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ØSTENSJØVANNET – A SHALLOW HYPERTROPHIC LAKE IN NORWAY WITH SIGNIFICANT INTERNAL PHOSPHORUS LOADING DURING SUMMER

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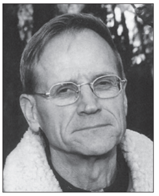

Abstract

Lake Østensjøvannet is a shallow hypertrophic lake situated about 30 km south of Oslo. The water quality in the lake during the last hundred years has deteriorated greatly. The main reason for this is supply of wastewater and drainage from agricultural activities. Investigations in the summers of 1977 and 1978 indicated very high internal phosphorus loading and rather insignificant values in 1987. In the two former years, the primary productivity was measured as high as 6 g C $m^{-2}day^{-1}$, a value which is roughly considered to be the highest obtainable in lakes. Cyanobacteria were the dominating phytoplankton. The expected phosphorus concentration in the lake water during summer was calculated and the difference between the measured and the expected values is assumed to represent internal loading. High concentrations of phytoplankton in the lake in summer and associated increases in pH through photosynthesis, stimulate phosphorus release and additional pH increase. Laboratory experiments with sediment cores suggest that the lake sediments could be a significant contributor to the internal phosphorus loading in the lake.

Key words – Photosynthesis, blue-green bacteria, high pH, lake sediments, phosphorus release, resuspension

Introduction

The classic explanatory model for internal phosphorus loading is phosphorus release from lake sediments. This presupposes anaerobic conditions and includes the reduction of iron and the release of phosphorus in the oxidized microzone of the lake sediments (Einsele, 1936; Mortimer, 1941 & 1942; Gächter, 1976; Golterman, 1995). The anaerobic release of phosphorus is an important mechanism in the internal phosphorus supply to the trophogenic layer of the lakes. However, it has also been shown that other mechanisms like high pH, resuspension, microbial activity and bioturbation can be of importance for internal phosphorus loading (Kamp-Nielsen, 1974, 1975a, 1975b; Lee et al., 1977; Gächter & Meyer, 1993; Kairesalo, 1995; Horppila, 1998; Koski-Vähälä et al., 2000, 2001; Gächter & Müller, 2003). This internal loading may explain why the water quality does not always improve after sewage diversion (Ryding, 1985; Carvalho et al., 1995).

The internal phosphorus loading can be explained by many factors, including:

1) Physical conditions such as diffusion, turbulent water movements and resuspension.
2) Chemical conditions such as redox potential and pH.
3) Biological conditions such as microbial activity and bioturbation.
4) Hydrological conditions such as sublacustrine ground water seepage.

In stratified lakes with anaerobic sediments and more or less anaerobic bottom water, the most important nutrient transport mechanism is diffusion (Håkanson & Jansson, 1983; Bostrøm et al., 1988). In shallow lakes, wind and turbulent water movements with resuspension are of greater significance (Håkanson & Jansson, 1983; Koski-Vähälä et al., 2000; Koski-Vähälä & Hartikainen, 2000, 2001). P loading directly on the lake surface by

