OCEANOGRAPHIC CONDITIONS IN THE SANDSFJORD SYSTEM, WESTERN NORWAY, AFTER A BLOOM OF THE TOXIC PRYMNESIOPHYTE *PRYMNESIUM PARVUM* CARTER IN AUGUST 1990

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As in 1989 the algal bloom was toxic and mortal to Atlantic salmon and rainbow trout in fish-farms. The brachish layer, with salinities between 5 and 25 ‰, was characterized by a high N : P ratio reflecting the low phosphate content in the freshwater supplied to the fjord system. An overflow discharge of freshwater close to the power plant at Hylen created a vigorous 'upwelling' and dominated the hydrographical conditions in Hylsfjorden and Sandfjorden during the bloom. As a result a compensation current in Hylsfjorden was created resulting in a prolonged residual time in the upper 1–2 m, where most of the *P. parvum* was observed. The entrainment of seawater into the brackish layer at Hylen was about four times greater than that under normal wind conditions in the fjord system. The calculated nitrate consumption in the fjord system was about 2 800 kg day^{-1} and compared well with the measured *in situ* production of about 900 mgC m^{-2} day^{-1}.

The supply of phosphate from fresh and seawater into the brackish layer could only support about 20 % of the theoretical normal phosphate requirements for phytoplankton growth. As in 1989 there was a close relationship between the start of the freshwater discharge, the associated upwelling at Hylen and the time of onset of a pelagical phase of the *P. parvum* bloom. It is suggested that the low salinity conditions, the prolonged residence time in the surface layer and the artifical 'upwelling' in Hylsfjorden set the stage for the bloom. The high N : P ratio and the associated phosphate limitation, probably played a major role in causing *P. parvum* to become toxic.

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INTRODUCTION

The phytoflagellate *Prymnesium parvum* CARTER have caused fish mortality in several locations in Europe and Israel (for a review see SHILO 1967). The investigations carried out after these events have resulted in *P. parvum* being one of the most studied toxic algae (SHILO 1981). In contrast to many other toxic algae, *P. parvum* excretes its toxins into the surrounding water (SHILO & ASCHER 1953). The toxins have several effects, being cytotoxic, hemolytic, and neurotoxic and its production is strongly stimulated when cells are grown under phosphorous deficiency (SHILO 1967), which recently also have been thought to be the case for the toxicity of the *Chrysochromulina polylepis* MANTON & PARKE bloom, another prymnesiophyte, that occurred in the Skagerrak region in May 1988.

The first bloom of *P. parvum* in Norwegian waters causing mortality of farmed fish took place in the Sandsfjord system, western Norway and the surrounding fjords in July–August 1989 (JOHNSEN & al. 1989; SKJOLDAL & AURE 1989). The total losses of farmed fish (Atlantic salmon and rainbow

trout) were about 750 tonnes representing a value of US $ 5 million. Mortality of salmon was initially observed in the inner part of Hylsfjorden and there were also reports of some wild fish mortality but no severe effects were observed on the fauna in the littoral and sublittoral areas (JOHANNESSEN 1989).

The upper layer environmental conditions in the Sandfjord system are strongly influenced by the large freshwater run-off resulting in a well developed brackish layer with salinities between 4 and 25 ‰. This brackish water was in 1989 characterized by high N : P ratio, reflecting the low content of inorganic phosphorous in the freshwater supplied to the system. *P. parvum* occurred at densities up to $2 \cdot 10^6$ cells 1^{-1} together with another prymnesiophyte, *Chrysochromulina ericina* PARKE & MANTON, which reached densities of more than $5 \cdot 10^6$ cells 1^{-1} (F. Rey pers. obs.). A fact that distinguished this bloom from previous ones in other areas was the presence of *P. parvum* growing on benthic algae and other substrates along the littoral zone (JOHNSEN & LEIN 1989).

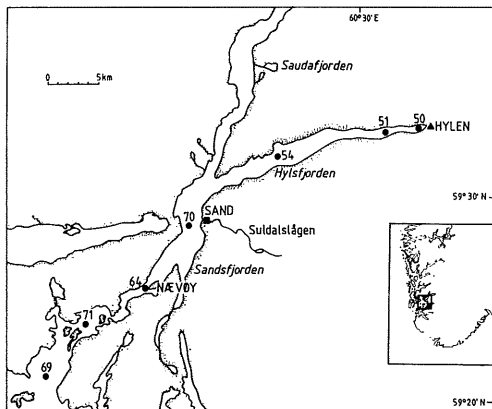In late July 1990 a new bloom of *P. parvum* de-

Fig. 1. Stations (filled circles) and location of the hydroelectric power station at Hylen (triangle).

veloped in the Sandsfjord system and a research cruise was conducted to the area in order to investigate the oceanographic conditions during the bloom. This report presents some of the results obtained from the hydrographical and biological investigations carried out during the cruise. Unfortunately the bloom was of shorter duration than in 1989 and at the time when the investigations were carried out the bloom peak was already over.

