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Multiple techniques for lake restoration

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Abstract

Lake Finjasjön is a shallow, eutrophic lake (area 1100 ha, mean depth 3 m, maximum depth 13 m) in southern Sweden. In the 1920s, the lake was clear, with a summer Secci depth of about 2 m. During the first half of the 20th century, untreated sewage from the town polluted the lake. In the 1930s, the lake began to show eutrophic characteristics, and in the 1940s, the cyanobacterium *Gloetrichia echinulata* dominated in summer. In 1949, the first municipal sewage treatment plant was built. The treatment was, however, insufficient, since the lake continued to be the recipient of the effluent with the result that the occurrence of cyanobacteria became more frequent. Species such as *Microcystis* and *Anabaena* caused skin rash and allergic symptoms among swimmers. The phosphorus load on Lake Finjasjön increased as the population of Hässleholm grew and reached a peak value of 65 tons annum^{-1} in 1965. In 1977, the sewage plant was rebuilt to include chemical flocculation, reducing the total external phosphorus load to about 5 tons annum^{-1}. Despite this improvement the lake did not recover from its chronic and toxic cyanobacterial blooms. Phosphorus-leaking black sediments were identified as the cause of the lake's failure to recover. Some 60% of lakebed area is covered with sediments on average 3 m thick. Dredging the sediments was started on a large scale in 1987. Five years later, 25% of the sediment area had been removed but the dredging was stopped since phosphorus continued to be released into the water from these areas. In 1992, a new restoration policy, a combination of further reduced external nutrient loading and food-web manipulation was initiated. A constructed wetland (30 ha) to reduce phosphorus and nitrogen was created in connection to the effluent from the sewage treatment plant. Protection zones along the feeder streams into Lake Finjasjön were also established. A cyprinid reduction programme by trawling was carried out between 1992 and 1994. When it started, the fish community was composed of 90–95% bream and roach. After two years of trawling, the ratio between piscivorous and planktivorous fish was 1:1. In 1994 and 1995, the transparency increased due to a considerably reduced biomass of phytoplankton and a radically altered phytoplankton community. The monoculture of *Microcystis* was replaced by a diverse phytoplankton community. The increased transparency made possible the development of submerged macrophytes such as *Elodea, Myriophyllum* and *Potamogeton*. The internal loading of phosphorus decreased dramatically in 1994 and 1995, possibly as a result of reduced sedimentation of phytoplankton.

Introduction

Lake Finjasjön (latitude 56° 08′, longitude 13° 42′, 43.2 m above sea level) is a eutrophic, shallow lake in southern Sweden, situated near the town of Hässleholm. It has a mean depth of 3 m, a maximum depth of 12 m and an area of 1110 ha. The retention time is three months. The lake has five feeder streams and one outflow (Figure 1). The catchment area of 260 km^2 is covered by mostly coniferous and deciduous forests with about 10–15% used for agriculture.

In the 1920s, the lake was clear, with a summer transparency of about 2 m. During the first half of the 20th century, untreated sewage from the town of Hässleholm started to pollute the lake. In the 1940s, the cyanobacterium *Gloeotrichia echinulata* domin-