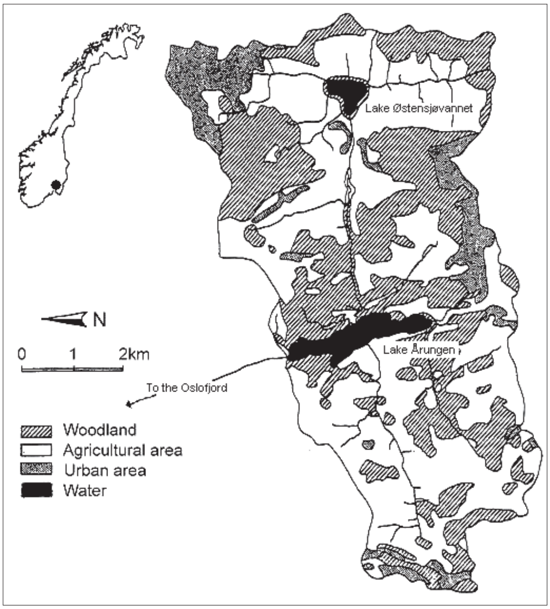

Fig. 1. *Map of the catchment of Lake Østensjøvannet and Lake Årungen.*

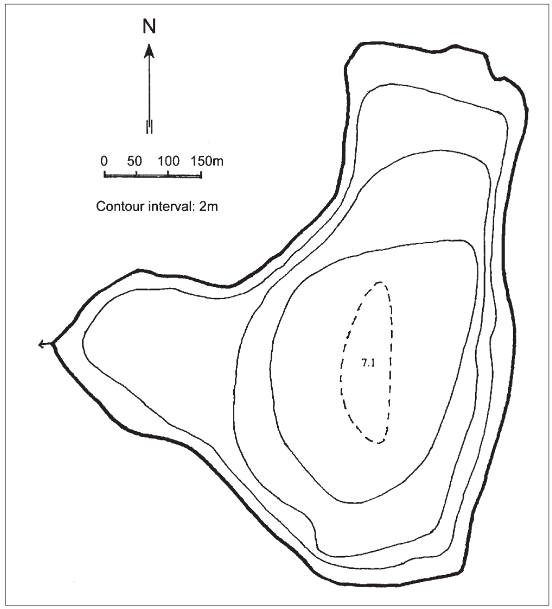

Fig. 2. *The bathygraphical map of Østensjøvannet.*

waterfowl (Manny et al., 1994) could be a disturbing element.

This paper is an attempt to indicate the magnitude of internal phosphorus loading in shallow lakes in summer by measuring and calculating (based on inflow/outflow only) the phosphorus increases in the lake water. The difference between the measured and calculated values should represent internal loading.

The paper is based on many data from almost 30 years ago and should have been published earlier. But owing to lack of scientific research capacity the data have been stored in the office. But now the data are of increasing importance, especially due to new interest of the lake and the watercourse connected to possible climate change and the implementation of The EU Water Framework Directive.

Description of the studied area

Østensjøvannet is a shallow lake situated in the rural area of Ås, approximately 30 km south of Oslo (Fig. 1). The lake is rich in nutrients owing to its location in an agricultural area and input of urban wastewater. Agriculture comprises ca. 50 % of land-use. Woodland and urban areas constitute ca. 30 and 15 % of the catchment, respectively. The lake outflow runs into Lake Årungen, which is a valuable water resource with regard to recreational activities in the region. This lake receives nearly 30 % of the yearly catchment runoff from Østensjøvannet and the water quality in Årungen could be significantly affected by the water quality in Østensjøvannet.

The catchment of Østensjøvannet is situated below the marine limit and is a typical moraine landscape with quarternary deposits, consisting mainly of marine clay and glacial till. The bedrocks consist of Precambrian granite and gneiss.

Lake and water characteristics

The morphometric values (Table 1), together with the bathygraphical map (Fig. 2), indicate a good basis for Østensjøvannet to circulate down to the bottom during the ice-free season. The water masses may be only able to stratify slightly during periods, depending on weather conditions. This gives a reason to suppose that resuspension is an essential factor for determining the water quality of the lake.

For the period 1977–1979 the following data have been measured in Østensjøvannet: Transparency 0.2–1.0 m, primary productivity up to 6 g C m^{-2} day^{-1}, and the chlorophyll a concentrations 80–120 µg L^{-1} (Borgstrøm et al., 1980). A sediment core from Østensjøvannet, taken at the deepest part of the lake in winter 1992, indicates a change in the lake ecology during the last 100 years (R. Sørensen, pers. comm.). The colour of the

