External nutrient supply to coastal waters, a comparison between different sources

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ABSTRACT

Monthly nutrient and salinity observations have been undertaken during the years 1982–1984 in the southeastern part of the Kattegat on the west coast of Sweden. The coastal zone (<10 km) in that area receives a heavy nutrient load, mainly as nitrate, from a couple of small rivers. The observations are presented as yearly mean concentrations of total nitrogen, total phosphorus, inorganic nitrogen and phosphate within three different water masses: one defined as local surface water within the Laholm bay, one as Kattegat surface water and the third as Kattegat deep water. The nutrient components are used as tracers to determine four "unknown" quantities: The "exchange" between the local water and the Kattegat surface water, the corresponding "exchange" with the deep water, and the assimilation of inorganic nitrogen and phosphate within the local water. The results indicate that more than 60% of the inorganic nitrogen supply to the local water is of land based origin while only about 10% of the phosphate supply is derived from land. Two thirds of the inorganic nitrogen supply to the local water is assimilated within the bay by the phytoplankton production. The rest is advected, mainly as nitrate to the Kattegat during the non-productive winter months. The supply of phosphate to the local waters is almost totally assimilated. Still, nitrogen is the limiting nutrient for the main part of the productive season.

INTRODUCTION

For more than ten years, various eutrophication effects have been seen in the southeastern Kattegat (Fig. 1), such as intensive algal blooms and oxygen deficit in the deep waters, leading to the elimination of bottom fishery. These effects culminated following a rainy summer in 1980. Severe oxygen deficit and hydrogen sulphide production occurred both in 1980 and 1981.

The waters in this area are characterized by a strong vertical salinity stratification, caused by the outflow of low salinity water from the Baltic Sea and an inflow of high salinity water of oceanic origin at deeper levels. The surface water has a salinity of 12–25, and a thickness of approximately 15 m. The deep water salinity is normally between 32 and 34.

In this part of the Kattegat the depth is generally less than 30 m implying that the deep water volume sometimes becomes small or even zero, at least in the Laholm bay where the depth does not exceed 20 m. The halocline depth (and the surface water salinities as well) is strongly influenced by the outflow from the Baltic, but varies also due to local winds which redistribute the surface waters and induces mixing, mainly as upward entrainment (but downward as well in the near shore areas).

The phytoplankton production in the Kattegat begins with a spring bloom period, usually in early March, when the winter
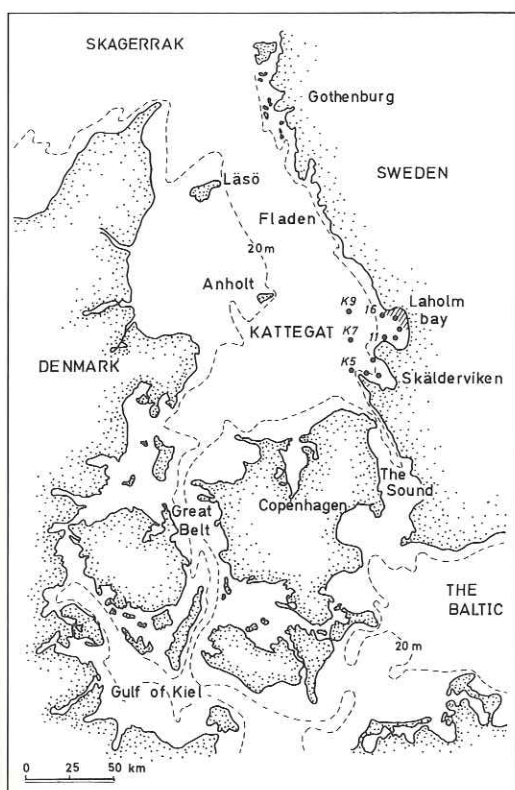
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Fig. 1.   Map over the Kattegat and the survey area.

nutrient pool is rapidly emptied, followed by a rather stationary summer production of the order 0.4 gC/m² day⁻¹. The production ceases in late October, and typically the annual primary production is just above 100 gC/m² year⁻¹ (Aertebjerg et al. 1981). The production in the outer part of the Laholm bay has been recently studied by Edler, who found a mean annual production of the order 150 gC/m² year⁻¹ (Edler, personal communication).

The Institute of Oceanography, University of Gothenburg, started an intensive field programme in the southeastern Kattegat in February 1982, with emphasis on the situation in the Laholm bay which receives a heavy nutrient load, especially inorganic nitrogen through the rivers Lagan and Nissan (Fig. 2b). A main goal was to deter-

mine to what extent the local supply of nutrients influence the severe oxygen conditions within the area.

From the beginning almost monthly surveys have been carried out, including hydrography and nutrient chemistry, at approximately 15 stations within the area. The surveys will be continued until November 1985. Although the programme is not yet finished, we believe that it is now (November 1984) possible to make a first estimate of the relative importance of the local land-based nitrate supply, based on yearly mean conditions.