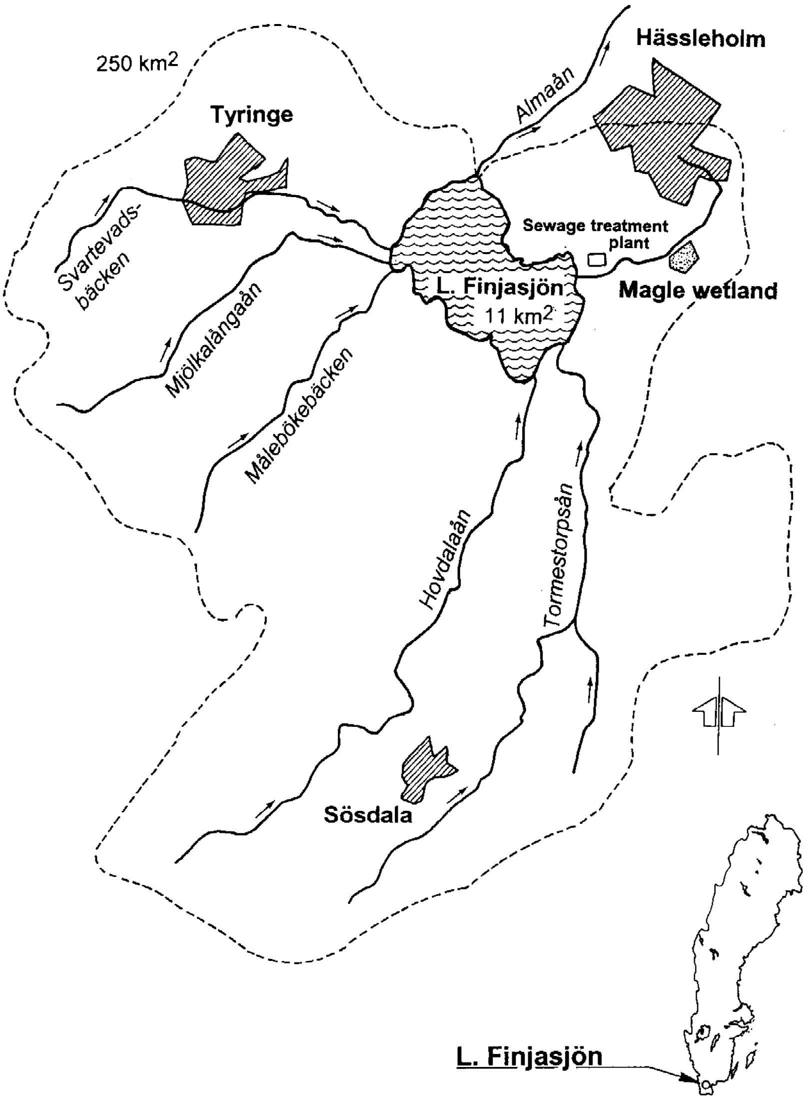

Figure 1. The catchment area of Lake Finjasjön, Sweden. The lake is the recipient for treated sewage water from the sewage treatment plant of Hässleholm. Before entering the lake, the treated sewage water is further treated by flowing through a constructed wetland.

ated during the summer. The bloom was occasionally heavy, making it necessary to prohibit swimming.

In 1949, the first municipal sewage treatment plant, equipped with a mechanical treatment step, was built (Figure 1). However, the blooms did not cease. The treatment was apparently insufficient and the lake was still the recipient of its effluent. Instead of disappearing, the occurrence of cyanobacteria became more frequent. Swimmers suffered from skin rashes and allergic symptoms caused by the increased biomass of the potentially toxic species *Microcystis* and *Anabaena* (Annadotter, 1993).

Despite the fact that the sewage treatment plant was improved in 1963 with an activated sludge step, the phosphorus load on Lake Finjasjön continued to increase due to growth of the population of Hässleholm, and reached a peak value of 65 tons annum^{-1} in 1965 (Figure 2).

At the beginning of the 1970s, the municipality wanted to relocate the outlet of the sewage treatment plant from the lake to its outflow, in order to improve the water quality of the lake. However, the county board of Kristianstad did not permit the municipality to procede with this plan, beacuse, among other things, it was considered unethical to discharge sewage downstream of the lake, and thus encumber the villages situated there. A further argument for not shifting the location of the effluent from the lake was that the lake water dilutes the sewage and a certain amount of purification was assumed to take place within the lake.

In 1977, the sewage plant was rebuilt with chemical flocculation and a three-media filter, reducing the phosphorus load to about 5 tons annum^{-1} (Figure 2). Despite this improvement, the lake did not recover from its chronic cyanobacterial blooms and, quite contrary to expectation, as the phosphorus load decreased dramatically the content of chlorophyll a increased. Diving ducks – goldeneye (*Bucephala clangula*) and pochard (*Aythya Ferina*) – disappeared from the lake when the transparency decreased towards the end of the seventies (Figure 3). During the 1980s, the lake became more hypertrophic and the politicians of the Hässleholm municipality became desperate about its condition, because it also served as the drinking water supply to 25 000 consumers.

A political consensus that the lake had to be restored existed and several limnological investigations were initiated. The municipality of Hässleholm started the lake's restoration in the middle of the 1980s, using the slogan: '*Lake Finjasjön – possible to swim in, in our time, for our children'.* Phosphorus release from anaerobic sediments was identified as the cause of the failure of the lake to recover from reduced loading and so dredging of the sediments was one recommended measure (Löfgren & Forsberg, 1984).

