Hydrobiologia **233**: 187–196, 1992.
L. Van Liere & R.D. Gulati (eds), *Restoration and Recovery of Shallow Eutrophic Lake Ecosystems in The Netherlands.*

The influence of flushing on nutrient dynamics, composition and densities of algae and transparency in Veluwemeer, The Netherlands

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Key words: eutrophication, lake restoration, flushing, Veluwemeer, algal species, transparency, phosphorus, nitrogen

Abstract

Total phosphorus and chlorophyll decreased significantly after reduction of the external phosphorus loading and the start of flushing Veluwemeer with polder water in 1979.

Flushing of Veluwemeer has had a large impact on nutrient dynamics. Especially in the first winter, dilution was the main cause of changes in water quality. On a longer term the increase of the inactivation of phosphorus in sediments is important. *Oscillatoria agardhii* has been brought to the margins of its habitat. Three successive cold winters were an additional causal factor in the disappearance of *Oscillatoria agardhii* and the dominance of diatoms and green algae from 1985 onwards.

Due to higher detritus and inorganic suspended matter concentrations transparency increased less than expected. Since 1985 chlorophyll only contributes for a small percentage to the transparency.

In the present situation further improvement of the water quality of Veluwemeer is questionable, as the phosphorus concentration in the lake and the polder water is almost the same. Therefore it is recommanded to shift flushing operations, at least in the winter period, from Veluwemeer towards Wolderwijd.

Introduction

Veluwemeer, the largest lake in a chain of shallow lakes situated in the centre of The Netherlands, is of great importance to recreation and nature. In the past twenty years eutrophication has caused severe water quality problems. Various measures have been taken in the past to reverse this undesirable situation (Hosper & Meijer, 1986). One of these measures was flushing of Veluwemeer and it proved to be extremely effective. Cooke *et al.* (1986) also reported several cases in which flushing achieved improvement in eutrophic lakes.

This paper examines the impact of flushing on nutrient dynamics, the composition and densities of algae species and transparency in Veluwemeer. It describes and discusses the basic mechanism on which the success of flushing is based, and evaluates the effects of the present flushing regime in relation to the water management of Veluwemeer and its neighbouring lakes in general.

Material and methods

Description of the area

The lakes Wolderwijd, Veluwemeer, Drontermeer, Vossemeer together form the Randmeren (Fig. 1). The lakes have a typical hydrology due to the special location between the 'old' land and the new made polder, lying *ca* 5 m below mean sea level. On one side of the lakes there is an inflow of groundwater and a number of streams, whereas on the other side there is a loss of water by infiltration into the polders.

Veluwemeer is the largest lake of the Randmeren, with a surface area 32.8 km^2, an average depth of 1.35 m and a retention time of the water of about 4 months. In the first years after its creation in 1956, the water was clear and there was a rich animal and plant life. In the second half of the sixties the lake detoriated rapidly, because of a sharp increase of the phosphorus loading. In the early seventies the lake was already characterized by cyanobacteria. According to Berger & Bij de Vaate (1983) the cyanobacterium *Oscillatoria agardhii* Gomont was the dominating species. The water became very turbid, Secchi disc visibility was limited to 0.2 m. The other lakes developed in a similar way.

The eutrophication of the Randmeren was controlled by reducing the external phosphorus loading. Phosphorus elimination was introduced at the sewage treatment plants discharging into Drontermeer in 1972 and Veluwemeer in 1979. In the latter lake the measures lead to a decrease of the external phosphorus loading from 3 to 1 gP m^{-2} y^{-1} (PER, 1986). The remaining phosphorus loading is caused 30% each by the discharge of effluents of the sewage treatment plant and several small streams and by rainfall, seepage and some minor discharges. Nutrient balance studies in Wolderwijd revealed that sediment release of phosphorus occurred during the summer season (PER, 1982), and such a release seemed to be also important in Veluwemeer, in view of the large increase in SRP during the first months of the growing season (Fig. 2).