MATERIAL AND METHODS

The sampling was carried out at the stations shown in Fig. 1. At each station temperature and salinity was measured with an 'Oceanographic salinity and temperature bridge model 5005' with an accuracy greater than 0.1 units (Kent Industrial Measurements Ltd., England). Water samples were collected with gentle vacuum through a hose equipped with a horizontal sampling mouth at its lower end. Sampling was carried out at every metre down to 10 m and then at 12, 15, and 20 m depth. Nutrients samples were analyzed about 2–3 hours after sampling with an autoanalyzer (Føyn & al. 1981). Samples for phytoplankton pigment analyses were brough to a laboratory ashore and concentrated on glassfiber filters (GF/F). The pigments were extracted in 90 % acetone at 4° C for 24 hours and after centrifugation their fluorescence was measured both before and after acidification with a Turner Designs fluorometer calibrated against pure commercial chlorophyll (Sigma Co.). Cell counting was done ashore with a Palmer-Maloney counting chamber. Primary production was measured *in situ* for 24 hours using the radioactive carbon method on 7 August at Stn 54. Chlorophyll *in vivo* fluorescence was measured with an *in situ* fluorometer. Current speed and direction was measured with moored Sensor Data 2000 and Aanderaa current meters placed at 1, 2, 4, 8, 12, and 17 m at Nævøy (Fig. 1).

RESULTS AND DISCUSSION

Topography and freshwater run-off

The Sandsfjord system in the inner Ryfylke area, western Norway, is composed of three fjordbranches, Sandsfjorden, Hylsfjorden, and Saudafjorden (Fig. 1). The total surface area inside Nævøy is about 75 km^2 for each fjordbranch. The fjord system has a threshold of about 110 m just outside Nævøy and the deepest part, about 500 m depth, is situated in Hylsfjorden. The natural outlet of the fjord system is situated at Nævøy where the fjord has a width of about 300 m with steep sides. The mouth area at this point over the threshold depth is about 32 000 m^2.

The freshwater run-off in the area has been artificially regulated in connection with a hydroelectric power plant, creating large changes in the freshwater supply to the fjord system. From August to May an average of about 135 m^3 s^{-1} is now regularly discharged to the inner part of Hylsfjorden at Hylen compared with negligible run-off prior to the regulation (GOLMEN & al. 1989). In years with large amounts of snowmelting, or precipitation, or both, the discharge can be dramatically increased in June and July in order to regulate the waterlevel at the lake Suldalsvannet and the run-off in the river Suldalslågen. The latter, an important salmon river, has to have a guaranteed run-off of at least 50 m^3 s^{-1}. The fjord system has also a considerable regulated freshwater run-off at Sauda.

In 1990, the total freshwater run-off to the fjord system increased gradually during June and reached about 400–500 m^3 s^{-1} at the beginning of July. In order to reduce the run-off in the river Suldalslågen, the overflow discharge at Hylen (Fig. 1) was then opened on the 5 July. During the first days this discharge increased to about 400 m^3 s^{-1} and stabilized afterwards at about 200 m^3 s^{-1} (Fig. 2). In the same period, the discharge from the river Suldalslågen and to Saudafjorden were regulated to 60 m^3 s^{-1} each increasing the total freshwater discharge to the fjord system to about 330 m^3 s^{-1}.

Hydrography and nutrients

The overflow discharge of freshwater at Hylen gave origin to a strong mixing in the upper 10 m in the inner part of the fjord (Stn 50, Fig. 1). The freshwater was mixed both with low salinity surface water (S < 10 ‰) and with deeper water with salinities up to 25 ‰, the latter originally from small scale fronts in the surface layers of the adjacent Boknafjorden situated outside the Sandsfjord system (SVENDSEN 1981). This mixing situation resulted in an outwards current in Hylsfjorden between 1–2

m and 5–6 m depth, with compensation currents above and below these depths. This type of circulation was also observed in 1989 by KAARTVEDT & SVENDSEN (1990).

