Nutrient Dynamics in Southwestern Kattegat, Scandinavia: Modelling Transport, Budget and Consequences of Reduced Terrestrial Loads.

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Abstract

The nutrient transport through southwestern Kattegat was predicted for a 4 year period using the numerical, hydrodynamic model "MIKE12". Model results were validated through direct measurements of nutrient concentrations in the study area, and through measurements of total-P and total-N deposition and resuspension rates. The local terrestrial supply of nutrients makes up only 2-5% of the total transport through the area, which was dominated by fluxes over Little Belt and Great Belt boundaries to the study area. A mass balance for 1990 showed that ~30% of the external N load and ~100% of the external P load was deposited in the sediment. This is in reasonable agreement with field measurements of yearly net deposition rates in the study area. Resuspension rates in the area were however much higher (on average 17 times) than net deposition rates.

Two scenarios were simulated for 1990, one with the actual local load of external nutrients and one with a local load reduction according to the national "Action Plan for the Aquatic Environment". A comparison between the two scenarios showed that after reduction, nutrient concentrations dropped significantly (same magnitude as load reduction) in the inner parts of fiords close to the nutrient sources. In the open water parts of the study area the resulting decrease in nutrient concentrations (15% for N and 2-5% for P) was mostly manifested in the spring after high fresh water discharges.

Keywords

Numerical model; nutrient budget; load reduction; Kattegat.

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Eutrophication is considered a major environmental problem in inner Danish waters (Miljøstyrelsen 1984a,b). In order to reduce the ecological problems caused by eutrophication, the anthropogenic external loads to these waters of the nutrients nitrogen and phosphorus should be reduced (Christensen et al. 1996). The external loads include river inputs from the open land (diffuse sources) and from industry and waste water treatment plants (point sources); they also include atmospheric deposition of nutrients.

Significant load reduction has, however, great impact on society in terms of costly waste water treatment and reduction in agricultural productivity. Methods which are able to quantify the effects of a given load reduction in terms of nutrient concentration in the marine environment are therefore of importance for environmental management.

The goals of the national "Action Plan for the Aquatic Environment" (Folketinget 1987) were a 50% reduction of the riverine nitrogen load and an 80% reduction of the riverine phosphorus load in the period from 1987 to 1993. Monitoring by local and national authorities has shown that inputs of nitrogen did not change significantly during this period of time (Miljøstyrelsen 1994). The phosphorus loads, however, have been reduced according to the goals of the national action plan. These findings and discussion concerning alternative measures for effective reduction of the nitrogen loads, underline the need for operational methods for estimating the effect of various reduction strategies.

The quantification of nutrient fluxes from rivers to open coastal regions is notoriously difficult (Balls 1994) and includes the following problems:

(1) Time scale: Terrestrial nutrient load processes and

estuarine transport processes may have time scales as short as days or hours (Funen County 1990). On the other hand, seasonal variability in these processes display annual variations. The relevant time scale for a complete description of the nutrient transport processes thus ranges from hours to years.

(2) 'Sink/source'-processes: Nutrients introduced into estuarine and coastal regions are subject to both physicochemical and biological processes so that the load entering a given study area does not equate with the load leaving the area towards the open sea. The coastal/estuarine areas will act as a sink when nutrients are removed from the water body (sequestered in sediments) and as a source when nutrients are released into the water (Schubel & Carter 1984). Important processes contributing to this non-conservative behavior of the nutrients include biogeochemical processes, deposition and resuspension of sediments (Christensen et al., 1996; Christiansen et al., 1996a).

(3) Hydraulic transport processes: Inorganic nutrient concentrations depend on biological activity and do not behave conservatively. In contrast, Total-N and Total-P as model parameters can in general be assumed to act 'conservatively' on time-scales of years and they will therefore follow the water masses. This gives the advantage that biological processes do not need to be included in the model.

The present work is part of a larger interdisciplinary project dealing with various effects of eutrophication in a coastal area, the southwest Kattegat, Denmark (Christiansen et al., 1995). The effects of sedimentation and resuspension on nutrient dynamics have been reported elsewhere (Christiansen et al., 1997).

The aim of the present work is to study to what extent local inputs of N and P affect the nutrient concentrations in a specific study area in the Danish inner waters. The area chosen is one where the nutrient load is relatively high due to the presence of major cities and industries. An existing hydrodynamical model, MIKE12 (Danish Hydraulic Institute 1992) was applied. The model is described below, but it meets two important strategic requirements. It is simple enough to be run on an operational basis by the local environmental authorities, and it is advanced enough to give answers to the specified hydraulic questions.

