Four Decades of Research on the Swedish Large Lakes Mälaren, Hjälmaren, Vättern and Vänern: The Significance of Monitoring and Remedial Measures for a Sustainable Society

Author: Willén, Eva

Source: AMBIO: A Journal of the Human Environment, 30(8) : 458-466

Published By: Royal Swedish Academy of Sciences

URL: https://doi.org/10.1579/0044-7447-30.8.458

Eva Willén

Four Decades of Research on the Swedish Large Lakes Mälaren, Hjälmaren, Vättern and Vänern: The Significance of Monitoring and Remedial Measures for a Sustainable Society

The large lakes of Sweden, Mälaren, Hjälmaren, Vättern and Vänern, have been subjected to water-quality monitoring for almost four decades. Physicochemical variables, plankton and benthic invertebrates have been regularly assessed. Hydrological and sediment conditions, macrophytes, fish, primary production, bacteria and attached algae have been periodically investigated. The human impact, including industrial activities, was reflected in excessive amounts of organic matter, nutrients, metals and persistent organic compounds. From the late 1960s all municipal sewage works in the catchments of the lakes were upgraded to the highest technical standard, including chemical precipitation of phosphorus, and phosphorus discharge from the sewage works was thereby reduced by 90–95%. In addition, industries were obliged to restrict discharge of harmful substances. The reactions of the lakes to the remedial measures are discussed as well as the value of various indicators. The studies were instrumental in designing a national lake monitoring program. Additionally, results from large lake monitoring have contributed to the establishment of national water-quality criteria including, physical, chemical, and biological indicators.

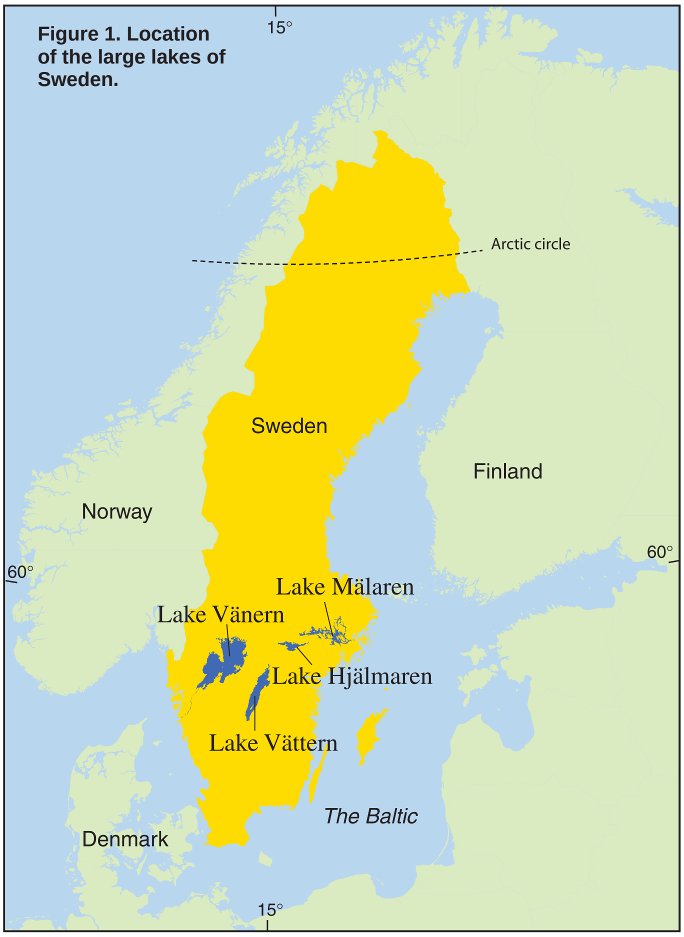


Figure 1. Location of the large lakes of Sweden.

INTRODUCTION

Large lakes are not only affected by their surroundings, they also exert a vital influence on the neighboring land by providing a reason for settling in the area and for bringing prosperity to the people living in the vicinity. Apart from being natural assets, often with spectacular beauty, they constitute important economical resources and contribute to the food supply over extended areas. Large lakes thus have a multiplicity of uses. In addition to serving many industrial ends they are a freshwater resource, and are used for irrigation, transportation, fishing, wastewater reception, recreation and tourism. Large lakes generally have a highly varied flora and fauna and a plentiful diversity of habitats, which lend further charm to outdoor life on the lakes as well as at the lakesides.

The Swedish large lakes Vänern, Vättern, Mälaren, and Hjälmaren cover a wide range of ecoregional, morphological and water quality gradients (Fig. 1). Together they comprise 22% of the total lake area of Sweden. They are all glacially formed or transformed, and appeared during the ice retreat after the last glaciation. As the ice receded, lowland areas were inundated by meltwater and water from the eastern and western coasts of the landmass, areas which now are known as the Baltic Sea and the North Sea. The water surface in central Sweden was then (ca 10 000 years ago) 150 meters (m) above the present level. The salinity alternated between fresh, brackish and salty, due to sea- and land-level changes. Just before the large lakes were isolated as freshwater basins they were all flushed by brackish water.

Because of the heavy load of ice the bedrock was pushed downwards, but began to rise successively as the ice retreated, first rapidly then more slowly. The large lakes were isolated from

Table 1. Marine glacial relicts in Lakes Vänern, Vättern, Mälaren, and Hjälmaren. Data: (5–9, unpubl. data from Institute of Freshwater Research, Drottningholm and Internet: www.ma.slu.se).

	Lake Vänern	Lake Vättern	Lake Mälaren	Lake Hjälmaren
FISH				
Coregonus albula L. (vendace)	X	X	X	
Coregaonus lavaretus L. (common whitefish)	X	X	X	
Coregonus nilssoni Valenciennes (lacustrine fluvial whitefish)	X			X
Coregonus peled Gmelin (peled)	X			
Coregonus pidshian Gmelin (humpback whitefish)	X			
Coregonus widegreni Malmgren (lacustrine fluvial whitefish)	X	X		
Osmerus eperlanus L. (smelt)	X	X	X	X
Salvelinus alpinus L. sp. complex (arctic char)		X		
Triglopsis quadricornis L. (fourhorn sculpin)	X	X	X	
CRUSTACEANS				
Bythotrephes cederstroemi Schoedler	X			
Eurytemora lacustris Poppe	X	X	X	
Limnocalanus macrurus Sars	X	X	X	
Monoporeia affinis Lindström	X	X	X	
Mysis relicta Lovén	X	X	X	X
Pallasea quadripinosa Sars	X	X	X	X
Relictacanthus lacustris Sars	X	X	X	
Saduria entomon L.	X	X		

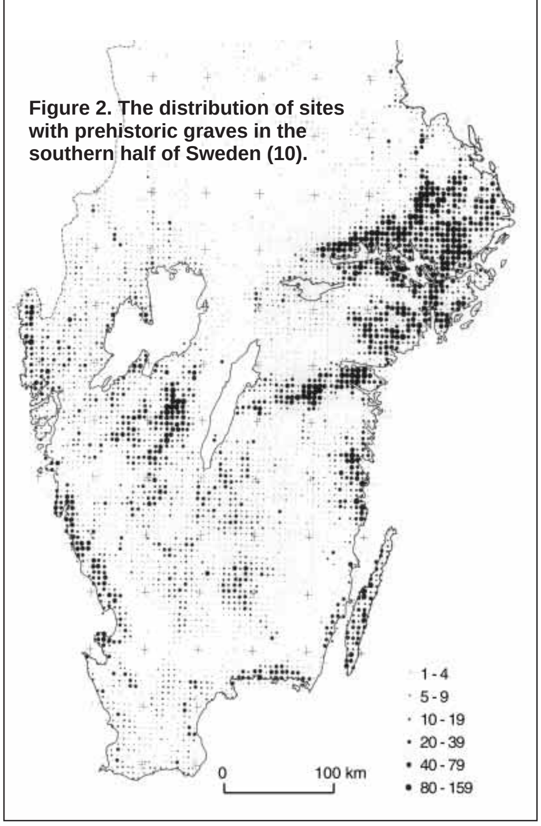


Figure 2. The distribution of sites with prehistoric graves in the southern half of Sweden (10).