The colder mixed waters from Hylsfjorden and the warmer waters of Boknafjorden can be easily indentified in the vertical distribution of temperature shown in Fig. 3A. The forceful mixing of fresh and seawater at Hylen resulted also in an increased entrainment of seawater into the brachish layer, a thicker brackish layer and an increased brackish water transport. The residence time of the brackish water in a fjord system generally decreases with increasing freshwater runoff. An exception to this rule was the situation found in Hylsfjorden where the inwards compensation current in the upper 1–2 m resulted in a substantial longer residence time in this layer. The discharge at Hylen was the dominating mixing mechanism for the freshwater in the fjord system in the first part of August 1990.
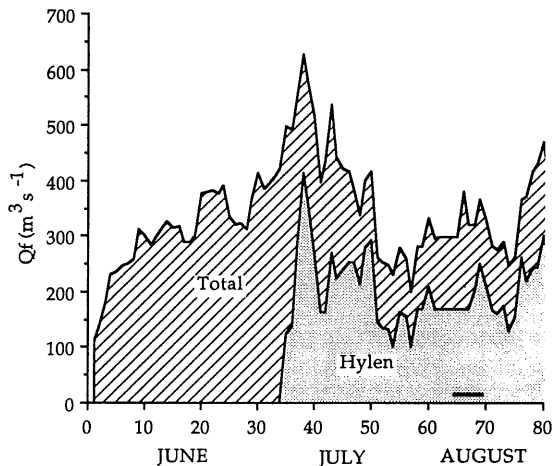

Fig. 2. Total fresh water runoff to the Sandfjord system and from Hylen hydroelectric power station (overflow) in June–August 1990. The thick line indicates the investigation period.
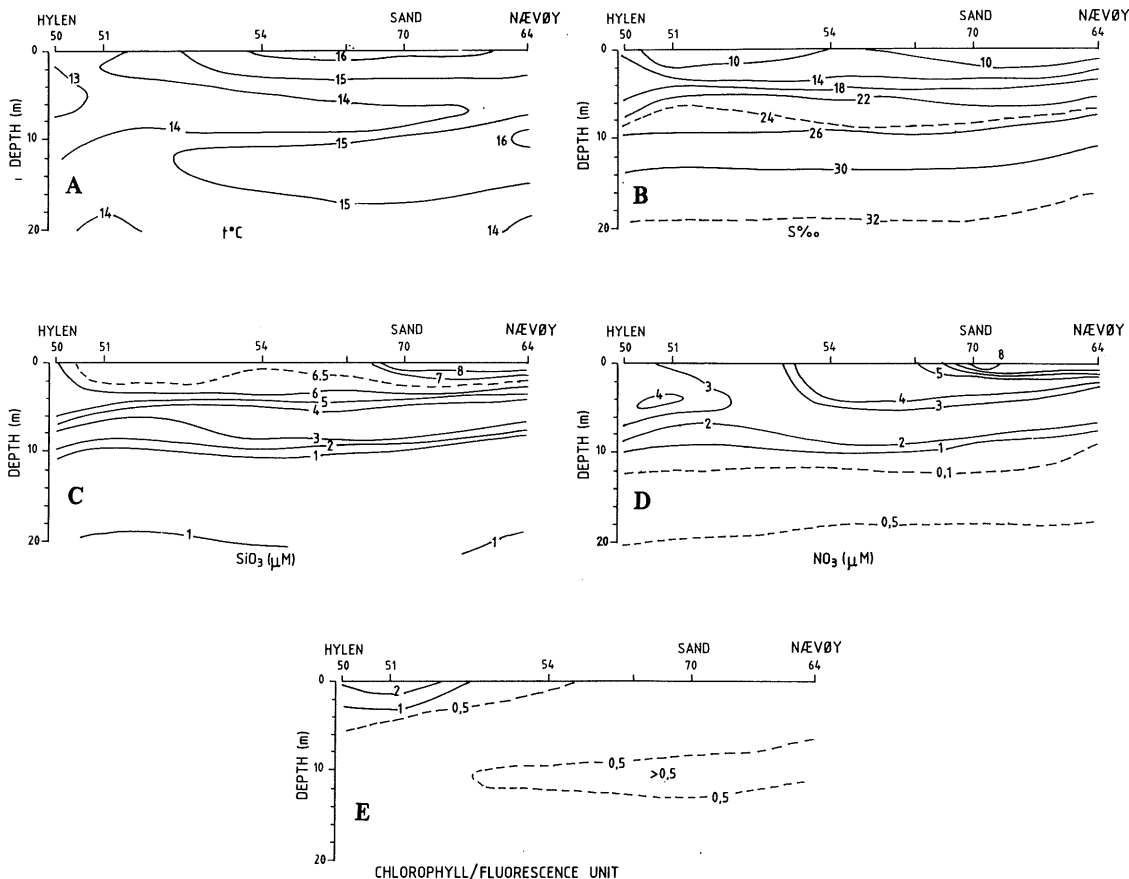