Study area

The study area (Figure 1) has a surface area of approximately $2*10^3$ km^2. Water depths vary between up to 10 and 15 m in the western and northern part of the study area and up to between 20 and 25 m in the central part. The average depth is 10 m. The tidal range is small (<0.4 m), and is far exceeded by meteorologically induced variations which may cause the sea-level to fluctuate between 1.7 m above and 1.5 m below mean sea-level (Christiansen et al., 1981). The study area is situated in the transition zone between inflowing bottom water of high density (30-34 PSU) from the North Sea and outflowing low density (8-10 PSU) surface water from the Baltic. Because of the circulation pattern, a strong pycnocline is present during spring and summer periods at a depth of 10-20 m (Stigebrandt 1983), whereas the water column is generally less stratified during autumn and winter. Evaluation of the sedimentary record, reveals a shift in the circulation system to more frequent bottom water inflows apparently since the beginning of

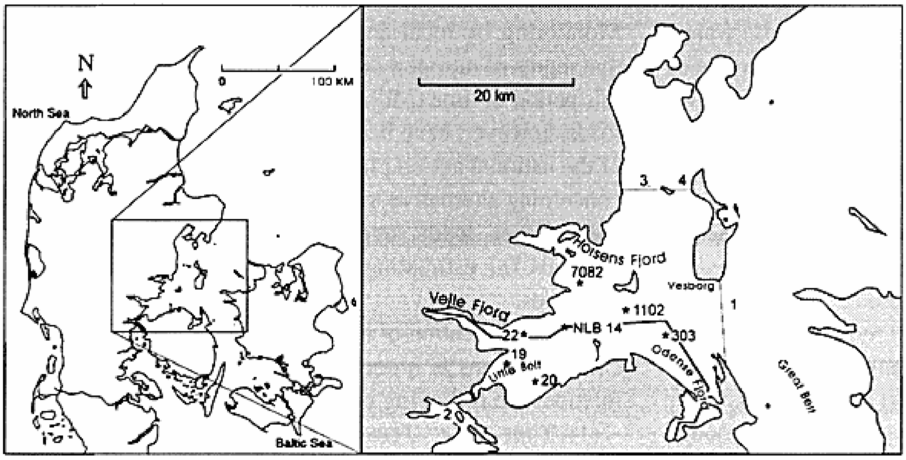

Figure 1: Map of the study area with the open boundaries:
1:Samsø (Great Belt)
2:Fredericia (Little Belt)
3: Aarhus
4: Endelave.
Also shown is the position of the profile (running from Vejle Fjord to Odense Fjord) shown in Fig. 3 and positions of sediment cores (asterisks) used for radiometric determination of deposition rates as well as place names mentioned in the text.

the 1970s (Christiansen et al., 1996b).

The concentration of suspended matter in the study area takes an intermediate position between background concentrations in the North Sea (3-6 mg l^{-1}) and the Baltic (1-3 mg l^{-1}) (Lund-Hansen et al., 1993). This is one of the reasons why both the concentration of suspended matter and the rate of sedimentation in the western part of southern Kattegat are highest when the area is dominated by inflow of North Sea water. Another reason is that inflow takes place below the pycnocline with a following high potential for resuspension during strong westerly winds which cause inflow (Lund-Hansen et al., 1993). The yearly terrestrial supply of nutrients to the study area in 1990 was 365 tons of P and 10.900 tons of N (including atmospheric deposition) according to Christiansen et al., (1996a).

Methods

The dominant physical processes to be simulated in the model are the barotropic and the baroclinic flows. Barotropic flow is forced by water level differences, air pressure differences and local wind impact. Baroclinic flow is forced by horizontal density differences in the water column and gives rise to density driven circulations.

It was decided to conduct the simulation of nutrient transport by means of the numerical hydrodynamical model "MIKE12" (Danish Hydraulic Institute 1992). The model has been successfully applied both in scientific and commercial projects (e.g. Sehested & Jürgensen 1994; Jakobsen & Møller 1994). The model is fully dynamical, i.e. it solves the governing differential equations for conservation of both mass and momentum. It also includes a module which solves the equation of conservation of mass of a dissolved or suspended material, i.e. the transport dispersion equation. The forcing boundary conditions that consist of measured time series of water level, pycnocline level, density and nutrient concentrations in two levels (above and below the pycnocline), input from tributaries, precipitation of nutrients, wind velocity and direction.