Monitoring of the water quality

Routine fortnightly measurements in the field were carried out by the Institute for Inland Water Management and Waste Water Treatment, Lelystad, The Netherlands. The lake was sampled at representative locations (PER, 1986). The field measurements included water temperature, Secchi-disc transparency and pH. Chlorophyll *a* was determined spectrophotometrically after ethanol extraction (Moed, 1973). The species composition of algae was measured microscopically, using counting chambers, on samples fixed with iodine-formaline. Inorganic suspended solids were de-

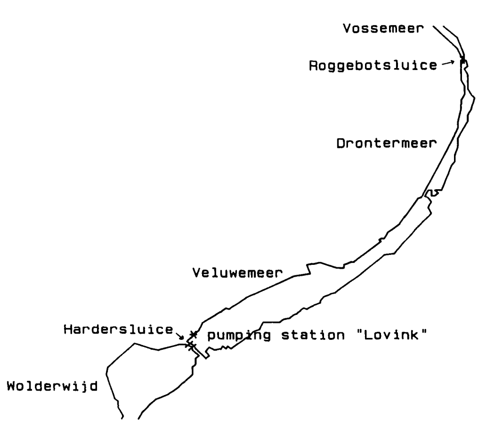

Fig. 1. Sketch of Veluwemeer and bordering lakes.

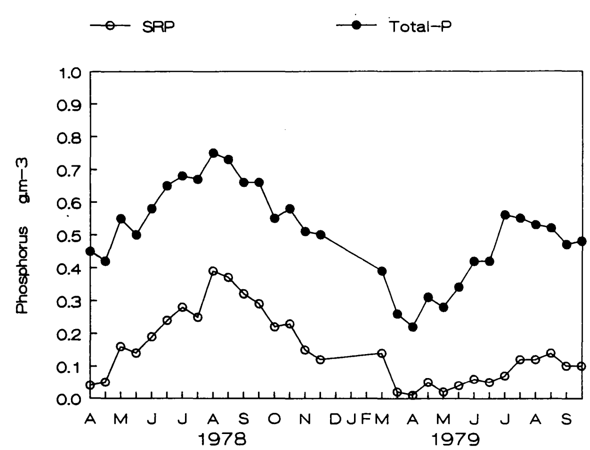

Fig. 2. Total- and soluble reactive phosphorus concentrations in Veluwemeer before the start of the winter flushing.

termined gravimetrically as loss on ignition at 550 °C of the seston (Dankers & Laane, 1983), after drying at 75 °C. All nutrients were analyzed on a HP 7673A auto analyzer. Soluble reactive phosphorus (SRP) and total phosphorus, after digestion with a sulphuric acid/persulphate mixture, are analyzed according to the modified molybdenum blue method (Murphy & Riley, 1962). Kjeldahl-nitrogen was measured as ammonium after digestion with potassiumsulphate/sulphuric acid and Wieninger selenium. Ammonium was measured spectrophotometrically after complexation with salicylate and chlorine. Nitrate was reduced to nitrite, using cadmium as electron donor and nitrite was complexed with sulfanilamide and α-naphtylethleendiamine-dihydrochloride before measurement (modification of the method described by Afghan & Ryan (1975)). Calcium was analyzed, also on the auto analyser, after complexation with cresolphtaleine in a diethylamine buffer. Particulate calcium is determined by the difference between total calcium and calcium after filtration with 0.45 μm Millipore filters.

Flushing

It is important to define the concept 'flushing' carefully, because during the winter months, when the excess water from the surrounding areas is pumped into the lake, there may already be a natural form of flushing. Our definition of 'flushing' is to deliberately supply more water than is necessary for maintaining the water level or a water reserve. The flushing discharge of Veluwemeer is calculated as the difference between the discharge supplied by the Lovink pumping station and the discharge to the bordering Wolderwijd (Fig. 1). The percentage of original lake water can be calculated as:

$$\text{percentage original lake water} = 100(e^{-(Qd/Ql)})$$

in which Qd is discharge volume in m^3, and Ql is lake volume in m^3.

It was assumed that during the winter months a reduction in the phosphorus concentration and a satisfactory reduction in algae biomass would enable to prevent the recurrent blooms of cyanobacteria. In order to achieve this objective a trial flushing of Veluwemeer was carried out. During the winter of 1979/1980 pumping station Lovink supplied an excess amount of high quality water from the adjacent polder Flevoland into the lake. The daily flushing rate was *ca* 0.01 d^{-1}. This is based on a monthly flushing discharge of 15 10^6 m^3, an average winter situation for Veluwemeer. The polder water has relatively low concentrations of total-P (0.09 gP m^{-3}) and algae (14 mg chlorophyll *a* m^{-3}), but is rich in calcium (140 g Ca m^{-3}) and nitrate (3.0 gN m^{-3} during the winter). As these winter flushings were successful, it was decided supplementary summer flushings were carried out from 1985 on (Table 1). This was aimed at preventing a 'concentration effect' (increasing nutrient concentrations due to infiltration and evapo-transpiration) and to dilute the phosphorus released from sediments.