To do this, we have defined three water masses: one which consists of Laholm bay surface water, one for Kattegat surface water and one for Kattegat deep water. By using mass balance equations for each of the nutrient components, viz. total nitrogen (TN), total phosphorus (TP), inorganic nitrogen (IN = Σ (NO_3 – N + NO_2 – N + NH_4 – N) and phosphate (IP), we will determine the exchange of nutrients between the different water masses, and the nutrient assimilation within the Laholm bay, which is one way of expressing the importance of the local supply.

From a biological point of view it is obvious that it will be necessary to study the monthly variations (i.e. monthly means) of the parameters involved in our calculations. This will be done once the measuring programme is fulfilled. In this communication we will, however, attempt to show that even annual mean values may reveal the main features.

OBSERVATIONS AND DATA TREATMENT

The monthly field programme included CTD profiling and discrete water bottle sampling with a rosette water sampler. At each of the 15 stations (see e.g. Fig. 3a) 2–6 water bottles were taken for analyses of salinity, oxygen, nitrate, nitrite, ammonia,
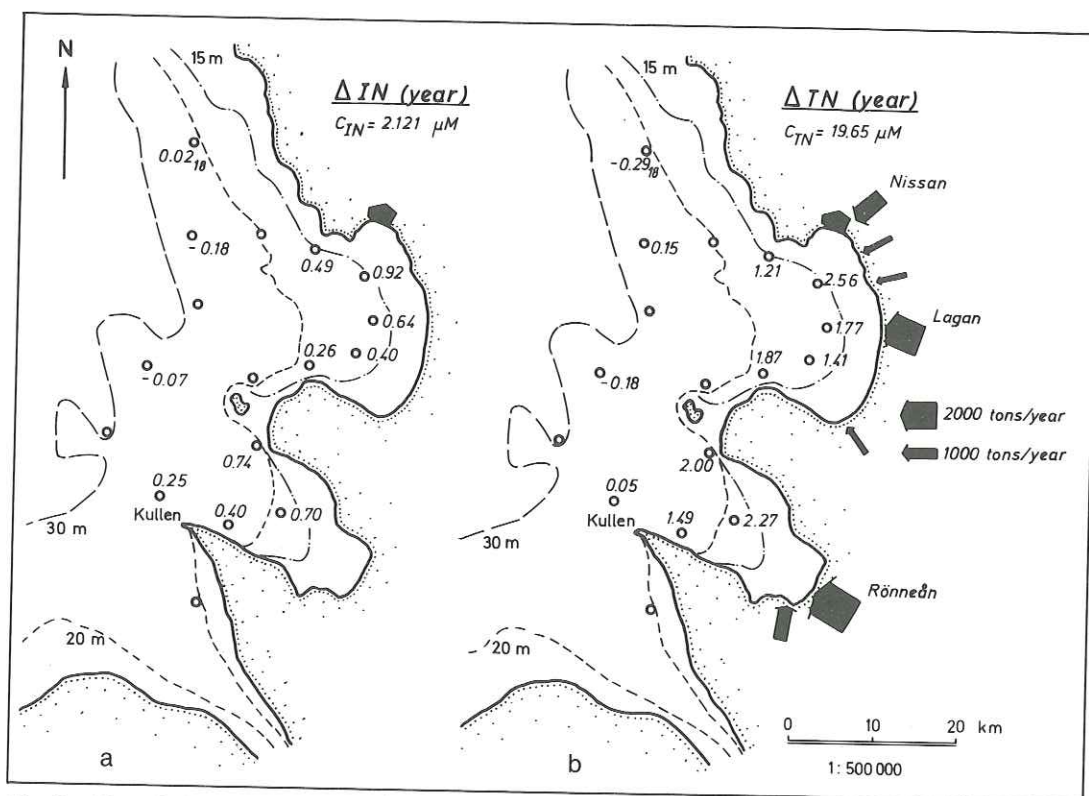
Fig. 2. Mean deviations, $\triangle C$ (μM) of the IN and TN surface water concentrations from the spatial mean values within the Kattegat surface water, $C_{IN} = 2.121$ μM and $C_{TN} = 19.65$ μM, from the observations at the stations K5, K7 and K9. For positions, see Figure 1. The mean values are based on 22 surveys from February 1982 to April 1984. (For time spacing, see Fig. 5). The size of the land based supply of TN (from Fleischer et al. 1985) is shown by arrows.

TN, IP and TP. The calculations are based on data from 22 expeditions from February 1982 – April 1984. Some more details concerning observations and methods are given in Rydberg (1985).