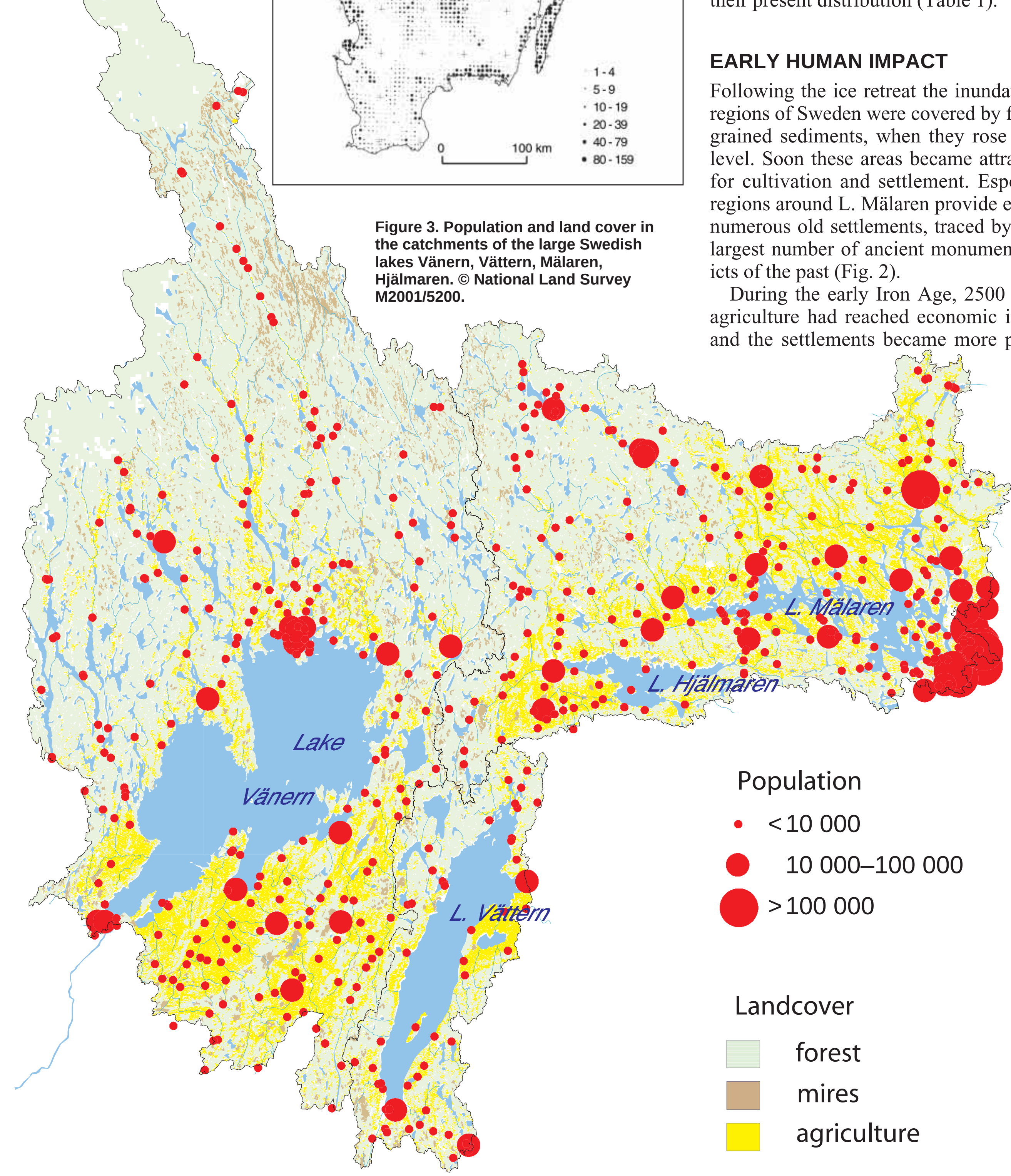


Figure 3. Population and land cover in the catchments of the large Swedish lakes Vänern, Vättern, Mälaren, Hjälmaren. © National Land Survey M2001/5200.

the surrounding seas one by one: Lakes Vänern and Vättern 9000 yrs ago (1–4). The foundation of Sweden's capital Stockholm at the outlet of Lake Mälaren was closely connected to the isolation of this lake.

Inflow of brackish water could, however, occur during events of high water level in the Baltic even in the 20th century. In order to totally avoid this inflow of brackish water, a dam was constructed in the 1940s in Stockholm, and a further improvement to hinder saltwater intrusion was made during the late 1960s.

The glacial origin of the large lakes is evident in a number of relicts, i.e. organisms that still exist in the lakes since the preisolation era, although the original habitats may be far from their present distribution (Table 1).

EARLY HUMAN IMPACT

Following the ice retreat the inundated central regions of Sweden were covered by fertile fine-grained sediments, when they rose above sea level. Soon these areas became attractive land for cultivation and settlement. Especially the regions around L. Mälaren provide evidence of numerous old settlements, traced by Sweden's largest number of ancient monuments and relicts of the past (Fig. 2).

During the early Iron Age, 2500 years ago, agriculture had reached economic importance and the settlements became more permanent.

From this time the cultivation of land gained a decisive influence on the landscape. The northeastern regions of L. Mälaren became the center of a kingdom with an expansive population development. These parts are still the most densely populated areas of Sweden. The wealth of the land was also supported by industrial development in the northwestern and western catchment of that lake, where metalwork, especially with iron, has a tradition dating back to the 13th century. This mining and smelting district—Bergslagen—had its grand period in the 17th century. The mining activities successively decreased and terminated definitely in the 1980s, whereas metal production continues even today.

Table 2. Morphometric data of the Swedish large lakes.

	Lake Vänern	Lake Vättern	Lake Mälaren	Lake Hjälmaren
Maximum lake length (km)	141	135	110	63
Area (km^2)	5650	1890	1120	480
Maximum depth (m)	106	120	66	20
Mean depth (m)	27	40	12.8	6.2
Water volume (km^3)	153	77.6	14.4	3
Length of shoreline including islands (km)	2000	460	960	290
Number of islands > 100 m^2	9585	813	1645	1062
Height above sea level (m)	44.5	8.5	0.7	21.9
Drainage area (km^2)	46830	6359	222603	4053
Mean water residence time (years)	9	58	3	3.5
Regulation amplitude (m) according to the water rights	1.7	0.3	0.95	0.5

Data from (14, 54, 55).

The sparser populations around the northern and western shores of Lake Vänern were also to a large extent engaged in iron smelting and forging, whereas the numerous eastern and southern shore inhabitants were farmers, like those around Lake Vättern. At the end of the 19th century, however, the expansive Swedish pulp- and paper industry was established upstream and along the shores of Lake Vänern (Fig. 3).

Early settlement, agriculture and industrial activity, subjected especially Mälaren and Hjälmaren to successive water-quality deterioration, because these lakes are relatively shallow in comparison with the other two (Table 2). Another factor which contributes to change and which often follows in the wake of eutrophication, is the continuing land rise, which still is 2–3 mm yr^{-1} in the area of Lakes Vänern and Vättern, and 4–5 mm yr^{-1} in the Mälaren-Hjälmaren region (1). This land rise has, before regulation of water levels, been responsible for an increase in the littoral zones in sites with gently sloping lake margins which are common in Mälaren and Hjälmaren, and in the northern archipelago areas of L. Vänern. These slopes were successively overgrown by vegetation which contributed to an extension of the reed zones.

All lakes have been subjected to anthropogenically induced regulation of water levels. This regulation has reduced water-level amplitudes. With time this promotes expansion of vegetation. The regulation of water levels was intended to prevent flooding and to gain fertile land, except in the largest lakes Vänern and Vättern where the main purpose was power generation. The surface in all the lakes except Vänern now fluctuates about 40 cm although they can fluctuate more according to the water rights granted by the authorities. In L. Vänern the amplitude is about 80 cm. The regulation of L. Hjälmaren is especially remarkable, because it was the most extensive project of its kind attempted in Sweden at the end of the 19th century. The water level was lowered 1.9 m, a measure which caused a 25% decrease in the water volume (Fig. 4). This reduced the expected life-time of the lake by about 1000 yrs based on calculations of an annual sedimentation rate of 2 mm (11).