Results

Situation up to 1985

During the winter 1979/1980 89 10^6 m^3 flushing water was supplied to the lake and the total-P

Table 1. Flushing discharges in Veluwemeer, corrected for summer supplements of *ca* 6.0 10^6 m^3 per month (winter discharges refer to 1979/1980, 1980/1981 etc.).

Year	Summer discharge (10^6 m^3)	Winter discharge (10^6 m^3)
1979	19.179	89.249
1980	14.596	79.075
1981	6.289	84.402
1982	19.425	82.797
1983	18.693	81.428
1984	69.258	116.117
1985	28.157	105.175
1986	101.270	68.824
1987	29.951	72.380
1988	86.081	58.814

concentration in the Veluwemeer decreased dramatically up to March 1980, when the concentration approximated the concentration in the polder water (Fig. 3). Soluble reactive phosphorus (SRP) decreased concomitantly to values around the detection limit. The chlorophyll *a* concentration also dropped dramatically, but already in January 1980 stabilization set in at a level of about 60 mg m^{-3}, which is above the average concentration in the water used for flushing. The particulate-N concentration in Veluwemeer dropped from 4.9 gN m^{-3} when flushing was started to less than 2.0 gN m^{-3} in May 1980 (Fig. 4).

The main cause of improvement of Veluwemeer water is the dilution with supply water. The concentrations of total-P, Kjeldahl-N and chlorophyll *a* in Veluwemeer were very much related to the fluctuations in the quality of the supply water ($r^2 > 0.95$). If the dilution of the water is the driving force for quality improvement, the nutrient concentration in Veluwemeer will start resembling the nutrient concentration in the supplied water more and more, as more polder water is supplied. Although this is the case for the total-P concentration in Veluwemeer, the situation for chlorophyll *a* and nitrogen is more complex.

The stabilization of the chlorophyll *a* concentration on a higher level than the polder water implies that flushing is counteracted by algal growth. Figure 5 shows growth curves for a number of algal groups derived from the algal growth model BLOOM (Los, 1991) and an average flushing rate. The curves are a function of the water temperature and have been calculated at optimum light- and nutrient situation. At water temperatures below 2 °C, the growth rate of algae will not offset the effect of lake's flushing, so that the algae will continue to be washed out. However the net wash out effect will be 20 to 30% per month. At water temperature above 2 °C algae can increase in numbers effectively, irrespective

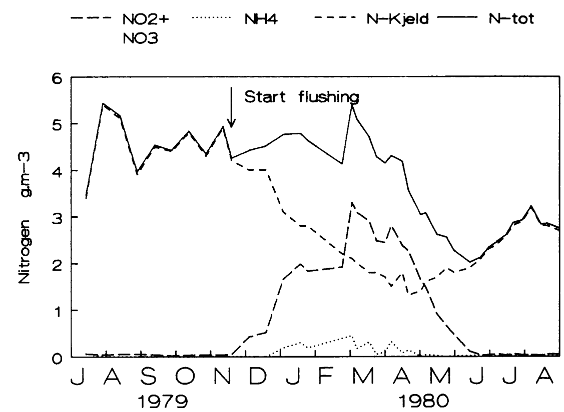

Fig. 4. Nitrogen concentrations in Veluwemeer, before and after the winter flushing of 1979/1980.

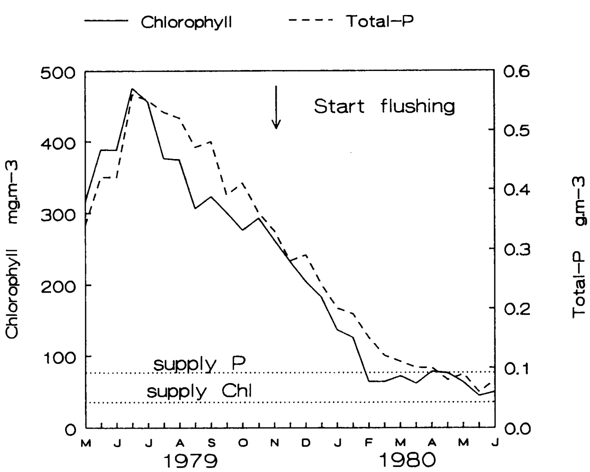

Fig. 3. The effects of the first winter flushing (1979/1980) on chlorophyll *a* and total-phosphorus concentrations (the horizontal dotted lines represent the concentrations in the supply water).