Table 1. *Morphometric and hydrologic values for Østensjøvannet.*

A_c (km^2)	A_l (Mm^2)	V (Mm^3)	z_{max} (m)	z_{mean} (m)	z_r (%)	Q_N (Mm^3)	T_w (days)
14	0.34	1.31	7.1	3.9	1.08	6.62	72

A_c = catchment area, A_l = lake area, V = lake volume, z_{max} = maximum depth, z_{mean} = mean depth, z_r = relative depth (88.6 z_{max} / $\sqrt{A_l}$), Q_N = normal inflow per year, T_w = hydraulic retention time (V/Q_N).

uppermost 10–15 cm was black with a gradual change to a more brownish colour downward. This change could be connected to increased loading with nutrients and organic matter, i.e. a gradual development upward towards anoxic sediments.

The dominating phytoplankton groups in Østensjøvannet were green algae and blue-green bacteria. The *Planktotrix* and *Scenedesmus* genera dominated the first half and the *Planktotrix* genera the second half of summer 1977. In the summer of 1978 the genera *Microcystis* and *Scenedesmus* dominated in the first half and *Microsystis* and *Planktotrix* in the second half. The concentration of zooplankton was high, with copepods in the first half of the summer season and cladocerans in the second half. There were also great amounts of rotifers. As regards bottom animals, there were high densities of primarily tubificids and chironomids at all depths. The macrophytes were dominated by *Phragmites communis* and *Scirpus lacustris.* These biological informations are taken from Erlandsen et al. (1980).

In 1987 Østensjøvannet was involved in a study of a new lake restoration technique using photozone (Grøterud 1988). This method consists of air treated with UV radiation, pumped into perforated hoses placed in a finger-like pattern just above the lake bottom. The aim was primarily to kill algae and bacteria. This technique did not succeed in the lake due to, among other things, insufficient capacity.

Materials and methods

Field observations

Bathymetry of Østensjøvannet was constructed from approximately 50 soundings taken with a sounding line from the ice cover (Fig. 2). Precipitation data were taken from the local meteorological station at Ås. Annual total water inflow (Q_t) and summer water inflow (dQ) to the lake were estimated in different ways owing to lack of direct measurements:

1. Inflow measurements to Lake Årungen 1977 ($Q_Å$ = 24.5 Mm^3) and 1978 ($Q_Å$ = 22.8 Mm^3) given by Grøterud and Rosland (1981), together with the ratio between the catchment area of Østensjøvannet and Årungen ($A_Ø/A_Å$ = 0.28). These were used to calculate the inflow to Østensjøvannet ($Q_Ø$) in 1977 and 1978 (Table 2).

2. Runoff measurements in a research field (RF) in the vicinity of Østensjøvannet catchment during 1984–2004 achieved by H. Lundekvam (pers. comm.). Runoff measurements (dQ_t) for May, June, July and August, together with precipitation data (dPr_t) during 1984 – 2004, gave the regression equation below (H. Lundekvam, pers. comm.):

$$dQ_t = 0.589dPr_t - 112.9$$
$$(r^2 = 0.77,\ p < 0.0001,\ n = 21,\ \text{units} = \text{mm}) \quad \text{(Reg)}$$

Table 2. *Precipitation, annual inflow ($Q_Ø$) and summer inflow ($dQ_Ø$) to Lake Østensjøvannet, and estimated average total phosphorous concentrations (TP_t) in summer inflow.* Precipitation was measured at the local meteorological station at Ås. The summer periods were; 1977 (13 June – 31. Aug), 1978 (6. June – 29. Aug.), and 1987 (15. June – 5. Sep). $Q_Ø$ is estimated by using inflow values to Lake Årungen ($Q_Å$) (see Fig. 1), multiplied with the lake catchment ratio between Østensjøvannet and Årungen (= 0.28). A regression equation was used to estimate the figures for $dQ_Ø$ (1977) and $dQ_Ø$ (1978) by adjusting for the number of days (see text). The figure for $dQ_Ø$ (1987) was estimated on basis on direct runoff measurements from a research field (see text).

