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Recovery from Eutrophication: Experiences of Reduced Phosphorus Input to the Four Largest Lakes of Sweden

In-lake concentration changes of phosphorus (P) and nitrogen (N) in lakes Vättern, Vänern, Mälaren, and Hjälmaren in response to diminished input has been examined from the mid-1960s onwards. In the former two deep and oligotrophic lakes with slow water renewal, drastic reductions in P-input from the middle of 1970s caused just minor reductions in P-concentration over a very long time. At the same time accumulation occurred in the water mass of inorganic N and possible reasons are discussed. In the latter two mesotrophic to hypertrophic lakes, two shallow basins in L. Hjälmaren showed slow recovery due to release of P from sediments. The same basins and two basins in L. Mälaren have suffered from N-deficiency, particularly during the pre-phosphorus reduction years, and nitrogen fixation was indicated. In two L. Mälaren basins recovery of in-lake P concentrations was better than expected in comparison to the so-called IMSA-model for lake recovery from nutrient pollution. In the other five lakes/basins chlorophyll concentrations after 20 years were similar compared to those modeled.

INTRODUCTION

The four large Swedish lakes Vänern, Vättern, Mälaren and Hjälmaren differ in many respects, not least in drainage area characteristics and basin morphometry (1). The differences also include water quality. Since nutrient chemistry of phosphorus (P) and nitrogen (N) in the lakes is of major concern, it has been treated by several authors (2–13). The hydrochemical studies started in 1964 and in an overview after 10 yrs, Ahl (14) placed phosphorus load and chlorophyll concentrations in these lakes into an international perspective (Fig. 1). This approach basically followed that of Vollenweider and others (15–18); i.e. in-lake nutrient concentration or trophic state (here as chlorophyll concentration) was expressed as a function of total input of nutrients to the lakes and basins. From Figure 1 it is obvious that the state of the different basins of L. Mälaren closely resembled those of the lower Laurentian Great Lakes, whereas conditions characteristic for the much less polluted lakes Vänern and Vättern corresponded to the upper Great Lakes.

This picture was typical for the end of the 1960s and the beginning of the 1970s, when nutrient inputs to the basins had high anthropogenic shares of both P and N. By a far-sighted decision (19) P-inputs to the basins were dramatically reduced by the introduction of chemical precipitation at municipal sewage-treat-

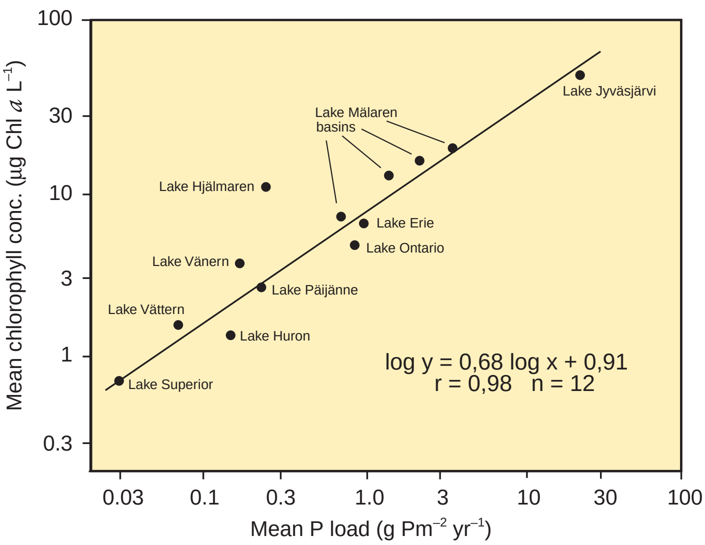


Figure 1. Annual area specific phosphorus loading and corresponding chlorophyll concentrations in the large Swedish lakes during c. 1967–1971, before measures to reduce phosphorus input were undertaken. Data from two large Finnish lakes and the Laurentian Great Lakes included. Redrawn from Ahl (4).

Box 1. Monitoring Programs and Analytical Methods

Water chemistry monitoring was launched in L. Mälaren in 1964 as part of a complete program including many biological variables (7). The program was expanded to L. Hjälmaren in 1965 and one year later monitoring of L. Vättern began. After a pilot study in 1969 the monitoring of L. Vänern began in 1973.