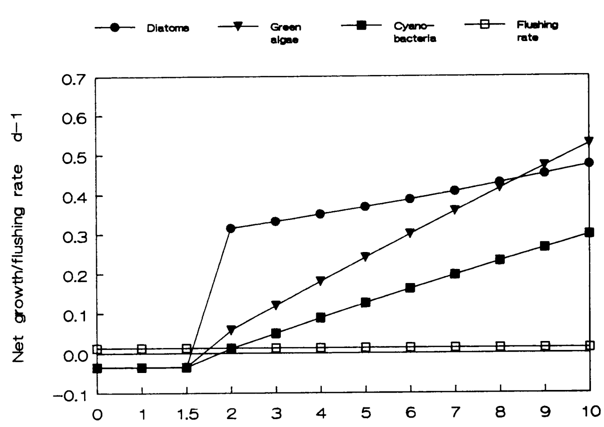

Fig. 5. Growth rates of the various algae species groups as function of the water temperature (from: Los, 1991) and the flushing rate in Veluwemeer.

of flushing. Thus, it is reasonable to assume that from early spring onwards (February/March) algal growth could prevent the chlorophyll *a* concentration from decreasing to the level of the supply water.

Comparing the concentrations of nitrogen compounds in Veluwemeer and the supply water, it appears that at the start of flushing the nitrogen in the lake water predominantly contains particulate-N and concentrations of nitrate and ammonium are low. The supply water, however, is rich in ammonium ($1\ gN\ m^{-3}$) and nitrate ($3\ gN\ m^{-3}$). When the two water types are mixed, the chlorophyll *a* concentration and the Kjeldahl-N concentration decrease, but concentrations of nitrate an ammonium rise rapidly to $2.5\ gN\ m^{-3}$ and $0.5\ gN\ m^{-3}$ respectively, in February and March (Fig. 4). In summer a decrease in nitrate and ammonium sets in, probably because of denitrification at rising temperatures. Algal growth exhausts the dissolved forms of nitrogen, with the result that in May 1980 all nitrogen in Veluwemeer occurred again in particulate form (Kjeldahl-N).

The dilution of Veluwemeer, started in 1979, gives rise to a permanent improvement of the water quality (Fig. 6). The flushing in winter 1980/1981 had, therefore, less impact than the flushing in 1979/1980 (Fig. 7). The differences in nutrient concentrations between supply water and lake water had already been reduced considerably. Figure 7 shows an increase in total-P concentration again in March 1981, presumably because of sediment release, but from 1981 onwards the phosphorus release from the sediment decreased and stabilized at a very low level from 1985 onwards (Fig. 8). The sediment release, calculated by the model SED (Van der Molen, 1991) and measured by continuous flow experiments according to Boers & Van Hese (1988), decreased proportionally more than the external load because of a number of processes, related to flushing:

– The reduced organic matter production and

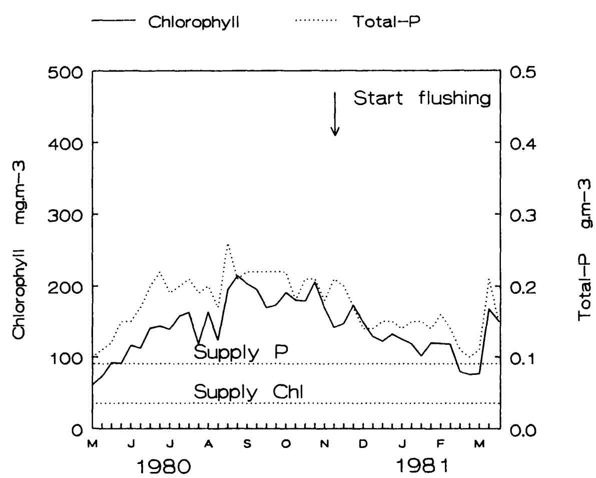

Fig. 7. The effects of the second winter flushing (1980/1981) on concentrations of chlorophyll *a* and total-P (the horizontal dotted lines represent the concentrations in the supply water).

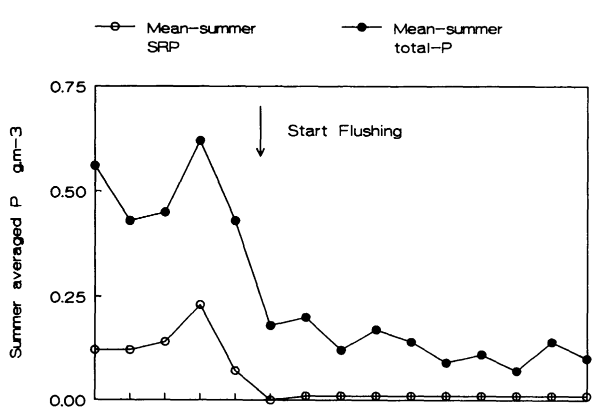

Fig. 6. Summer average total- and soluble reactive phosphorus during 1975–1989.