Another method of decreasing the internal phosphorus release was suggested by Ripl & Leonardsson (1980). They investigated the denitrification capacity of the sediments. By adding calcium nitrate to the sediments, they found that the speed of the denitrification process at 12 m depth was double that of 7 m. Efficient phosphorus retention occurred as a result of the denitrification. In systems without nitrate addition, high phosphorus release occurred, especially from the sediments at 12 m depth. Based on their results, they suggested that the municipality should add nitrified sewage effluent to the lake at depths greater than 8 m. They assumed that this step would cause denitrification at the sediment surface, thereby considerably

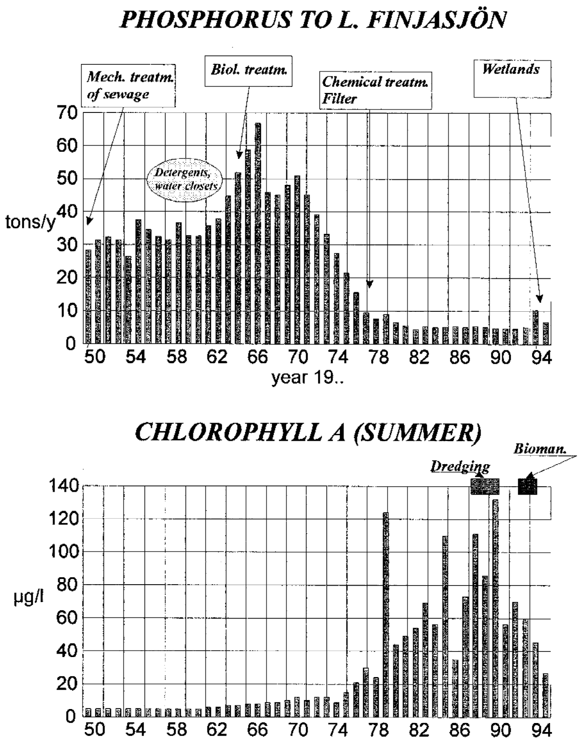

Figure 2. The external phosphorus load to Lake Finjasjön 1950–1995 and the summer values of chlorophyll *a* in Lake Finjasjön 1950–1994.

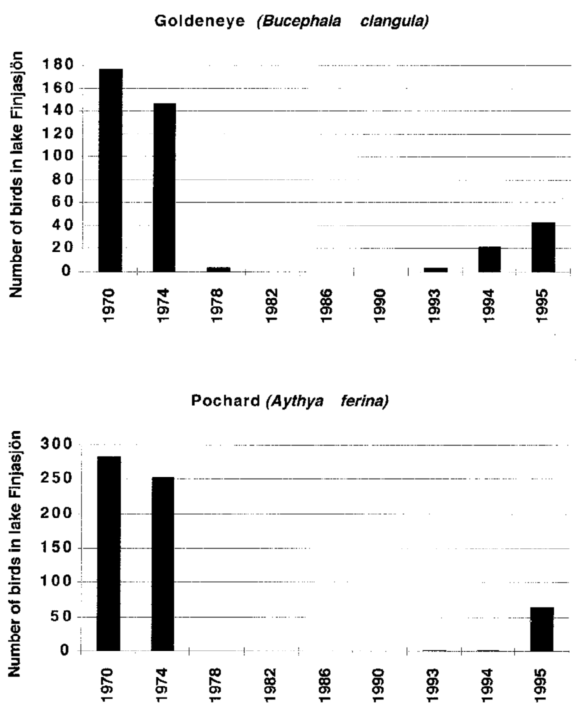

Figure 3. Numbers of goldeneye (*Bucephala clangula*) and pochard (*Aythya ferina*) in Lake Finjasjön 1970–1995.

enhancing sediment phosphorus. Injection of nitrate solution into the sediments ('Riplox'-treatment) was recommended as a complementary measure.

Faced with the choice of these two suggested methods, the Municipality decided to restore the lake by dredging. The politicians did not accept the idea of adding sewage water and nitrate to an already sewage-loaded and over-fertilised lake, whereas dredging the mud sounded more logical.