Two basic assumptions characterize the MIKE12 model:

(1) One dimensional assumption: The model topography is simplified to a network of one dimensional channels. Each channel segment is described with the relevant hydraulic properties (cross-section area, friction radius etc.).

(2) Two layer assumption: The channels are divided into two vertically stratified layers. The above mentioned differential equations are simultaneously solved for each layer. Entrainment between the layers is taken into account.

Relevant coefficients applied in the model are: Time steps of 2 minutes are necessary to ensure numerical stability; Dispersion: 100 m^2s^{-1}; Resistance: 60 $m^{1/3}s^{-1}$ (Manning); Bulk Flux Richardson No. (upward): 0.05; Bulk Flux Richardson No. (downward): 0.01.

The dispersion and resistance are found through calibration on the independent density parameter using data outside the study period. The results are relatively independent of the chosen dispersion, i.e. changing the dispersion by a factor of two does not give significant changes in the simulated concentrations. The Bulk Flux Richardson number for upward entrainment is the standard value from the literature (Pedersen 1986). The value for downward entrainment is found through calibration on density (Figure 2a). The reason for a relatively low value for downward entrainment is not understood in detail, but it is probably a consequence of the fact that the lower layer is often stratified with an almost linearly increasing gradient towards the bottom, whereas the model assumes a fully mixed lower layer.

The (area) specific resistance, denoted K, is defined from:

$$K = \Delta H/Q^2$$

where Δ H is water level difference and Q is discharge. The resistance value is larger than reported values for larger and wider flow channels in the inner Danish waters (Table 1). As a consequence realistic flows can be expected from the present model.

The simulations are performed in two steps:

1. a hydrodynamical simulation, by computing water level and discharges in the area.
2. an advective/dispersive simulation, by computing the transport of dissolved and particulate nutrients using the results from the hydrodynamical simulation.

In the following the open boundaries are named 'Århus-', 'Samsø-', 'Fredericia-' and 'Endelave-boundary', respectively (Figure 1). The study area is simplified to a net of channel branches. Data for the cross sections are specified at appropriate points along each channel, so that the correct surface area, depth, and cross sectional areas are applied in the computations. The relatively small water level

Table 1: Comparison of specific resistance values reported from the Kattegat and the Belt areas.

Area	*Specific resistance*	*Source*
Kattegat-Baltic	0.2 - 0.8	Pedersen, 1986
Øresund	1-2	Jakobsen &
Southern	2	Present work

differences which mostly exist between some of the open boundaries makes it difficult to apply time series of water level measurements measured independently at each boundary. Offset errors of the same magnitude as the levelling uncertainty (i.e. ± 1 mm) would have misleading effects on the hydrodynamic computations. In order to avoid this problem, the hydrodynamic computations were conducted for a larger model area, forced by one measured water level for the southern Kattegat and one measured water level for the south-western Baltic Sea. The mean difference of the water levels of the two time series over 4½ years was set to zero, resulting in an almost neglible average net yearly discharge through the area of 1410 m^3s^{-1} which is close to the long term average discharge of 1360 m^3s^{-1} through the Little Belt (Lund-Hansen et al., 1994b). From the larger model area, time series of the necessary hydrodynamic parameters were extracted at the boundaries of the actual and smaller model area shown in Figure 1.

The quality of the measured time series is crucial for the success of the simulations, and a major field measurement program was initiated (Christiansen et al., 1996a).

Results

Model validation

The results of the simulations were time series of 12 parameters computed at 100 computation points in the channel system. The parameters were computed for every 2 minutes and stored as averages for each hour. The hydrodynamical simulations were conducted for the period from January 1, 1990 to September 1, 1994. The advective and dispersive simulations were conducted for a slightly shorter period from January 1, 1990 to January 1, 1994, as the necessary nutrient loadings from the riverine inputs in

