Dissolved Loads of Rivers and Surface Water Quantity/Quality Relationships
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Nitrate load/discharge relationships and nitrate load trends in Danish rivers

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ABSTRACT On the basis of time series of discharge and nitrate concentration, the relation between nitrate load and discharge in Danish rivers is discussed. Recent changes in the nitrate load are related to probable causes, such as extreme climatic situations, increased fertilizer use, structural changes in Danish agriculture and drainage effects.

Relations teneurs en nitrate/débit et tendances de la teneur en nitrate dans les cours d'eau danois
RESUME La relation entre la teneur en nitrate et le débit des cours d'eau danois est examinée à partir de chroniques de ces deux paramètres. Les causes probables des variations récentes de la teneur en nitrate sont discutées: situations climatiques extrêmes, augmentation de l'utilisation d'engrais, changements du structure de l'agriculture danoise et effet du drainage des sols.

INTRODUCTION

During the late summer of 1981 and 1982 several cases of oxygen depletion were reported in Danish coastal waters. In summer periods, when the temperature is high and the vertical circulation of the water masses is low, oxygen is used up in near-bottom layers by the decomposition of organic matter, which often causes invertebrate and fish kills. For at least a considerable part of the year primary production in most Danish coastal and open waters is limited by nitrogen, so that a nitrogen conditioned eutrophication effect is a likely cause of the oxygen depletion problems. The present paper reports part of a study investigating the causes of oxygen depletion in Danish coastal waters, and in particular discusses if there is evidence for increased nitrate transport by rivers to the sea. Such an increase could be expected to result mainly from increased nitrogen fertilizer use in agriculture and from structural changes in Danish farming.

The use of chemical nitrogen fertilizer in Denmark has increased rapidly over recent decades (Fig.1). The consumption has nearly doubled from 1967-1968 to 1979-1980 when respectively 7.8 and 13.5 t N km^{-2} were used (Statistical Yearbook, 1982). Furthermore, the manurial value of manure from livestock is not often assessed, so that too much nitrogen is applied to the fields (Sommer, 1982). Investigations of drainage water have shown that nitrate leaching increases when the application of N-fertilizer increases. When a certain level is reached further fertilizer application sharply

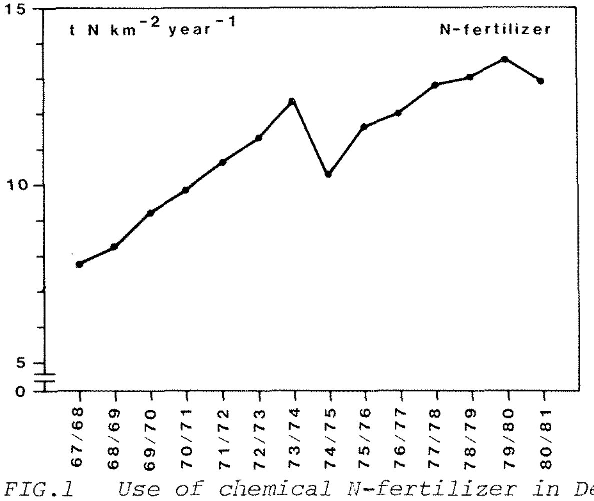

FIG.1 Use of chemical N-fertilizer in Denmark.

increases the nitrate concentration in drainage water. In experiments with barley cultivated on clayey soil this limit was 11 t N km^{-2} (Andersen, 1979). Recent years have also seen considerable changes in the structure of Danish farming. There has been a strong trend towards perennial barley culture, and at the same time the area used as grassland and for root crops has decreased. Experiments have shown that only half as much nitrogen was leached from a grass field as from a barley field, although the amount of fertilizer used on grass was more than three times higher (Bennetzen, 1978). Furthermore, cattle and pig stocks have been concentrated in fewer but larger holdings, and manure is now applied at higher levels in more restricted areas. Surface runoff from manure heaps, overflow from liquid manure tanks and silage containers also frequently cause increased nitrogen loading of rivers, even though these discharges in general are prohibited by law.

In the last few years, increased levels of nitrate have been noticable in the groundwater in certain parts of the country. This has caused alarm, since 98% of the drinking water supply in Denmark comes from groundwater. In the present paper time series of nitrate transport in selected Danish rivers are discussed in order to elucidate if in fact there has been increased nitrate runoff from representative basins in Denmark since 1967.