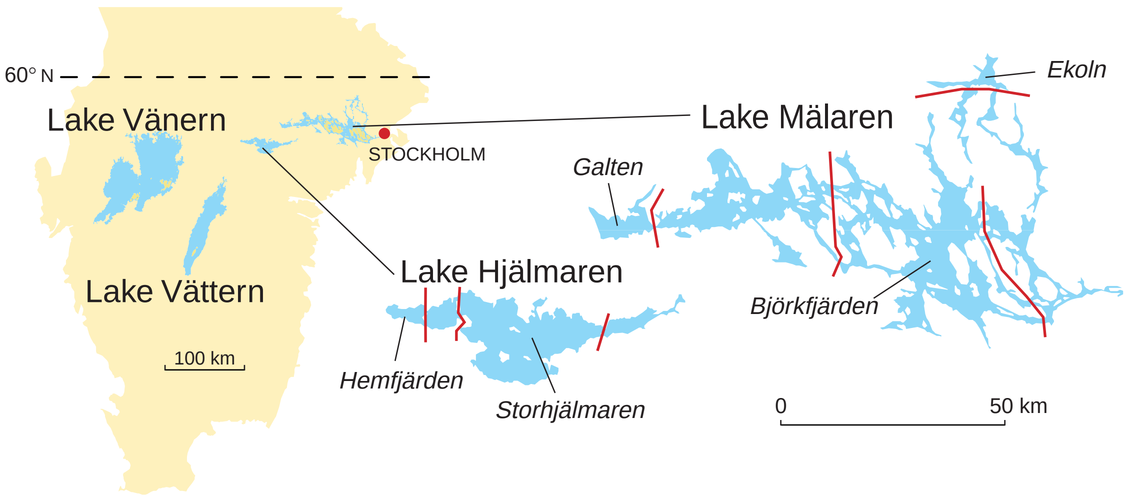
Lake sampling was concentrated to the ice-free season with 4 to 7 sampling occasions. In addition, Mälaren and Hjälmaren were sampled in February–March, usually from ice.

Monthly chemical monitoring of major tributaries commenced simultaneously or even before lake sampling. Eleven tributaries entering L. Mälaren, 14 to L. Vänern, 8 to L. Vättern and 3 entering L. Hjälmaren have been monitored. Nutrient transport in the streams was calculated by multiplying daily to fortnightly measured water discharge by corresponding interpolated concentrations. Transport from unmonitored areas of the watersheds was estimated using area specific losses of nutrients from adjacent monitored representative drainage basins. Deposition of inorganic nitrogen on the lake surface was calculated from monitored concentrations of inorganic nitrogen in bulk deposition samplers at close-to-lake sites within the *Swedish Deposition Network* multiplied by recorded precipitation at several nearby stations. P deposition was calculated from recorded precipitation and an assumed total P-concentration in rainwater of 10–12 µg P L^{-1} (9). Input from point sources was compiled from environmental reports for the sewage-treatment plants and industries concerned. Estimates of nutrient losses for small sewage works were based on *per capita* equivalents.

The analytical program included nutrient fractions, major ions, organic matter and chlorophyll. All methods have been identical or intercalibrated throughout the period (22).

Significance of trends over the recorded period or parts thereof were calculated by the Kendall method.

Figure 2. Map of the large lakes as well as major lake basins; Galten, Björkfjärden and Ekoln in L. Mälaren, Hemfjärden and Storhjälmaren in L. Hjälmaren.



ment plants during the period 1970–1975 (somewhat later around L. Vänern). In the case of L. Mälaren, 3 tunnels also diverted treated municipal sewage to the Baltic. A number of actions for reducing industrial pollution were also taken.

In the case of Mälaren and Hjälmaren these measures cut the P load to half whereas N input was only slightly altered (9, 10). The P input to Vättern was reduced c. 60% while the N input remained fairly constant (8, 20). In L. Vänern, a c. 50% reduction for P and a c. 30% increase for N were reached (12, 21).

The conditions described in Figure 1 are thus historic and have drastically changed to date. A transition to new nutrient conditions and trophic status would then be expected. The pace of the recovery, the present-day status, and deviations from expectations are discussed here for P and N in particular and with outlooks into phytoplankton changes over time. Key processes such as retention, nitrogen fixation and denitrification are also treated.

LAKES AND BASINS

The lakes Vänern, Vättern, Mälaren, and Hjälmaren (Fig. 2) are situated in central Sweden and thus are subjected to similar climatic conditions, even though the ice cover varies from more than 3 months duration to frequent ice-free winters in Lake Vättern (23). In most physical aspects the lakes differ from each other (1). The large and deep lakes Vättern and Vänern have one and two basins, respectively, with good large-scale water exchange and are bordered by bays and archipelagos, which may have restricted water exchange with the open basins. Significant water-quality dissimilarities therefore are not expected in the open basins, and data from several sampling sites are combined in this presentation. Vättern and Vänern both have a slow water turnover, in the case of L. Vättern extremely slow (Table 1). These lakes are classified as ultra-oligotrophic and oligotrophic, respectively.

Lakes Hjälmaren and Mälaren are shallow, especially in their western parts. Both have distinct sub-basins and L. Mälaren in addition has a huge archipelago giving rise to a number of straits. In the evaluation of L. Mälaren the lake has been treated not as one unit but often as five or more different basins (Fig. 2). These basins are connected so that there is basically a west–east and a north–south flow between the basins to a mixing basin (Björkfjärden) close to the outlet at Stockholm. Data from the shallow westernmost basin (Galten), with rapid water turnover, the deep basin to the far northeast (Ekoln), and the deep central basin (Björkfjärden) are chosen for presentation here. L. Mälaren displays conditions from highly eutrophic in the distal basins to mesotrophic in the central basin.

