P from STP or experienced associated dense blooms of Cyanobacteria. P was largely removed from the beginning of STP discharges. The P to support phytoplankton production, therefore, comes largely from diffuse-source inputs, advection of bottom waters from the P-rich Baltic, and, as in the Stockholm archipelago, internal recycling from bottom sediments, the latter stimulated by anoxic conditions in these brackish waters (Blomqvist et al. 2004). Chlorophyll a levels in the central Himmerfjärden (H4) were substantially higher a few years after the STP began discharging than they are today, but did not increase as N loadings increased from the STP between 1977 and 1985 (Figures 2.14 and 2.15). The reason for this is made clear by Figure 2.17, which suggests that phytoplankton growth under these N-enriched conditions was generally P-limited (Elmgren and Larsson 2001a). The excess N available supported higher biomass, but the production of that biomass was probably regulated by allochtonous or regenerated P sources controlled primarily by climactic variability, e.g., mixing that erodes density stratification (Figure 2.18), thus making regenerated P from deeper waters available to support production in surface waters.

Reductions in N loading from the STP began after the shift in climatic conditions (to warmer temperatures with earlier springs and fewer storms) that also depressed chlorophyll *a* concentrations. Although STP inputs of TN are small in comparison to the diffuse-source loadings, as in the Stockholm Archipelago, a notable decline in DIN in the receiving waters was observed concomitant with N removal at the STPs. This is apparent in the declining DIN:DIP ratio that began to approach and occasionally fall below the Redfield ratio (Figure 2.17) from 1992 on. From that point N became the more regularly limiting nutrient with N discharges from the STP (mostly as DIN) regulating the annual average chlorophyll *a* concentrations (Figure 2.14). With the increased N-limitation, Cyanobacteria able to exploit the available P by fixing N realized a competitive advantage in the late 1990s. At that point, the operators of the STP began to experiment with reducing the rate of N-removal. However, doubling the N input from the STP in 2001-2002 did not affect the observed chlorophyll *a* concentrations (Figures 2.14 and 2.15). The two short periods of experimentally increased release of nitrogen (2001-2002) and phosphorus (1983-1984) appear to have been too small and/or too short to cause a noticeable response in chlorophyll *a* concentrations.

2.2.6 Conclusions for the Himmerfjärden

- The Himmerfjärden was never eutrophic and also never experienced the dense Cyanobacteria blooms that were found in the inner Stockholm Archipelago when it received large phosphorus emissions from sewage treatment plants. The treatment (up to 96% P removal) of STP discharges into the Himmerfjärden that began in 1974 avoided that response.
- Although there is a lack of data prior to the start up of this STP discharge, it is likely that it resulted in modest eutrophication of the Himmerfjärden as evidenced by elevated chlorophyll *a* levels. The increased biomass was stimulated by N discharges from the STP, but controlled by the available P in the receiving waters,

which in turn is regulated primarily by internal recycling and allochthonous sources rather than by point source emissions.

- Reduction of N discharges from the STP (by as much as 85%) in the late 1990s lowered DIN levels and, once they were reduced to limiting levels with respect to available P, eventually reduced chlorophyll *a* levels and increased water clarity. From this perspective, the advanced waste treatment accomplished its objective of reducing eutrophication. However, there is disagreement among committee members regarding of the degree to which nitrogen removal by the STP reduced chlorophyll *a* levels and eutrophication.
- However, as the system became more regularly nitrogen limited, Cyanobacteria populations (*Aphanizomenon*) increased in mid-summer, although apparently not to levels that are noxious or contribute a large new source of fixed N. Limited experimental efforts to increase N discharges to control Cyanobacteria blooms were not successful. Balancing the benefits of N reduction in reducing phytoplankton organic production with the risks of Cyanobacteria blooms remains an important management challenge.
- A definitive evaluation of the effects of nitrogen removal on ecosystem properties other than chlorophyll and phytoplankton requires further assessment.
- Attempts to remove more nitrogen or phosphorus at the STP will not make a significant difference in the condition of the bay because nutrient inputs are low compared to remaining diffuse and internal sources.

3 Open Baltic Proper

3.1 Symptoms and trends of eutrophication

3.1.1 Development of eutrophication in the Baltic Sea

The first concerns about the eutrophication of the Baltic Sea emerged in the 1960s when long-term trends in declining oxygen concentrations in the deeper waters between 150 and 400 m were reported in the deep basins raising concerns about loss of fish habitat and production for demersal fishes (Fonselius 1969; Rosenberg et al. 1990). These deep basins lie within the Baltic Proper (*sensu* Rahm and Danielsson 2001) that lies south of the Gulf of Bothnia and excludes the shallower Gulf of Finland. Concern about extent of anoxia in these deep basins of the Baltic Proper continues today although the extent of the anoxic areas is known to fluctuate over years and decades. Extent of anoxia is strongly dependent on the flows of more saline waters into the Baltic Sea through the Straits of Denmark and intervening periods of stagnation (Stigebrandt 2001; Conley et al. 2002; Fonselius and Valderrama 2003). The anoxic conditions result from the strong stratification causing isolation of the annually mixed and ventilated waters above the halocline (currently at approximately 70 m depth) and the loading of organic matter by sedimentation through the halocline. Eutrophication of surface waters aggravates this natural deoxygenation of deeper waters when surface waters become more productive of organic matter in response to increased anthropogenic loading of critical nutrients that stimulate algal growth, and the resulting growth sinks and decomposes in deeper waters. This eutrophication effect is imposed on physical changes in the Baltic Proper due to changing balance of freshwater inflow and marine saline inflows. Fonselius and Valderrama (2003) found no trend in salinity in the Baltic over the twentieth century despite significant fluctuations due to variability in seawater inputs and freshwater flows. They identified a continuing century-long decline in oxygen concentrations in deep water, and concluded that there was evidence of a warming in intermediate deep waters on the order of one to two degrees over the century. Such warming could accelerate the deoxygenation of waters below the halocline by increasing the rates of decomposition of sedimenting organic matter.

Increased abundance of phytoplankton that absorb and scatter downwelling light can affect light penetration measured as the Secchi depth. Therefore, reduced Secchi depth is also an early and progressive symptom of eutrophication. This simple measure provides perhaps the first quantitative evidence of declining water quality in the Baltic. Comparison of visibility measurements made between 1914 and 1939 in the surface waters of these deep basins of the Baltic Proper with similar measurements between 1969 and 1991 indicate a mean rate of visibility loss of 5 cm per year. A trend analysis of regular measurements between 1969 and 1991 indicates a continuing decline of similar magnitude (Sanden and Håkansson 1996). This decline in visibility can be related to an increase of primary productivity by >1% per annum in the phytoplankton over that time period or nearly a doubling in the annual rate of primary production. Based on such an increase and assuming a constant proportion of the annual production is lost to sediments, a two-fold increase in annual loading of organic matter from phytoplankton production to the deep waters likely has occurred. Increased loading of organic matter to the deep water below seasonal thermoclines and haloclines will lead to increased oxygen consumption which can exceed the rate of reoxygenation that is dependent on mixing downward of well oxygenated surface waters. If rates of oxygen consumption are high enough compared to rates of exchange with surface waters, anoxia can result. The areal spread of anoxia over time has been documented in sediment cores (Persson and Jonsson 2000). This stratigraphic analysis indicated that anoxia began to increase in the deeper waters of the Baltic in the 1940s and extended into shallower isolated basins in the Stockholm Archipelago where anoxic bottoms expanded rapidly in the 1960s. Ratios of stable nitrogen isotopes in the sediment profile of a Swedish coastal embayment indicate that catchment yields of nutrients already began to increase in the late 1800s (R. Elmgren, personal communication). Eutrophication has been occurring for at least a century in the Baltic Proper, and it is likely that is has been accelerating along with population growth and economic development since the 1950s. Today the Baltic Proper is the most productive of the major basins of the Baltic (Hagström et al. 2001) and experiences nuisance, and potentially toxic, algal blooms. Consequently the Baltic Proper is a focus of concern and a target for restoration, but there is debate about the most effective means to accomplish restoration of the Baltic Proper because of its complex nutrient loading and cycling characteristics.