MATERIALS AND METHODS

Discharge and nitrate transport by four Danish rivers (Gudenå, Karup å, Odense å and Skjern å, "å" means river in Danish) have been investigated over the period from 1967 to 1981. The location of the rivers and the measurement stations is shown in Fig.2, and the major characteristics of the study basins are presented in Table 1. Records of daily water discharge and at least monthly measurements of nitrate nitrogen (NO_3-N) concentration of water samples taken at fixed stations have been used to calculate nitrate transport. These data have been published in part earlier (IHD, 1971, 1973, 1977; EEC, 1979,

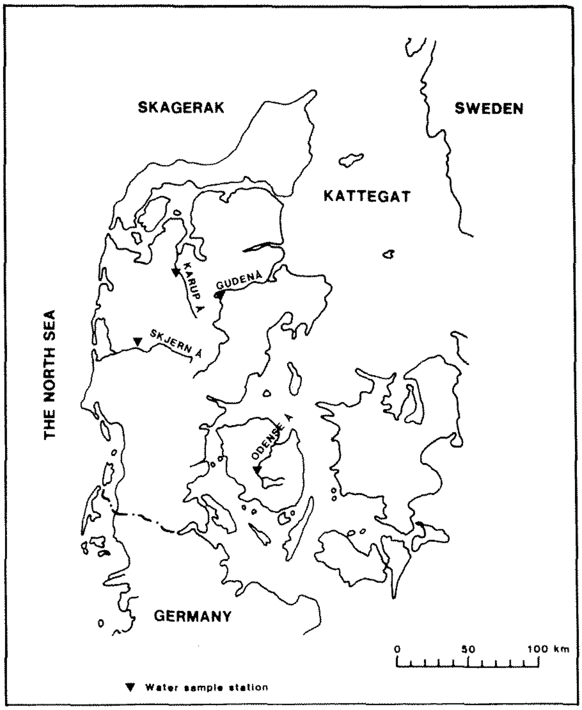

FIG.2 Location of the investigated rivers.

1981, 1982a, 1982b) and more recent information has been supplied by the Danish Geological Survey (Jacobsen, personal communication) and from the regional water authorities responsible for the particular river basins. In the case of Gudenå, Odense å and Skjern å, monthly nitrate transport was calculated by multiplying monthly measurements of nitrate-N concentration with corresponding values of monthly mean discharge. For Karup å, the mean of the nitrate measurements for

TABLE 1 Characteristics of the study basins

River (station)	Drainage area (km^2)	Topography/geology	Agricultural land use (% of total area)*	Daily mean discharge (1967-1981) ($m^3 s^{-1}$): Max.	Mean⁺	Min.	Waste water load (approximate % of total nitrate load)
Gudenå (Tvilumbro)	1290	Hilly; many lakes; moraine landscape; subglacial stream trenches; good soil permeability	66	40.6	15.8	4.5	20
Karup å (Hagebro)	522	Lowland; outwash plain	65	15.7	6.0	4.1	10
Odense å (Nr. Broby)	303	Hilly; moraine landscape	68	19.8	2.8	0.2	20
Skjern å (Ahlergård)	1040	Lowland; outwash plain; mainly sandy soil with good permeability	62	85.0	14.5	5.8	20

*Calculated from VKI (1982).
⁺Based on about 20 years for Karup å, and on 60-70 years for the other rivers.

each month was multiplied with the mean of the discharges for the corresponding days. Annual transport was calculated by summation of the monthly values.

RESULTS AND DISCUSSION

Linear regressions were calculated from synchronous measurements of nitrate concentration and discharge. Figure 3 shows the observations plotted for the Gudenå data. These regressions were used to estimate nitrate concentrations for periods for which only discharge data were available. In the regressions all available data were used except for nine outlier points in a total of 146 observations for Odense å (January, February 1974; December 1975, January, February, March 1976; January, February, March 1977), which represent unexplained high nitrate concentrations. Total discharge and nitrate transport per hydrological year are shown in Table 2, and these values have also been

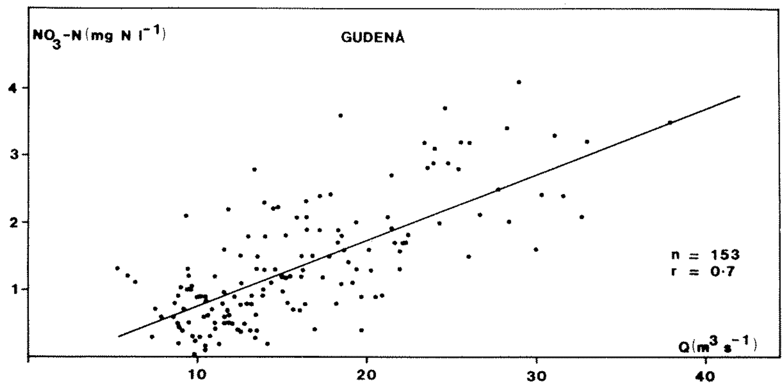

FIG.3 Nitrate concentration plotted vs. discharge for Gudenå, 1967-1981.