L. Hjälmaren has a fairly large shallow central basin (Storhjälmaren) (Fig. 2) preceded by embayments or basins of which the westernmost (Hemfjärden) is chosen for presentation. It is very shallow, polluted, and has a rapid water turnover. This basin is hypertrophic, whereas the central basin is eutrophic.

The combination of low total-P values and relatively high nitrate concentrations in Lake Vättern and Lake Vänern is conspicuous while the other two lakes are characterized by fairly high to high total-P values, and in general relatively low but varying N concentrations.

CHANGES OF INPUT AND IN-LAKE CONCENTRATIONS OF PHOSPHORUS

Continuous data on P-input are available for Vänern, Vättern, and Mälaren, whereas total input to L. Hjälmaren basins only is available for consecutive 5-yr periods. The nutrient loading is here expressed as potential concentration, i.e. the summed transport of P to the lake or basin divided by the water input during the same period.

Vättern and Vänern

In the most oligotrophic lake, Vättern, P-input has been hindcasted to the 1960s when sewage treatment, at best, included biological treatment. Potential concentration then was 140–160 μg P L^{-1} (8). Chemical precipitation at sewage-treatment plants, started in 1975, led to a drastic reduction of P-input. From 1970 onwards we consider the calculated inputs to mirror the true input reasonably well (Fig. 3a). The Kendall test showed a significant ($p < 0.002$) drop in potential P-concentration.

Throughout the 25 yrs displayed, the assayed P-concentration in the lake has been very low as compared to the potential concentration and also fairly constant over time in view of the changing potential concentration.

Table 1. Lake and input characteristics. Water turnover time and 95% of phosphorus equilibration time (Eq. 1) calculated as long-term means.

Lake	Basin	Area km^2	Mean depth m	Water turnover-time (Tw) years	Equilibration time for P years
Vättern		1890	39	56	13
Vänern		5650	25	9	8
Mälaren	Galten	61	3.4	0.05	0.3
	Ekoln	30	15.7	0.5	1.0
	Björkfjärden Prästfjärden	500	16.9	1.8	3.2
Hjälmaren	Hemfjärden	25	1.0	0.04	0.1
	Storhjälmaren	377	6.9	3.3	5.0

The very small P-output from L. Vättern as compared to input is due to an extremely high P-retention (Fig. 3a). In fact, the retention coefficient has been calculated to 0.90–0.95 (ratio in-lake concentration/potential concentration), from a long-term dynamic model (8).

In L. Vänern a similar pattern was found (Fig. 3b). The lake concentration of P has been stable although the decrease in potential concentration has been going on throughout the entire study period. The Kendall test showed significant ($p < 0.002$) reduction of potential concentration. A retention coefficient of 0.7 was calculated for the period 1970–1989 (21).

Both Vättern and Vänern have long water turnover times (Table 1) and therefore response times to changed inputs may be long, which has to be considered, among other things, when retention is calculated or recovery examined. The 95% equilibration time (i.e. 95% of the time required to reach a new equilibrium between a new level of input concentration and in-lake concentration) was calculated according to Equation 1 (17).