3.1.2 Nutrient concentrations and sources to the Baltic Proper

Carbon, nitrogen and phosphorus are critical nutrients for all phytoplankton and silicon is essential for the growth of diatoms, an abundant phytoplankton group that is efficiently used by invertebrate consumers and is often a critical component of productive aquatic food webs. These nutrients are delivered to the Baltic Proper by quite different pathways. Carbon is taken up as CO_2 from solution. Geochemical weathering and the atmosphere maintain dissolved CO_2 concentrations through relatively rapid atmospheric exchange. Consequently CO_2 is not expected to limit phytoplankton photosynthetic rates except perhaps in dense algal bloom conditions. For nitrogen inputs there are three main pathways: rivers (waterborne), atmospheric deposition and biological N fixation. In 2000, rivers transported approximately 757 kilotonnes (KT) of N to the Baltic Sea (HELCOM 2003). The main proportion of river-carried nitrogen is from diffuse sources (59%), especially from agriculture with the remainder from natural background sources (32%) and point sources (10%). Not all N inputs to coastal waters reach the Baltic Proper due to denitrification and burial in coastal sediments. N inputs in river runoff carry a distinctive isotopic signature that led Voss et al. (2005) to conclude that riverine inputs were largely (85%) retained or denitrified in coastal areas in the vicinity of inflowing rivers. Although 85% loss seems high in comparison to the global literature (Seitzinger et al. in press), this would indicate that about 115 KT of N from river transported N reaches the Baltic Proper, which may be a minimum estimate. Wet and dry deposition directly to the surface waters of the Baltic Proper provide approximately 185 KT per year (Voss et al. 2005) to the Baltic Proper. Biological fixation of nitrogen gas (also supplied from the atmosphere) by Cyanobacteria likely ranges between 300 to 400 KT per year (Wasmund et al. 2001a; Larsson et al. 2001), although Wasmund et al. (2005) recently concluded that the N fixation may be as high as 400-700 KT per year. In any case, N fixation is very likely now the single largest source of N to the Baltic Proper. In contrast to C and N, P and Si contributions are almost entirely river-borne, with a small addition through atmospheric precipitation. Most P from runoff is associated with particles of which a portion can be exchanged into solution to provide dissolved inorganic P for plant uptake. Phosphorus concentrations in rivers and ultimately P loading are dependent on the geology and land use of the catchments and also on the population densities of humans and animals. Si concentration is generally independent of flow and relatively constant so loading fluctuates with river flow as runoff and ground water mobilize dissolved Si out of soil horizons. All these sources were providing these essential nutrients to the Baltic Proper prior to the onset of eutrophication over a century ago, but cultural activities have accelerated the loadings of P and N.

3.1.3 Loading trends over time

Annual N and P loadings to the entire Baltic Sea at the turn of the 20th century have been estimated (Larsson et al. 1985) to be on the order of 300 KT N and 10 KT P, and are thought to have increased by factors of 4 and 6, respectively, to the current loading rates (Grimvall and Stalnacke 2001), which results in a lowering of the N:P loading ratio from approximately 30:1 to 20:1. Si loadings would fluctuate with hydrologic years but would not be expected to respond to anthropogenic activities and can be considered stable over the last century and earlier. N concentrations in loading by atmospheric wet and dry deposition increased dramatically after 1965, approximately doubling from previous values, but leveled off by the early 1980s (Granat 2001). Regulatory action to control atmospheric emissions in Europe would project a fall in these concentrations and proportionally loading over the next decade. In contrast, estimates of P loading by rivers have apparently not significantly changed since 1970 (Grimvall and Stalnacke 2001), when Baltic population growth began to slow and land use patterns stabilized. Most of the increase in P loading from earlier in the last century must have occurred prior to 1970, although the time course is undefined. Estimates of biological nitrogen fixation by the Cyanobacteria have also increased from earlier estimates of 130 KT to current estimates of between 300 and 400 KT. However, this apparent increase is in part methodological (Wasmund et al. 2005). Indirect evidence for increasing N fixation rates are increasing chlorophyll *a* (July-August) trends for the Baltic Proper through at least the 1990s (SMHI SHARK database) and increasing frequency of N fixing blooms (Finni et al. 2001). Biological N fixation is now the single largest source of N to the Baltic Proper and was estimated to directly support 45% of the N accumulating in sediment traps at 140 m off Gotland during the 1996-1997 growing season based on stable isotope ratios (Struck et al. 2004). However, land-based anthropogenic nitrogen apparently contributes significantly to the sediments of the basin through lateral advection in the benthic boundary layer. Struck et al. (2004) concluded that this lateral import of isotopically heavier N is balancing the effect of nitrogen fixation on deep-water nitrate inventories.

3.1.4 Recent trends in nutrient concentrations

For the Baltic Proper, high quality nutrient data are only available after 1970. During this period, riverine P loading and N loading from the atmosphere have been essentially unchanged (Grimvall and Stalnacke 2001; Granat 2001). However, nutrient concentrations within the Baltic Proper have been quite variable over this period. Winter nitrate concentrations in Baltic Proper surface water (Figure 3.1) apparently increased quickly in the early 1970s, but then little change occurred through 2000 (Nausch et al. 1999; Voss et al. 2005). This was followed by a decline over the last five years. Winter dissolved inorganic P (DIP) had a significant upward trend over the period of record but with a significant dip in the mid-1990s (Voss et al. 2005), followed by a recent increase (Figure 3.2). When the winter ratios of DIN to DIP are compared, a precipitous drop is evident in recent years after a prior period of rising or stable values earlier in the record (Figure 3.3) in response to both falling nitrate and rising DIP concentrations. TN and TP are also consistent with these trends for the inorganic fractions based on examination of the SHARK database of SMHI. Salinity shows a similar temporal pattern with DIP over time and a highly significant correlation with TP over the period of record (Figures 3.4 and 3.5). Winter dissolved Si concentrations show a consistent and persistent downward trend over the available record since 1970 (Rahm and Danielsson 2001). Explanation for these differing trends lies not within the loading data that have been relatively stable over the last 25-30 years, but rather within the physical and biogeochemical processes in the Baltic Proper.

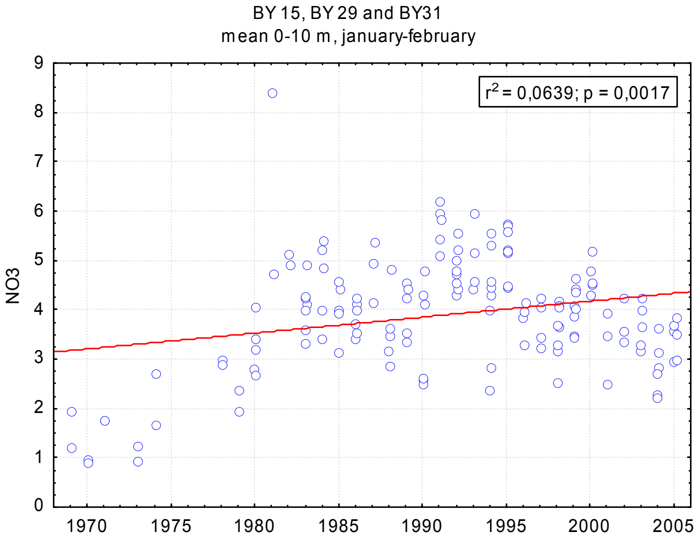


Figure 3.1. Trends in winter surface water nitrate concentrations for three deep stations in the Baltic Proper Swedish monitoring database SHARK at Sweden Oceanographic Data Center at SMHI (www.smhi.se). Long-term trend is highly significant but note recent (post-2000) reversal towards lower concentrations.

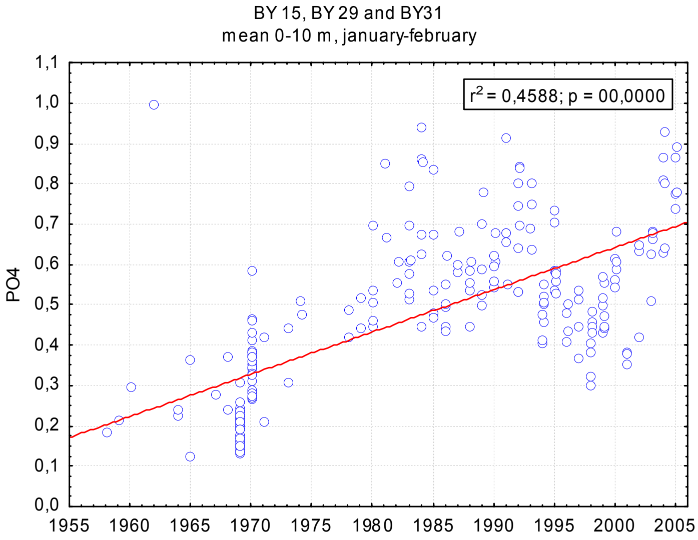


Figure 3.2. Trends in winter surface water dissolved phosphate concentrations for three deep Baltic Proper stations over the past 50 years from Swedish monitoring database SHARK at Sweden Oceanographic Data Center at SMHI (www.smhi.se). Long-term trend is highly significant, but note recent steep increase after the period of decline in the 1990s.

3.1.5 Saline inflows, stratification, organic loading and biogeochemical processing

Salinity increases in surface waters generally follow major inputs from the Kattegat that, in turn, are dependent on wind events extending across the North Sea. The "inflow index" for the Baltic shows intense activity through the 1960s and 1970s followed by a long period of quiescence since 1980, except for a strong event in 1993 (Conley et al., 2002) and a moderate 2003 event (http://www.fimr.fi/en/itamerikanta/bsds/2489.html). Periods of strong saline input displace less dense, but nutrient rich Baltic Proper deep water towards the surface, causing increased nutrient availability in surface waters especially of P (Figure 3.5). P is more sensitive to this displacement because DIN recycling in hypoxic deep waters can be short-circuited by denitrification and this maintains a low DIN:DIP ratio during winter mixing (Figure 3.3). The saline inflow events also provide oxygenated, higher salinity surface waters from surface of the Kattegat, which flow downslope into depths within the Baltic Proper, dependent on their density characteristics. Although initially providing oxygen to the depths they occupy, these denser inflow waters can reinforce the density difference across the haloclines in the Baltic Proper and restrict vertical mixing and ventilation with the atmosphere. This expansion and reinforcement of the halocline subsequently contributes to spreading anoxia over large areas of the Baltic Proper (Conley et al. 2002).