Fig. 3. Vertical distribution in the upper 20 m of temperature (A), salinity (B), silicate (C), nitrate (D), and chlorophyll *in vivo* fluorescence (E) between Hylen and Nævøy, 8 August 1990.
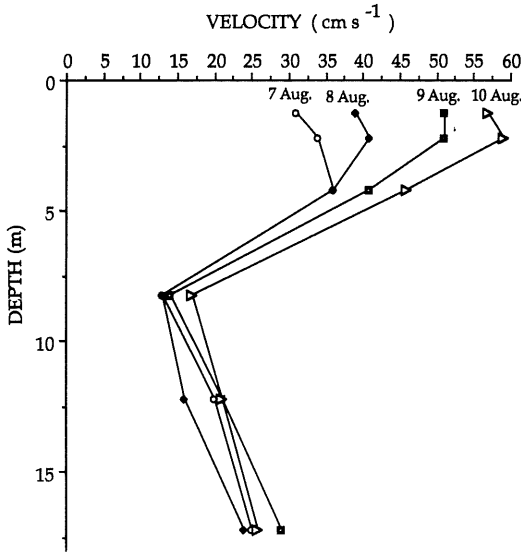
Fig. 4. Vertical distribution of daily mean current velocity at Nævøy between 7 and 10 August 1990 (0–17 m).

The freshwater discharges to the Sandfjord system contained high concentrations of both nitrate (avg.: 10.9 ± 0.2 μM, n = 3); and silicate (avg.: 11.2 ± 0.1 μM; n = 3) while it was nearly depleted for phosphate (< 0.1 μM). In addition the subsurface seawater that mixed with freshwater contained low concentrations of all three nutrients (Fig. 5). It seems therefore that phosphate was eventually the limiting nutrient for phytoplankton growth. The high N : P ratios in the freshwater discharge were also observed in the water masses with salinities below 25 ‰ down to about 8–10 m depth (Fig. 5B). The silicate supplied with the freshwater was found to behave in an almost conservative form when mixed with seawater in the fjord apparently with very little consumption (Fig. 5A). Nitrate concentrations, on the contrary, were found to decrease markedly in water masses with salinities below 22 ‰ and at depths from the surface down to 5–6 m (Fig. 5A). Since both silicate and nitrate had similar concentrations in the freshwater a comparison of the difference between the concentrations of the two nutrients in the fjord would presumably give a quantitative idea of the amount of nitrate that had disappeared. Such disappearance was quite evident in the upper 5–7 m in Hylsfjorden (Fig. 3C and 3D). It was here also where the highest phytoplankton concentrations were found, as indicated by the chlorophyll *in vivo* fluorescence (Fig. 3E), suggesting that a substantial part of the nitrate disappearance could be explained by its consumption
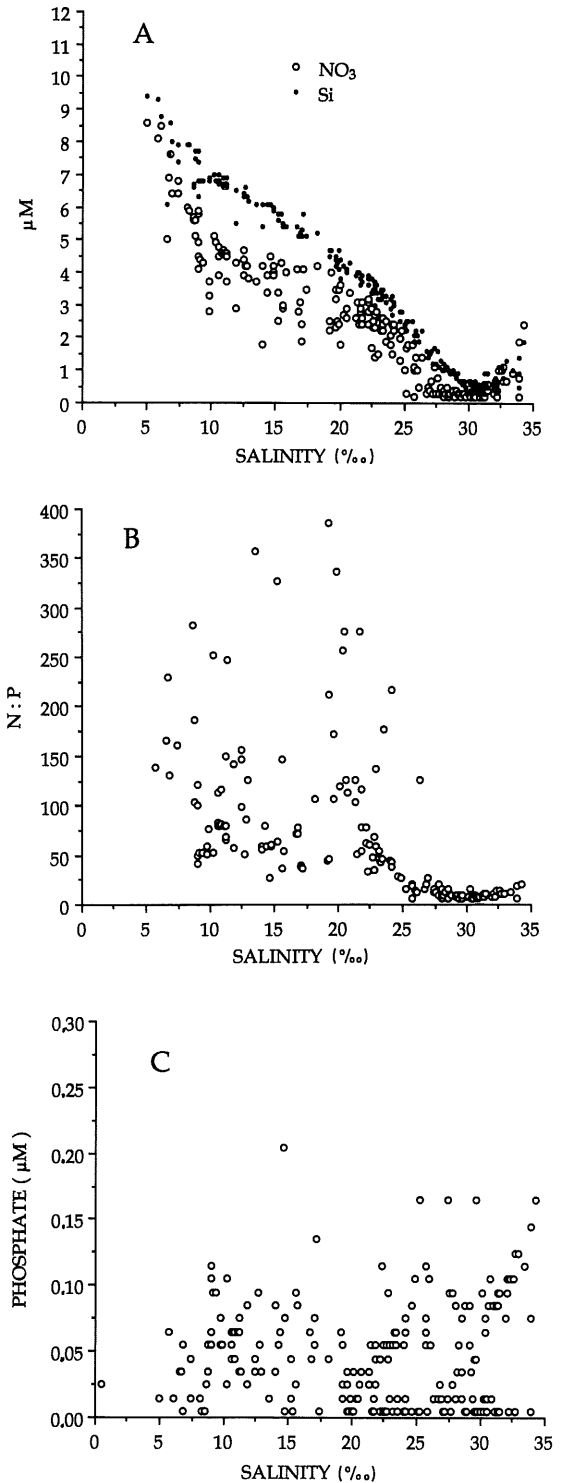