$$T(95\%) = 3 \cdot T_w(1-R) \qquad \text{Eq. 1}$$

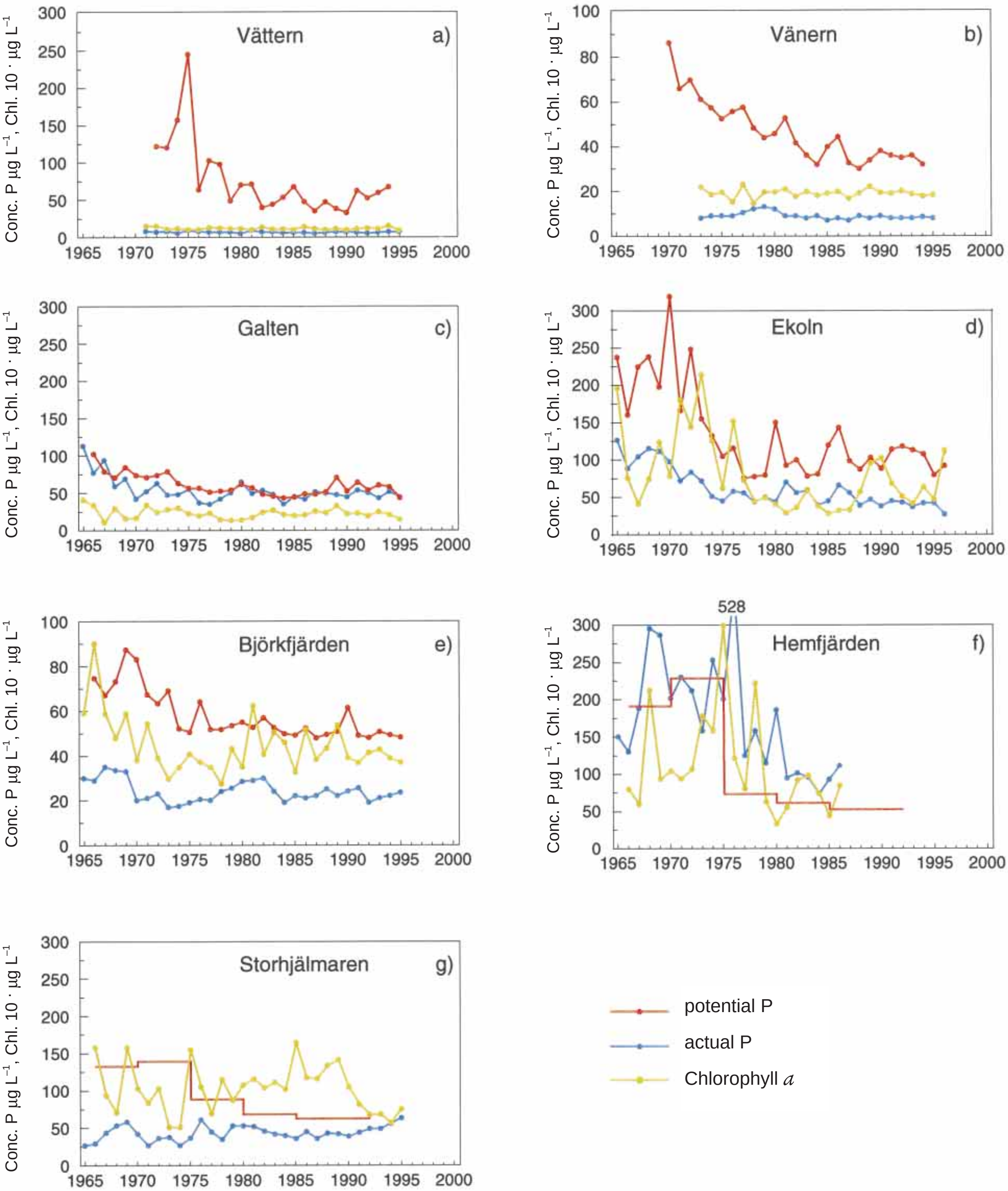
where

$T(95\%)$ = time for reaching equilibrium to 95% (year)

T_w = hydraulic retention time (year)

R = retention coefficient for the element (output/input).

Figure 3 a–g. Time series of potential (summed P input/summed water input) and measured concentrations of total P and chlorophyll *a* (note various scales) for lakes/basins; a) Vättern, b) Vänern, c) Galten, d) Ekoln, e) Björkfjärden, f) Hemfjärden and g) Storhjälmaren.



In the calculations both the water turnover time and the retention coefficient of the substance are considered. After a change in load the time to reach a new equilibrium is about 3 times the hydraulic retention time for a conservative element, but in the case of nonconservative substances such as nutrients the retention has to be taken into account.

In L. Vättern, the equilibrium concentration for P would be reached after c. 13 yrs and in L. Vänern after c. 8 yrs whereas the equilibrium would be reached within a couple of years, at most, in the other lakes. Response to remedial measures implemented during the 1970s is thus expected to reach full impact well before the end of the presented monitoring period. In cases with a gradually changing input a corresponding prolonged equilibration time is expected. It should be noted though, that equilibration with sediment P-stores is not included in this calculation which may cause an even longer delay (17, 24–26). Soon after a decrease in P-load especially shallow lakes exhibit a net release of P from P-saturated sediments and the above calculation is not applicable.

Mälaren

Due to the presence of narrow straits and to high flows, the transports of water are in general unidirectional from the distal basins Galten and Ekoln and calculations of basin inputs become straightforward.

Reduction in nutrient input to the westernmost basin, Galten, mainly occurred during the latter half of the 1960s thanks to reduced P and N discharges from a nearshore fertilizer plant. During the mid-1970s the reduction of sewage P affected primarily Ekoln. For Björkfjärden the decreasing P-input is expected to basically mirror that of Galten.

As can be seen, the potential concentration of Galten (Fig. 3c) was of the same magnitude as those of the oligotrophic lakes Vättern and Vänern whereas the in-basin concentration was 5 to 10 times higher due to very low retention.

Ekoln, the other distal basin, had the highest potential concentration during the high-load period followed by an extremely rapid reduction (Fig. 3d). However, an advantageous basin form and lower water turnover rate (Table 1) acted to give a high retention, keeping concentrations reasonably low during the initial period.

The central and most nutrient-poor basin (Björkfjärden) of L. Mälaren receives most of its nutrients from bordering western basins. It has an advantageous (deep) basin form and similar turnover time as Ekoln, and consequently, also a P-retention coefficient of the same magnitude. Since the input also had a low potential concentration (Fig. 3e), primarily due to retention in upstream western basins, the in-basin concentrations were lowest in L. Mälaren. In the same way as for L. Vättern and L. Vänern the concentrations in this basin did not respond in direct proportion to the reduced P-input. The decrease in potential P-concentration was highly significant for all the Mälaren basins whereas the trends for in-lake concentrations were significantly negative (Kendall, $p < 0.006$) in Galten and Ekoln, but insignificant in the central basin Björkfjärden.