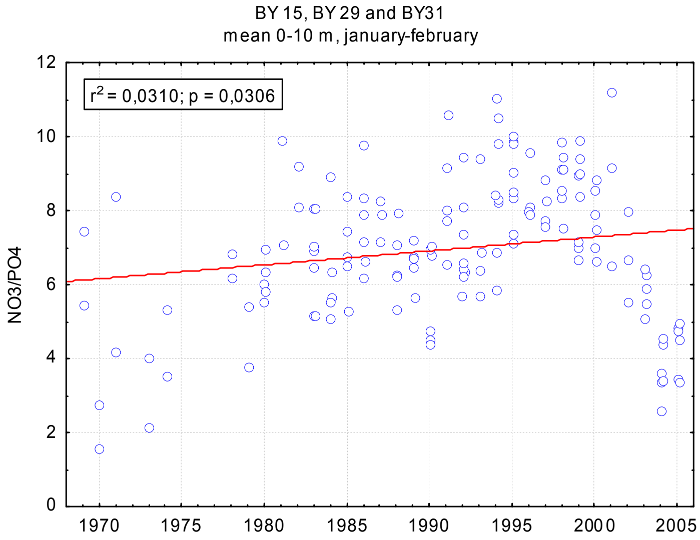


Figure 3.3. Winter surface water nitrate to phosphate ratios (by moles) for three deep stations in the Baltic Proper from Swedish monitoring database SHARK at Sweden Oceanographic Data Center at SMHI (www.smhi.se). Recent (post-2000) rapid decline has reversed a longer term trend towards increasing N:P ratios in winter waters. The decline may be a cause for the recent increases in Cyanobacteria blooms.

The 1993 event was unusual in that it did not flow down to form new bottom waters, but interflowed and oxygenated water at intermediate depths (Conley et al. 2002 and Figure 3.6). This singular strong inflow event of the last two decades reduced the DIP inventory in deeper waters (Conley et al. 2002) by precipitation on ferric hydroxides, and this oxygenation of intermediate waters also caused a decline in surface winter DIP values in the Baltic Proper (Figure 3.2). However, because it was a singular event the reduction in anoxic bottom area and volume was rapidly reversed as a result of increased density stratification and oxygen consumption from settling organic matter. Consequently the 1993 inflow had a short-lived effect on surface water DIP. By 2000 the long-term upward trend resumed in both deep and surface DIP (Fonselius and Valderrama 2003 and Figure 3.2). These hydrodynamic events of the last three decades were played out after external loadings of N and P had already reached their current high levels. These records illustrate how internal cycling within the Baltic Proper alters the availability of the N and P on annual and decadal time scales, and this can make it difficult to determine long-term trends.

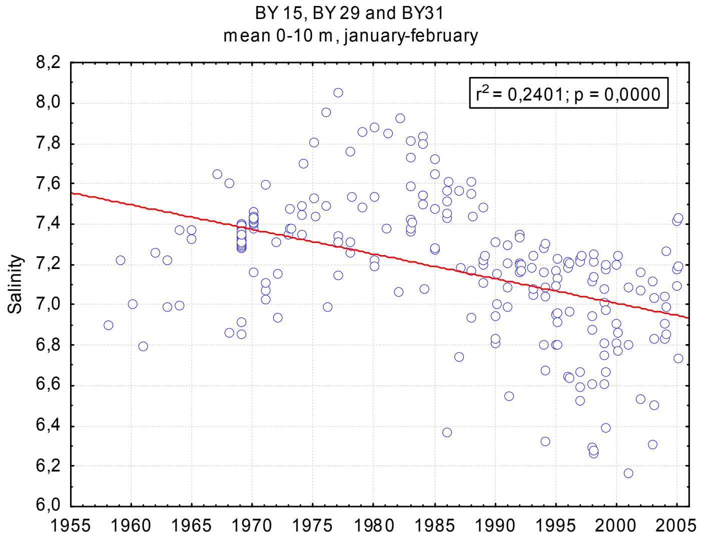


Figure 3.4. Surface water salinity in the Baltic Proper from Swedish monitoring database SHARK at Sweden Oceanographic Data Center at SMHI (www.smhi.se). High inflows through the Kattegat in the 1960's and 1970's (Conley et al 2002) raised the salinity of surface waters in the Baltic Proper by displacing saline bottom waters towards the surface. A period of quiescence in Baltic flows in the 1980s then allowed freshwater inflows to dilute surface waters. The most recent few years appear to reverse this trend.

The effect of episodic saline high inflows on P availability in surface waters might also be expected to be seen in N because DIN regenerates from algal debris sedimenting below the mixed layer so that DIN concentrations are higher in bottom waters than surface waters. Upward displacement of deeper water would be expected to initially increase N availability also (Figure 3.1). However Baltic Proper deep waters have low DIN:DIP ratios (6-8:1 by moles) so increased deep-water supply imposes on surface waters an imbalance of these nutrients relative to algal requirements (approximately 16:1, molar ratio). This low DIN:DIP ratio results from differential recycling of N and P under hypoxic and anoxic conditions. Denitrification occurs under very low-oxygen conditions and leads to loss of N from the water column as nitrogen gas. Very low-oxygen and anoxic conditions also liberate DIP from being bound to insoluble ferric hydroxides that can lead to inorganic sedimentation of P from the water column. The same conditions that lead to denitrification also can enhance recycling of DIP back into the water column and so these processes lower the DIN:DIP ratio. The effect of saline inflows on the interaction of oxygen and nitrate concentrations over the period of record is evident if the depth distributions of their concentrations are compared (Figures 3.6 and 3.7). The very strong 1993 saline inflow effectively reoxygenated all the depths at the deepest station in the Baltic and this oxygenation persisted for several years. The oxygenation effectively reduced denitrification rates especially in intermediate depth waters from 70-200 m and allowed higher nitrate concentrations to persist over several years. By the late 1990s, oxygen conditions were again falling to low levels, and denitrification began to erode the nitrate reservoir so that the subsurface depth interval of detectable nitrate was reduced and the nitrate concentrations available for winter mixing were falling. This trend was evident in the falling winter surface nitrate concentrations and even more rapidly falling DIN:DIP (Figure 3.3) as DIP concentrations concurrently were increasing because anoxic water was rising closer to the depths of winter mixing (Figure 3.6).

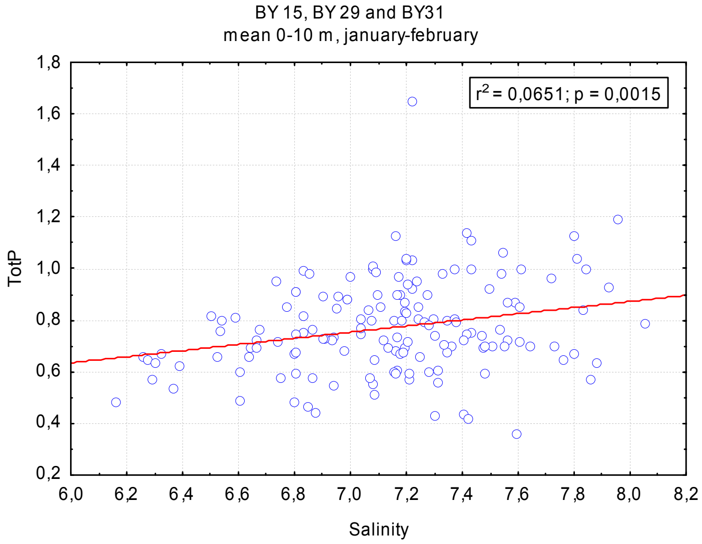


Figure 3.5. Total P and salinity in winter surface waters in the Baltic Proper (1971-2004 SMHI database). Increased inflows of saline water in the Kattegat vertically displace deep water in the Baltic Proper and transport more saline and P-rich deep waters towards the surface.