	Precipitation (mm)	$Q_Å$ (Mm^3)	$Q_Ø$ (Mm^3)	$dQ_Ø$ (Mm^3)	TP_t (μgL^{-1})
1977	708	24.52	6.89	0.29	464
1978	608	22.78	6.40	0.34	498
1987	907			0.76	322

(Reg), together with precipitation data, were used to estimate the water inflow during the two summer periods 1977 and 1978.

3. Direct measurements from RF during 1987 ($Q_Ø$) and for the summer period ($dQ_Ø$) (H. Lundekvam, pers. comm.).

The relevance of using both Årungen and RF to estimate the inflow to Østensjøvannet 1977, 1978 and 1987 was indicated by the ratio between precipitation and inflow values these years. The ratio for Årungen in 1977–1978 ($Q_Å$/Pr) and RF in 1987 ($Q_Ø$/Pr) was equal (= 0.72), which may be considered as a support for the estimation employed.

The mean total phosphorus concentration in the inflow to Østensjøvannet in 1977, 1978 and 1987 was estimated by using the total phosphorus loading (TP_L) on Østensjøvannet, which again was an adding up of the estimated point sources plus 40 % of diffuse sources (Erlandsen et al., 1980), and the quantities of inflow to Østensjøvannet ($Q_Ø$) for the respective years.

Physical and chemical water analyses were carried out *in situ* and *in vitro* some days after sampling. Temperature was recorded *in situ* with an ordinary thermometer inside the water sampler. The following were measured *in vitro*: Oxygen according to the Winkler titration method, pH with a Radiometer pH-meter 29 with a combined electrode, soluble reactive phosphorus on filtered water after reaction with molybdate and reduced by ascorbic acid (RP), and total phosphorus (TP) on unfiltered water as RP after persulphate digestion. Whatman glass fibre paper (GF/C) was used in the filtration procedure. The primary productivity was measured by the oxygen method (Cole, 1983).

Bench scale experiment

The sediment-water exchange experiment was carried out with the uppermost 10 cm of the sediments, taken with a sediment core sampler at 3 m depth in the lake. The sediments were mixed and divided in 9 small glass vessels with a basal area of 7.1 cm^2 and a height of 9.5 cm. Ten grams of sediments and 50 ml of distilled water were added to each glass vessel. The experimental temperature was 20°C. Air was added to provide aerobic conditions and circulation in the water without resuspending the sediment particles. Additions of NaOH were used to adjust pH. The phosphorus concentrations in the glass vessels were measured after 24 hours. Only limited phosphorus release was observed after this time period.

Hydrology and phosphorus concentrations in the inflow to Østensjøvannet

Precipitation quantities measured at the local meteorological station at Ås, and inflow and runoff values accordingly of Østensjøvannet, are shown in Table 2. The normal value 1930–1960 was 785 mm. In summer 1978 and especially in summer 1977 precipitation and runoff in the catchment were lower than normal, while the amount were higher than normal in 1987.

The regression equation (Reg) was used to estimate the values for runoff to Østensjøvannet during the summer periods ($dQ_Ø$) in 1977 and 1978 by adjusting for the number of days (Table 2). In 1987 $dQ_Ø$ was estimated on basis of direct runoff measurements from the research field (RF) (Table 2).

The main sources of annual phosphorus loading from the catchment (TP_L) according to Erlandsen et al. (1980) were point sources from the urban areas and the agricultural activities (2280 kg), and diffuse sources from the sparsely built-up areas and agriculture (910 kg). The mean annual total phosphorus concentrations in the inflow to Østensjøvannet ($TP_t = TP_L/Q_t$), when estimating the TP_L to be point sources + diffuse sources = 3190 kg, are shown in Table 2.