SCIENTIFIC FOCUS ON A NATURAL RESOURCE

The role of science in restraining an accelerating exhaustion of Swedish natural resources was recommended in the 1950s by some members of the Swedish Natural Science Research Council (SNSRC). After some years of administrative negotiations a basic organization was formed within the SNSRC, which was concerned with biological-ecological relations with Man at the center. Among the most important questions to be dealt with were those connected to water pollution. Wilhelm Rodhe, the late professor of limnology at Uppsala University, advanced the need for a survey of L. Mälaren's water quality and ecology. In 1964, a large-scale investigation of the lake and its catchment commenced and "Mälarundersökningen"—the Lake Mälaren Research Project—was founded. L. Mälaren, which is a very complicated system of waters, differentiated by numerous bays of various shapes and depth, was the first object chosen, because it was considered to suffer from the heaviest nutrient load of the four large lakes, caused by an increasing population pressure and insufficient treatment of municipal and industrial waste water. Signs of eutrophication didn't attract public interest until the 1950s, and they were the same in all affected lakes: increased growth of filamentous algae and emergent vegetation in the littoral zone, decreasing number of submerged aquatic plants, prolonged blooms of nuisance algae (mainly cyanobacteria), decreasing transparency, increased frequency of diatom-clogged fishing nets and decreasing catches of fish as well as oxygen depletion in the bottom water. The project had 2 main sections, a physical-chemical section headed by professor Thorsten Ahl, a limnologist with special competence in water chemistry, and a biological section headed by professor Torbjörn Willén, a botanist with phycology as his specialty. Students were enrolled from various disciplines: botany, zoology, limnology, microbiology, hydrology, and sedimentology. In the beginning, the sampling covered some 100 sites all over the lake with analyses of water chemistry, phytoplankton, primary production, chlorophyll-*a*, bacteriology and zooplankton. These variables were believed to respond rapidly to water quality changes, and there was Swedish expertise for each of these variables. After some years, investigations were expanded to include hydrology, aquatic macrophytes, benthic invertebrates, fishery biology, sedimentology and substrate-associated (attached) algae. The core of the extensive initial sampling net of the 100 sites, distributed fairly evenly over the lake, was some 20 sites which had been established during earlier investigations in the 1930s. In addition to the lake sites, all the main inflows were monitored, thus there was coverage of the chemical impact from the most important sub-watersheds of the lake. Measurements of water discharge were performed by the Swedish Meteorological and Hydrological Institute (SMHI). The project had the foresight to realize that a lake should not be considered in isolation but as a part of a catchment, something which was soon recognized internationally (12).

Some years after the Lake Mälaren Research Project was initiated, investigations were set up in Hjälmaren and Vättern in 1966–1967. Regular samplings in L. Vänern started in 1972. In Mälaren and Hjälmaren, basic eutrophication problems deriving from municipal sewage outlets and agriculture were addressed. In Lake Vättern, the eutrophication problems were not so pronounced, but still needed documentation and remedial measures. The low productivity would also make this lake vulnerable to toxic emissions, and the high share of lake surface of the watershed (30%) made the lake particularly sensitive to airborne pollutants. In L. Vänern, on the other hand, the predominant pollution sources were lake-shore and upstream pulp and paper in-

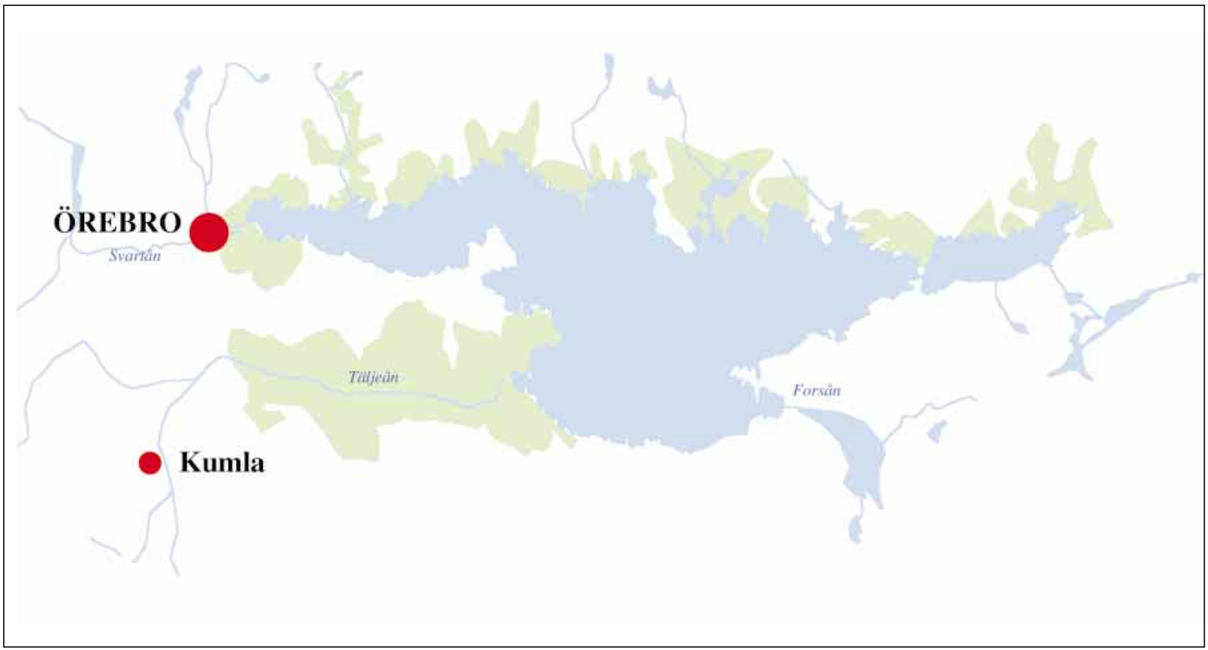


Figure 4. Drained areas after the regulation of Lake Hjälmaren in the 1880s: 190 km² of land was gained.

dustries as well as related industries such as cellulose-acetate and chloralkali factories with emissions of mercury. In L. Vänern, only the embayments suffered from more evident eutrophication.

The studies of L. Vänern were also directed towards a general knowledge of the status of that lake, since it is the largest in Sweden, and ranked as number 29, by surface area, among the lakes of the world (13). Another aim was to build models and create scenarios for alternative future water use (14).

In all the lakes, earlier investigations of varying intensity had been performed, though often restricted in areal distribution, and number of measured variables. Examples of chemical and physical variables that had been analyzed were Secchi disc transparency, water color, conductivity, pH, ionic composition and organic matter. Frequently used biological indicators were phytoplankton, zooplankton, bottom fauna and fish. The early measurements were often an effort of single investigators without much technical assistance – admirable achievements *per se* resulting in data for future comparisons, although with methodological divergencies (i.e. 7, 15–21) and for L. Vänern, much unpublished material of both local and synoptic character.

OBJECTIVES, PERFORMANCE AND PRESENTATIONS OF RESULTS

With the start of the comprehensive and long-term investigations of the Swedish large lakes generic objectives of the following kind were assessed (22):

- to contribute to increased knowledge of importance to theoretical research and its practical application.
- to identify "normal values".
- to create uniform standards for studies of recipient waters.
- to promote cooperation between different institutes, university departments and authorities for the benefit of water research.
- to make results available nationally and internationally.
- to contribute to the education of experts within aquatic science.

Although the ambition was to keep at least a monthly sampling frequency during the ice-free season (April/May–October) for pelagic variables, economical realities reduced the frequency to a minimum of 4–5 samplings after some years. However, this sampling schedule now extends to cover all months of the growth season. Since the late 1960s, sampling has been financed by the Swedish EPA, and it has recently been a part of the national monitoring program performed by the Department of Environmental Assessment of the Swedish University of Agricultural Sciences, which also is responsible for analyses and evaluation of results.