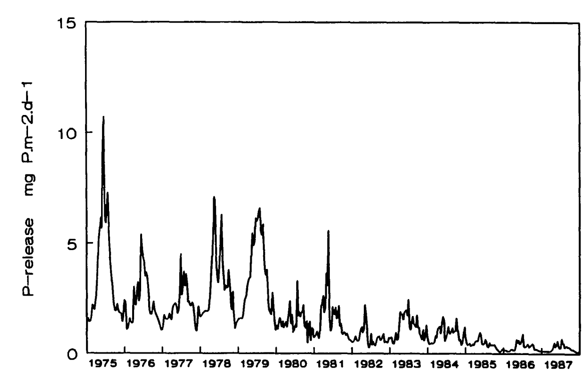

Fig. 8. Release of phosphorus in Veluwemeer based on model SED (from: Van der Molen, 1991).

the considerable supply of nitrate in the polder water have caused improvement of the sediment oxidation.

- Moreover, the supply of calcium and to a lesser extent the supply of iron with the polder water (Brinkman & Van Raaphorst, 1986; Van der Molen, 1990) have possibly led to an increased fixation of phosphorus in the bottom and a decreased release rate.

Further, flushing has caused a decrease in the biovolume of the cyanobacteria (Fig. 9), while the number of algae remained unchanged high (Fig. 10). There was no distinct shift in the composition of the algae species up to 1985. This means that flushing did not initially lead to the realization of the objective to prevent the cyanobacteria dominance. However, the decrease in biovolume resulted in an increased transparency (Fig. 11).

Situation since 1985

The cyanobacteria disappeared from 1985 onwards, although the phosphorus concentrations had already decreased considerable. In Fig. 12 the number of the cyanobacteria, as a percentage of the total number of algae, have been plotted, as

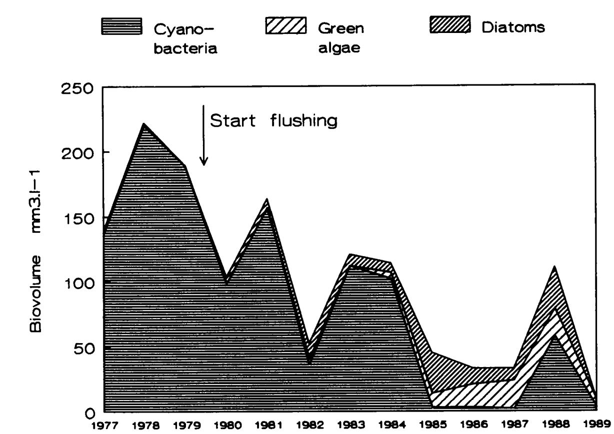

Fig. 9. Stacked presentation of the summer average of the biovolume of algae in Veluwemeer per species group over the period 1977–1989.

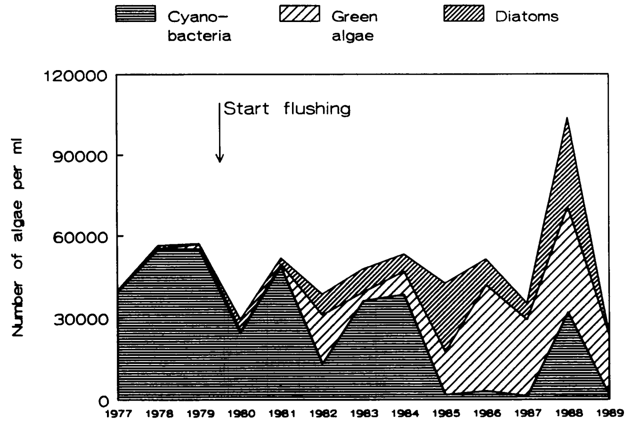

Fig. 10. Stacked presentation of the summer average of the densities of algae in Veluwemeer per species group over the period 1979–1989.