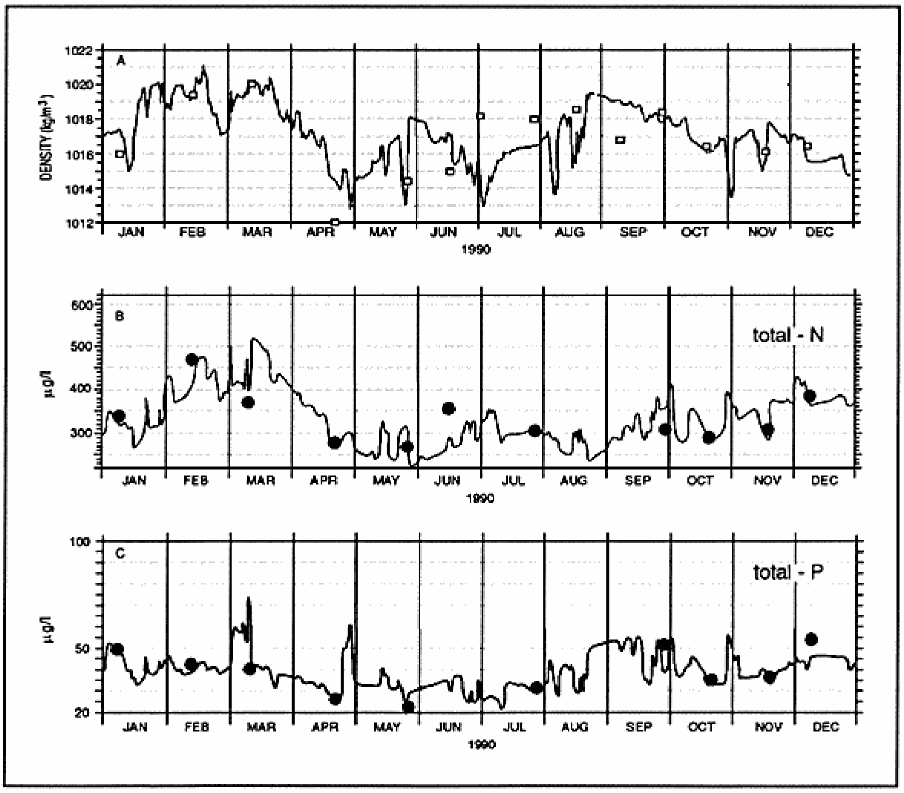

Figure 2: Validation of the model output for the surface layer at station NLB14 (Fig. 1) using: A) Density based on measured temperature and salinity; B) Total-N; C) Total-P.

the remaining period were not available.

Validations of the hydrodynamical and advective simulations covering surface water on station NLB 14 (Fig.1) are given in Fig. 2 A,B,C. There is good agreement between modelled and measured water densities and nutrient concentrations in the surface water masses. Modelled (average) concentrations in the bottom water masses (not shown) are generally smaller than measured (1 m above the bottom). This is consistent with the observed linear increase in concentration values from the pycnocline to the bottom.

Boundary impact

Simulations of the nutrient fluxes over the model boundaries make it possible to give a quantitative comparison of the different boundary transports and their impact on the nutrient concentrations in the model area. The boundary impact in the present analysis is interpreted as the interaction between the water masses inside and outside of the boundary. The traditional parameter used in interaction analysis is the mean value of the flux. Because of the cyclic characteristics of the flow in the present study area, a mean value analysis is considered to give irrelevant, and therefore misleading information about the concentration interactions and hence about the boundary impact. In mathematical terms, this type of interaction may be better described by the standard deviation (st.dev.). The standard deviation is considered a simple and suitable term as the boundary fluxes have a pronounced cyclic character with an average of about zero.

The standard deviations for fluxes of water and nutrients are determined for monthly subsamples of the simulations. These monthly deviations are in the following called "exchange rates". The entire simulation period of approximately 4 years includes about 48 exchange rates for each parameter at each boundary. Monthly subsamples are chosen in order to show possible seasonal variations. In Table 2 the exchange rates are shown in terms of means and standard deviations of the 48 exchange rates. Table 2 demonstrates that the boundaries at Fredericia (Little Belt) and Samsø (Great Belt) are by far the dominat boundaries, i.e. the major impacts on the nutrient concentrations come from the Little Belt and from the Great Belt. These two boundaries have about the same influence on the concentrations in the model region, whereas the two remaining boundaries Århus and Endelave are clearly of minor importance. Table 3 shows that the exchange rates over the boundaries have relatively small seasonal variations.