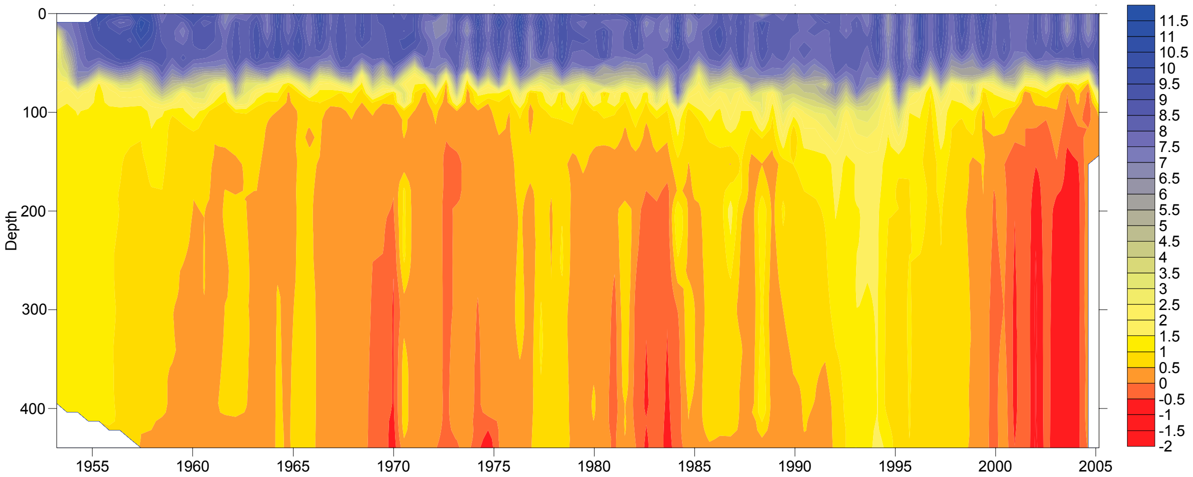


Figure 3.6. Isobaths of oxygen concentrations in the Landsort deep, data from Swedish monitoring database SHARK at Sweden Oceanographic Data Center at SMHI (www.smhi.se). Note persistent low oxygen below 70 m and the effect of 1993 inflow event on oxygenating the whole column.

The selective recycling of N and P from sedimenting organic material under low and anoxic conditions creates a chronic nitrogen deficit for phytoplankton growth when deeper waters are returned to the surface during winter mixing. As a result, the availability of nitrogen limits the size of the spring bloom. However, as the nitrogen is depleted to low levels during the summer, slow-growing Cyanobacteria species that can fix atmospheric nitrogen have selective advantage in utilizing the available phosphorus. Nitrogen-fixing (NF) Cyanobacteria cannot be limited by N, and therefore their relative abundance in the phytoplankton will increase until their NF activity adjusts the N content of the mixed layer to approximately the Redfield ratio (7:1 on weight basis; 16:1 on a molar basis). Once the N:P ratio becomes adjusted and regeneration of the fixed N makes N available to other phytoplankton they outcompete the NF species for DIP and the bloom collapses.

This phenomenon of N fixation compensating for an N deficit in trophogenic waters is well known from lakes (Schindler 1977; Hecky 1997; Hellström 1996; Elser et al. 2000). It is not the winter DIN:DIP ratio alone that dictates the duration and intensity of the summer N-fixation but also the spring DIP levels. In the early 1970s DIN:DIP ratios were as low as in 2004 and 2005 (Figure 3.3), but winter DIP concentrations in 2004-05 were approximately double the DIP concentrations in the 1970s so the residual DIP after the spring bloom will be twice as high. Consequently, the historic highs in Cyanobacteria blooms in the last few years are not surprising.

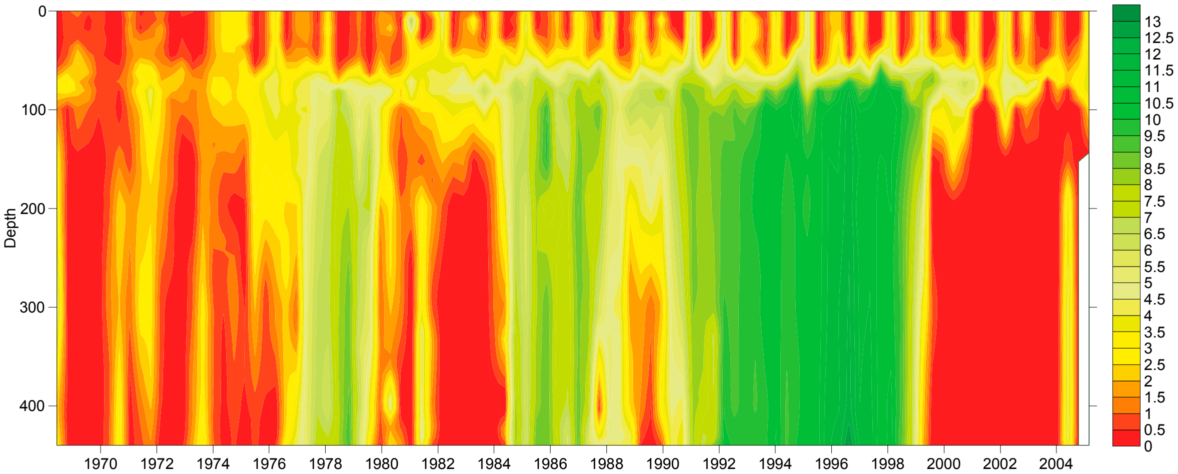


Figure 3.7. Nitrate isobaths for Landsort deep showing effect of 1993 inflow on increasing the nitrate reservoir and allowing nitrate to persist throughout the water column until the late 1990s and the loss of nitrate especially between 200 and up to 80 m depth early in the new century. Seasonal mixing in upper waters is clearly evident in alternating colors showing high winter values in surface waters and low summer values.

The continuing effect of eutrophication in changing the nutrient balances in the Baltic Proper is best exhibited by the continuous downward trend in dissolved Si in winter surface waters (Figure 3.8) throughout the recent decades (Kuparinen and

Tuominen 2001). Unlike N or P, Si loadings have likely not increased over time. The increased demand by diatoms that require Si, fueled by the increased availability of N and P from eutrophication, continues to exceed Si loadings and therefore internal stores continue to fall. The dissolution of diatoms settling from the surface layers is also much less affected by redox and salinity conditions than DIN and DIP. Similar to the long-term trend in Secchi depth (Sandén and Håkansson, 1996), the continuously declining dissolved Si concentrations may be indicative of continuing progressive eutrophication, i.e., no stabilization of external and internal (recycled) N and P loadings has been accomplished yet. However, for dissolved Si to be an indicator of eutrophication, an analysis should be made of the possible effect of altered river flows and reservoir construction through the last part of the century to determine if there has been an effect on Si inputs from the catchment to the Baltic and consequently reduced Si concentrations in the Baltic. If no significant change in Si inputs has occurred or if upstream storage of Si has stabilized, then dissolved Si becomes a monitorable indicator for Baltic Proper recovery just as it has been in the Laurentian Great Lakes of North America (Barbiero et al., 2002). Although winter Si concentrations are still high relative to DIN and would not be considered strongly limiting (R. Elmgren, personal communication), Wasmund et al. (2001b) reported that dinoflagellates are an increasing proportion of the spring bloom algal community in the southern Baltic Proper and suggested that falling Si concentrations may be responsible.

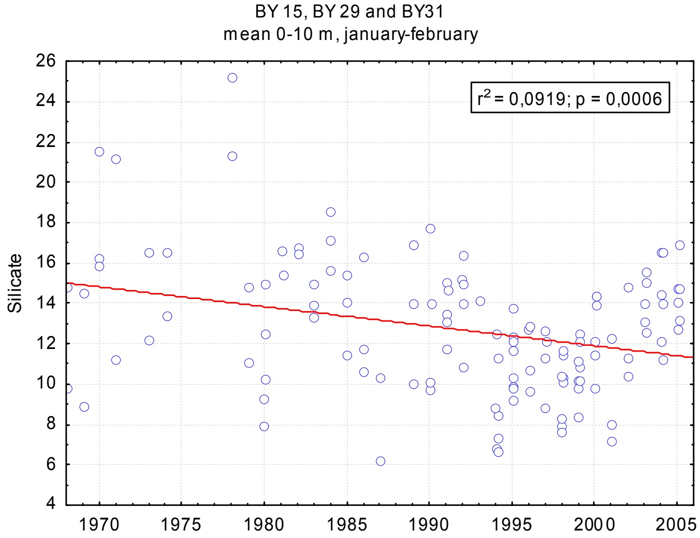


Figure 3.8. Winter silicate concentrations in surface layer of Landsort station in the Baltic Proper. Downward trend indicates the silicate demand and sedimentation by diatoms has been exceeding supply from rivers over at least the last four decades.

3.1.5 Phytoplankton chlorophyll and production

The immediate response variable to the increased nutrient loading in many aquatic systems on annual, decadal and century time scales is phytoplankton growth, which becomes evident as increased primary production and usually chlorophyll *a* concentrations as a measure of phytoplankton biomass. Hagström et al. (2001) describe response patterns for these variables in the Baltic Sea including the Baltic Proper. The Baltic Proper is the most productive region of the Baltic having nearly 10 times the primary production of the Bothnian Bay and more than double the phytoplankton production of the other major areas of the Baltic Sea. Remarkably, the offshore Baltic Proper waters also have higher production rates than the coastal areas of the Baltic Proper in contrast to what is observed in most coastal seas and large lakes. The explanation for this higher productivity is largely found in the mid summer period of July and August when the Baltic Proper exhibits a period of high production while the other Baltic regions and coastal areas are exhibiting minima in primary production.