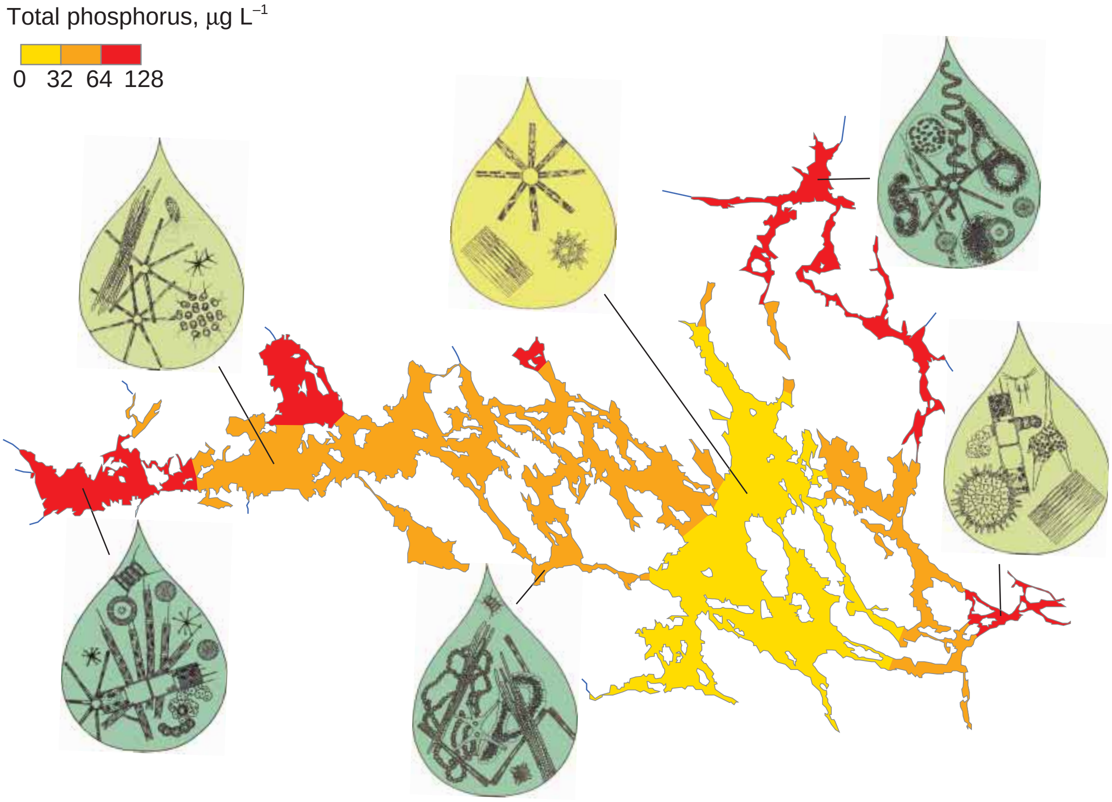
Benthic invertebrates were originally sampled 1–2 times per year, which still is the case. Attached algae and macrophytes were followed in surveys during late summer mainly during some years. Samplings were initially performed from various hired boats and by hydroplanes until a specially designed research vessel "Ancylus" was constructed with a more modern laboratory and time-saving equipment. This vessel was mainly intended for the investigations in Vättern and Vänern. Nowadays, the sampling takes place from a number of boats suitable for the different lakes.

From the beginning, data from the regular program were organized in a computerized database—a pioneering work for a monitoring project at that time. This database now contains analyses from 54 000 different samples from the large lakes and 23 000 from their inlets/outlets where 30% are biological. A large part of these data, as well as other results from monitoring programs initiated later in lakes and watercourses all over the country, are now included in an extensive database available on the Internet (http://www.ma.slu.se). These data are presented from separate sampling occasions, as well as from chosen periods and sites to facilitate simple statistical calculations.

When the first results of the water-quality investigations from Mälaren and Hjälmaren were published in the Swedish media, they stirred up interest of unexpected intensity. The situation in basins or embayments adjacent to population centers was considered to be much worse than expected. Heavy loads of phosphorus and nitrogen were shown to have caused large changes in biological productivity and general water quality. In the press, headlines like "Build fences around the lakes", "Cattle must be protected from the water of the lakes", "Lake Mälaren is a sewer", etc. were common. Pedagogical and comprehensible pictures and diagrams were produced by the leaders of the project, and presented to the public, which until then had very little experience of interpreting the causes and effects of eutrophication (Figs 5, 6).

The significance of the Lake Mälaren Project was manifested

Figure 5. Illustration of the trophic state of Lake Mälaren published in a Swedish magazine 1967 under the heading "The Stinking Queen". The colors in the map represent various concentrations of total phosphorus and the drops illustrate the biomass and character of plankton organisms where a spectrum from dark green to yellow depicts high to lower concentrations.



internationally for the first time at the *Uppsala Symposium on the Management of Large Lakes and Impoundments* organized by the OECD in conjunction with the Swedish Royal Commission on Natural Resources in 1968 (23). The aim then was to examine the development of scientific research required for the management of large lakes. Case studies were presented and discussed among scientists and national administrators responsible for the management of water-resource systems. The importance of formulating a plan of management for recovery of eutrophied large lake basins was stated as well as a cooperation plan for scientists and managers. Further presentations of results from investigations of the Swedish lakes were made at international congresses (24–27). Other more profound treatments were presented in well-reputed international journals (e.g. 28, 29).

The success in making results available rapidly both internationally and nationally, and in an understandable way, also elicited a political response within the country. The alarming deterioration of L. Mälaren, demonstrated to be caused by input of nutrients from the watershed through the calculation of a nutrient budget for the lake, induced the Swedish Government to refuse the establishment of a new pulp industry in the western basin area of the lake. The decision was entirely due to the predicted effects on the water quality, even though such an industry would have benefited many landowners in a region so rich in forests. Such an extraordinary decision led professor Wilhelm Rodhe in his presidential address at the *World Congress of the International Association of Theoretical and Applied Limnology* in 1968 to make the following statement: "This was the first time in Sweden that Nature took priority over business, and in the long run it will certainly be to the benefit of Man himself to make such decisions, when they are necessary" (30).

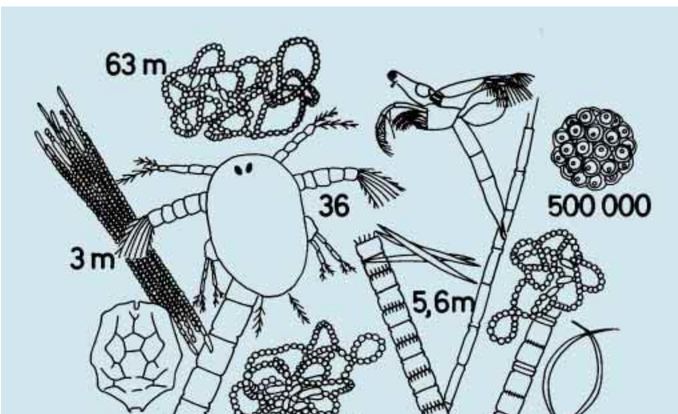


Figure 6. Number of planktonic organisms (16 million 100 ml^{-1}) possible to ingest with an involuntary gulp of water from Lake Hjälmaren close to the city of Örebro in 1969. (Published in several Swedish journals from an idea of T. Willén).

REMEDIAL MEASURES

In the late 1950s and early 1960s, the county boards had formed management associations for each lake with the purpose of coordinating measures to solve problems concerning drinking water maintenance, fishery interests, and other water-related matters. These organizations promoted the introduction of efficient water conservation measures based on the status of the lakes as elucidated by environmental monitoring. At a very important meeting in 1969, the Director-General of the recently established Environmental Protection Agency together with local politicians, staff of the county boards, and scientists, reached an agreement on the necessity of upgrading all municipal sewage works in the drainage area of L. Mälaren to the highest technically possible degree of treatment. Most sewage handling at that time, at least in urban areas and other population centers, included only mechanical and biological treatment. Inclusion of a third treatment stage, which involved a phosphorus precipitation step, caused a paradigm shift in Swedish water-quality work. Phosphorus was recognized as the most important cause of eutrophication and the value of reducing its level in eutrophied lakes was publicly approved. The chemical precipitation facilities were financed by governmental support of at least 50% of the construction costs. The Director-General stated that there is no reason to claim that the costs are too large to achieve this treatment. On the contrary, the costs would be low in relation to the effect on water quality. In addition to the decision concerning public sewage-treatment plants, industries were forced to restrict their discharge of harmful substances by negotiations and legal means. After 5 yrs the whole project to improve effluent treatment had been completed (Fig. 7).