Hjälmaren

L. Hjälmaren receives the major P input from the river Svartån and the town of Örebro into the small shallow Hemfjärden basin. Potential P concentrations calculated for this basin (Fig. 3f) to 190–230 μg L^{-1} during two consecutive 5-yr periods before the onset of P-reduction in the upstream sewage plants slightly exceeded those of Basin Ekoln. Yet, the in-basin concentrations during the ice-free season were found at even higher levels with large interannual variations until 1976, the second year after the great reduction of sewage P-input; a cut by about two thirds. A negative or close to zero retention was then calculated for the cited pretreatment periods, and it was quite evident that major summer P-releases from the sediments occurred (cf. below). Later on, P-concentrations seemingly stabilized at c. 100 μg L^{-1}, i.e. in a highly eutrophic or even hypertrophic state. Retention during the three 5-yr periods following input reduction was clearly negative, again basically due to P-release from overloaded sediment (10).

Storhjälmaren, the central basin of L. Hjälmaren, initially had potential concentrations of the same magnitude as L. Vättern and Galten, but these were cut to half by the remedial measures (Fig. 3g). No concentration change due to input reduction was recorded, which indicated that a large and gradual decrease in P retention took place, from 68% to c. 20% calculated for the 5 consecutive periods (cf. below).

GENERAL CONCENTRATION RESPONSE TO PHOSPHORUS INPUT CHANGES

Experiences of lake recovery from nutrient pollution have been reported for a number of Swedish lakes (27) and internationally (28) as well as in a number of European case studies which have been analyzed in the so called IMSA-model presented by Sas (25). The latter evaluation mainly differed from that of OECD (17) in that recovery from pollution in individual lakes was followed in time series and that only European lakes were handled. Characteristics of individual lakes like pretreatment ratios between P-input, lake P-concentration and chlorophyll concentration were considered in the evaluation of post-treatment effects in contrast to the OECD analysis where general lake behavior regardless of prehistory was examined.

A major question in the IMSA-evaluation was to what extent the in-lake P-concentration responded to reduced P-loading (Subsystem 1 according to IMSA). A second question was to what extent indicators of algal community development responded to ambient P-level (termed Subsystem 2). When treating the linkage between load and lake P-concentration, a distinction was made between a transient to a new state and a final equilibrium state. The equilibrium will not be reached until excess P has left both the water mass and sediment. According to IMSA (25), equilibrium as regards sediment P is indicated when no net P-losses on an annual basis can be observed whereas summer release of P from the sediment was considered natural. In fact, all thermally stratified lakes in the IMSA-analysis fulfilled this requisite. Apparently this is also the case in lakes Vättern, Vänern and the Mälaren basins Björkfjärden and Ekoln in the present study. Their postreduction P-concentrations, measured during the last 5-yr period presented were therefore compared to those predicted by the IMSA model (Eq. 2) based on the in-lake P-concentration in each lake during the prereduction period and the ratio between pre- and post- P-inputs according to IMSA (25):

$$P_l \text{ post} = P_l \text{ pre} \cdot (P_i \text{ post}/P_i \text{ pre})^{0.65} \qquad \text{Eq. 2}$$

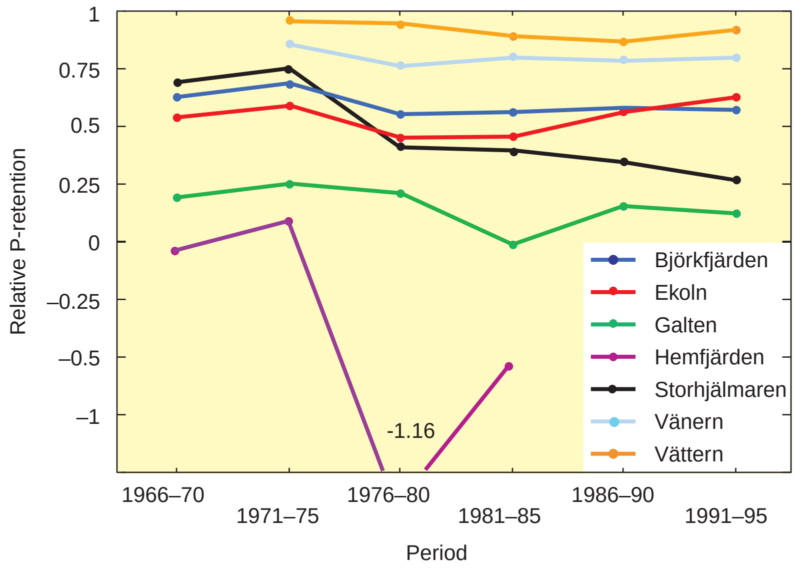
where:
P_l = in-lake total-P concentration (May–Oct.); P_i = potential total-P concentration (annual)
and indices; pre = pretreatment period; post = new equilibrium period.

In order to smoothen interannual variations we used 5-yr means both for pretreatment and posttreatment (equilibrium) periods. Still, natural differences between 5-yr mean values occur. This is the most probable reason for different retention behavior during the 2 initial 5-yr periods, the former with a rather normal water flow and the second with an extremely low water flow as compared to all other periods (Fig. 4). We preferred to use period 1 for pretreatment data for five of the basins, but for lakes Vänern and Vättern only data for period 2 were available. Sum-

Table 2. Measured and predicted 5-yr means of tot-P in the lakes/basins studied. Equation 2 (IMSA-model according to Sas (25) is used for predictions.