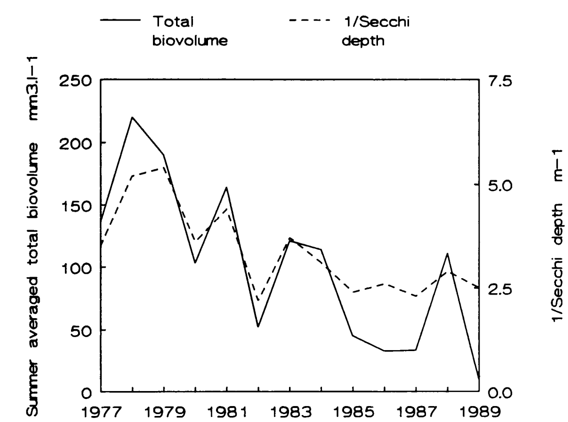

Fig. 11. Summer averages of the biovolume of the algae and the reciprocal Secchi depth values in Veluwemeer for 1977–1989.

they occurred in the growing seasons (April–October) of 1980 to 1989 in Veluwemeer and Wolderwijd respectively. During the period 1985 to 1987 three successive cold winters occurred. The number reduction was probably influenced by the reduced productivity in winter (low temperatures), poor light conditions under the ice cover (Adams *et al.*, 1984) as well as by increased sedimentation under the ice cover. During a similar cold winter in 1978/1979 the cyanobacteria dominance was not broken, but only temporarily reduced under prolonged ice cover (Fig. 13).

The following qualitative model can be devel-

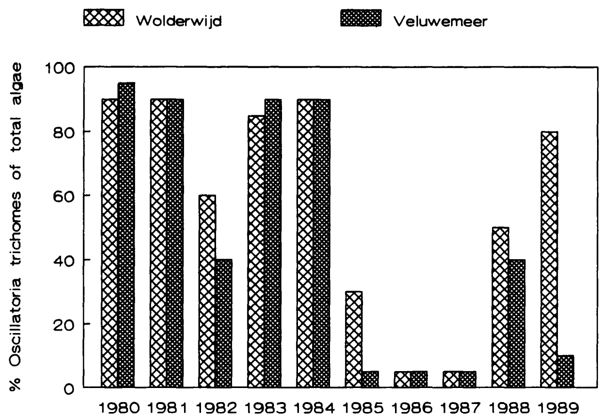

Fig. 12. Percentages of the *Oscillatoria agardhii* in the algae population in Veluwemeer and Wolderwijd during the period 1980–1989.

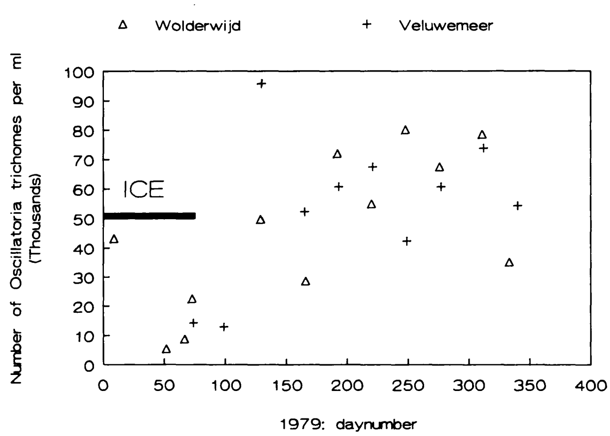

Fig. 13. Influence of a period of prolonged ice coverage on the numbers of cyanobacteria in Veluwemeer and Wolderwijd during the winter of 1978/1979.

oped to explain the shift in algae composition during the period 1985–1987 in Veluwemeer and Wolderwijd. *Oscillatoria agardhii* has a relatively low growth rate, particularly at high light intensities (Loogman, 1982), but it can maintain its position because the loss rates are low also. This species is hardly eaten by zooplankton and its sedimentation rate is low (Reynolds & Walsby, 1975). Therefore, the number of cells at the beginning of a growing season are important for the dominance in the growing season. The combination of a severe winter and scarcity of phosphorus has the following effect: the densities of *Oscillatoria agardhii* will decrease dramatically during ice coverage and as soon as the water temperature exceeds the critical value of 2 °C diatoms and green algae will take up all the available phosphorus. This causes a further deterioration in the competitive position of the cyanobacteria. Table 2 shows this process after the winter of 1984/1985. The direct contribution of flushing to the reduction of cyanobacteria in Veluwemeer in the winter of 1984/1985 is limited.

Although phosphorus levels still were relatively low, the number of cyanobacteria started to increase again after the mild winter of 1987/1988. Low numbers of cyanobacteria in 1989 in Veluwemeer, compared to Wolderwijd, are caused by low availability of phosphorus.