The observations have been used to determine the annual mean surface water concentrations of IN and TN (Fig. 2a, b), IP and TP (Fig. 3a, b) and salinity (Fig. 4b) for each station separately. The surface water is defined as the water between 0 and 10 m, or when the halocline is shallower than 10 m (has happened once) as the water with salinities $S < 30$. Figure 4a shows the annual mean salinity 1 m above the bottom, which for the deeper stations (K5, K7 and K9, the only stations where deep water, with salin-

ities $S > 30$ was always present) have been added together to give the mean annual "deep water salinity", shown in Figure 6. The annual mean concentrations of IN, IP, TN and TP 1 m above the bottom at the stations K5, K7 and K9 (see Fig. 1 for positions), were also calculated but are not shown here. The spatial mean values for these stations will be used as "deep water concentrations" (like deep water salinity), and are shown in Figure 6.

The nutrient concentrations within the surface waters vary strongly throughout the year, mainly due to the variable phytoplankton production, but also due to a variable nutrient supply. As one example, we show in Figure 5 the spatial mean concen-
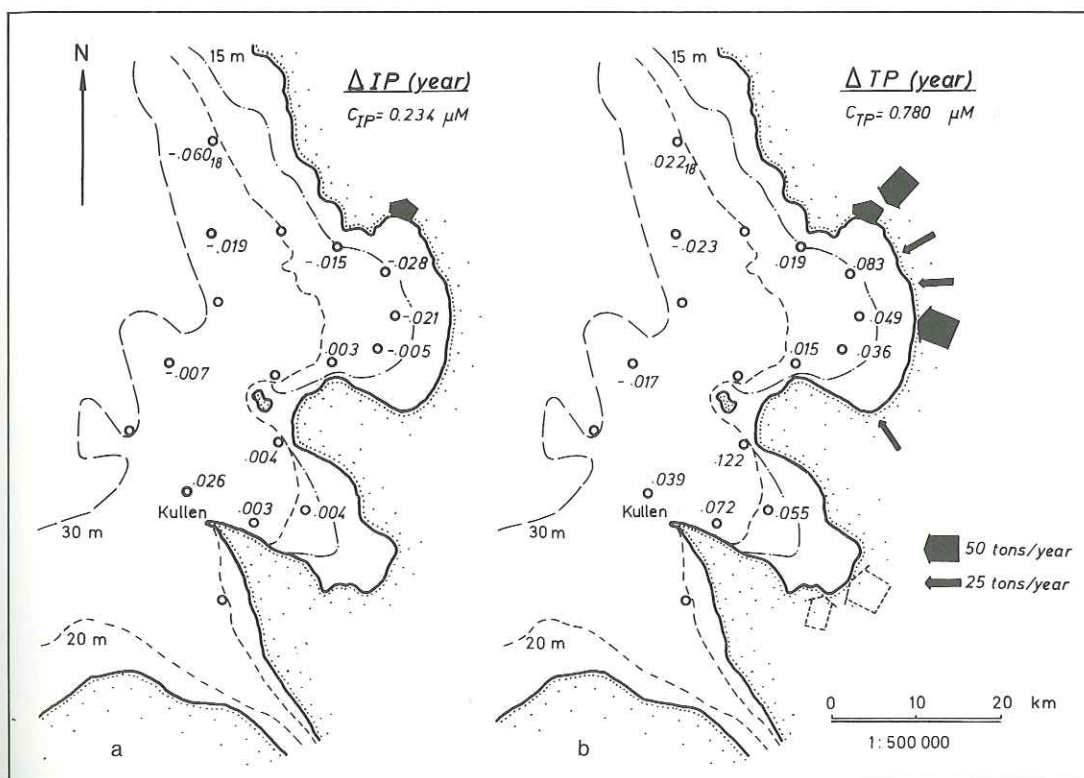
Fig. 3. Mean deviations, $\triangle C$ (μM) of the IP and TP surface water concentrations from the spatial mean values within the Kattegat surface water, $C_{IP} = 0.234$ μM and $C_{TP} = 0.780$ μM, from the observations at the stations K5, K7 and K9. For positions, see Figure 1. The mean values are based on 22 surveys from February 1982 to April 1984. (For time spacing, see Fig. 5). The size of the land based supply of TP is shown by arrows.

trations of IN and IP inside the Laholm bay including the Skälderviken (the eight inner stations) and in "the open sea" (stations K5, K7 and K9). We note the rapid decrease in concentrations after the spring bloom, as mentioned in the introduction, very low IN concentrations until October but slowly increasing IP concentrations during the summer.

A SIMPLE BOX MODEL

Let us now define three water masses in the following way: Laholm bay surface water (box L, indexed L), identified by the spatial mean surface water concentrations at the stations 16, 15, 14, 13 and 11 (with half weight for stations 16 and 11); Kattegat surface water (indexed 1), identified from the mean surface water concentrations at the stations K7 and K9; and finally Kattegat deep water (indexed 0), from the mean concentrations 1 m above the bottom at the stations K5, K7 and K9.