Fig. 5. Relationships of salinity to silicate and nitrate (A), to the N : P ratio (B) and to phosphate (C) in the fjord system.

by phytoplankton in spite of the low phosphate concentrations in the upper 20 m (< 0.1 μM).

Currents and volume transport

An outward current was observed in the upper 20 m at Nævøy during the measurement period. Fig. 4 shows the daily mean current velocities down to a depth of 17 m, between 7 and 10 August. The current was strongest in the upper 5 m and increased markedly during the period. Below 5 m depth the current was more stable with a minimum at about 8 m and a gradual increase of the outward current to about 25 cm s^{-1} at 17 m depth.

The outgoing freshwater driven current in the upper 5–6 m had salinities less than 22 ‰, while the current minimum just below was probably coupled to the estuarine compensation current with salinities between 21 and 27 ‰. The outward current below 10 m depth was connected to the so called intermediary current between the brackish layer and the sill depth. This type of circulation is driven by the density (pressure) variations along the coast (SVENDSEN 1981; STIGEBRANDT 1990). Increasing density at the coast (upwelling) gives outflow in the upper layer and reversal inflow in the lower layer, as observed in this case. The opposite circulation happens with decreasing densities at the coast (downwelling).

The total water transport (Qt) at Nævøy 7 and 9 August, in 5 m intervals, for the upper 20 m, is shown in Fig. 6A. During this period Qt in the upper 5 m increased from 500 to 700 m^3 s^{-1} while it was relatively constant in the lower layers. Most of the freshwater transport (Qf) left the fjord in the upper 5 m and was about 50 % of Qt, increasing from about 250 m^3 s^{-1} to 350 m^3 $^{-1}$. Consequently the entrainment of seawater (Qs = Qt − Qf) into the brackish