TABLE 2 Nitrate-N transport (t N year^{-1}) and discharge ($10^6 m^3 year^{-1}$) for hydrological years

Hydrological year	Gudenå: N	Q	Karup å: N	Q	Odense å: N	Q	Skjern å: N	Q
1967-1968	823.2	576.6	372.0	226.4	575.9	110.4	1054.8	584.9
1968-1969	852.8	532.3	343.9	207.8	463.7	76.9	975.5	540.5
1969-1970	738.4	475.4	281.9	181.7	535.6	86.3	778.9	440.2
1970-1971	719.7	492.7	320.2	191.7	603.4	87.3	964.3	488.3
1971-1972	677.7	490.8	329.6	185.0	480.7	79.8	831.4	427.7
1972-1973	517.6*	422.1	341.9	172.0	392.3	63.6	770.0	395.4
1973-1974	773.6	441.5	281.0	158.9	664.9	74.3	866.5	397.3
1974-1975	886.9	515.1	331.2	163.5	758.8	100.9	1164.5*	486.2
1975-1976	435.2	348.8	266.4	149.2	393.2*	44.7	735.7*	360.6
1976-1977	773.7*	413.9	327.2	158.2	473.0*	53.4	980.5*	387.7
1977-1978	1070.4*	502.8	312.2*	171.4	645.2*	84.5	1144.2*	475.0
1978-1979	920.8*	483.9	273.7*	163.5	464.7*	71.7	1558.2	489.0
1979-1980	778.8	514.8	297.4*	171.2	577.0*	87.4	1410.4	464.1
1980-1981	1613.3*	745.6	530.5*	256.3	1122.3	153.6	2070.3	714.5

*Data partly or wholly based on estimated values.
N: Nitrate-N transport; Q: discharge.

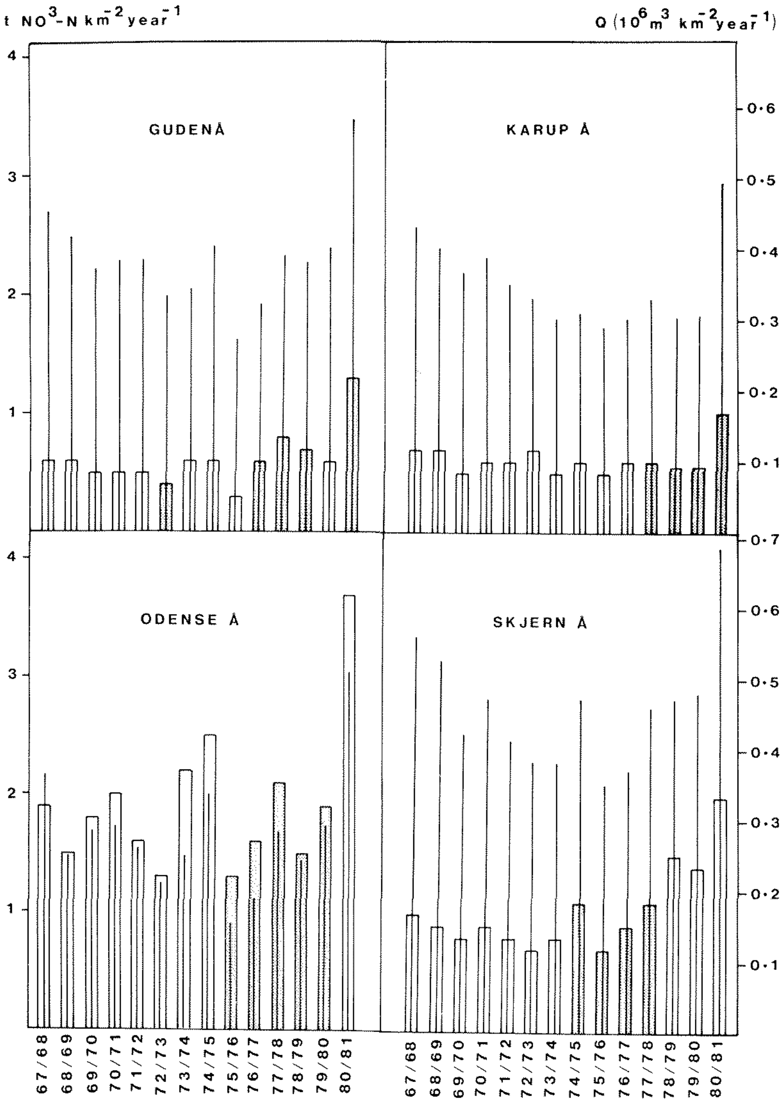

FIG.4 Annual NO_3-N transport (rectangles) and water discharge (lines) per unit area. Shaded rectangles represent estimated values.

converted to yields per unit area of drainage basin (Fig.4).