The first seasonal peak in primary production occurs all over the Baltic in the spring phytoplankton bloom that is driven by improving light conditions and high availability of nutrients following winter mixing. This bloom is terminated when inorganic nitrogen becomes limiting. The excess DIP left from the spring bloom is available to promote the mid-summer blooms of NF Cyanobacteria that are not limited by lack of DIN. This has apparently long been the case in the Baltic Proper, as plant pigment biomarkers and stable isotopes in the sediment record show that Cyanobacteria were prevalent in the Baltic Proper as much as 7,000 years ago (Bianchi, et al. 2000). This mid-summer productive period allows the NF Cyanobacteria sometimes to reach nuisance bloom proportions, especially since the 1960s (Finni et al. 2001). This is because with increased nutrient loading over the past century and the more efficient internal cycling of P compared to N (Blomqvist et al. 2004) in increasingly hypoxic waters more residual DIP is now left at the end of the spring bloom. During the productive summer period there is a net accumulation of TN in the upper mixed layer that, together with mixing of nitrate from deeper waters, restores TN to concentrations comparable to the winter maxima (Larsson et al. 2001) when little or no algal growth occurs. Struck et al. (2004) estimate that the summer period of N fixation provides 45 % of annual new production in the Baltic Proper, and this could account for most of the difference in annual primary production between the Baltic Proper and the other Baltic waters. Also because the Baltic Proper is the most productive basin of the Baltic, this summer production is likely an increasingly important proportion of the primary production over the past century as a response to eutrophication.

Loading by N-fixation within Cyanobacteria cells contributes directly to Cyanobacteria growth, but the process is dependent on availability of P and the blooms may eventually be P limited (Walve and Larsson in press; Hecky 1997). The intensity and duration of the summer Cyanobacteria bloom is dependent on the availability of excess DIP after the spring bloom (Figure 3 in Larsson et al. 2001) which in turn depends on the winter DIN:DIP ratio and DIP concentrations Lower ratios will favor stronger blooms especially if DIP concentrations are also rising. Winter DIN:DIP ratios have been unusually low in recent years (Figure 3.3) as winter DIP concentrations have been high since 2000, returning to values characteristic of the 1980s and early 1990s, i.e. the period of long stagnation before the 1993 ventilation event (Figure 3.2). To the degree to which these sources contribute to available N in the Baltic Proper, the imposition of N removal at treatment plants and the anticipated reduction of N in atmospheric deposition could aggravate the DIN/DIP ratio and move the Baltic Proper into more acute N deficiency. We suggest therefore that increasing the winter DIN:DIP ratio and/or reducing winter DIP concentrations will reduce the summer Cyanobacteria blooms. The DIN/DIP ratio responds to hydrodynamic events within the Baltic Proper, which is not manageable under any current technology, and we do not suggest that attempts should be made to manage the hydrodynamics of the Baltic Proper. Therefore, the reduction of P loading is the most direct way to reduce DIP in order to reduce rates of nitrogen fixation and large Cyanobacteria blooms in the Baltic Proper.

3.2 Possible Management Actions

While there are multinational commitments to reduce hypoxia and improve the trophic structure supporting fisheries in the Baltic, concern for the Baltic Proper is currently focused on the Cyanobacteria blooms, which have increased in intensity and duration (Finni et al. 2001) since the 1960s. These multiple management objectives should be kept in mind as they may be more or less tractable and have different solutions. Also, it should be appreciated that Cyanobacteria blooms are a characteristic feature, unlikely to be completely eliminated by management actions (Bianchi et al. 2000).

In the short term, there is little that can be done to improve the Cyanobacteria bloom or hypoxia situation as the internal dynamics of the physically driven upward advection of water by Kattegat inputs and the intensity of winter mixing that erodes the pycnocline are under climatic control (Conley et al. 2002). These factors will determine the availability of P in surface waters over annual to decadal time scales. These physical factors will also determine the areal extent of the pycnocline and associated hypoxia and anoxia that determine the relative availability of DIN and DIP that are brought into surface waters during winter deep mixing. Nitrogen fixation is driven by the relative supply of DIN and DIP to surface waters during winter mixing, and therefore is not controllable except through P loading reduction (excluding a massive fertilization with DIN to balance the N deficit annually, which might have unintended consequences).

There are different perspectives within the Baltic science community and, indeed, among members of this committee about whether there would be benefits from reduction of nitrogen loading to the Baltic Proper. Some argue that external N loading plays a significant role in determining the amount of N that is available to support the spring bloom and that the spring bloom is disproportionately important in the supply of organic matter to deeper waters where it drives oxygen depletion (Blomqvist and Heiskanen 2001; Elmgren and Larsson 2001b). This enhanced supply of organic matter, together with extended periods of stagnation with regard to exchange through the straits, is important in determining the extent of anoxia, which in turn plays a large role in supplying DIP to surface waters. Worsening hypoxia and mobilization of vast P reservoirs (Pitkänen et al. 2001, they would submit, is the fundamental cause of worsening Cyanobacteria blooms, rather than "undersupply" of N. Other scientists stress the importance of Cyanobacteria in contributing to the spring N supply and cite evidence that summer production by Cyanobacteria contributes a significant part of organic matter settling into bottom waters. Excess phosphorous loading, they would submit, is the fundamental cause of worsening Cyanobacteria blooms, which are in turn increasing production and exacerbating anoxia. Reducing the supply of N would at least risk making matters worse. The committee believes there are uncertainties surrounding this dispute that result from the inherently complex feedbacks in this system, the relative paucity of directly relevant data, and differences in the interpretation of results (e.g., recent studies of stable isotopes). However, we note and join the broad agreement among Baltic scientists that substantial reductions in P loading must be an essential part of a strategy to reverse eutrophication in the Baltic Proper. Further resolution of the nitrogen dispute should be a high priority for Baltic science.

The external nutrient fluxes to the Baltic Proper that are amenable to management are the input of nitrogen from atmospheric precipitation and the N and P loading in rivers. The N loading in rivers is currently the smallest component of the N loading to the pelagic waters of the Baltic Proper. Consequently, efforts to control N loading in the river catchments and at point sources will have less effect on the N deficiency in the Baltic Proper compared to reduction of the quantitatively much larger nitrogen fixation and atmospheric precipitation loadings. European countries have plans to regulate their nitrogen emissions to the atmosphere, and it is anticipated that these emissions will decrease over the next decades. Because of the relatively rapid turnover times of NH_3 and NO_x in the atmosphere, effective regulation might generate a relatively rapid return to lower N deposition over the Baltic. If this important goal were achieved along with its environmental benefits, it could aggravate the N deficit in the Baltic Proper and result in prolonged periods of N fixation and potential blooms. This concern for the Baltic should not be an argument against reducing atmospheric emissions of nitrogen because of the substantial benefits to terrestrial, freshwater and more marine ecosystems; rather, it should be used as a reason to accelerate programs of P management targeting substantial decreases in P loading to the Baltic.

The panel was extremely concerned and surprised that little or no significant progress has been made by the Baltic countries, in aggregate, to reduce riverine P loading to the Baltic over the last 30 years (Grimvall and Stalnacke 2001). This is especially surprising because there are significant opportunities in domestic practices (such as removal of P from detergents) and, reductions in diffuse sources, and sewage waste management at point sources to effect significant reductions in P loading to the Baltic. HELCOM (2005) concludes that approximately 30% of the total anthropogenic P load to the Baltic comes from point sources, largely in the new EU countries bordering the Baltic and from Russia. Aggressive investment in reducing these point sources would give significant improvement to conditions in the Baltic Proper over a 20-year time frame (Savchuk and Wulff 2001) while improvement in the shorter term may be obscured by short term physical forcing on saline inflows at the Kattegat, which would increase P concentrations in the Baltic Proper. Aggressive action on non-point sources of P that account for 70% of the anthropogenic P load to the Baltic will yield benefits over a longer time frame as many soils are approaching P saturation through fertilizer applications and agricultural activities of any kind generate some loss of particulate and dissolved P to the riverine loading. Recovery will not be a smooth decrease in TP or DIP concentrations but rather a “sawtooth pattern” imposed by hydrodynamic variability on a long downward trend. Our conclusions in regard to possible benefits of P reduction are consistent with the modeling efforts of Savchuk and Wulff (2001) and Neumann and Schernewski (2004). Reduction of P loadings will bring significant improvement in anoxia and nuisance blooms to the open Baltic Proper. As in lakes, considerable hysteresis in response of the system is expected, and a decade or more may be necessary before responses to nutrient loading can be detected in phytoplankton blooms or bottom water anoxia.