layer in the fjord was about the same magnitude as the freshwater supply i.e. c. 300 m^3 s^{-1}. The entrainment of seawater into the brackish layer of a fjord depends normally on the wind velocity when the topography and freshwater runoff are given (STIGEBRANDT 1981). The low salinity in the upper 2 m during the cruise indicated weak wind velocities in the fjord system in the first part of August. With a wind velocity of about 3 m s^{-1}, the natural entrainment of seawater would have been about 80 m^3 s^{-1}. This imply that the vigorous freshwater discharge at Hylen resulted in a fourfold increase of the entrainment of seawater into the brackish layer. An overview of the water transport in the upper 5 m of the fjord system, based on the observations at Nævøy, the freshwater supply and the entrainment of seawater is given in Fig. 7A.
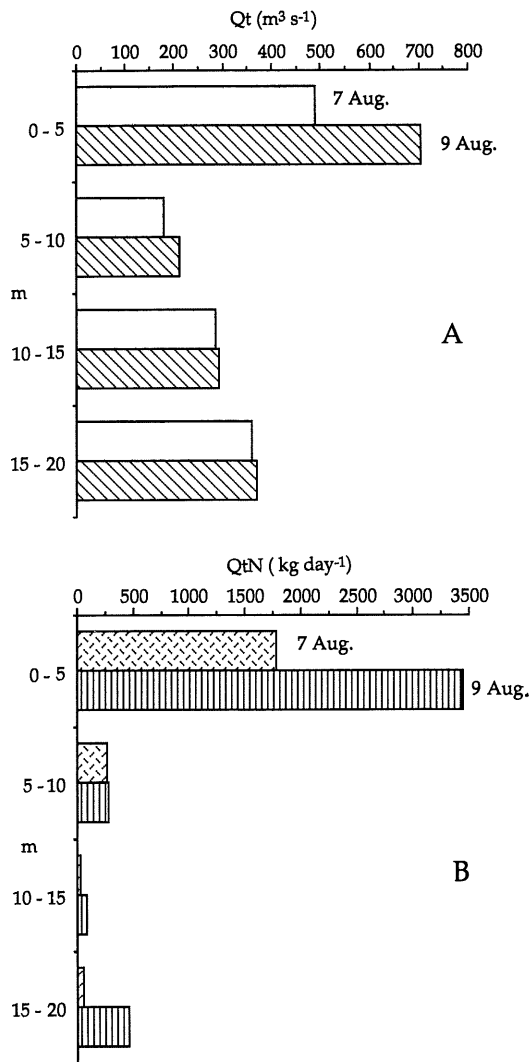

Fig. 6. Water volume transport (A) and nitrate transport (B) at 5 m intervals at Nævøy in August 1990.

Transport and consumption of nutrients

The transport of nitrate out of the fjord system at Nævøy occurred mainly in the upper 5 m and as in the case of water transport increased in the observation period from about 1 800 to 3 500 kg day^1 (Fig. 6B). In the same period the average nitrate supply from freshwater runoff, as calculated by the mean concentration of 10.9 μM and total runoff to the fjord system, was about 4 300 kg day^{-1}. The entrainment of seawater into the upper 5 m was calculated to about 300 m^3 s^{-1} and took mainly place in connection with the freshwater discharge at Hylen. Considering an average nitrate concentration of 2.5
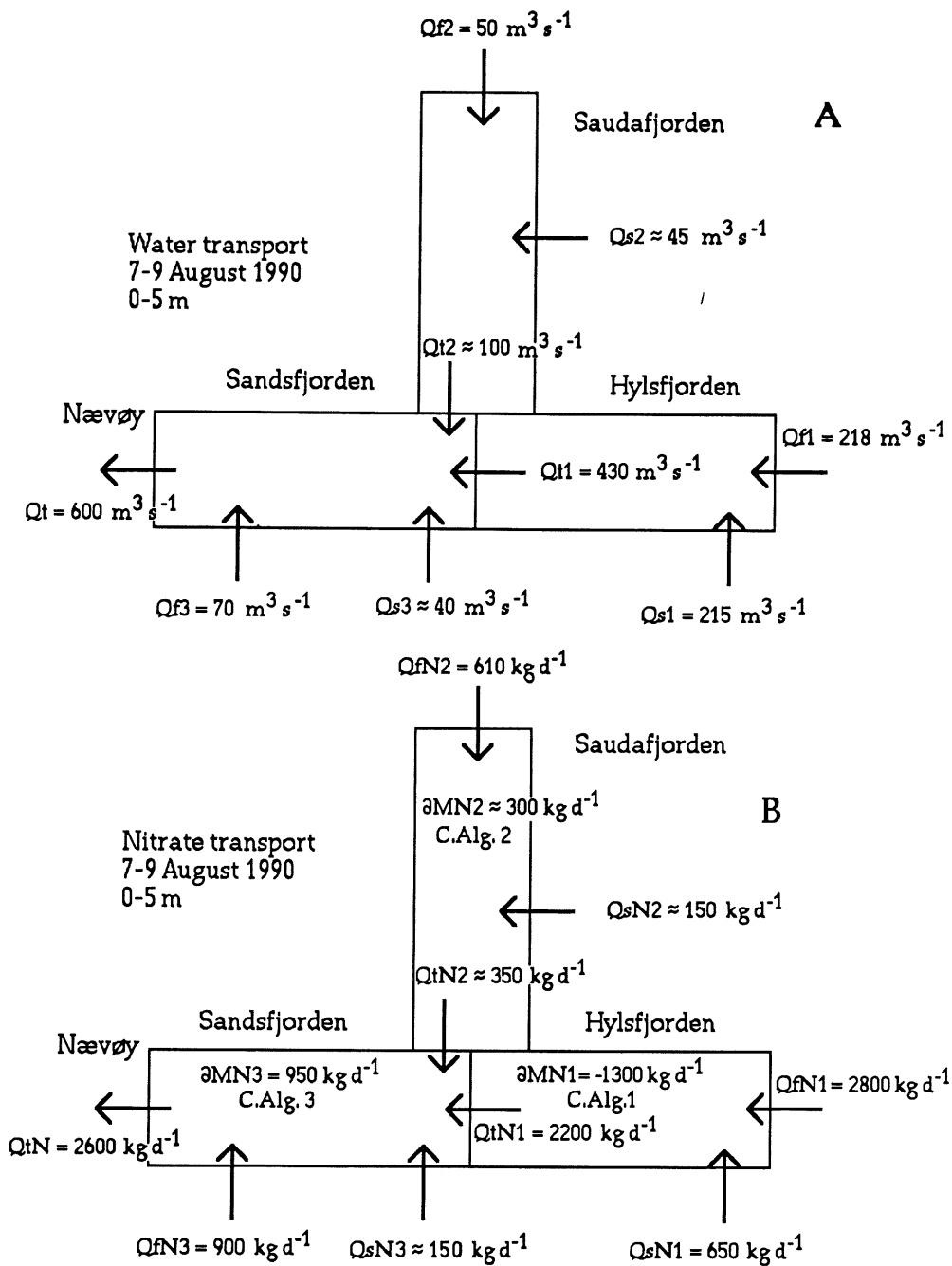
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Fig. 7. Upper layer (0–5 m) budgets of water (A) and nitrate (B) transport in the Sandsfjord system from 7 to 9 August 1990.