The time series contain years with rather extreme conditions. 1975/1976 and 1976/1977 were very dry years with low discharges and low nitrate transport in all four rivers, whereas 1980/1981 was an extremely wet year with very high discharge and nitrate transport. In the latter period, oxygen depletion caused problems in coastal waters. A considerable part of the variability in nitrate transport during the study period is undoubtedly due to variations in discharge. This indicates that diffuse leaching provides the main source of nitrate in the study rivers since point sources, such as waste water discharges to the rivers, would depend to a lesser degree on variations in the annual precipitation. Figure 4 does not indicate any marked trend in nitrate transport over the period investigated. Besides the high yield in all the basins during 1980/1981, only Skjern å exhibits a tendency for higher nitrate transport in the period since 1977/1978 compared to earlier years. This result was not unexpected and is considered to reflect the high permeability of the unsaturated zone and the aquifer of Skjern å, as well as high application of nitrogen fertilizer in this part of the country.

It appears from Fig.4 that the annual nitrate transport per unit area in Gudenå and Karup å is nearly the same. Gudenå has a number of lakes upstream from the measurement station, which act as a sink for nitrate partly by sedimentation and partly by denitrification. Point discharges of waste water are less significant in Karup å than in Gudenå and probably there is a relatively higher input of drainage water in Gudenå than in Karup å. Odense å has the highest annual nitrate transport per unit area of the rivers considered. Waste water discharges which contribute not more than 20% of the total nitrate load of the river cannot explain this significant difference from the other rivers. However, comparison with shorter and more

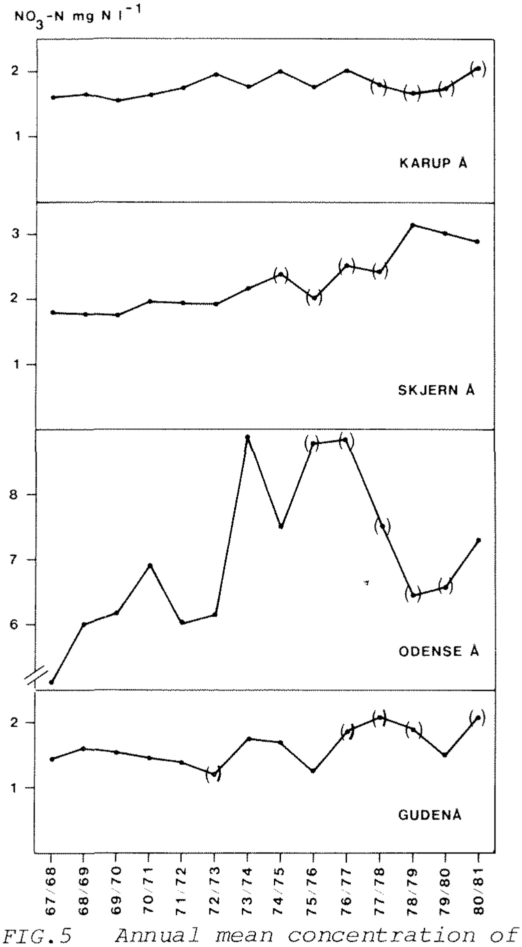

FIG.5 Annual mean concentration of nitrate-N. Values in brackets are estimates.

incomplete time series of nitrate transport in other rivers on the Danish islands show that the nitrate transport in Odense å is quite representative of this area. It is known that groundwater supply plays a relatively large role in rivers in Jutland, while rivers on the islands generally are supplied to a large extent by drainage water. This is most likely the main reason for the higher nitrate transport in Odense å compared to the other rivers which all are situated in Jutland. The relatively large input of drainage water is probably also the cause for the large fluctuations in nitrate concentrations seen in Odense å as well as in other rivers on the islands.

In order to remove the effects of varying discharge on nitrate transport, the yield values have been manipulated in various ways. Firstly, the annual nitrate transport data were divided by annual discharge values to calculate annual mean concentrations of nitrate (Fig.5). This step does not fully cancel out the role of discharge on nitrate transport since, as demonstrated earlier (Fig.3), nitrate concentration itself is also positively correlated with discharge. However, the time series for annual mean concentration exhibit a positive trend in all four rivers, and again this tendency is most clearly marked for Skjern å. The high nitrate concentrations in Odense å for 1973/1974, 1975/1976 and 1976/1977 mainly reflect the extreme outliers mentioned earlier. These outlier values for nitrate concentration have not been excluded from the transport calculations, but only from the regressions used to make estimates of nitrate concentration for months without actual observations. However, even if the annual concentration values influenced by these outliers are neglected, Fig.5 clearly indicates the much higher level of nitrate concentrations in Odense å compared to the other rivers.