Such efforts were also undertaken in the drainage areas of the other three large lakes as well as in many other parts of the country, but at a slower rate. During the same period a major part of sewage water from the western suburbs of Stockholm was diverted through tunnels from L. Mälaren, after full treatment, to the Baltic. This measure was of considerable importance for the water quality of L. Mälaren close to the city, where the water conditions had long been a source of much complaint.

In the other lakes, remedial measures directed towards their special problems were undertaken. The organic loading from paper and pulp industries on Lake Vänern had caused a significant coloring of the water since the beginning of the 20th century as evidenced by a fourfold increase in organic matter. In the early 1960s the peak in this kind of pollution was reached, after which discharge of organic substances was reduced by 80% due to the closing of several unprofitable factories and a more efficient circulation of water within the existing ones, as well as improved water-treatment processes. The initial period of recovery in the lake served as a platform for modelling the continued process including the recovery and final equilibrium with present day input of organic substances (Fig. 8).

Among potentially toxic pollutants, studies of largely airborne pesticides like DDT and PCB were also made. DDT, which received substantial attention after the publication of Rachel Carson's book "Silent Spring", was analyzed in the plankton and sediments of L. Mälaren by the Swedish Museum of Natural History. Fortunately, very low concentrations were recorded. In L. Vättern, on the other hand, concentrations in salmonid fish were close to the recommended limit for human food consumption in the early 1960s. Prohibition against the use of these pesticides caused rapid reductions, especially for DDT, while concentrations of PCB in fish decreased more slowly (Fig. 9) (31).

In Lake Vättern, metal contamination was also of concern, and potentially toxic discharges from a zinc mine at the northern end of the lake were strongly reduced.

A probably more severe threat was the emissions of mercury (Hg) to L. Vänern from a chloralkali plant utilizing mercury for electrolysis. Lake sediments over huge areas were found to be Hg-contaminated and it turned out that the concentrations of Hg in pike in L. Vänern exceeded the recommended value for human consumption (1mg Hg kg^{-1} muscle) at that time (32).

The industry later took steps to change its internal processes in order to drastically decrease or prevent Hg-discharges. As mercury leaches from the sediment long after input is curbed, it takes many years before concentrations in the biota decrease.

The mercury debate which flourished during the 1970s caused an economical backlash for many fishermen in all the large lakes because people avoided inland-water fishes in general, even from waters where the problem didn't exist.

Discharges of chlorinated organic compounds from the bleaching process used by paper mills was another topic of concern and led to special studies both in Vänern and Vättern (33). At a later stage new legislation led to a change of bleaching methods. Several toxic substances including dioxins, mercury and lead are still under observation in these lakes. These sources of input nowadays are largely airborne, however, and transboundary transport makes them unacessible by Swedish legislation. Remedial measures in such cases are to be achieved by international negotiations.

Figure 7. Wastewater treatment in Swedish urban areas. The early inclusion of a phosphorus precipitation step, in addition to biological treatment in the Lake Mälaren catchment is indicated (grey) in relation to the rest of the country.

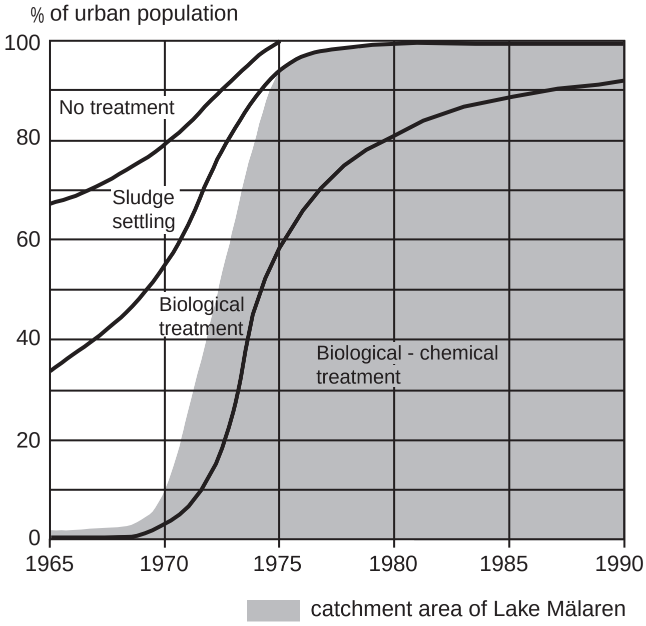
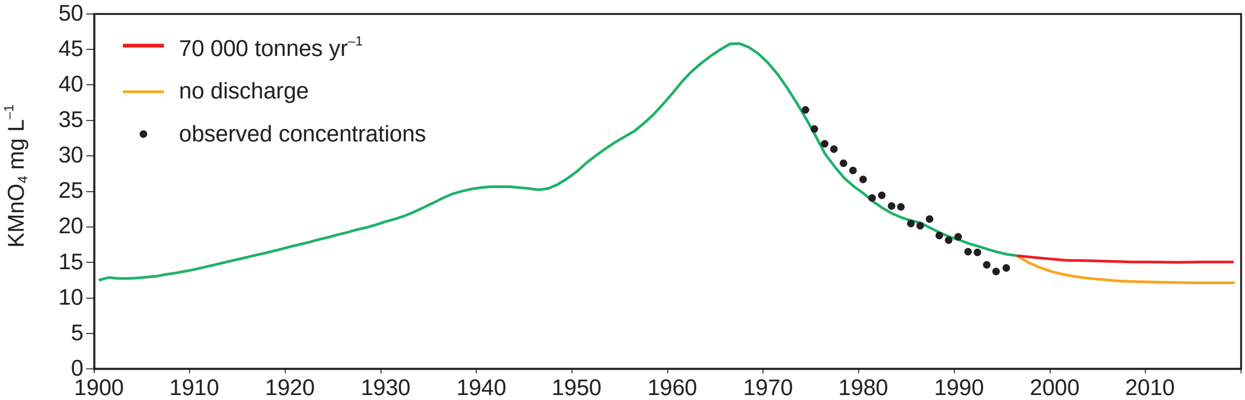


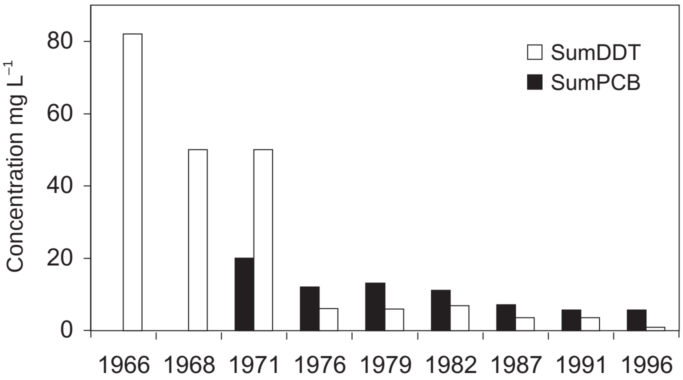
Figure 8. Modelled concentrations of organic matter ($KMnO_4$-consuming substances) in Lake Vänern 1900–1994. From 1994 onwards the line gives prognostic values with a 65% decrease of the industrial discharge of organic matter reflecting the present situation. The alternative with no industrial discharge is also indicated. Measured concentrations since 1973 are marked with a dot.



ENVIRONMENTAL TARGETS

The desired outcome of the remedial measures taken up to 1975, to halt ongoing deterioration of the water quality in the large Swedish lakes was not formulated in quantitative terms regarding the physicochemical parameters, and still more vaguely con-

Figure 9. Decreasing concentrations of the pesticides DDT and PCB in muscle tissue of Arctic char in Lake Vättern 1966–1996.