Lake	Basin	In-lake tot-P µg P L^{-1}	Predicted tot-P µg P L^{-1}
Vättern		6	4
Vänern		8	6
Mälaren	Björkfjärden	22	22
	Ekoln	42	63
	Galten	48	53
Hjälmaren	Storhjälmaen	52	28
Hjälmaren	Hemfjärden	92	29

Figure 4. Calculated retention of P (lake concentration/potential concentration (input)) for 5-yr periods in the studied lakes/basins.



mer means for in-lake concentrations were used here instead of annual means used by Sas (25).

Predictions of equilibrium in-lake concentrations (Table 2) were within 2 µg P L^{-1} for all deep basins except Ekoln where measurements showed a 21 µg P L^{-1} lower P concentration (= 34% lower) than predicted. On the other hand, concentrations in L. Hjälmaren were 14–22 µg P L^{-1} higher than predicted. In the case of the shallow Hjälmaren as a whole, and the western basin Hemfjärden in particular, this is expected due to P-release from sediments causing negative P-retention, which was still prevailing during the latest assessment period. The assessed transients during the equilibration period are even better described by the retention changes for the consecutive 5-yr periods (Fig. 4). A lower ratio between measured and potential concentration after remedial measures as compared to before will correspond to a decreasing retention and an exponent less than 1 in Equation 2. An exponent close to unity would on the other hand signal similar pre- and post-treatment equilibria. From the Figure it is obvious that no lake/basin so far has returned to the pretreatment retention except for Basin Ekoln where the retention increased and even exceeded the initial retention during the last two periods. However, during two 5-yr periods prior to that an expected slightly declining retention occurred in Ekoln parallel to that of Björkfjärden (Fig. 4).

Among the shallow basins, Basin Hemfjärden had a pretreatment retention close to 0 and even showed negative retention during at least ten years of the post-treatment period. This poor behavior is expected and caused by P-release from supersaturated sediments. A large decrease in P-retention following reduced P-input is also seen in Basin Storhjälmaren. Also here the possible cause is a periodical net P-release from sediments leading to a higher-than-predicted P-concentration, even if there is no net P-release on an annual basis. It contrasts to the opinion of Sas (25), who claims Equation 2 to be true as long as there is no net P-loss from sediments on an annual basis. This seems to be an oversimplification, though, of a more gradual change. The decrease in retention in Storhjälmaren still continued after 20 years and has not returned to an original higher retention, which would bring about the, so far, unseen reduction of the in-lake P-concentration (cf. Fig. 4).

In Basin Galten the development contrasts to that of Storhjälmaren in spite of a similar basin form and unstratified conditions. However, its water renewal is much faster, which gives a low P-retention, c. 13%. The retention diminished only during the period following input reduction, after which it stayed close to the pretreatment level. Consequently, there was no prolonged P-release from the sediments and in-lake concentrations were reduced like in the deep basins.

In summary, there are thus 3 major deviations in the measured in-lake concentration from the predicted one (i.e. malfunction or delay within Subsystem 1). One, unexpected and rewarding deviation giving lower than predicted concentrations in Ekoln, a second, expected and inconvenient deviation for the shallow Hemfjärden, generated by high annual net sediment P-release, and finally a third, expected but cumbersome as to magnitude and duration, in Storhjälmaren.

Response of Phytoplankton Communities to Altered P-Levels

In the conceptual framework of the IMSA recovery model "Subsystem 2" deals with the extent to which indicators of algal community development respond to ambient P-level. Basic information about phytoplankton biomass development was gained by chlorophyll *a* and the chlorophyll level expected at equilibrium was modeled analogous to Equation 2 and based on lake P-concentrations.

$$Chl_s\ post = Chl_s\ pre \cdot (P_i\ post/P_i\ pre)^k \qquad \text{Eq. 3}$$

where: Chl_s = summer chlorophyll *a* concentration (May–Oct.) µg L^{-1}; P_i = total-P concentration (annual) µg L^{-1}
and indices pre = pretreatment period; post = new equilibrium period; k is 0.6 for deep lakes and 1.4 for shallow lakes according to Sas (25).

"Equilibrium" chlorophyll concentrations were forecasted using the exponent 0.6 suggested (25) to be valid for deep lakes. Good agreement between model data and measured "equilibrium" concentrations was found for all deep basins (Table 3). The shallow Galten and the two shallow Hjälmaren basins behaved much as deep basins. Estimates using the suggested constant for shallow basins (1.4) increase the differences between modeled and recorded data.

According to Sas (25) there would be gradual changes in phytoplankton following P-input reduction. During a first stage *i*) a P-concentration decrease would reduce algal abundance only if a situation with P-regulation and excess N was prevailing or reached. Otherwise, if N-availability was low and regulating phytoplankton, a reduction of the (excess) P-concentration would not affect phytoplankton. Apparently Sas considers nitrogen fixation unable to fill the N-demand up to balance relative to P.