Sediments cover 60% of the bottom of the lake, on average to a depth of 3 m. Investigations of the sediments showed that the top layer, about 0.5 m thick, had a 30% higher phosphorus concentration and a slightly higher phosphorus/iron ratio than the rest of the sediment profile. The municipality was advised to remove this top layer (Löfgren, 1991) although, after the dredging, a 2 m thick layer of dark, phosphorus-rich sediment still remained.

Suction-dredging of the sediments was started on a large scale in 1987, with the purpose of dredging the whole area of 6.6 square kilometres of sediment. The cost was estimated as at least 100 million Swedish crowns, (SEK), approximately £10 million sterling. Ten sedimentation dams were constructed adjacent to the lake for the purpose of separating the water from the sediment. Three years later, several aspects of the restoration strategy were strongly criticised (Annadotter, 1990), mainly because of the small difference in sediment chemistry between dredged and non-dredged sediments and a lack of awareness of the catchment nutrient load on the lake.

With the purpose of evaluating the success of suction dredging, an investigation of the sediments was carried out in 1990 and 1991. Contents of total phosphorus and iron in dredged and non-dredged sediments were compared. Dredged areas contained 30% less total phosphorus (Nilsson, 1991) and 15% less phosphorus in the pore water, differences which were not considered to be sufficiently great. The sediments remaining after dredging were still typical of sewage-loaded, dark sediments with a low phosphorus retention capacity. There is no explicit relationship between the trophic level of a lake and the phosphorus content of sediments, while the phosphorus concentration in the pore water is believed to reflect the trophic state of a lake (Håkansson & Jansson, 1983). This showed that continued dredging would not produce a clear water lake. By 1991, the dredging had cost about 50 million SEK, (£5 million sterling). Despite the removal of 134 tons of phosphorus from the bottom of Lake Finjasjön, the dredging had not diminished the extent of cyanobacterial blooms.

Between 1987 and 1993, the cyanobacterial toxicity of Lake Finjasjön was found to vary strongly from year to year, as well as over the course of a bloom season (Annadotter, 1993; Annadotter, unpubl.). Because of the occurrence of these toxic species, swimming was still prohibited in Lake Finjasjön, although the lake was still used for drinking water. Cows that drank water from the outflow of the lake suffered liver damage, associated with hepatotoxic blooms, which cows drinking well water did not develop. (Annadotter et al., 1990). The cyanobacteria in the photic zone were toxic, while those sampled below this zone were not (Annadotter et al., 1993). It was unfortunate that the intake to the water works was situated at the outflow of the lake, thus pumping surface water with the highest algal concentration and the highest toxicity to the water works. Apart from the fear of distributing toxic drinking water to consumers, algae caused technical problems, including blocked filters in the water treatment plant.

Thus, several reasons for continuing the restoration of Lake Finjasjön existed even though it was evident that dredging was an inappropriate method. However, an alternative strategy had been suggested in 1990, when the external nutrient load on Lake Finjasjön was evaluated and found to be substantial using Vollenweiders phosphorus loading model (Vollenweider, 1976; Nilsson, 1990). To investigate whether the lake would be suitable for attempted restoration by biomanipulation, a standardized test fishery was carried out, which showed that the fish community was dominated by cyprinid fish (72% cyprinids, 28% piscivorous fish) (Collvin & Månsson, 1990) (Figure 4).

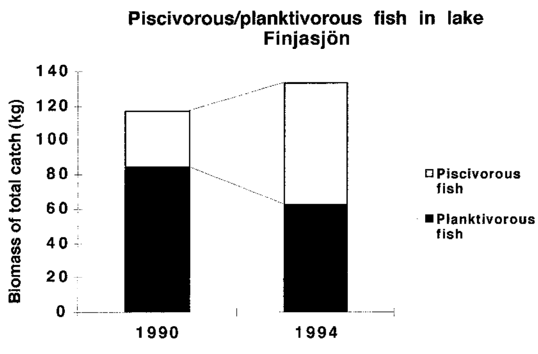

Figure 4. The ratio between piscivorous and planktivorous fish in Lake Finjasjön 1990 and 1994 (before and after the fish reduction).

The new restoration strategy

A new strategy was formulated, based on the idea that it was possible to reduce the internal phosphorus loading, which was still the main problem of Lake Finjasjön, without removing the sediments (Annadotter et al., 1992). This was based upon the following two strategies:

1. The creation of a 'top-down' effect on the phytoplankton by manipulating the food web through cyprinid reduction.
2. Further reduction of external nutrient loading, both from the catchment and from the sewage treatment works.