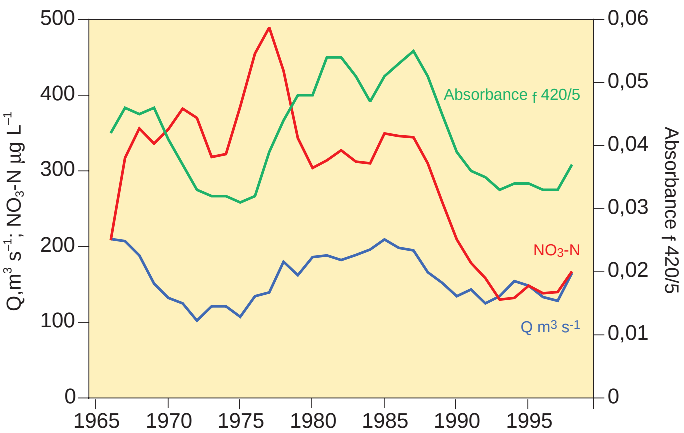
cerning the biological response. Not until 1990 were quantitative goals officially suggested for some environmental variables in the lakes, mostly related to the nutrient state and the content of metals (34). The desired biological state was expressed as empirical relations between environmental variables and the expected reaction of the biota. The water-quality targets in the large lakes were, in general, based on the available published guidelines for variables assessing nutrient state, oxygen situation, light climate, acidity state and metal concentrations valid for Swedish lakes and watercourses (35, 36). These targets were formulated in relation to estimates of natural background values defined as a state that would have prevailed in an undisturbed landscape. The primary quantitative objective with regard to eutrophication was set for phosphorus as the main regulator of planktonic algal production in fresh waters. A state which exceeds the natural background value by, at most, a factor 2 was set as a goal for remediation efforts. During the elaboration of the guidelines it was suggested, where possible, to keep total phosphorus concentrations in mesotrophic-eutrophic lakes in general to ≤ 25 $\mu g\ L^{-1}$, in order to avoid long-lasting water blooms. The target concentrations for the large lakes were intended to be reached in several steps up to the year 2020. Further refinements of the goals, also including other water-quality degrading substances, have successively been worked out by the county boards and water-management associations. Furthermore, the Swedish Parliament decided in the mid-1980s to cut the anthropogenic nitrogen discharge to coastal areas by 50%, an effort which to a large extent involved the large lakes and their watersheds, which either drain directly to the sea or *via* a river (37). This goal was a response to an international agreement within the framework of the Helsinki Commission and the North Sea Commission (38). With nitrogen reduction measures, the effect of eutrophication along parts of the Swedish coast and sea areas is expected to be reduced, where nitrogen is the main growth limiting nutrient.

Recently, more comprehensive Swedish environmental quality criteria were published where assessments of biological conditions were included, in addition to physical and chemical indicators (39). The biological indicators treated are phytoplankton, periphytic diatoms, aquatic plants, benthic fauna and fish. For variables assessing nutrient state and phytoplankton, experience from the large lakes constitutes a substantial part of the knowledge on which these criteria are based. Assessment of current conditions consists on the one hand of a classification scale based on knowledge about levels in Sweden in relation to expected effects, and on the other hand on the extent to which measured values deviate from an established reference value. By using these new assessment criteria, water quality can be expressed in quantitative terms and in a uniform way both concerning the environmental variables, and the biological response. If a relevant reference value (baseline value) is calculated either by comparison with suitable reference objects or calculated statistically, an acceptable deviation can be defined and used as an easily understood target also for non-experts. The targets concerning phosphorus concentrations in Vänern and Vättern have already been reached with total phosphorus concentrations in central areas well below 10 $\mu g\ L^{-1}$, while the situation in the most eutrophied basins of Mälaren and Hjälmaren has further to go. Here an additional period of 20 yrs, as suggested in 1990, might be a more realistic time-span, but there are uncertainties. As deviation from a reference value is used as a target for restoration the establishment of such values is a delicate commission. In lowland lakes, with catchments exposed to human influence since the early Iron Age, this is not an easy task. A palaeolimnological project analyzing sediment cores from various parts of L. Mälaren is underway, but not yet evaluated. An acceptable deviation from a once existing pristine state, which is no longer approached, has then to be decided. A realistic reference value might be to adopt a situation existing before the great industrial expansion occurred and well before the rise of the living standard for the majority of people, which occurred at the expense of the water quality.

POLLUTION RECOVERY AND ABATEMENT SUCCESS

An important question is whether the remedial measures to improve the water quality of the large Swedish lakes have been a success. A reduction of pollutants was necessary, because nothing else is acceptable from a conservation point of view, in lakes of the sizes discussed here. In the case of lakes such as Vänern and Vättern, their rehabilitation may be considered more than a national responsibility. The conclusion is that the measures have been successful, but to various degrees. L. Vänern has reached the phosphorus goal, and water transparency has returned to a value similar to that at the beginning of the 20th century, which means an increase of the Secchi depth from 2.5 to > 5 m (40). L. Vättern has returned to an ultraoligotrophic state. Remaining nutrient problems in both lakes are connected to raised nitrogen concentrations, mainly by nitrate. These lakes have a substantial nitrogen excess in relation to phosphorus with ratios of 80–100 in the pelagial water. The reasons for the raised nitrogen concentration are an increased leakage of nitrogen compounds from agricultural areas, a lower uptake of nitrogen by algae because of decreased phosphorus availability, and decreased denitrification due to lower primary production (40). Additionally, the atmospheric deposition of nitrogen compounds increased steadily in central parts of the country during the post-

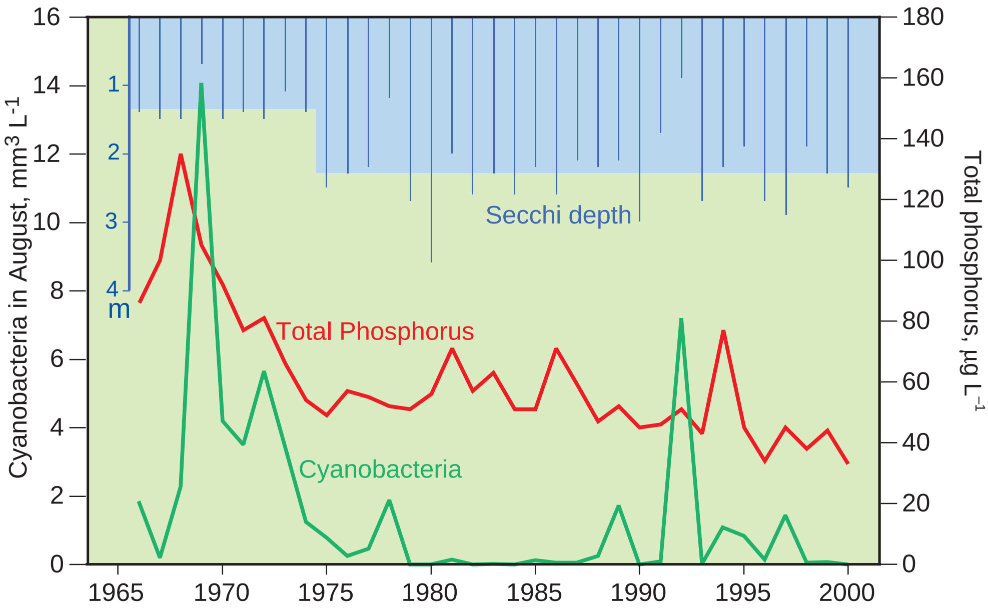
Figure 10. The effluent of organic material in Lake Mälaren closely follows the water discharge, $m^3\ sec^{-1}$. Among nutrients, especially nitrogen covaries with water discharge. These oscillations in water quality may also be reflected in the biota.



war years, and was not curbed until the 1990s.

In Mälaren and Hjälmaren, the phosphorus concentrations have been halved in the most eutrophied basins, and reduced to a somewhat lesser extent in mesotrophic basins. The nitrogen load is substantially reduced in some basins, but in those with agriculture-dominated catchments the concentrations rose into the 1990s. The heavy, long-lasting water blooms extending over the summer-season have been substantially reduced in time and mass since the mid-1970s. Shallow and unstratified basins and smaller bays close to major towns still have disturbing waterblooms, but these are restricted to a late summer period (41, 42). To substantially decrease the phosphorus input, which supports the blooms in shallow areas, the sediment phosphorus pool has to be reduced, and that will take a considerable amount of time. Improvements in such a direction have been measured in the surface sediments of some of the basins of Lake Hjälmaren, where a halving of the concentration from 2.3 to 1 mg P g ds^{-1} occurred over 11 years (41).