μM in the seawater, the entrainment gives a nitrate supply of c. 950 kg day^{-1}. This results in a total supply of nitrate to the upper 5 m of the fjord system of 5 250 kg day^{-1} and an average loss at Næv-øy of about 2 600 kg day^{-1}. The difference of c. 2 600 kg day^{-1} was assumed to have been utilized by the phytoplankton, resulting in a reduction of the nitrate concentration in the upper 5 m of the fjord system. The assumed nitrate utilization by the phytoplankton may also be calculated in another

way by using the observed freshwater and seawater transport 7 and 9 August at Nævøy and the associated nitrate concentration. The transport of nitrate without loss inside Nævøy 7 and 9 August is then respectively 4 400 and 6 100 kg day^{-1}. The observed nitrate transport at Nævøy 7 and 9 August is given above and the difference both 7 and 9 August was about 2 600 kg day^{-1}. This indicates that the nitrate assumed to have been utilized by the phytoplankton inside Nævøy was quite constant between 7 and 9 August. An overview of the nitrate transport in the fjord system between 7 and 9 August, is given in Fig. 7B.

Based on the information in Fig. 7B it is possible to estimate the total nitrate consumption of algae (C. Alg) in the fjord system:

$$C.Alg = QfN + QsN - QtN - \delta MN$$

where QfN = 4 300 kg day^{-1} is nitrate from freshwater runoff, QsN = 950 kg day^{-1} is suplied from seawater entrainment, QtN = 2 600 kg day^{-1} is loss of nitratre at Nævøy and δMN ~ $-$ 50 kg day^{-1} is the loss of nitrate in the upper 5 m between 7 and 9 of August.

Inside Nævøy the apparent total nitrate consumption of algae in the observation period then was c. 2 800 kg day^{-1}. A similar type of calculations in other parts of the fjord system tells us that c. 2 550 kg day^{-1} of the total consumption took place in Hylsfjorden, while it was insignificant in the other parts of the fjord. By using a mean observed C : N ratio of 7.9 this nitrate consumption would correspond to a primary production of about 800 mgC m^{-2} day^{-1}. This is in accordance with the measured *in situ* production of 887 mgC m^{-2} day^{-1}, corroborating the suggestion that most of the nitrate that disappeared was consumed by the phytoplankton.