Nutrient sources

Table 4 illustrates the computed mass balance (1993) for nitrogen and phosphorous. The balance includes the loadings from external sources (from the land and the atmosphere), the advected load across the study boundaries and the concentration change over the study period. The difference between the combined external sources and advected mass and the concentration change represents the internal sources (including also the numerical uncertainty of the model).

The internal sources (net sedimentation) in Table 4 show two important features: For nitrogen, net sedimentation is found to be about 1/3 of the external sources, for phosphorus the ratio between net sedimentation and external load is near 1. The nitrogen ratio of about 1/3 implies that some part of the nitrogen is removed from the water by the sedimentation, the rest is assumed denitrified or transorted into the adjacent open sea areas. On the other hand, area are generally in the range of 469-757 g m^{-2} y^{-1} (Table 5). Very high rates (4290 g m^{-2} y^{-1}) are observed near the mouth of the Little Belt. These net sedimentation rates are small compared with gross sedimentation rates measured by sediment traps (Christiansen et al. 1996a).

Multiplying net sedimentation rates with sediment organic matter and nutrient concentrations, the yearly

Boundary	*Århus*	*Samsø*	*Fredericia*	*Endelave*
Discharge	9200±1400	54700±2200	65400±3100	4900±200
tot-N	250±40	1610±70	1960±100	140±5
tot-P	26±6	182±9	208±6	14±1

Table 2: *Mean values and standard deviations (±) for the monthly exchange rates of water, total nitrogen and total phosphorous for the boundaries of the study area. Note the strong impact from the Samsø (Great Belt) boundary and the Fredericia (Little Belt) boundary.*

Table 3: Relative variation of the monthly exchange rates for water, total nitrogen and total phosphorous at the study boundaries. The values are expressed as standard deviation divided by mean value from Table 2.

Boun	*Årh*	*Sam*	*Frederic*	*Endelave*
Disc	15%	4%	5%	4%
tot-N	16%	4%	5%	4%
tot-P	23%	5%	3%	7%

Table 4: Mass balance of nutrients for 1993. Positive transports are directed into the water masses of the study area.

	Total-N 10^3 *T/year*	*Total-P* 10^3 *T/year*
External	+9.3	+0.19
Advective	-10.7	+0.23
Concentratio	+4.5	-0.22
Internal	-3.1	-0.20

deposition for the total study area is 35,769 tons of organic matter, 1,340 tons of nitrogen and 477 tons of phosphorus (Table 5). These independent measurements of nutrient sequestering rates are of the same order as the rates predicted from model computations (Table 4) and thereby also increase confidence in model estimations.

Concentration response and residence time

Two scenarios for nutrient concentrations in the study area have been simulated for 1990, with the primary goal of describing what effect load reduction has on the coastal nutrient concentrations. The first scenario simulates the actual nutrient load conditions for that year, and the second scenario simulates the reduced load conditions of the national action plan, i.e. 50% nitrogen load reduction and 80% phosphorus load reduction. The results (Figure 3) show coastal concentration reductions of the same order of magnitude as the load reductions in the inner parts of the fiords close to the sources. In the outer parts of the fiords the effect is smaller. High concentrations in the three larger fiords (Odense, Vejle and Horsens) are closely related to load events. The concentration decay after a major load event indicates a time scale of about 1 week for the fiords with respect to the load induced over-concentrations (Funen County 1990).

In the open, central part of the model area, i.e. the deepest water, the concentration reductions were much smaller than the load reductions. The reason for this reduced effect in the open areas is the interaction between the model area and the adjacent marine areas. The high exchange rates over the boundaries give rise to an almost complete nutrient dilution in the open parts of the model area. The entire Kattegat-Belt Sea region (including the model area) experiences elevated nutrient levels due to run-off from land during winter seasons (Funen County 1995). The present model will not show this because the measured boundary conditions for nutrients are within the affected region and therefore include the effect of a general higher nutrient level during winter. Hence, the present model setup is not primarily designed to give an answer to questions concerning larger, regional scale effects.