In order to further cancel out the effect of discharge on nitrate transport and thus to get a clearer picture of a possible long term trend in nitrate transport, the following procedure has been applied (Viborg amtskommune, 1982). For each year and each river a "normalized" nitrate transport was estimated, which represents the nitrate transport corresponding to the average daily mean discharge (based on about 20 years for Karup å and on 60-70 years for the other rivers). Figure 6 shows how the estimated nitrate-N

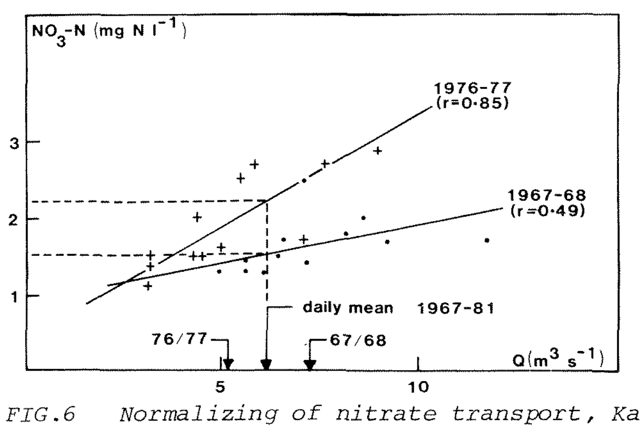

FIG.6 Normalizing of nitrate transport, Karup å (for explanation see text).

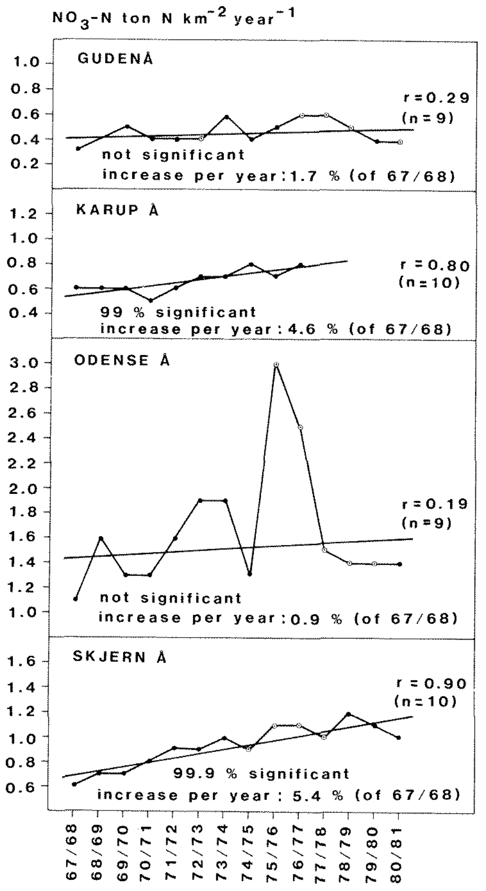

FIG.7 "Normalized" nitrate transport. Open circles represent estimated values.

concentration corresponding to the average daily mean discharge has been derived for Karup å in the years 1967/1968 and 1976/1977. All measurements of nitrate concentration and discharge are plotted for an individual hydrological year and a linear regression is calculated. The nitrate-N concentration corresponding to the average daily mean discharge is then found from the regression line, and the "normalized" annual transports are calculated by multiplying this nitrate concentration with the average annual discharge for the long term period. Figure 7 shows the resulting time series of "normalized" annual nitrate transports for the four rivers. Excluding estimated annual values from the trend analysis, Skjern å and Karup å exhibit a significant increase in nitrate transport over the study period but Gudenå and Odense å only display weak and insignificant positive trends.

The overall conclusion of this study is that the annual transport of nitrate in the study rivers is largely influenced by varying climatic conditions. Only Skjern å discharging to the North Sea shows a long term positive trend in nitrate transport which is distinguishable from variations due to climatic effects. However, when the climatic effect is filtered out Skjern å and Karup å both exhibit a significant positive trend in nitrate transport, which probably is correlated with increases in fertilizer use and structural changes in agriculture, since waste water discharges of nitrates have only a relatively unimportant influence in these rivers. For Gudenå and Odense å no significant trend has been found.

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