Phosphate concentrations in the freshwater were near the detection limit (0.05 μM), while in the seawater below the brackish layer in Hylsfjorden the concentrations were lower than 0.1 μM. Based on a mean freshwater discharge of 220 m^{-3} s^{-1} this would mean a maximum total phosphate supply of 90 kg day^{-1} divided into 30 kg day^{-1} from the freshwater and 60 kg day^{-1} from seawater. Assuming an atomic ratio of N : P = 15, although this is only attained at near maximum growth rate, the observed nitrate consumption of 2 550 kg day^{-1} should have required a phosphate supply of about 380 kg day^{-1}, at least four times as much as the assumed real supply. Even taken into account an estimated supply of phosphate from the fish-farms itself of 10 kg day^{-1} (S. Kaartvedt pers. commn) still there was a high phosphate deficiency. Earlier observations
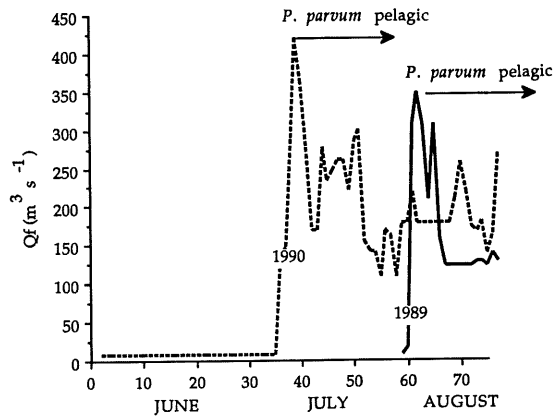

Fig. 8. Freshwater discharge from Hylen power station (overflow) in the summers of 1989 and 1990. Start of the pelagic phase of *Prymnesium parvum* is indicated.

(SHILO 1967) have shown that *P. parvum* increased its toxin production by 10- to 20-fold under phosphate limitation, even before markedly affecting growth. The observed phosphate deficiency in the brackish layer could then have explained the toxicity observed during the bloom. But the possibility of *P. parvum* satisfying its phosphorus requirements through another sources cannot yet completely be ruled out. One of the possible sources could have been organic phosphorus supplied to the brackish layer through the vigorous artificial upwelling at Hylen since *P. parvum* is known to growth heterotrophically using a wide range of organic phosphorous compounds (McLAUGHLIN 1958). Another is that *P. parvum* during its substrate-attached phase could utilize phosphorus released from the benthic algae. Some observations (T. Johnsen pers. commn) have shown that most of the *P. parvum* cells were usually found in zones of the benthic algae that were disrupted or in poor physiological conditions. Unfortunately none of these sources have yet been confirmed and the question still remains open.

The bloom itself

JOHNSEN & LEIN (1989) described the presence of extremely high concentrations of *P. parvum* associated with macroalgae in the fjord during the 1989 bloom. This lead in 1990 to a monitoring program to observe the presence of *P. parvum* attached to the macroalgae. The first signs of a significant increase in the *P. parvum* concentrations were found in early July (T. Johnsen pers. commn). At the time of the investigation the bloom of *P. parvum* was already collapsing and concentrations were in the range of 0.2–1·10^{6} cells 1^{-1}, while the maximum

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concentration in late July, at the peak of the bloom, was about $3 \cdot 10^6$ cells 1^{-1}. Although there is yet not clarity with respect to the factors triggering the bloom, the sudden and strong freshwater discharges at Hylen creating the vigorous artificial upwelling of seawater from below the pycnocline and an outward current, were probably significant factors in the overall spreading of the bloom in the fjord system. Both in 1989 and 1990, for instance, there was a close relationship between the start time for the discharge and the time when *P. parvum* was found in the water column (Fig. 8). The bloom of *Chrysochromulina polylepis* in the Kattegat-Skagerrak during May–June 1988 occurred in water with an anthropogenic nutrient signal and a high N : P ratio (SKJOLDAL & DUNDAS 1991). The blooms of *P. parvum* in 1989 and 1990 are another examples of toxic blooms in an environment with a high N : P ratio. This could be indicative of a more general relationship between phosphorous deficiency and growth of toxic algae.

In summary, we suggest that the low salinity conditions suitable for the growth of *P. parvum*, the prolonged residence time in the surface layer caused by the compensation current and the artificial 'upwelling' in Hylsfjorden set the stage for the pelagic phase of the bloom. The high N : P ratio and the associated phosphate limitation probably played a major role in causing *P. parvum* to become toxic.

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