Although the present model topography is not designed to show large scale effects such as the consequence for the total inner Danish waters, an attempt can be made by considering the time scales involved for residence of nutrients. The time scale (calculated as volume divided by flow) for the open areas of the present model is determined to be 4-5 days, due to the strong barotropic forcing through the area. Based on intensive monitoring (Funen County 1995), the regional time scale of the southern Kattegat, the Great Belt and the northern Little Belt is estimated to be approximately 1 month. A simple relation between time scale and

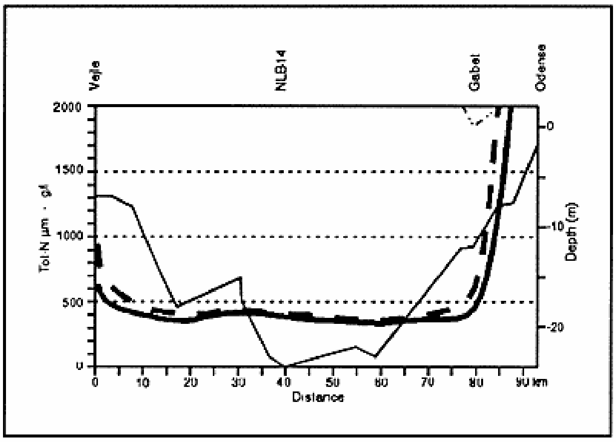

Figure 3: Simulation of nitrogen concentration values along the transects across the study area (see Figure 1). The thick dashed line represents the 1990 simulation for the actual loadings and the thick solid line the simulation with the reduced loadings. The thin solid line is the depth profile.

Station	*Sed. Rate*	*Area m²*	*Sed. Rate T/year*	*Org.m. %*	*Org.m. T/year*
19	4290	$1.73 \cdot 10^7$	74131	2.9	2150
20	757	$7.38 \cdot 10^7$	55866	13.8	7720
22	510	$12.06 \cdot 10^7$	61506	10.9	6723
303	625	$13.76 \cdot 10^7$	86000	10.5	9047
1102	479	$14.04 \cdot 10^7$	67156	12.1	8139
7082	469	$3.16 \cdot 10^7$	14820	13.4	1990
Sum		$5.2 \cdot 10^8$			35769
Station	***N %***	***N T/year***	***P %***	***P T/year***	
19	0.099	73.4	0.055	40.8	
20	0.490	273.7	0.174	97.2	
22	0.394	242.3	0.153	94.1	
303	0.418	359.0	0.140	120.4	
1102	0.458	307.6	0.152	102.1	
7082	0.567	84.0	0.151	22.4	
Sum		1340.0		477.0	

Table 5: Net deposition rates of organic matter and nutrients in the study area. Positions of stations are shown in Fig. 1.

concentration reduction can be made applying linear reservoir theory (Shaw 1988). The decay after a single standard load event can be described as:

$$C(t) = Co \cdot \exp(-t/T),\ t>0 \qquad (1)$$

where C(t) = concentration, Co = specific (initial) concentration, t = time coordinate, and T = time scale.

Integrating the effect of numerous standard events over the time gives:

$$C(t) = Co \int_0^t \exp(-t/T)dt \ = Co\, T(1-\exp(-t/T)) \qquad (2)$$

The model predicted an over-concentration of nitrogen of C(t) = 8 μgN/l during spring time (see Figure 4), a time scale of T = 4-5 days and a typical load period during high spring runoff of t = 100 days , which according to (2) results in a specific concentration of 1.8 μgN/l

Applying this specific concentration and a time scale for nutrients in the region (T = 30 days (Funen County 1990, 1995)) in the same formula, a concentration reduction C(t) can be estimated to 50 μgN/l. This is in close agreement with the measured increase of nitrogen during the spring season.

The background concentration is 330 μgN/l (Funen County 1990,1995). The relative concentration decrease during spring is therefore about 15%.

The corresponding over-concentration of phosphorus in the model setup was C(t) = 0.25 μgP/l (see Figure 4), and with the same time scale and typical load period as for nitrogen a specific concentration is found for phosphorus:

Co = 0.06 μgP/l
C(t) = 1-2 μgP/l

This is supported by monitoring results showing that P does not increase during spring. The background concentration is 40 μgP/l (Funen County 1990,1995). The relative concentration decrease during spring is therefore about 2-5%.

Discussion

As indicated by the large differences between net sedimentation (from radiometric dating) and gross sedimentation (from traps) the study area is subject to frequent resuspension events. Christiansen et al. (1996a) showed that resuspension occurs for 15-35% of the year in shallow water areas and for <3% of the year in deep water areas. As a consequence of resuspension an amount of sediment-bound nutrients equal to 17 times the external load was recycled to the water column (Christiansen et al (1996a). Such a large flux of nutrients is not discerned in the model, which only gives net sedimentation rates.