Different scientists had various opinions about the exact cause of the internal phosphorus loading (e.g. low redox conditions, high pH, sedimentation of algae on the sediment surface). Since all these conditions were caused by a high phytoplankton biomass, the main focus of the new restoration strategy was to minimize this biomass in spring and early summer in order to prevent the subsequent internal phosphorus loading.

In 1992, suction dredging was discontinued. The new restoration strategy was a political minority decision. The former political consensus was broken and the new restoration strategy was strongly questioned by sceptics from the very beginning. Despite the fact that no scientist recommended further dredging of Lake Finjasjön, several politicians and civil servants in the municipality wanted to continue the sediment pumping.

The cyprinid reduction was carried out from 1992 until 1994 by trawling. Two boats were specially designed for trawling in Lake Finjasjön and equipped with a sorting table. The boats worked together using a trawl of 7 × 30 m in the pelagic zone. After one year, it was evident that their capacity was not sufficient. Therefore, in the autumn of 1993, two smaller boats were set to trawl in the littoral zone concurrently with the larger, pelagic trawlers. All the predatory fish caught were released alive into the lake as soon as they had been sorted.

The theoretical catchment phosphorus load to Lake Finjasjön results in a lake total phosphorus concentration of approximately 40 μg l^{-1}. In order to decrease the external load, the most important streams were identified by Krug & Walker (1991) and Vought & Lacoursiére (1992, 1994), and agreements with the landowners drawn up, to give 5 m wide buffer zones which will not be fertilised, ploughed or used for agriculture. The cost of these was 3000 SEK (£300) ha ann^{-1}.

A further reduction of the phosphorus from the sewage treatment works was necessary. The yearly external phosphorus supply to Lake Finjasjön was 5 tons, of which 1 ton came from the sewage treatment plant. While the phosphorus coming from the feeder streams, to a large extent appeared as particulate phosphorus, the phosphorus from the sewage treatment plant appeared as PO_4-P, easily available to phytoplankton. In the summer, when several of the feeder streams had low flow rates, the effluent from the sewage treatment plant became an important and constant inflow with a PO_4-P concentration of about 150 μg L^{-1}, amounting to about 40% of total load.

A 30 ha wetland was constructed to further reduce the phosphorus and nitrogen in the effluent from the sewage treatment plant (Figures 1 and 5).

The success of these measures was evaluated through monitoring of water quality, plankton and fish. Samples for physico-chemical and plankton analyses were taken weekly from the deepest part of the lake. Plankton was sampled once a month in 1992 and 1993, and weekly in 1994 and 1995. Test fishing was carried out according to a standardised test fishing method with survey nets, developed at the Institute of Freshwater Research of the Swedish National Board of Fisheries (Nyberg & Degerman, 1988).

Results of the strategy

By the autumn of 1994, when fish catch weights had been reduced to 20% of initial ones catches, 400 tons of cyprinids had been removed. The ratio between piscivorous and planktivorous fish in test fishing with benthic survey nets was approximately 1:1 (Figure 4), which implies a balance in the fish community (Jeppesen pers. comm.). At this point the fish reduction was stopped.

Evident signs that the fish reduction had had an effect on the plankton community were observed in the summer of 1994. High peaks of daphnids, *Daphnia cucullata* and *Daphnia galeata*, appeared in July (Figure 6), a new phenomenon interpreted as the consequence of reduced predation pressure on large cladocerans. The change in zooplankton community during the season was accompanied by changes in the phytoplankton community. The toxic and chronic *Microcystis* blooms were replaced by a diverse phyto-

Figure 5. Aerial view of the constructed wetland in Hässleholm. Photo: Heléne Annadotter.