Figure 11. Effects of decreasing phosphorus load on P-concentration levels, water transparency (Secchi depth), and biomass of summer-cyanobacteria in one of the most deteriorated parts of Lake Mälaren, the Ekoln Basin.



What about the tempo of the recovery? Although there is no reason to expect a response reaction to a disturbance created by decades of exposure within a short time period, the water quality in some stratified basins, especially in Lake Mälaren, was perceived to have been ameliorated already after a couple of years, i.e. much faster than expected. The phosphorus precipitation which reduced the P-load from sewage works by 90–95%, coincided with a dry period with an extremely low water flow to the lakes during several years. This weather-caused situation resulted in a decreased discharge from the catchment of water loaded with organic material and nutrients (Fig. 10). Together with the improvement in waste treatment this more or less instantly reduced the turbidity of large basins in the lake, increasing the Secchi depth.

This unexpectedly quick response made the whole costly project, which ultimately was defrayed by revenues, a clear success in the mind of the public. In the most nutrient-loaded basins of both L. Mälaren and L. Hjälmaren phytoplankton biomass reductions kept pace with the reduced phosphorus loading. The first biological indicators of an ongoing change were mainly decreases of cyanobacteria and spring blooming diatoms (41, 43, 44) (Fig. 11).

With a time lag of several more years, the zooplankton biomass declined, mainly due to changes in the community composition with a decrease among rotifers and cladocerans. The macrozoobenthos in profundal areas did not react significantly, since the immigration of new taxa has to be preceded by changes in the texture of the still organic-rich sediments, a process which needs a rather long period of time. In lakes where sediments were contaminated by mercury or other metals, e.g. in the northern bays of L. Vänern, the bottom fauna have been very responsive to improvements and turned out to be good indicators of decreased toxic loadings. Here the amphipod *Monoporeia affinis* has increased substantially from 1995 onwards as a result of decreased mercury discharge initiated in the 1980s. The time-lag for a response to mercury input reductions seems to be around 10 yrs (45).

Changes in the littoral vegetation were also noticed, as water turbidity decreased. The submerged aquatic vegetation, which had been very sparse in the formerly hypertrophic basins of L. Mälaren in the 1960s and 1970s, recovered during the 1980s and 1990s.

The time-lag for attaining a height and density of the vegetation that the public reacted to, was about 10 yrs after a fulfilled nutrient diversion. Experiences from other manipulated lakes show a successive increase in the expansion and shoot length of the submerged vegetation during more than 10 yrs. Water transparency and plant growth form are, however, crucial factors for the outcome of the growth (46).

In addition to the primary goal of combatting ongoing eutrophication in at least three of the four lakes, other measures have also been successfully accomplished. Such undertakings have included reductions of colored organic matter in L. Vänern and the abatement of discharge of metals and toxic substances to all lakes.

EXPERIENCES AND SPIN-OFFS

Experience gained during the studies of the large lakes has provided a framework for the design of the present national monitoring program initiated in the late 1980s by the SEPA.

Other spin-offs like identification of "normal values", and creation of uniform standards for assessment of recipient waters are elaborated and accounted for in assessment criteria for lakes and watercourses—an official tool for use in water-quality investigations (39). Experiences from the sampling and analysis of physical, chemical or biological water-quality indicators form the basis for a national manual for methods in connection with monitoring. This manual is readily used by investigators outside the proper national monitoring projects, which increases the comparability with results in a broader context. The comprehensive database from the lakes is available for further analysis and the development of models for integrated assessments. The large amounts of biological data are also suited for deeper examinations of current biodiversity issues. More special studies could also be designed to solve new problems identified by the monitored data. The value of uninterrupted long-term studies is important to establish, and many planners and persons responsible for environmental issues are becoming more and more aware of this, thanks in part to the usefulness of such data from the large lakes. Difficulties in separating true changes from weather-induced fluctuations need particularly long-term measurements with as few changes as possible in the sampling design. The comprehensive lake monitoring has also contributed to the education of a large number of trained scientists. When people have changed to other careers in society their insights in environmental issues have been useful (47). Even if the primary aim has never been to produce results for science but to provide a basis for management, there are many findings that have significant scientific value. Such examples are the role of sediments in the distribution of contaminants, factors affecting bottom dynamics and sedimentation, the potential coupling between diatoms and the development of some benthic invertebrates, weather oscillations and influences on nutrients and biota (e.g. 11, 48–50). Examples of important evaluations of monitoring data which have provided insights of a practical and political kind are related to the effects of eutrophication (51), the use of biological indicators (52, 53) and the abovementioned Environmental Quality Criteria (39).

In 1999, the Swedish Parliament established a number of objectives for achieving an ecologically sustainable environment within the next 20–25 yrs. These objectives are directed towards control of pollutants, prevention of the spreading of nonindigenous species, protection of recreational and scenic values, and support of the biota in viable populations. These more general goals are to be achieved through a number of quantifiable targets. Politically constituted goals are also reflected in new targets that have been set for the Swedish large lakes. In addition to ongoing programs, much more focus will be directed towards embayments and littoral areas where many environmental changes are first detected. The sediments and their role as traps or sources for contaminants as well as historical archives will also receive more attention. Interactions among biota such as oscillations of fish populations, among other indicators, is another subject for further evaluation as are comprehensive biodiversity studies.