Frequent resuspension episodes and resulting large suspended matter concentrations may help to explain why phosphorous removal to the sediment (~100%) is much higher than nitrogen sedimentation (~30%) (Table 4). In contrast to nitrogen, dissolved phosphate is influenced by adsorption onto particulate phases. It has long been recognized that the interaction with sediment and/or suspended material, the 'phosphate buffer mechanism', has strong control over dissolved concentrations (see review by Froelich 1988) and that this control is highest in turbid water. The uptake of phosphate on particles by adsorption is rapid (minutes-hours) (Lund-Hansen et al., 1994b), therefore this process may be important in the study area in spite of a relatively short residence time. In contrast to this, the small nitrogen net sedimentation may be due to resuspension. Wallin & Håkanson (1992) suggested that resuspension of organic particles leads to increased nitrogen mineralization and results in higher water concentrations of inorganic nitrogen.

The local terrestrial supply of nutrients made up 10.900 tons of N and 365 tons of P. Compared to transport rates (Table 2) the local supply contributed only a small (2-5%) amount to the yearly nutrient transport through the study area. Therefore, the modelled reduction of terrestrial load was only of significant impact in the model in the inner parts of the fiords near the terrestrial sources themselves. In open waters, the effects of a local reduction in nutrient supply could only be discerned during the early spring, during periods of large freshwater discharges. However, smaller open water nutrient concentrations at this time of the year may reduce the phytoplankton spring bloom and therefore have the additional benefit of subsequently lower risk of oxygen deficit later in the year. The present study thus indicates that effective reductions in large nutrient concentrations in open water areas with short residence times can only be achieved by national and international cooperation. Outside the periods of large freshwater discharges, local terrestrial loads in such areas have only a small impact on open water nutrient concentrations.

The use of transport modelling in local monitoring strategies may help to explain the degree to which monitored nutrient concentrations depend on either local supply to the

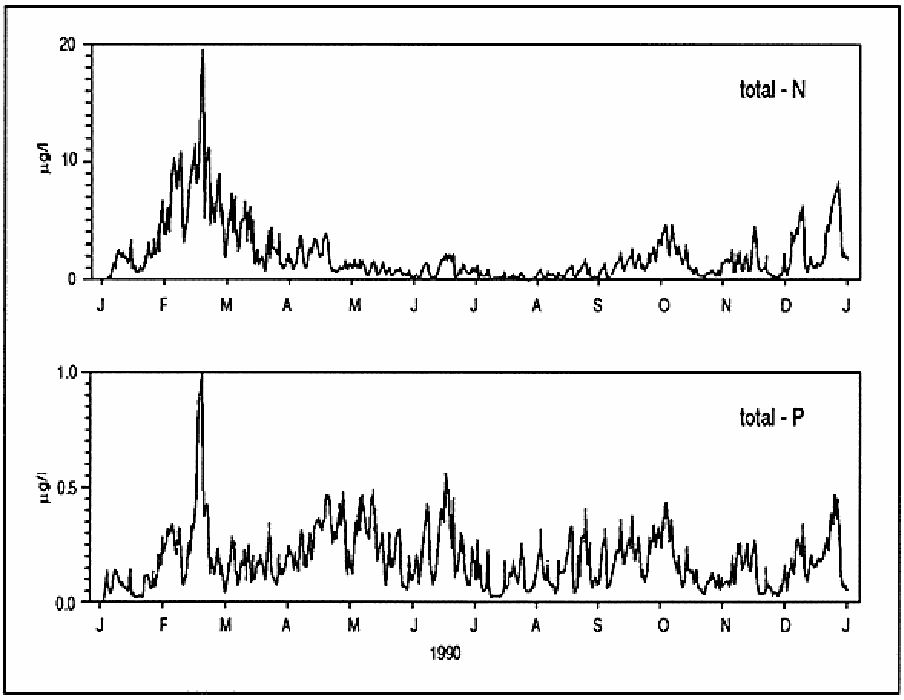

Figure 4: Modelled nutrient concentration differences between the two scenarios for station NLB14 in the open, central section of the study area for the year 1990. Load reductions in external supply is 50% of N and 80% of P.

marine environment or advective transport. Further, nutrient concentration modelling may help to throw light on concentration variability in between monitoring and thereby help to optimize monitoring strategies (Christiansen et al., 1996c).

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