During the summer another mechanism may play a role in the disappearance of *Oscillatoria agardhii.* The photosynthesis capacity of *Oscillatoria agardhii* gradually decreases and may even be reduced to zero at higher light intensities (Loogman, 1982). The increased transparency during summer from 1985 onwards therefore contributes to unfavourable conditions for *Oscillatoria agardhii.*

Effects on lake-transparency

The transparency in Veluwemeer increased, but less than expected. Figure 11 showed a continuing decrease of the total biovolume since 1985, whilst stagnation occurs in the (reciprocal) Secchi-depth values. The improvement of trans-

Table 2. Number of algae per ml in Veluwemeer during the winter period 1984/1985

Month	Cyano-bacteria	Green algae	Diatoms
Oct 1984	52775	4238	1038
Nov. 1984	33038	2138	600
Dec 1984	29700	3075	375
Jan 1985	10650	1050	0
Feb 1985	54575	5138	75
Mar 1985	2425	2160	1250
Apr 1985	2871	16019	50699
May 1985	4156	17265	32840

parency compared with the decrease in chlorophyll *a* is also much lower than expected. The change in the algae species composition and the role of other fraction in the water may have contributed to this less than expected increase in transparency.

Since 1985 the species composition has shifted from cyanobacteria towards diatoms and green algae. Per unit dry weight diatoms and green algae contribute less to the extinction of light than cyanobacteria; they have a lower specific extinction (Los, 1991). The biovolume/dry weight ratio is *ca* the same for both groups, therefore further transparency improvement is expected but not observed. Apparently, suspended materials other than live algae contribute more to the transparency.

Detritus has a delayed reaction on the decrease in chlorophyll or biovolume, because a fraction of dead algae decomposes very slowly. Lacking a cellulose cell wall, detritus from cyanobacteria has less resistance to mineralization than detritus from other algae, such as diatoms and greens (Gunnison & Alexander, 1975; Jewell & McCarthy, 1971). The turn-over rates of diatoms and green algae are higher (Los, 1991). Consequently, relatively more detritus will be formed by diatoms and green algae than if cyanobacteria were dominant.

The flushing of Veluwemeer has led to a four-folds increase in the calcium load (Van der Molen, 1990) and the concentration increased from 60–80 $g\ m^{-3}$ before 1980 to 80–140 $g\ m^{-3}$ after 1980. Calcium is present in predominantly soluble form. Because of algal growth and high buffer capacity, chemical balance shifts such that calcium carbonate can be formed. Only a few per cent of the calcium is present in particulate form. In the summers since 1987 the concentration of particulate calcium in Veluwemeer varied between 2 and 8 $g\ m^{-3}$, contributing *ca* 5 to 10 $g\ m^{-3}$ to the concentration inorganic suspended matter in the water. Compared with the situation before 1980 loss on ignition of the seston increased by 2.8 $g\ m^{-3}$ (Van der Molen *et al.*, 1989). Since the start of the deliberate summer flushings in 1985 loss on ignition has been significantly higher than in the first years after 1980. The low value of loss on ignition in 1989 is possibly caused by a further decrease in productivity and therefore in formation of calcium carbonate. Beside the increase in inorganic suspended matter through calcium carbonate formation, the contribution of increasing densities of diatoms is also significant from 1985 onwards.

Discussion

Cooke *et al.* (1986) reported that flushing can achieve improvement in eutrophic lakes in two ways:

1. reduction in the concentration of the limiting nutrient (dilution) and
2. increasing water exchange rates (wash out).

We observed an additional effect, at least for Veluwemeer, namely increase of inactivation of phosphorus in the lake sediment.

Although the effect of reduced sediment release is important, the first observed positive effects in Veluwemeer depend mainly on dilution of the total-P concentration. This is demonstrated by the initial quick response of the lake towards flushing, followed by a slow down in recovery as nutrient concentrations tend to become equal to supply water concentrations. Cooke *et al.* (1986) found that, of the mechanisms induced by flushing, dilution provoked the most pronounced effect in recovery of Green Lake and Moses Lake (USA). In Moses Lake algal biomass declined as a result of reduced nitrogen concentrations, as supply water was poor in nitrates. In most part of the lake dilution rates ranged between 0.01 and 0.10 d^{-1} (Veluwemeer *ca* 0.01 d^{-1}). Only in Parker Horn, an arm of the lake nearby the inflow, did the dilution rates exceed 0.20 d^{-1} for short periods, and under these circumstances some wash out of algal cells was noted. As in many cases the availability of dilution water will be limited, wash out of algal cells will usually be of limited significance. However, under special conditions wash out may become significant. In Veluwemeer, at low water temperatures (below

2 °C and preferably under ice cover) algal growth rates fall to zero level or even less due to increased mortality and sedimentation. This provides conditions for obtaining some additional effect of flushing by wash out of algal cells.