3.3 Conclusions

- Episodic saline inflows through the Straits of Denmark ventilate and oxygenate the deep waters of the Baltic Proper but also reinforce haloclines; subsequent periods of stagnation can then cause declining oxygen concentrations and formation of laminated sediments. This physical forcing of vertical circulation in the Baltic Proper is natural. There has been no long-term trend in salinity of the Baltic Proper over the last century.
- During the last century, anthropogenic nutrient loading to the Baltic began to increase and there has been a long-term eutrophication trend in the Baltic Proper evident in decreasing oxygen content in deep water and decreasing Secchi depth in surface waters. The Secchi depth trend is consistent with an approximate doubling in annual primary productivity over the century.
- Eutrophication has increased organic loading to the deeper waters of the Baltic Proper and increased oxygen consumption above natural rates both under the seasonal thermocline and the primary halocline through the last century; a century long trend of warming has raised deep-water temperatures by 1-2 C and this could contribute to increased oxygen consumption rates.
- During the last half of the twentieth century when reliable nutrient analyses became available, there has been a long-term upward trend in phosphorus concentrations and a long-term decline in dissolved silicate consistent with the longer-term trends in deep-water deoxygenation and Secchi depth over the same time period.
- Dissolved inorganic phosphate (DIP) and nitrate concentrations are both sensitive to hypoxia and anoxia with nitrate being lost to denitrification while phosphate is released from ferric hydroxide compounds when oxygen conditions are very low.
- As a result of preferential release of P and loss of dissolved inorganic nitrogen (DIN) under low oxygen conditions, winter DIN:DIP ratios in the mixing layer of the Baltic Proper are chronically low relative to algal requirements for growth and have declined markedly in the last five years due to spreading anoxia
- The spring bloom of phytoplankton is limited by DIN but, because of the low DIN:DIP ratio, DIP remains available in the surface mixed layer after the spring bloom and fuels the growth of nitrogen fixing Cyanobacteria in the summer.
- The summer blooms of Cyanobacteria in some years are eventually limited by P, and they may provide approximately 45% of the annual net productivity and organic matter sedimentation to the Baltic Proper; therefore, P currently limits the annual

productivity of the Baltic Proper and is important in controlling the loading of organic material to the deeper waters of the Baltic Proper.

- Since 1999 the winter DIP concentrations have risen sharply and DIN concentrations have fallen in response to deoxygenation of the upper water column (70-200m depth); this decline in DIN: DIP and rise in DIP have increased the potential for summer blooms of N fixing Cyanobacteria and has led to the most recent concern about the intensity and duration of these summer blooms.
- Climatic factors, as well as food web dynamics, are also likely important factors affecting the interannual variation in intensity and duration of summer blooms.
- There is broad agreement that phosphorus concentrations should be reduced over time to reduce the rates of N fixation as well as the resultant Cyanobacteria blooms and some of the sedimenting organic load to the deep water. On the other hand, opinions within both the Baltic scientific community and the review committee differ on the effectiveness of nitrogen load reductions in reducing primary production and oxygen depletion in the Baltic Proper and on whether reductions of N loading from atmospheric or other sources could stimulate greater Cyanobacteria blooms by aggravating the chronic N deficiency.
- 30% of the current anthropogenic phosphorus load to the Baltic occurs at point sources and can be removed relatively quickly with aggressive application of existing technologies; the remaining anthropogenic load comes from non-point sources that will require a longer-term strategy especially in the agricultural sectors of Baltic countries. Removal of phosphorus from detergents should also be considered to reduce costs of point source treatment and to contribute to reducing of non-point loads.
- Over two to three decades, the Baltic Proper will improve with reductions in phosphorus loading; but the recovery trend will not necessarily be smooth as the surface waters will continue to be affected by periods of ventilation and stagnation that will impose shorter-term periods of improvement and deterioration in regards to the Cyanobacteria blooms in the Baltic Proper.

4 Swedish West Coast, Kattegat, Skagerrak

The recipient waters considered here include the Öresund, Kattegat and Skagerrak and the many bays and fjords that characterize the Swedish west coast; these are collectively referred to as the West Sea. These environments differ from those in the Baltic Proper and the Swedish east coast in a number of important respects including higher salinity (10-34 psu in contrast to 5-7 psu on the Baltic coast) and biotic diversity, and greater tidal range (>20 cm) and currents. West coast waters are also greatly influenced by the dynamics of the North Sea as well as by robust meteorological forces.

4.1 Symptoms and Trends of Eutrophication

4.1.1 Nutrient sources and trends

The nutrient loading to the Skagerrak and Kattegat is complex, coming not only from the surrounding land and atmosphere, but also from the adjacent Baltic and North seas. Because of its large volume and short residence time of surface waters, the offshore Skagerrak is much more influenced by nutrient supply from deep waters and the North Sea than the Kattegat (Gustafsson 2000). Based on estimates provided in Håkansson (2003) for the Kattegat and Skagerrak, 60% of the total phosphorus (TP) comes from the surrounding land, but only 26% of the total nitrogen (TN) does, with atmospheric deposition being a large source of TN (46%). The Baltic Sea contributes 40% of the TP to the Skagerrak-Kattegat, but only 7% of the TN, while the North Sea contributes 21% of the TN. However, Rasmussen and Gustafsson (2003) demonstrated that for the Kattegat exchanges of nutrients with the Skaggerak and Baltic are quite variable among years and over decades. This undoubtedly affects nutrient supply and, therefore, eutrophication trends. Significant dissolved inorganic nitrogen inputs, originally emanating from large continental rivers (the Elbe and Rhine), are transported into the region by the Jutland coastal current. This external nitrogen loading source appears to have increased as a result of the reduction of phosphorus discharges from these rivers, causing phosphorus limitation of phytoplankton production in the coastal plume and transport of unassimilated nitrogen with the northward-flowing coastal current (Hansson et al. 2001).

Beyond these overall budgets, however, it must be remembered that land-based sources (both point and diffuse) are very important in relatively confined recipients, such as fjords and even the open Öresund and Kattegat. An estimated 33,900 tonnes/yr of nitrogen and 1,170 tonnes/year of phosphorus are discharged from Sweden to the Öresund and Kattegat (Håkansson 2003; 1985-1999 averages). In this region point sources are relatively important for phosphorus (40%), while diffuse sources dominate the delivery of nitrogen. Leaching from arable land along the southwestern Swedish coastal area provides the majority of nitrogen delivered from land-based sources. Atmospheric deposition of reduced and oxidized nitrogen is also very important, delivering an estimated 22,330 tonnes to the Kattegat and 36,510 tonnes to that Skagerrak in 1999.

TP loads from Swedish rivers and point sources into the Kattegat and Skagerrak increased by 50% from the 1970s to the 1990s, while TN loads increased by 40% (Håkansson, 2003). Concerted efforts have been made to abate eutrophication in the region since the 1980s.

4.1.2 Nutrient concentrations and dynamics

The mean DIN levels in the Kattegat are estimated to be 150% of background levels, while approximating background in the open Skagerrak (Håkansson 2003). When corrected for salinity effects dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) concentrations in the Kattegat and Skagerrak are seasonally variable and show no statistically significant trends since 1970. However the DIN:DIP ratio shows an increasing trend since 1985 (reflecting relative increases in DIN and/or decreases in DIP), recently exceeding the Redfield ratio of 16 (on a molar basis) in the inshore waters and approaching 16 in the offshore Skagerrak, while remaining below 16 in the Kattegat except during some winters. This is consistent with Rasmussen and Gustafsson's (2003) finding that both DIP and TP pools in the Kattegat have decreased, while nitrogen pools have been variable, but not clearly declining.

Recycling of nutrients, particularly the seasonal releases of DIP and DIN from sediments, plays an important role in the nutrient dynamics of the Kattegat and Belt Sea (Rasmussen et al. 2003). Release of DIP and DIN during the winter adds to the pool of nutrients available for the following spring bloom. Both advection and the autumn-winter release of P exceed the land load of P. Therefore, reductions in P loadings cannot be expected to significantly change the availability of P for phytoplankton production, at least over the short term. However, the N load from land and the atmosphere exceeds the N supplied by internal net release and advection, in part because of losses due to denitrification. Reductions in N load thus have a significant influence on availability of N for primary production (Rasmussen et al. 2003).

4.1.3 Phytoplankton chlorophyll and production

Chlorophyll *a* concentrations during the growing season are highly variable in space and over years. Because of this variability there are no detectable trends from 1980 to 2002. Higher chlorophyll *a* concentrations are found with salinity around 20 psu in the Kattegat and 25 psu in the Skagerrak, indicating a response to mixing of fresher, nutrient-rich waters with more saline waters.

Primary production in the Kattegat region is estimated to have increased by 2 to 3-fold since the 1950s due to eutrophication, from less than 100 to more than 230 g C m^{-2} yr^{-1} by the early 1990s (Richardson & Heilmann 1995). More recently, Carstensen et al. (2003) found that estimated new production in the Kattegat was significantly related to nitrogen loading from the land and atmosphere. Based on measurements outside the mouth of the Gullmar Fjord, Lindahl et al. (2002) argued that the observed continued increase in primary production during the 1990s was due to climatic forces resulting from a strong positive North Atlantic Oscillation (NAO) index, which increased the availability of deepwater nutrients.

Based on both DIN:DIP ratios and on *in vitro* nutrient addition experiments, phytoplankton production in the Kattegat has been long thought to be nitrogen-limited (Granéli et al. 1990). In contrast to the low salinity Baltic Proper Cyanobacteria blooms are very infrequent (Carstensen et al. 2004) and there is no evidence that nitrogen fixation supplies significant nitrogen to the ecosystem. While there is validity to many of Söderström's (1999) criticisms of drawing conclusions concerning nutrient limitation simply based on concentration ratios and enrichment experiments, his assertion that phosphorus is fundamentally the limiting nutrient in the Kattegat and Skagerrak and that management measures to reduce nitrogen inputs are doomed to failure do not take into account the rates of denitrification and phosphorus regeneration typical of marine environments (Blomqvist et al. 2004) and are at odds with both the observational record and the strong consensus of opinion of Danish and Swedish scientists working in these systems.