The water masses form the basis for a simple box model shown in Figure 6, where we have also inserted the calculated spatial mean concentrations for IN, TN, IP, TP and S. The fluxes between the boxes are defined as follows: q_i diffusive volume flow between box L) and 1) – doubly directed; q_f fresh-water supply, advective volume flow from box L); q_0 diffusive volume flow between box 1) and 3) – doubly directed; q_e
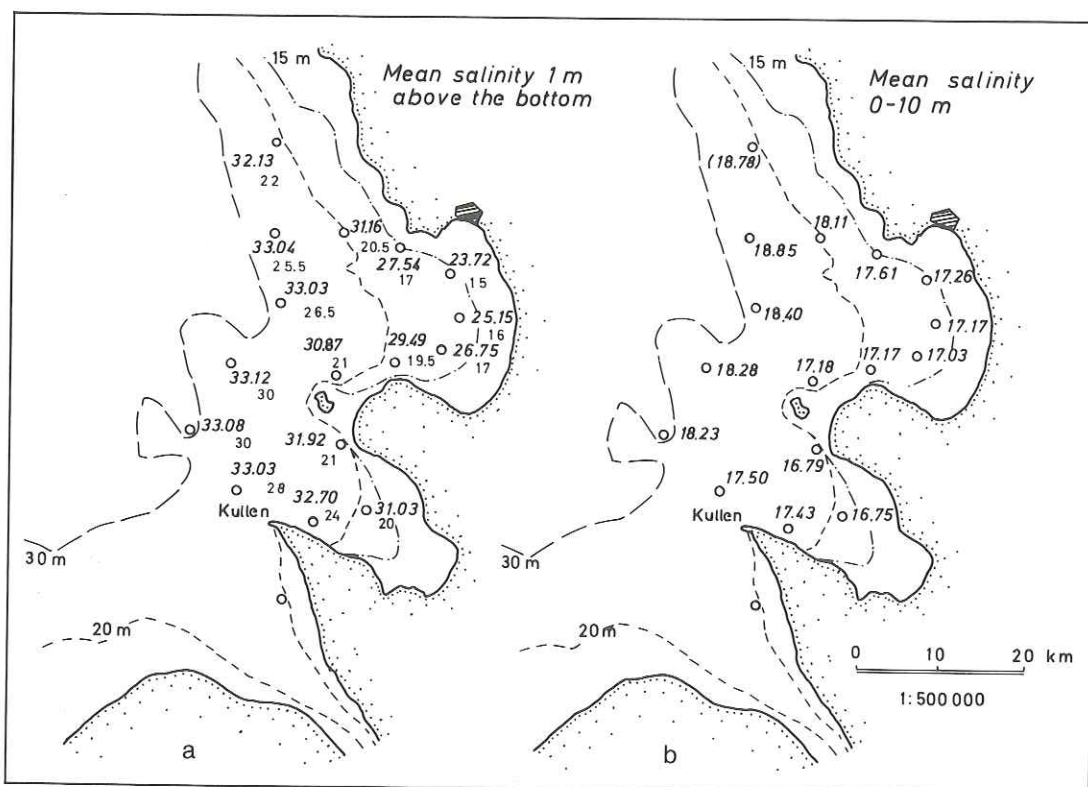
Fig. 4. Mean salinity of the surface water (0–10 m) and mean salinity 1 m above the bottom respectively. Small numbers indicate depth at each station. The mean values are based on 27 cruises from February 1982 to October 1984.

net upward entrainment flow. We implicitely assume that the Kattegat volumes are infinite, and include an effective horizontal mixing, implying that the fluxes from box L) do not influence the properties in the other boxes. These fluxes may in fact enter other volumes than those defined here. The entrainment flow, q_e, an advective flow from box 0) to box L) which also adds an extra term to the outflow from box L) has been included in the diffusive fluxes q_1 and q_0, respectively. The fact that it does not show up in the following set of conservation equations (for which the definitions are given in Figure 6) does not mean that it is omitted.

$$q_1 \cdot \triangle C_{TN1} + q_f \cdot C_{TNL} - q_0 \cdot \triangle C_{TN0} - r_{TN} = 0 \quad (1a)$$
$$q_1 \cdot \triangle C_{TP1} + q_f \cdot C_{TPL} - q_0 \cdot \triangle C_{TP0} - r_{TP} = 0 \quad (1b)$$
$$q_1 \cdot \triangle C_{IN1} + q_f \cdot C_{INL} - q_0 \cdot \triangle C_{IN0} - r_{IN} + \hat{r}_{IN} = 0 \quad (1c)$$
$$q_1 \cdot \triangle C_{IP1} + q_f \cdot C_{IPL} - q_0 \cdot \triangle C_{IP0} - r_{IP} + \hat{r}_{IP} = 0 \quad (1d)$$
$$q_1 \cdot \triangle S_1 + q_0 \cdot \triangle S_0 - q_f \cdot S = 0 \quad (1e)$$

where $\triangle C_{TN1} = C_{TNL} - C_{TN1}$;
$\triangle C_{TN0} = C_{TN0} - C_{TNL}.....$;
$\triangle S_1 = S_1 - S_L$ and $\triangle S_0 = S_0 - S_L$.