Inflow measurements of phosphorus to Østensjøvannet between 2. June – 21. September 1987 (Vekterli 1989), have been estimated to be 460 kg phosphorus. Taking into consideration the runoff recorded in the research field (RF), gave a concentration of 314 $\mu g\ L^{-1}$. Vekterli mentioned that 460 kg could be too low owing to some unrecorded seepage waters. The TP_t value in 1987 of 322 $\mu g\ L^{-1}$ (Table 2) seems therefore to be likely and indicates also that the TP_t values for 1977 and 1978 are reasonable.

Results

Phosphorus concentrations during summer in the lake water

The development of phosphorus concentrations and other variables at 3 m depth in Østensjøvannet during the summer 1977 and 1978 are shown in Fig. 3. The values from 3 m depth are chosen to be representative for the water body, especially with respect to the sediment effect. The other observations are not given here, but the variations with depth were small. The most striking observations are the very high pH values already in June and the considerable increase of phosphorus throughout the summer. In summer 1977, the pH values were generally lower than in 1978. This also applies to the oxygen content. The water temperatures were relatively high and quite similar during the two summers. This implies a relatively high rate of the chemical and biological reactions occurring in the lake.

Østensjøvannet was involved in a new study 1987 (Vekterli, 1989). During the summer, phosphorus content and other physical-chemical data were determined (Figure 4). The data indicate the same trends as recorded in 1977 and 1978, but the phosphorus values were significant lower. This can presumably be associated with more than one unit lower pH values, particularly in June.

P supply from the catchment and internal lake loading

If the lake behaves like a reactor, with no transformation of the supplied components, the differential equation of Rainy (1967) could be used to estimate the concentration change of the components with time in the lake as a result of change in the input rate. In an integrated form, the equation is:

$$C_t = C_i + (C_o - C_i)\, e^{-q\, t/V} \qquad (*)$$

C represents concentration (µg L^{-1}), C_i in the input, C_o in the lake at the start and C_t after time t (days), q (m^3 day^{-1}) the water flow through the lake and V the total lake volume (m^3).

By using eq. (*) on the stipulated data for the summer period 1977, C_i = 464 µg L^{-1}, C_o = 155 µg L^{-1} (Fig. 3), V = 1.31 Mm^3, qt = $dQ_Ø$ = 0.89 Mm^3, the concentration in the lake would have been *216 µg L^{-1}* if phosphorus had only been supplied from the catchment. But the value of phosphorus after a period of 79 days, taken from Fig. 3, was *781 µg L^{-1}*. The difference between these two values, *565 µg L^{-1}*, may mainly be due to internal loading. If lake volume, area and time are incorporated in the calculation, the rate of internal phosphorus loading was 27.7 mg m^{-2} day^{-1}.

For summer 1978, based on C_i = 498 µg L^{-1}, C_o = 226 µg L^{-1} (Fig. 3), V and $dQ_Ø$, the calculated phosphorus concentration was *226 µg L^{-1}*. Based on the observed concentration after a period of 84 days, *873 µg L^{-1}* (Fig. 3), the rate of internal phosphorus loading was 29.9 mg m^{-2} day^{-1}.

For summer 1987, based on data from Vekterli (1989), C_i = 322 µg L^{-1}, C_o = 50 µg L^{-1}, V and $dQ_Ø$, the calculated phosphorus concentration was *170 µg L^{-1}*. Based on the observed concentration after a period of