In a second possible stage *ii*), phytoplankton would change behavior and disperse to deeper and more nutrient-rich water layers in thermally stratified lakes, whereas the amount per unit surface area would remain essentially unchanged. This stage is not feasible for analysis here due to limited vertical resolution of phytoplankton analyses.

In the third stage *iii*), common to all lakes where P regulates phytoplankton appearance, phytoplankton biomass would be reduced corresponding to P-concentration. Parallel to this, in a fourth stage *iv*), qualitative changes among groups and species would occur (19).

Apparently, the third stage was reached at the last presented period aimed to represent equilibrium conditions (cf. Fig. 3; Table 3). Measurements thus conformed to the prediction and showed no signs of N-deficiency (cf. above and Table 3). However, the occurrence and effect of N-deficiency during earlier years will be elucidated.

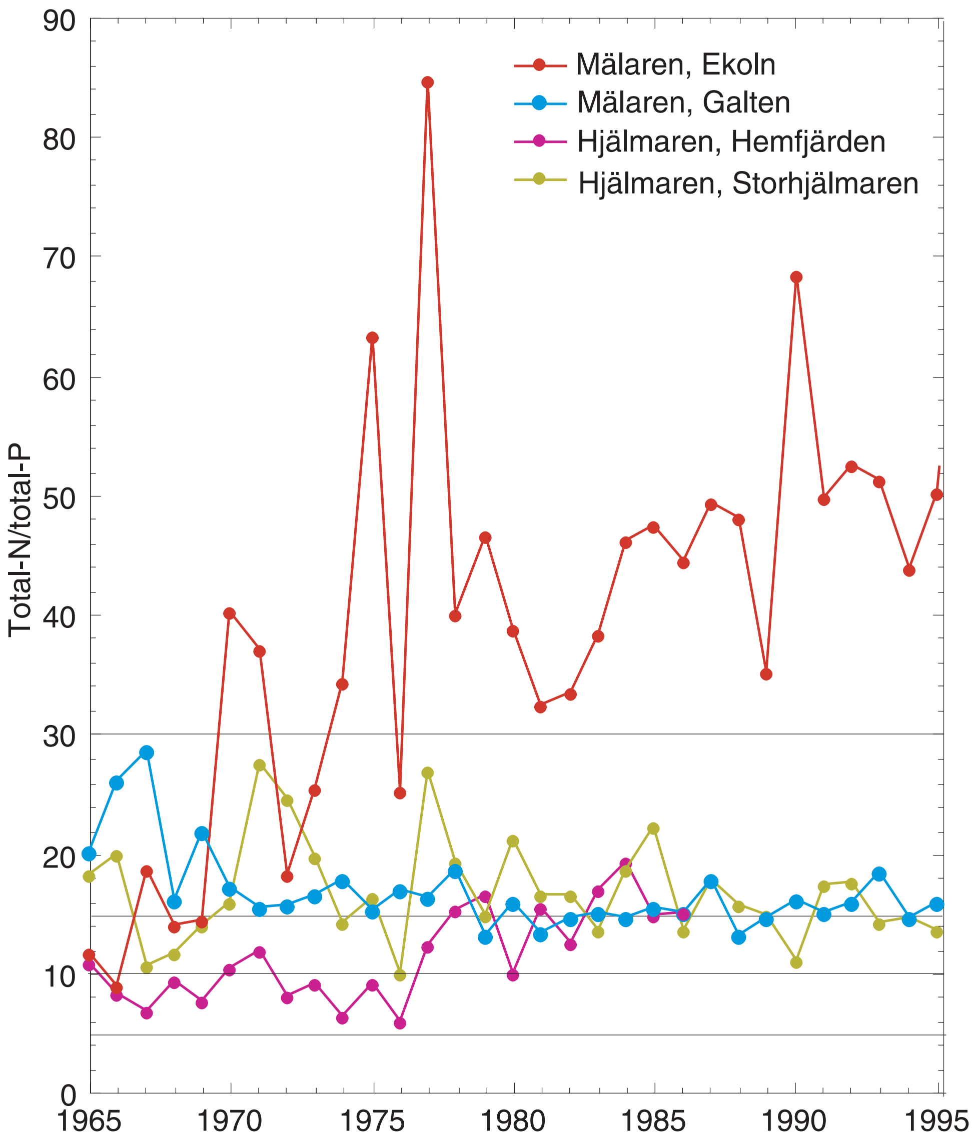


Figure 5. Time series of total-N/total-P concentration quotients for four heavily affected basins in Mälaren and Hjälmaren. The lines are status criteria for from below extreme N-deficiency to excess N (cf. 31).

SHORTAGE OF NITROGEN AND NITROGEN FIXATION

Any deficiency of either N or P as compared to demand is usually judged by comparisons of the N/P ratio in algal nutrient demand (generally 7:1 on a mass basis) and N/P ratios in the wa-

Table 3. Measured and predicted and 5-yr means of chlorophyll *a* in the lakes/basins studied. Equation 3 (IMSA-model according to Sas (25)) is used with exponent 0.6 for all basins.