r_{TN} and r_{TP} are the supplies from land of total nitrogen, and total phosphorus respectively, while $\hat{r}_{IN}$ and $\hat{r}_{IP}$ are the assimilation of IN and IP respectively within box L), which together with q_0 and q_1 are the unknowns to be solved. It is assumed that TN and TP are conservative, which is not quite true (see discussion), and, in fact, that other effects than assimilation by phytoplankton may enter the terms $\hat{r}_{IN}$ and $\hat{r}_{IP}$. The omittance of
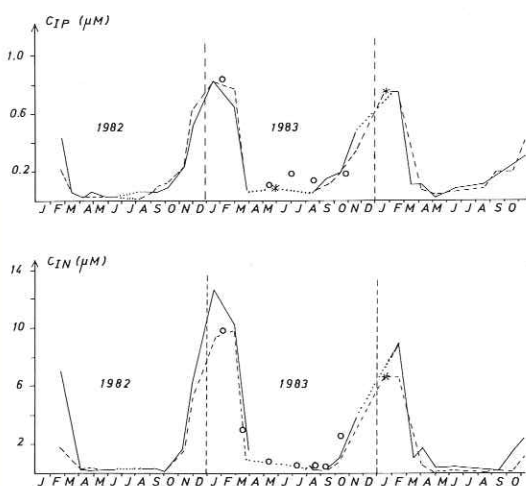
Fig. 5. Spatial mean concentrations (μM) within the Laholm bay and the Skälderviken (——) and within the Kattegat surface water (– – – –) for IN and IP respectively. The mean values are based on the eight inner stations (——) and the three outer stations K5, K7 and K9 (– – – –). For positions, see Figure 1. Special characters (o and *) denote observations performed by other investigators.

q_e may need a short explanation: If we rewrite eq. (1a) including q_e, we get the following expression:

$$q_1 \cdot \triangle C_{TN1} + (q_f + q_e) C_{TNL} - q_e \cdot C_{TN0} - q_0 \cdot \triangle C_{TN0} - r_{TN} = 0$$

where the extra terms,

$$q_e \cdot C_{TNL} - q_e \cdot C_{TN0} = -q_e \triangle C_{TN0}.$$

It is thus clear that q_e may be incorporated into q_0. By combining the eqs. 1a and 1b, we can find expressions for the diffusive flows, q_0 and q_1 respectively:

$$q_0 = \frac{r_{TN} \cdot \triangle C_{TP1} - r_{TP} \cdot \triangle C_{TN1} - q_f [C_{TNL} \cdot \triangle C_{TP1} - C_{TPL} \cdot \triangle C_{TN1}]}{\triangle C_{TP0} \cdot \triangle C_{TN1} - \triangle C_{TP1} \cdot \triangle C_{TN0}} \quad (2a)$$

$$q_1 = \frac{r_{TN} + q_0 \triangle C_{TN0} - q_f \cdot C_{TNL}}{\triangle C_{TN1}} \quad (2b)$$

while the uptake terms, $\hat{r}_{IN}$ and $\hat{r}_{IP}$ may be determined from eqs. 1c, d. By inserting the concentration values shown in Figure 6, in the above mentioned expressions, the var-

ious fluxes ($q_1 \cdot \triangle C_{TN1},\ldots\ldots$) and uptake terms may be determined. The results are shown in Figures 7a, b.

DISCUSSION

The main results from the box model and the corresponding equations 1a–d are the fluxes of inorganic nitrogen and phosphorus to and from the Laholm bay surface water (Fig. 7b). The IN supply is dominated by the transport from land, 79.3 g/s, while the supply from the deep water is 48.8 g/s. There is an outflow through the surface layer of 55.4 g/s and a planktonic assimilation of 72.8 g/s.

The external supply of IN, deep water as well as land based, is largest during the winter, when the uptake is low, indicating that the supply during the productive season (May-October) is almost totally consumed within the bay. The true supply from land could be larger due to mineralization of the TN supply within the bay, but this extra term is probably small, as the retention time for the surface water within the bay is short, approximately 1 week (the surface water volume is $\approx$ 3 km^3 and the diffusive exchange $q_1 \approx$ 5000 m^3/s), while remineralization of TN is likely to be a slow-going process. Another source which has not been considered is the atmospheric supply. It is small but not negligible (<10 g/s TN, mainly inorganic). It is almost evenly distributed, however, and it is not clear whether a supply of that kind should at all be considered, at least not in cases where the topographic effects are small.