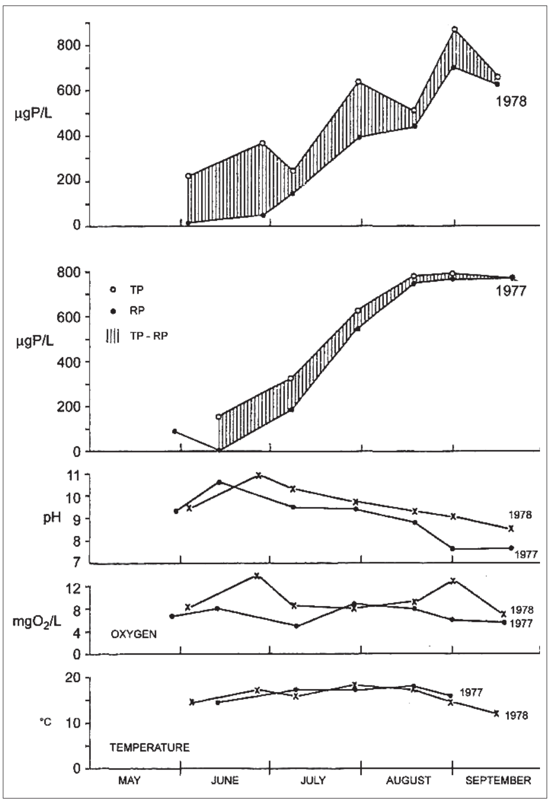

Fig. 3. *The development of phosphorus concentrations, pH, oxygene concentration and lake temperature during the summers of 1977 and 1978 at 3 m depth in Østensjøvannet. TP = total phosphorus, RP = soluble reactive phosphorus.*

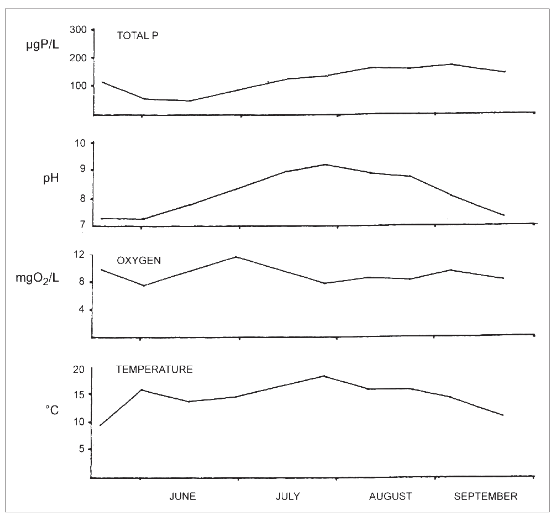

Fig. 4. *The development of phosphorus concentrations, pH and temperature at 3 m depth during summer 1987 in Østensjøvannet.*

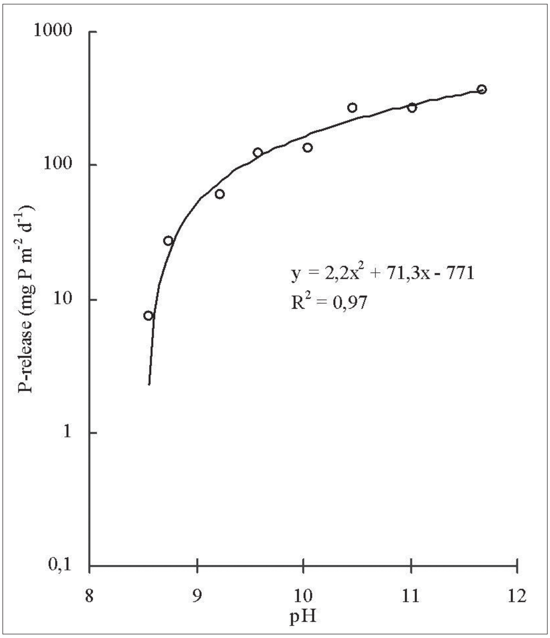

Fig. 5. *Release of soluble reactive phosphorus in relation to pH in water.* Results from *in vitro* experiment with sediments from Østensjøvannet.

82 days, *174 µg* L^{-1} (Vekterli, 1989), the internal phosphorus loading was 0.2 mg m^{-2} day^{-1}. This small amount of internal loading should be seen in light of the relatively high water inflow ($dQ_{Ø}$ in 1987), the water quality (pH) and the lake restoration experiment in Østensjøvannet already reported. The only assumed positive restoration effect may have been a temporary increased redox potential in the sediment surface, which again may have reduced the P release somewhat (Grøterud, 1988).