A particular concern on the Swedish west coast is blooms of toxic dinoflagellates and raphidophytes which can cause fish mortalities (in the wild and in aquaculture) or poisoning of humans consuming shellfish that have accumulated toxins. There is significant evidence from experiments and observations elsewhere, that some harmful algal bloom (HAB) forming species undergo rapid growth under nitrogen-enriched conditions (Riegman et al. 1992), particularly when organic nitrogen is supplied (Anderson et al. 2002). HABs are notoriously episodic; thus it is difficult to detect trends in their frequency. No clear trends in their occurrence are evident in the Kattegat and Skagerrak since 1986 (Håkansson 2003).

4.1.4 Macrophytes

Narrowing of the depth range of *Fucus* spp. growth and greater prevalence of filamentous algae in the littoral zone have been documented in several areas along the Swedish west coast, similar to what has been observed in the Baltic (reviewed in Lundberg, 2005). In a few places where there is a long observational record this seems to have occurred during the 1970s and early 1980s, but these symptoms are now widely observed and intensely manifest locally. The algal flora of the west coast is much more diverse than in the Baltic and shifts in the depth distribution of various other brown and red algae and a dramatic decline in species richness in the lower littoral have been noted and attributed to increased light limitation associated with eutrophication (Pedersén and Snoeijs 2001; Eriksson et al. 2002). Extended occurrence of ephemeral macroalgae (mainly *Cladophora* and *Enteromorpha*) began to occur in shallow bays (0-1 m depth) of the Swedish west coast in the mid 1970s. During the period 1992-1994 ephemeral macroalgae covered 10 to 100% of the bottom sediment in nine bays studied along the Skaggerak coast where they have changed the characteristics of these areas and have important consequences for trophic interactions (Pihl, et al. 1996)

The rooted marine vascular plant *Zostera marina* (eelgrass) has also declined in abundance as a result of eutrophication in a pattern consistent with the demise of seagrasses around the world. Along the Swedish Skagerrak coast, a 60 % decline in eelgrass was observed since the late 1980s (Baden et al. 2003), in part due to the reduction of depth at which it has sufficient light to live, which in turn was closely related to total nitrogen concentrations (Nielsen et al. 2002).

4.1.5 Bottom waters

The Kattegat has shown progressive decline in autumn dissolved oxygen concentrations in bottom waters since 1970 and now experiences recurrent hypoxia (Håkansson 2003). It is a shallow but highly stratified system (halocline at 15 m depth), with a relatively small volume of bottom water and dynamic processes that allow regeneration of nutrients to surface waters while maintaining stratification sufficient to keep bottom waters hypoxic. The increased delivery of sedimenting organic matter drives the depletion of oxygen in this limited and confined water mass. Because the Kattegat is dynamically influenced by inflows and outflows to and from the Baltic and North seas and because it is also greatly affected by climatologically variable wind forcing, it is not surprising that the extent and severity of bottom water hypoxia vary greatly from year to year. While summer-fall hypoxia re-occurred through the 1980s, conditions improved somewhat during the 1990s, but hypoxia was serious and extensive again in 2002 and 2003 (Ærtebjerg et al. 2003). The longer-term trends, however, seem to have been driven by increased nutrient delivery to the Kattegat (Andersson 1996; Conley et al. in press). This is particularly evident on a subregional scale. For example, Rosenberg et al. (1990) correlated the expansion of seasonal hypoxia with a more than 3-fold increase in input of nitrogen during the 1960s and 1970s via rivers entering the Laholm Bay. There also seems to be a trend of declining autumn dissolved oxygen concentrations in bottom waters of the Skagerrak (Håkansson 2003). The inshore areas of the Skagerrak with restricted water exchange are particularly affected.

4.1.6 Benthic biota

The effects eutrophication on macrobenthos were apparent in comparisons made based on samples collected in 1984-1985 with the observations of Johannes Petersen in 1911/12 (Pearson et al. 1985; Rosenberg, et al. 1987). Biomass was higher in the Skagerrak than it was in the early 20th century, presumably as a result of trophic enrichment, but markedly lower in the Kattegat, which by then had begun to experience stress of hypoxia resulting in the elimination of sensitive mollusks, echinoids and crustaceans. By the early 1980s, mass mortalities of benthic invertebrates in the Kattegat had begun to occur. Catches of Norway lobsters (*Nephrops norvegicus*) had initially increased, because they became more susceptible to trawl capture as they left their burrows under oxygen stress, and subsequently collapsed completely in the southern Kattegat as they succumbed to the lack of oxygen. Catches of bottom fish have also dramatically declined in the Kattegat and Skagerrak since the 1980s (Håkansson 2003). While overfishing is surely partly responsible, the increase of bottom water hypoxia seems also an important factor in this decline. Benthic communities have also experienced increasing hypoxia and related changes in many of the fjords of the Skagerrak coast, including several that are not recipients of nutrient inputs from land. This suggests that these environments have experienced the effects of regional eutrophication affecting the coastal zone (Håkansson 2003).

4.2 Actions Taken and Their Effects

Concerted efforts have been made to abate eutrophication in the region since 1989. Inputs of nutrients into the Öresund and Kattegat from land (point and diffuse sources) were reduced between 1989 and 2002, particularly from Denmark and relatively more for phosphorus (as a percentage of the input) than for nitrogen (Carstensen et al. in press).

Phosphorus inputs from land into the coastal waters of the Skagerrak declined somewhat between 1990 and 1998 due to the removal of about one-third of the point source phosphorus load, mainly in Norway and Denmark—Sweden had earlier moved to reduce phosphorus in point sources. Land-based sources of nitrogen, on the other hand, did not decline and point sources were reduced only in Denmark (Hansen et al. 2001).

Based on Swedish EPA estimates, land-based loadings of phosphorus into the West Sea region declined more significantly between 1995 and 2000 than for nitrogen (Figure 1.3). Emissions of nitrogen from sewage treatment works declined by 38% during that time period, but this had relatively little effect on total nitrogen loadings, which are strongly dominated by diffuse sources on the west coast.

Although there have been some reductions in emissions of nitrogen oxides from Sweden between 1995 and 2001, atmospheric deposition of nitrogen was relatively unchanged between 1990 and 2000 (Naturvårdsverket, 2003). Thus, there are yet no clear trends in atmospheric deposition to the Kattegat-Skagerrak region.

There is newly emerging evidence that aggressive efforts to reduce nutrient inputs that have been taken in Denmark are beginning to have an effect, at least in terms of documentable reductions at estuarine and open-water stations (Carstensen et al. in press). Phosphorus concentrations have declined by 22 to 57% from the early 1990s, mainly due to improved treatment of urban and industrial wastewater. In the last five years nitrogen levels have decreased up to 44% when interannual variations in freshwater discharges were accounted for.

There have been several efforts to forecast ecosystem responses to future reductions in nutrient loading. Based on a regression analysis Carstensen et al. (2003) predict declines of between 20 and 47% in annual net primary production from a 50% reduction in nitrogen loading to the Kattegat.

A recent summary of monitoring data from the Bohuslän fjords of the Skagerrak coast shows that nutrient loading reductions have not been large enough to produce results that can be distinguished from the highly variable riverine inputs for most of the region (Axe et al. 2005). One exception appears to be the Byfjorden where in 1995 STP inputs of N were reduced from 150 to 50 tonnes per year (P removal had been accomplished previously), resulting in a 30 % reduction in TN land-based loading. DIN concentrations declined over most of the year and summer-fall chlorophyll-*a* levels were greatly reduced and less variable (Figure 4.1).

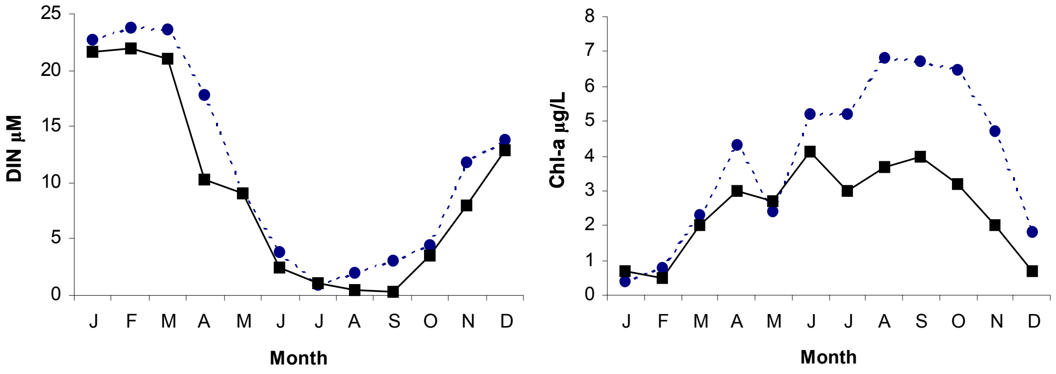


Figure 4.1. Monthly mean concentrations of DIN and chlorophyll-a in the Byfjorden before (dashed lines) and after (solid lines) nitrogen waste treatment (Axe et al. 2005).