The phytoplankton production within the bay may also result in a loss of TN (and IN),
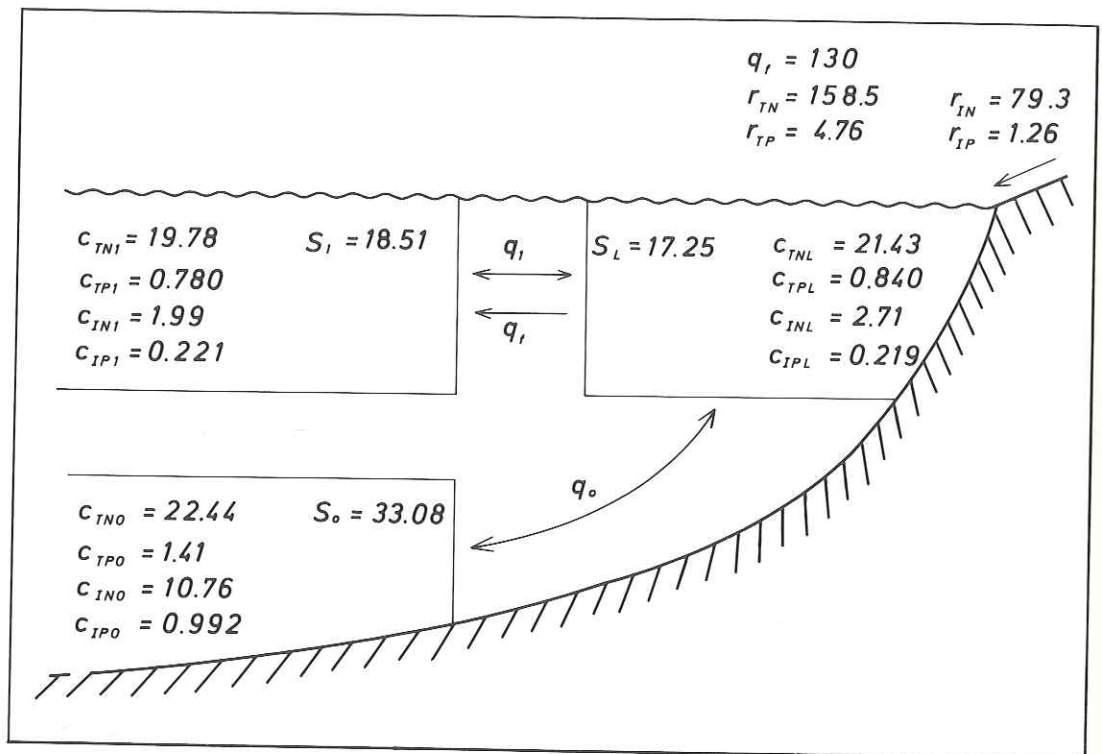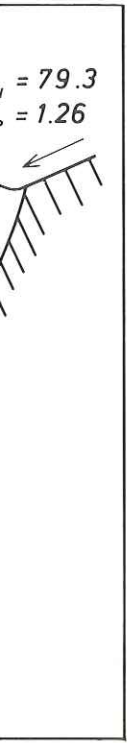
$q_f = 130$
$r_{TN} = 158.5$ $r_{IN} = 79.3$
$r_{TP} = 4.76$ $r_{IP} = 1.26$

$c_{TNi} = 19.78$ $S_i = 18.51$ q_i $S_L = 17.25$ $c_{TNL} = 21.43$
$c_{TPi} = 0.780$ $c_{TPL} = 0.840$
$c_{INi} = 1.99$ q_i $c_{INL} = 2.71$
$c_{IPi} = 0.221$ $c_{IPL} = 0.219$

$c_{TNO} = 22.44$ $S_o = 33.08$ q_o
$c_{TPO} = 1.41$
$c_{INO} = 10.76$
$c_{IPO} = 0.992$

Fig. 6. A box model for the Laholm bay and the SE Kattegat, showing observed mean concentrations (μM) within each of three water masses defined in the text. The supply terms (yearly mean values) for IN, TN, IP and TP are given in g/s, the fresh water flow in m³/s.

due to sedimentation of organic matter. This effect was not included in the equations. The sedimentation can be important after the spring bloom. Otherwise it is probably small, as again the time required for organic matter to sink from the surface to the bottom is of the order of 1 month (Rydberg 1985), while the retention time is shorter.