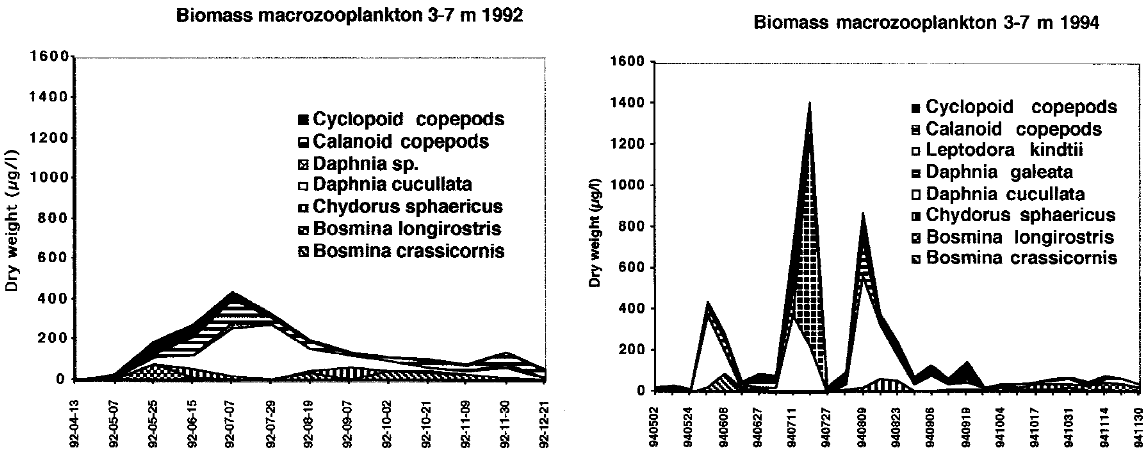

Figure 6. Biomass of macrozooplankton, 1992 and 1994 (before and after the fish reduction).

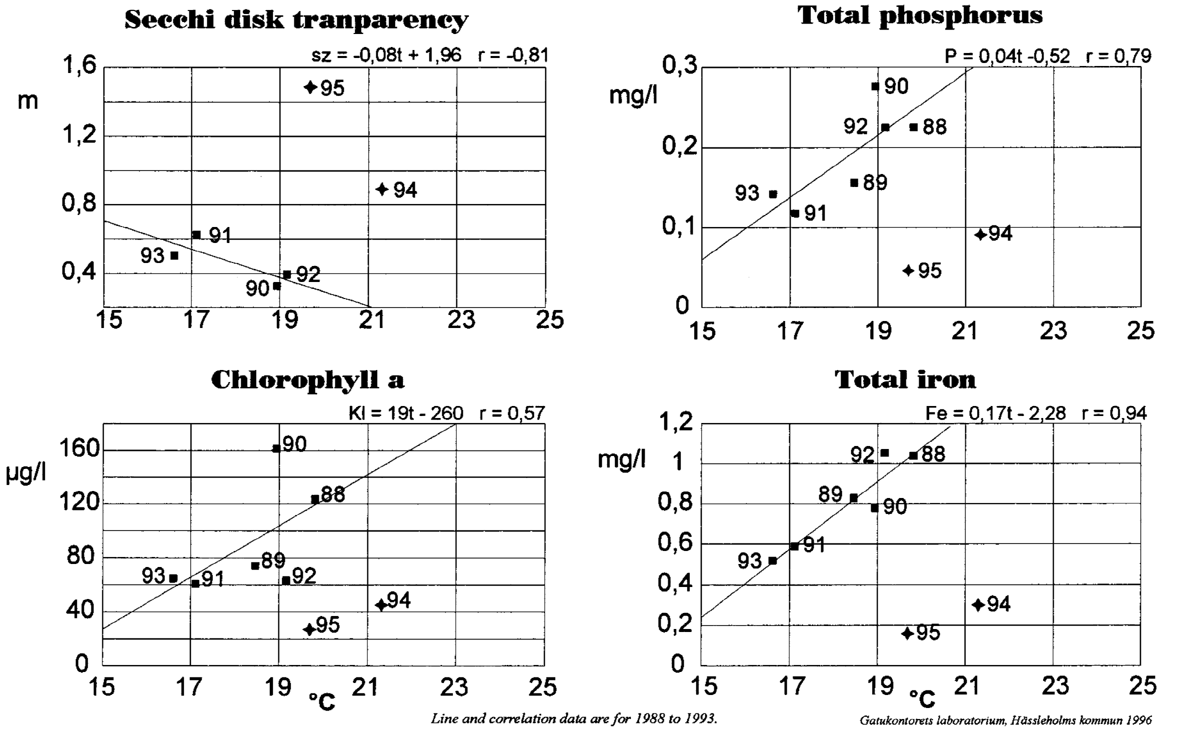

Figure 7. Summer average variations with temperature for Secchi disc transparency, chlorophyll *a*, total phosphorus and total iron in Lake Finjasjön 1988–1995.

plankton community of diatoms, cryptomonads, cyanobacteria, chrysophytes and dinoflagellates.