The calculation periods have varying length owing to somewhat different starting and ending point with regard to the phosphorus increase.

These estimated values seem reasonably compared with other published studies (e.g., Jensen & Andersen, 1992).

Phosphorus release from the sediment in vitro

The measured release of soluble reactive phosphorus (RP) from the sediments in relation to pH is shown in Fig. 5. The values for phosphorus release are presented as quantity per area, which seems most relevant because the transport is through the sediment surface. The release of phosphorus seems to begin at a pH of about 8.4, and increases significantly with increasing pH-values. The result of this rather simple experiment agrees with results from experiments with other lake sediments (Erlandsen et al., 1980). The amount of phosphorus measured in this experiment does not represent the true level of released phosphorus at actual pH levels in lakes, but it suggests roughly the order of magnitude.

Discussion and conclusion

The summer observations more than 25 years ago showed that the possible mean internal phosphorus loading in Østensjøvannet might have been 25–30 mg m^{-2} day^{-1}. The estimated values of internal phosphorus loading in the field, compared with the values from the laboratory experiment, indicate a significant phosphorus release from the lake sediments, and that this may be partly connected to the pH conditions. By using the regression equation in Fig. 5, the phosphorus release from the sediments at pH 8.8 was approximately 27 mg m^{-2} day^{-1}. pH in the water just above the lake sediments, measured in the sediment core sampler in connection with the bench scale experiment, gave the value 9.0. This is an indication of the lake sediments as a phosphorus source for Østensjøvannet during summer. The low estimated internal phosphorus loading from the summer of 1987 should also, as already remarked, be seen in relation to pH.

The indicated increase in the lake is mainly considered in relation to the photosynthesis of the algae and bacteria by assimilating CO_2 (HCO_3^-), which in turn is stimulated by the released phosphorus, which subsequently leads to an additional pH increase, a typical feedback mechanism. In addition, the redox state in the sediments may also be involved. Decreasing redox potential e.g. may also give increasing pH.

Anaerobic conditions in the sediments and bottom water could occur even if the water masses generally circulate during summer. This could happen in relatively short periods with transistory temperature stratifications in the lake. In these cases, the phosphorus mobilization from the sediments provides an efficient phosphorus source, which subsequently keeps the phosphorus in solution by the high pH (Roden & Edmonds, 1997). The most probable phosphorus release from the sediments to the water masses in Østensjøvannet during summer seems to be controlled by increased phosphorus diffusion rate after increased photosynthesis (Bostrøm et al., 1988). The phosphorus is then kept in solution by increased ambient pH and finally transported throughout the water masses by turbulent water flow (Portielje & Lijklema, 1993). In addition, resuspended sediments may have taken part in the phosphorus distribution process in the lake water, depending upon the equilibrium value between the solid and solution phase (Koski-Vähälä et al., 2000).

Østensjøvannet is strongly polluted and has accumulated great amounts of phosphorus in the sediments during many years (P_{AL} = plant available phosphorus = 1.1–1.9% in 0–14 cm sediment layers, R. Sørensen pers. comm.). In recent years, the internal loading may have decreased, but sporadic measurements indicate very varying phosphorus concentrations in the lake. In the period 1992–2004 the variation of the mean value was 72–265 µg L^{-1}, with the highest value in 2000 (A. Yri , pers. comm.). Nevertheless, the lake is still hypertrophic, with high concentrations of algae and blue-green bacteria which is still of importance for the downstream Lake Årungen, particularly connected to possible climate change with some otherwise precipitation pattern. The latter lake is an important lake for many activities, especially for rowing competition and hopefully for swimming in the future. About 15 years ago, it was decided to give Østensjøvannet status as a nature reserve for waterfowl and water quality measurements have only been sporadic carried out after this time. The decisive factor for the development in summer seems to be the phosphorus concentration in the lake water at the start of the algal growing season.

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