Erlandsson and Johannesson (2005) reported a decline in filamentous algae in the recipient zone of the Rya wastewater treatment plant near the mouth of the Göta Älv as loadings of nitrogen and phosphorus from the plant were reduced. However, neither they nor Isæus et al. (2005) could find a reliable basis for predicting further declines in filamentous algae or phytoplankton biomass that would result from additional reductions of P concentrations in the discharge from 0.4 to 0.3 mg P/l. Diffuse and regenerated sources of P now dominate, such that further reductions in point-source P loading would make little difference in P availability.

4.3 Conclusions

- The coastal regions and shallow seas off the west coast of Sweden were affected by rapid eutrophication from the 1960s through at least the 1980s. This appears to have been driven primarily by increased nitrogen inputs from agriculture and atmospheric deposition; however point source discharges of both nitrogen and phosphorus have had impacts in confined inshore waters.

- The effects of greatest concern are diminished values of habitats due to organic sedimentation and oxygen depletion and the loss of seagrass and macroalgal beds, although nuisance macrophyte growth and harmful algal blooms are also a concern.

- Improvement in these conditions will require significant reductions in inputs of nitrogen. In contrast to Baltic waters, there is no evidence that harmful

Cyanobacteria blooms or other undesirable consequences result from reductions in nitrogen loads in these more saline waters. Reductions in phosphorus inputs would also have positive results, but only if accompanied by nitrogen reductions, because of the presently high levels of loading of both nutrients.

- While reductions in point sources of nitrogen would contribute to achieving eutrophication reduction goals, these goals cannot be approached, except locally, without significant reductions in diffuse sources and atmospheric deposition.

5 Recommendations

Eutrophication is a process that results from increases in essential nutrients (particularly nitrogen and phosphorus) that stimulate plant growth. As the examples for Swedish seas illustrate, alleviating eutrophication should not be addressed as a single choice among controlling phosphorus only, nitrogen only, or nitrogen and phosphorus in combination. Limiting nutrients may differ from one environment to the other (e.g. Gulf of Bothnia, Baltic Proper, and Kattegat), along gradients (e.g. estuarine coastal gradients), and over time (seasonally and over years). Furthermore, Swedish seas and coastal systems are bidirectionally interconnected and measures taken to reduce nutrient inputs into one can have spillover consequences to another. Reliance on simple decision metrics such as nitrogen:phosphorus ratios may lead to the wrong conclusions. With these considerations in mind, we offer the following recommendations:

1. *Reduce phosphorus inputs to the open Baltic Proper.*

Views among Baltic scientists and, indeed among the members of this panel, differ regarding the benefits or risks of reducing nitrogen inputs to the Baltic Proper; however, there is broad agreement that phosphorus inputs should be reduced to alleviate eutrophication, particularly the extensive Cyanobacteria blooms currently plaguing the Sea. Efforts should begin with removing phosphorus from detergents in the basin and from point sources. HELCOM estimates indicate that current P loading to the Baltic Sea catchment is about three times the “background, natural loading” and 30% of the anthropogenic loading still originates from point sources. The proportion of the point source loading to total P load is even higher in some countries along the eastern and southern coasts. A review of P loading to the Baltic indicates that there has been little or no change in P loading to the Baltic over the past 30 years and the quickest way to initiate a downward trend in P loading is to address point sources. Preserving and, where possible, restoring nutrient phosphorus-retentive features of the landscape must be an important part of a longer term nutrient control strategy because diffuse loads currently dominate the anthropogenic P loading. Additional phosphorus removal by Sweden alone from point sources is not likely to have a significant impact on the open Baltic Proper because of Sweden’s past aggressive action on point-source P loading. Sweden may want to consider investing in P removal at significant point sources in other Baltic countries to accelerate recovery of the Baltic Proper because the most important point sources of phosphorus loading are along the eastern and southern coasts of the Baltic

2. *Reduce atmospheric nitrogen deposition.*

Atmospheric deposition is the main external source of nitrogen to the Baltic Proper and the western seas of Sweden. Efforts to reduce atmospheric deposition of nitrogen should be pursued because of accompanying beneficial effects to terrestrial and freshwater ecosystems in the watershed of the Baltic Sea. The documented effects of high nitrogen deposition include soil and water acidification and losses of calcium and magnesium from forest soils. Without accompanying removal of phosphorus from land-based sources there is a risk of enhancing growth of bloom forming nitrogen fixing Cyanobacteria in the Baltic Proper as reduced atmospheric inputs of nitrogen may give the Cyanobacteria an increasing advantage over other algal groups.

3. *Reduce nitrogen inputs to the waters of the Swedish west coast.*

Reduction of eutrophication problems in the West Sea and associated coastal waters will require significant reductions in inputs of nitrogen. In contrast to Baltic waters, there do not appear to be risks of N-fixing Cyanobacteria blooms. Reductions in phosphorus inputs would also have positive results because of the presently high levels of anthropogenic loading of both nutrients, but only if accompanied by nitrogen reductions. While reductions in point sources of nitrogen would contribute to achieving eutrophication reduction goals, these goals cannot be approached without significant reductions in diffuse sources and atmospheric deposition.

Increases in primary production, development of hypoxia, and changes in benthic communities and attached vegetation in coastal regions during the latter 20th century, in the Kattegat in particular, have been well documented and shown to be largely related to increasing anthropogenic nutrient inputs. While phosphorus can limit primary production seasonally and in low salinity regions, nitrogen seems to limit organic production overall. In contrast to less saline Baltic waters, there is no evidence of significant nitrogen fixation to alleviate nitrogen deficiency. Anthropogenic nutrient inputs apparently have not increased since 1990 as a result of countermeasures and declines in agriculture. Phosphorus loadings have decreased over the past decade, but there is little evidence that nitrogen loadings, which are dominated by diffuse sources and atmospheric deposition, have yet decreased significantly. Nonetheless, recent Danish monitoring is beginning to show declines in nitrogen concentrations in recipient waters as a result of aggressive countermeasures there, indicating that the ecosystems will respond from reductions in nutrient loading but will take some time to recover from eutrophication.

4. *Appropriately reduce nutrient inputs in enrichment-sensitive areas of the Swedish east coast.*

Phosphorus is now removed at all sewage treatment plants in Sweden. Diffuse sources are still important in some areas. Additional measures such as removal of phosphorus from detergents and replacement of septic tanks with pumpouts, composting or combustion toilets that do not release nutrients to coastal waters can be undertaken with little cost. P removal from the Stockholm STPs by 1970 led to significant reductions in algal biomass and blooms of Cyanobacteria and imposed P limitation on algal production in the Stockholm Archipelago. Further reduction of external P loading will require addressing anthropogenic non-point sources of P. The prolonged period of high P loading has increased internal loading from sediments of the Stockholm Archipelago especially when oxygen concentrations in overlying water are low. The magnitude of this internal loading, although not fully quantified, is substantial. Phosphorus concentrations in bottom waters of the innermost archipelago have declined since 1998, most likely due to increased oxygen concentrations, which reduce the rate of release of P from sediments. Decline in this internal loading will affect the longer-term recovery of the system because P inputs from STPs are now small. More detailed study of the dissolved oxygen-phosphorus dynamics of bottom waters is needed in order to quantify the importance of internal P loading and reduce uncertainties about its projected decline over time.

Nitrogen loading was reduced in many sewage treatment plants in Sweden beginning in the 1990s, including those discharging to the Stockholm Archipelago and Himmerfjärden. The Committee is divided about the benefits of nitrogen removal to the fjords and coastal waters of the Swedish east coast. Some conclude that where eutrophication effects exist, removal of nitrogen is warranted and consider that its effects have been clearly demonstrated. At the same time they recognize that extensive nitrogen removal may stimulate nitrogen-fixing Cyanobacteria if not otherwise limited by phosphorus. Other members consider that the available data do not demonstrate benefits of nitrogen reduction in these waters and that emphasis should continue to be directed at phosphorus removal only for the next several years until additional data may provide a more convincing case for the benefits of nitrogen removal.

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Eutrophication of Swedish Seas

RAPPORT 5509

NATURVÅRDSVERKET
ISBN 91-620-5509-7
ISSN 0282-7298

Expert group suggests extended measures to reduce phosphorus discharges to the Baltic Sea.

An international group of highly qualified scientists has evaluated the scientific background concerning the eutrophication of the seas surrounding Sweden. Their investigation has now been reported to the Swedish Environmental Protection Agency. Focus has been on what nutrients that are of importance for algal production, including the extensive algal blooms in recent years. Also the overall strategy to combat discharges of nitrogen and phosphorus has been evaluated, and the expert group now comes up with suggestions how the eutrophication problems in the seas may be reduced.

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