The high peaks of *Daphnia galeata* in July, coincided with high occurrence of cryptomonads, probably an effect of heavy grazing pressure on phytoplankton.

In addition to the pronounced changes in the phytoplankton community, total phytoplankton biomass and the chlorophyll *a* values were considerably lower than normal and the average summer Secchi disc transparency was twice that of previous years (Figure 7).

The constructed wetland started to function in February 1995. For the rest of that year, the average total phosphorus (mostly phosphate) values were reduced on average by 25% and the average total nitrogen (mostly nitrate) values by 32%. The nitrogen reduction was, as expected, highest during the summer and varied between 31 and 57% during the period May–October.

In 1995, the phytoplankton biomass and chlorophyll *a* levels were considerably lower than in 1994, and the species composition showed less eutrophic characteristics than in 1994. The average summer Secchi disc transparency was 1.5 m in 1995 compared to 0.9 m in 1994.

Before restoration, the Secchi disc transparency and the concentrations of chlorophyll *a*, total-phosphorus and total-iron used to depend on the temperature in the summer (Figure 7). However, in 1994 and 1995, the values deviated from the normal pattern. The internal loading decreased dramatically in 1994 and 1995. In 1995, the values of phosphorus and iron in the lake were the same as the average value of the inflow and the internal phosphorus loading had practically ceased (Figure 8). These results imply that, in certain lakes, it is possible to reduce an internal phosphorus loading without dredging or adding chemicals to the sediments.

When the food web manipulation started in 1992, only about 1% of the area of the lake was covered with submerged macrophytes. In 1995, 20% of the area was colonised by submerged macrophytes such as *Myriophyllum spicatum*, *Elodea canadensis* and *Potamogeton* spp.

As a consequence of the increased transparency and recolonisation of submerged macrophytes, the

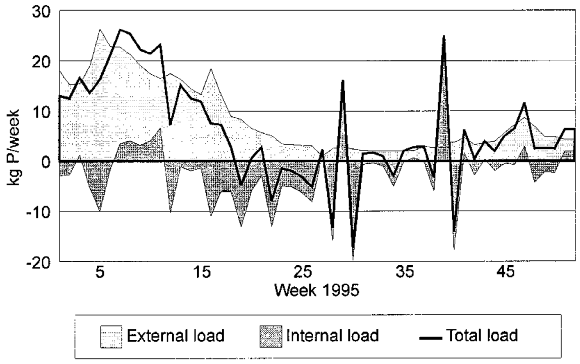

Figure 8. The internal, external and total phosphorus load on Lake Finjasjön, 1995.

birds that had disappeared when the transparency became very low in the middle of the seventies, returned to Lake Finjasjön in 1994 and 1995 (Figure 3).

The cost of the fish reduction was approximately 5 million SEK (£0.5 million), and of the constructed wetland, 6 million SEK (£0.6 million). This is equivalent to £100 000 km^{-2}.

The fact that a single municipality has been able to raise 70 million Swedish crowns including the dredging costs, (£7 million) in order to restore a lake, mainly for recreation purposes, is remarkable. Two factors were crucial in this achievement. The first was the fact that the town of Hässleholm did not have any alterative lake for recreation and not even an outdoor swimming pool.

The second, probably even more important, was that the lake and almost all the catchment are situated in a single municipality. In Sweden, restoration of water is normally financed by the municipalities according to the polluter pays principle. The municipality of Hässleholm polluted Lake Finjasjön, and consequently, the municipality – not the state – had to pay for the restoration.

If several municipalites have to share the costs for a restoration, intrinsic difficulties exist; how to split the costs between the different municipalities? Whether according to the number of inhabitants, according to the area of the lake belonging to each municipality, or according to how much each municipality contributed to the pollution of the lake, could be the source of long and complex argument.

The future water quality, plankton and fish studies in Lake Finjasjön will clarify the question of whether the present situation with clear water, a diverse phytoplankton community and almost no internal phosphorus loading will remain stable or not.

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