Looking at phosphorus, the supply of IP from land is an order of magnitude smaller than the supply from the deep water. Our observations in the river Nissan indicate, however, that the land based supply of IP is probably underestimated, but still the deep water supply dominates strongly. In contrast to IN, there is hardly any flux of IP out from the bay (there is even a diffusive inflow of IP), and the assimilation of IP is obviously very effective, indicating phosphorus deficit. The atmospheric contribution of phosphate is also negligible. On the other hand, the external supply of IP may be underestimated due to remineralization of a fraction of the TP supply, a source which can be of some importance.

The very large local supply of nitrogen makes it tempting to assume that phosphorus should limit the phytoplankton production, at least locally, but it is obvious from our measurements that this is not the case. In fact, nitrogen limits the production during the larger part of the productive season, also within the Laholm bay, while phosphate may be limiting after the spring bloom (see e.g. Rydberg and Sundberg 1984; Rydberg 1985). This is also indicated from the IP concentration within the sur-

= 79.3
= 1.26

$q_f = 130$
$r_{TN} = 158$
$r_{TP} = 4.7$

$S_1 = 18.51$ | TN ADV = 39 | $S_L = 17.25$
TN DIFF=126
TP ADV = 3.4
TP DIFF = 9.9

TN DIFF 6.8
$S_0 = 33.08$ | TP DIFF 8.6

a

s (μM) within
l TP are given

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c contribu-
ble. On the
of IP may
neralization
, a source
.
of nitrogen
t phospho-
on produc-
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uction dur-
ve season,
hile phos-
the spring
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o indicated
in the sur-

$q_f = 130$
$r_{IN} = 79.3$
$r_{IP} = 1.3$

$S_1 = 18.51$ | IN ADV 4.9 | IN ASS 72.8
IN DIFF 50.5 | IP ASS 11.5
IP ADV 0.9
IP DIFF 0.3
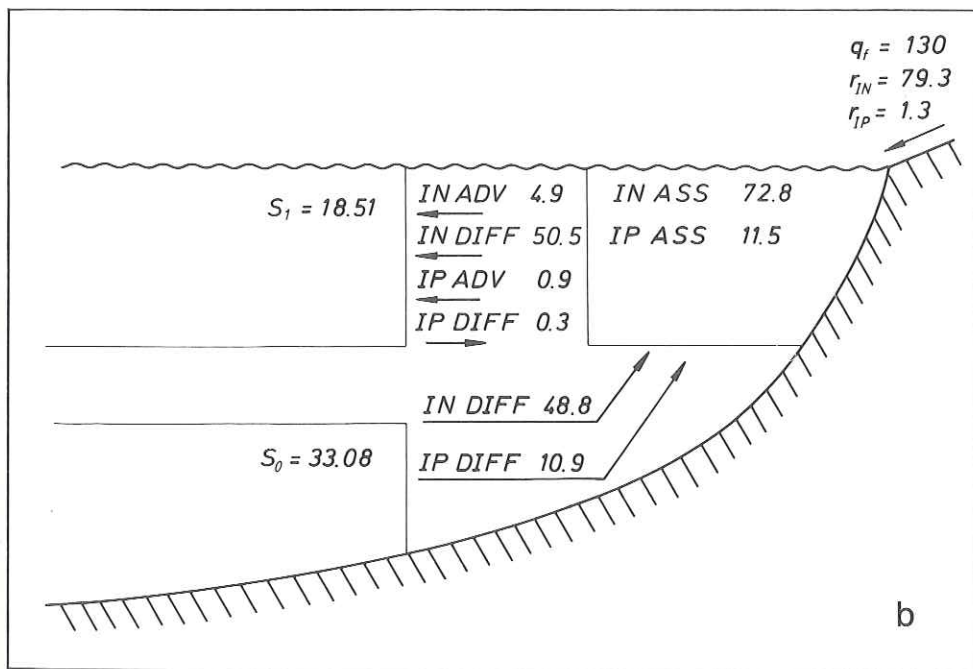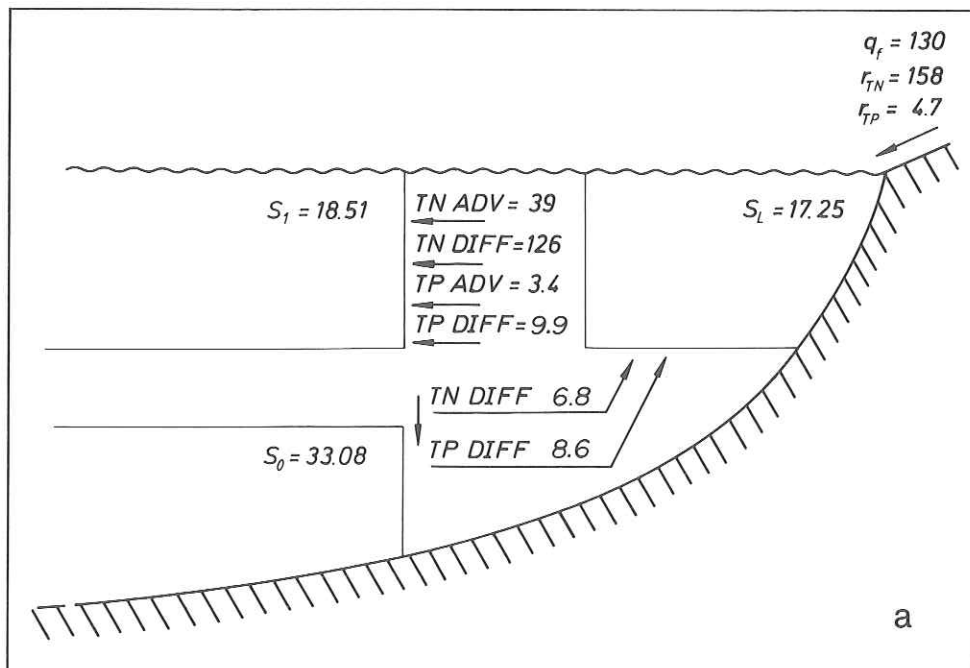
IN DIFF 48.8
$S_0 = 33.08$ | IP DIFF 10.9