The winter flushing started in 1979 appears to have been very successful, resulting in transparency improvement due to a reduction in biovolume. The projected decrease of the cyanobacteria dominance, however, did not lead to transparency improvement, although this had been expected. Figure 14 schematically summarizes the influence of flushing on the composition of the algae species and transparency in Veluwemeer. As long as the nutrient concentration of the supply water is below concentration in the lake, dilution will occur. High calcium and nitrate concentrations in the supply water had a positive effect on the binding of phosphorus in the sediments, therefore decreasing the phosphorus availability for algal growth. The decrease of available nutrients results in a reduction of the algae biovolume and consequently transparency improves. A decrease in nutrient availability further influences competition between the various algae groups. This is particularly important in spring,

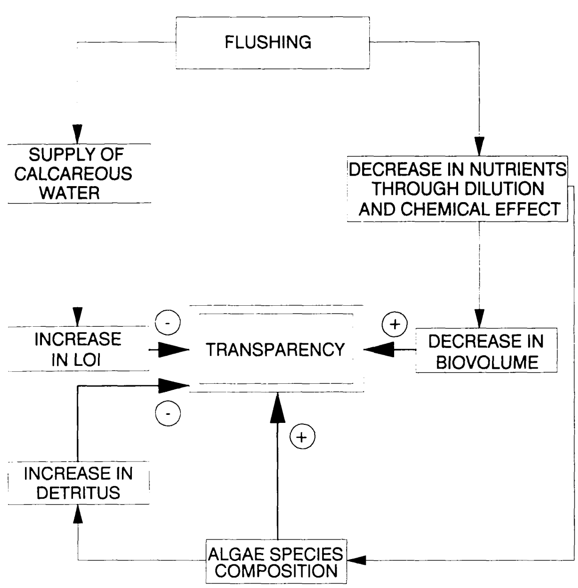

Fig. 14. Scheme of the most important effects of the flushing in Veluwemeer on transparency.

and especially after a long period of ice coverage.

After 1985 dominance of *Oscillatoria Agardhii* is broken and diatoms and green algae become the most important species. Because the specific light-extinction per unit of diatoms and green algae is lower than that of the cyanobacteria, a transparency improvement was expected. However, the increase in detritus concentration because of the lower decomposition rates of diatoms and green algae, combined with a high turnover rate, delayed further improvement of the transparency. The left hand side of Fig. 14 shows that flushing leads to the supply of calcareous water. This had led to an evident increase in loss on ignition and a decrease in transparency in Veluwemeer.

Conclusions

We have to acknowledge that the flushing of Veluwemeer has unmistakably led to water quality improvement. *Oscillatoria agardhii* densities has been brought to the margins of its habitat because of the reduction of the phosphorus concentrations in Veluwemeer. The severe winter conditions is an additional causal factor for the disappearance of *Oscillatoria agardhii.* In Veluwemeer, the importance of flushing as a means to reduce the spring concentration of cyanobacteria is very limited when aimed for a direct wash out of algal cells, whereas the effect of flushing on the total-P concentrations is of great importance.

Higher detritus and inorganic suspended matter concentrations affect the transparency negative. Chlorophyll *a* only contributes for a small percentage to the transparency. It is therefore not surprising that as from 1985 transparency has hardly increased during the summer.

In the present situation improvement by dilution is minimal. On average over the past 4 years, the summer average of the total-P concentration in Veluwemeer is about the same or even lower than in the supply water. Dilution by flushing is not longer of great significance under such circumstances. During the summer period under average circumstances, a loss of water of about 36

10^6 m^3 may occur due to infiltration and evapotranspiration. These losses must be compensated, for maintaining a certain water level. In order to maintain the original total-P concentration in Veluwemeer, *ca* 50 10^6 m^3 will be additionally required during the summer period to compensate for the 'concentration effect'.

In view of the really acceptable (phosphorus) quality of Veluwemeer in the present situation, it seems that the efficiency of flushing is low at present. The quality of water in the bordering lake Wolderwijd offers more prospects for improvement. Therefore, we recommend to shift the flushing operations from Veluwemeer towards Wolderwijd in the coming years.

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