References and Notes

1. Fredén, C. 1994. Mountain and soil. In: *Sveriges Nationalatlas*. Bokförlaget Bra Böcker, Höganäs. 307 pp. (In Swedish).
2. Norrman, J. 1964. Lake Vättern. Investigations on shore and bottom morphology. *Geogr. Annal. 1–2*, 1–238.
3. Robertsson, A-M. 1999. From sea to lake. The Lake Hjälmaren depression and its environmental development during 6000 years (10 000–4000 år B.P.). In: *Lake Hjälmaren. From Bergslag to Farmer's District. Yearbook of the County of Örebro and its Local History Alliances and the County-museum of Örebro*, Skoghäll, L. (ed.) pp. 22–26. (In Swedish).
4. Miller, U. 1982. Shore displacement and coastal dwelling in the Stockholm region during the past 5000 years. In: Aartolahti, T. and Eronen, M. (eds). Studies on the Baltic shorelines and sediments indicating relative sea-level changes. *Annal. Acad. Scient. Fenn. A III, 134*, 185–211.
5. Ekman, S. 1940. Die schwedische Verbreitung der glazialmarinen Relikte. *Verh. Internat. Verein. Limnol. 9*, 37–58.
6. Kottelat, M. 1997. European freshwater fishes. *Biologia 52, Suppl. 5*, 1–271.
7. Stålberg, N. 1939. Lake Vättern. Outlines of its natural history, especially its vegetation. *Acta Phytogeogr. Suec. XI*, 1–52.
8. Svärdson, G., Filipsson, O., Fürst, M., Hanson, M. and Nilsson, N.-A. 1988. The significance of glacial relicts for the fish fauna of Lake Vättern. *Inf. Sötvattenlab. Drottningholm 15*, 1–61. (In Swedish).
9. Svärdson , G. 1998. Postglacial dispersal and reticulate evolution of Nordic coregonids. *Nordic J. Freshw. Res. 74*, 3–32.
10. Hyenstrand, Å. 1981. Excavations at Helgö. VI. The Mälaren area. *Kungl. Vitterhets-, Historie- och Antikvitetsakad*. Stockholm, Sweden.
11. Håkanson, L. 1984. Aquatic contamination and ecological risk. An attempt to a conceptual framework. *Water Res. 18*, 1107–1118.
12. Vollenweider, R. A. 1968. *Scientific Fundamentals of the Eutrophication of Lakes and Flowing Waters, with Particular Reference to Nitrogen and Phosphorus as Factors in Eutrophication*. OECD Committee for Research Co-operation, Paris, 159 pp.
13. Tilzer, M. and Serruya, C. (eds). 1990. *Large Lakes. Ecological Structure and Function*. Springer Verlag. Berlin. 691 pp.
14. Lundström, S. 1978. *Lake Vänern, a Natural Resource*. Swedish Environmental Protection Agency, Liber distribution. 372 pp. (In Swedish).
15. Alm, G. 1917. Investigations of features and fishing in Lake Hjälmaren. Centraltryckeriet. Stockholm. (In Swedish). *Meddn. Kungl. Lantbruksstyr. 204.3*. Stockholm, 211 pp. (In Swedish).
16. Alm, G. 1927. Investigations of the bottomfauna in Lake Mälaren. *Meddn. Kungl. Lantbruksstyr. 263*. Stockholm. (In Swedish).
17. Board of Health of the City of Stockholm 1936–1940. Plankton-material from S. Björkfjärden, Ekeröfjärden at Norsborg and from Klubben east of Stockholm (unpublished records). *Stockholm Vatten*. (In Swedish).
18. Cleve-Euler, A. and Huss, H. 1912. Waters in lakes and water-courses in Stockholm and surroundings II. Plankton investigations. *Bihang II till Stockholms Stads Hälsovårdsnämnds Årsberättelse 1911*. Stockholm. (In Swedish).
19. De Toni, G.B. and Forti, A. 1900. Contributo alla conoscenza del plankton del lago Vetter. *Atti Reale Inst. Veneto di Scienze, Lettere ed Arti 59*, 537–829. (In Italian).
20. Ekman, S. 1915. Die Bodenfauna des Vättern, qualitativ und quantitativ untersucht. *Internat. Revue gesamt. Hydrobiol. 7*, 146–204, 275–425.
21. Junell, S. 1953. Das Phytoplankton des Sees Hjälmaren. *Svensk Bot. Tidskr. 41*, 47–93.
22. Ahl, T. and Willén, T. 1965. The Lake Mälaren research – an introduction. Svensk Naturvetenskap pp. 301–316. *Årsbok Statens Naturvetenskapliga Forskningsråd*. (In Swedish).
23. Milway, C.P. (ed.). 1970. *Eutrophication in Large Lakes and Impoundments*. Symposium in Uppsala, May 1968, Sweden. OECD. Paris. 560 pp.
24. Ahl, T. 1972. Plant nutrients in Swedish lake and river waters. *Verh. Internat. Verein. Limnol. 18*, 362–369.
25. Ahl, T. 1975. Effects of man-induced and natural loading of phosphorus and nitrogen on the large Swedish lakes. *Verh. Internat. Verein. Limnol. 19*, 1125–1132.
26. Willén, T. 1972. Biological aspects on the large lakes in South Sweden. *Verh. Internat. Verein. Limnol. 18*, 370–378.
27. Willén, T. 1975. Biological long-term investigations of Swedish lakes. *Verh. Internat. Verein. Limnol. 19*, 1117–1124.
28. Ahl, T. 1972. River discharges of total nitrogen, total phosphorus and organic matter into the Baltic Sea from Sweden. *Ambio Special Report 1*, 51–56.
29. Willén, T. 1972. The gradual destruction of Sweden's lakes. *Ambio 1*, 5–14.
30. Rodhe, W. 1969. Limnology, social welfare, and Lake Kinneret. *Verh. Internat. Verein. Limnol. 17*, 40–48.
31. Persson, G., Olsson, H., Wiederholm, T. and Willén, E. 1989. Lake Vättern, Sweden: a 20-year perspective. *Ambio 18*, 208–215.
32. Håkanson, L., Nilsson, Å. and Andersson, T. 1988. Mercury in fish in Swedish lakes. *Env. Pollut. 48*, 145–162.
33. Lindell, M.J., Bremle, G., Broberg, O. and Larsson, P. 2001. Monitoring of persistent organic pollutants (POPs): examples from Lake Vättern, Sweden. *Ambio 30*, 545–551.
34. SEPA 1990. Large lakes; environmental state and suggested measures. *Swedish Environmental Protection Agency, Report 3839*, 78 pp. (In Swedish).
35. SEPA 1991. Quality criteria for lakes and watercourses. *Swedish Environmental Protection Agency Informs*.
36. Gustafsson, J-E. 1992. Ambient water quality classification and water management in Sweden. *Europ. Water Pollut. Contr. 2*, 33–38.
37. A healthy environment 1990. *Proposition of the Swedish Government 1990/91:90*. Stockholm, 585 pp. (In Swedish).
38. Helcom 1988. Ministerial declaration regarding nutrient load reductions. Helsinki. (Internet: www.helcom.fi).
39. SEPA 2000. Environmental quality criteria. Lakes and watercourses. *Swedish Environmental Protection Agency, Report 5050*, 102 pp. (Internet: www.internat.environ.se/documents/legal/legal.htm).
40. Wallin, M. (ed.). 1996. Lake Vänern's environmental quality and development 1973–1994. *Swedish Environmental Protection Agency, Report* 4619. 64 pp. (In Swedish).
41. Persson, G. (ed.). 1996. Lake Hjälmaren during 29 years of study. *Swedish Environmental Protection Agency Report 4535*, 74 pp. (In Swedish).
42. Wallin, M. (ed.). 2000. Lake Mälaren. Environmental quality and development 1965–98. *Mälaren's Water Protection Association, Report*, 94 pp. (In Swedish).
43. Willén, E. 1987. Phytoplankton and reversed eutrophication in Lake Mälaren, Central Sweden, 1965–1983. *Br. Phycol. J. 22*, 193–208.
44. Willén, E. 1992. Long.term changes in the phytoplankton of large lakes in response to changes in nutrient loading. *Nord. J. Bot. 12*, 575–587.
45. Christensen, A. (ed.). 2000. *Lake Vänern. Theme: Biodiversity*. Lake Vänern Water Conservation Association, Report 11, 22 pp. (In Swedish).
46. Lehmann, A. and Lachavanne, J-B. 1999. Changes in water quality of Lake Geneva indicated by submerged macrophytes. *Freshwater Biol. 42*, 457–466.
47. Wiederholm, T. and Wallin, M. 2000. Monitoring of large lakes in Sweden – some experiences. *Univ. Joensuu, Publ. Karelian Institute 129*, 330–337.
48. Håkanson, L. 1981. On lake bottom dynamics, the energy-topography factor. *Can. J. Earth Sci. 18*, 899–909.
49. Johnson, R. and Wiederholm, T. 1992. Pelagic-benthic coupling. The importance of diatom interannual variability for population oscillations of *Monoporeia affinis*. *Limnol. Oceanogr. 37*, 1596–1607.
50. Weyhenmeyer, G. The response of phytoplankton in European lakes to changes in the North Atlantic Oscillation. *Verh. internat. Verein. Limnol.* (In press).
51. Persson, G. 1994. Eutrophication of soil, fresh water and the sea. *Swedish Environmental Protection Agency, Report 4244*, 207 pp.
52. Wiederholm, T. 1980. Use of benthos in lake monitoring. *J. Water Pollut. Control Fed. 52*, 537–547.
53. Willén, E. 2000. Phytoplankton in water quality assessment-an indicator concept. In: *Hydrological and Limnological Aspects of Lake Monitoring*. Heinonen, P., Ziglio, G. and Van der Beken, A. (eds). John Wiley & Sons Ltd, pp. 58–80.
54. Håkanson, L. 1978. Lake Hjälmaren, a physical geographical description. *Swedish Environmental Protection Agency Report PM 1079*, 53 pp.
55. Swedish Register of Lakes 1996. Swedish Meteorological and Hydrological Institute. Norrköping. (In Swedish)

56. I would like to express my gratitude to professors Kevin Bishop, Department of Environmental Assessment, Swedish University of Agricultural Sciences, and Curt Forsberg, Department of Limnology, Evolutionary Biology Center, Uppsala University, for constructive criticism of the manuscript and to my colleagues associate professor Gunnar Persson and Dr. Berta Andersson. Their views have been of great importance for the final content and framing of the text of this paper.

Eva Willén is a senior scientist in ecological botany at the Department of Environmental Assessment of the Swedish University of Agricultural Sciences. She holds a position as an associate professor with special competence in algae and biodiversity issues. She has taken part in the national long-term monitoring projects since the mid-1960s and has been responsible for those parts dealing with planktonic algae and their use in water-quality assessment. Her address: Swedish University of Agricultural Sciences, Department of Environmental Assessment, P.O. Box 7050, SE-750 07 Uppsala, Sweden.
E-mail: eva.willen@ma.slu.se