b

Fig. 7a, b. The calculated fluxes of TN and TP, IN and IP (g/s) between the different water masses. The fluxes from the Laholm bay water do not necessarily enter the Kattegat surface water.

face waters (Fig. 5), which starts to increase rather soon after the spring bloom, while the IN concentrations remain very low until October, and furthermore this is indicated from enrichment experiments with water from the bay (Nyman and Graneli 1983). The most reasonable explanation for the nitrogen limitation seems to be a more effective and/or rapid regeneration of phosphorus than of nitrogen. One contributing process is probably denitrification occuring in the oxygen depleted bottom areas in this part of the Kattegat.

A comparison between the assimilation of IN and IP shows an uptake ratio IN/IP = 14 (Fig. 7b) which is in good agreement with that normally found in the ocean.

The use of salinity as a tracer (eq. 1e) is dependent on our insight into the dynamics of the area. This is complicated, however, by a highly variable outflow of low salinity water from the Baltic. The "jet stream" which sometimes enters the Kattegat from the Sound causes intensive mixing north of Kullen, and is influenced by the earth's rotation. As is seen from Figure 4, the horizontal salinity gradients perpendicular to the coast are as large in the Skälderviken as they are in the Laholm bay, although the fresh-water supply to the Skälderviken is small (20 m³/s compared to 130 m³/s for the Laholm bay). This is just an indication that the local freshwater supply to the Laholm bay is too small to allow the use of salinity as a tracer.

In fact, it is possible to estimate the salinity difference due to the freshwater alone, $\triangle S_f$ from the expression $q_1 \cdot \triangle S_f = q_f \cdot S_L$, which gives $\triangle S_f = 0.45$. The observed salinity difference is larger (1.36 according to Figure 6), indicating that the dynamic effect on the horizontal salinity difference is sub-stantially larger than the freshwater effect. It would of course have been desirable to model the dynamics of this area so that the basic salinity difference — the dynamic effect — could have been calculated. For the moment this seems impossible at least to a degree which is necessary to make use of eq. 1e. Thus, we are left with the equations 1a, b (the TN- and the TP-equation) to determine q_1 and q_0. TN has a very strong signal from land, while the TP signal from the sea is relatively weaker. This implies that eq. 1a is the most useful one, while an alternative to eq. 1b might be at least equally good, for example an equation which determines the entrainment flow based on wind data, vertical salinity gradients and depth of the upper layer. It is hoped that the remaining measurements will give us some more indications on the usefulness of the various approaches. At the end of 1985 we will have completed 40 surveys instead of 22 in April 1984.

REFERENCES

Aertebjerg, G., T. Jacobsen, E. Gargas and E. Buch 1981. The Belt Project. Evaluation of the physical, chemical and biological measurements. The National Agency for Environmental Protection. Copenhagen, 122 pp.

Fleischer, S., Rydberg, L., Stibe, L. and J. Sundberg 1985. Temporal variations in nutrient transport to the Laholm bay (English summary and figure texts). Vatten, 41: 29–35.

Nyman, U. and E. Graneli 1983. Alkaline phosphatase activity in the Laholm bay, southeastern Kattegat. Sarsia, 68: 275–279.

Rydberg, L. 1985. Some observations of nutrient fluxes through the coastal zone. ICES C. M. 1984, 62, 7 pp. (mimeo).

—— and J. Sundberg 1984. On the supply of nutrients to the Kattegat. Rep. No. 44, Institute of Oceanography, University of Gothenburg, Gothenburg, Sweden, 17 pp.