Lake	Basin	In-lake Chlorophyll µg Chl *a* L^{-1}	Predicted Chlorophyll µg Chl *a* L^{-1}
Vättern		1.0	1.0
Vänern		2.0	2.0
Mälaren	Björkfjärden	4.1	5.1
Mälaren	Ekoln	9.0	9.0
Mälaren	Galten	22	17
Hjälmaren	Storhjälmaren	7	13
Hjälmaren	Hemfjärden	85	73

Table 4. Compilation of chemical criteria used to predict the existence of nitrogen fixation. Quotients and dissolved inorganic N (DIN) concentrations are given as 5-yr means May–September.

Lake	Basin	Criterion	Pre-period 1966–70	Post-period 1991–95
Mälaren	Galten	TN/TP	24.4	16.9
		DIN/TP	3.8	1.6
		Min DIN	284	14
Hjälmaren	Hemfjärden	TN/TP	9.1	15.6*
		DIN/TP	15.6	1.7*
		Min DIN	19	55*
Hjämaren	Storhjälmaren	TN/TP	14.9	13.8
		DIN/TP	1.2	1.5
		Min DIN	14	10

* Period 1981–1985

ter. Since measurements of inorganic fractions of N and P may be troublesome at low concentrations, judgements are often based on the quotient tot-N/tot-P. Empirical and experimental data indicate a threshold quotient in Swedish lakes of c. 15 with an interval of 10–17 (29). Below this threshold, nitrogen fixation will most often be triggered and planktonic nitrogen-fixing cyanobacteria appear. Basically a lower quotient mirrors a deficiency of inorganic N from early summer and throughout the season. Mean tot-N/tot-P-quotients during the period June–September are used here (30, 31).

As a second criterion for nitrogen deficiency we used the ratio dissolved inorganic N (DIN)/tot-P concentration (32). N-deficiency is indicated at a ratio below 0.5 (or rather within an interval 0–4). Finally, another simple but cruder criterion may be an insignificant DIN concentration in the water mass during late summer. However, concentration minima are easily missed since the sampling frequency is low in the present study (monthly samples). Therefore, we consider N-deficiency to appear at measured DIN concentrations of 30 μg N L^{-1} or lower.

These 3 indicators of N-deficiency were thus used to discriminate between basins with possible nitrogen fixation and other basins. The high in-lake tot-N/tot-P quotient directly eliminated Vättern and Vänern and Björkfjärden in Mälaren as possible for nitrogen fixation (N/P-quotients > 30). In all these a possible lag phase or low chlorophyll to P-ratios during the transient period to equilibrium should have causes other than N-deficiency. Among the other basins, Ekoln showed a quotient well below 15 during the initial 5-yr period, but changed to a situation with N-excess already before the reduced input of sewage P (Fig. 5). Hemfjärden suffered from the greatest deficiency whereas the remaining two basins stayed at variable quotients around 15, a level which was also attained by Hemfjärden after the reduced input of sewage P (Fig. 5). Since the in-lake quotient is a consequence of many balancing processes one must consider N-fixation to tentatively occur even at quotients slightly above 15, but that its role will decline at higher ratios (33). The other indicators of nitrogen fixation were gathered for one 5-yr period preceding the P-reduction and for one late period, well after P-reduction (Table 4).

For Galten these criteria signal a N-excess during the initial period changing over time to a possible N-deficiency (see also Fig. 5). An initial N-deficiency transformed to likely excess is indicated for Hemfjärden whereas N-deficiency is signaled for both periods in Storhjälmaren. Evidently, the indications are not uniform. The DIN/TP criterion appears to be not quite in harmony with the others even when the widened limit up to 4 is accepted. Nevertheless, all indices are useful to indicate N-deficiency and the potential for nitrogen fixation to occur.

The presence of N-fixing cyanobacteria was largest in Hemfjärden followed by Galten. In Hemfjärden cyanobacteria, and among them a dominant proportion of potential N-fixers, made up to 80% of the phytoplankton biovolume prior to the reduction of P-input (10). The mean cyanobacterial biovolume then was c. 12 mm^3 L^{-1} with large interannual variations. During the following 10 years the cyanobacteria diminished to c. 2 mm^3 L^{-1} and held a much lower fraction of the total biovolume.

In Galten the cyanobacterial biovolume prior to nutrient reduction was c. 4 mm^3 L^{-1} after which it fell to c. 2 mm^3 L^{-1}. Furthermore, the proportion of the well-known N-fixer *Aphanizomenon flos-aquae* both at the beginning and end of the monitoring period was very high (84 and 74%, respectively). In this case, both N and P diminished in parallel, which would favor a similar proportion of N-fixers over the period. On the other hand the initial N/P-ratio (like other N-deficiency indices, Table 4) in the basin is not supposed to favor nitrogen fixation. More knowledge of the preferences of this species therefore is needed.

Storhjälmaren had a prereduction cyanobacterial biomass of 0.9 mm^3 L^{-1} which declined to 0.16 mm^3 L^{-1} after P-reduction. The fraction of potential N-fixers was 24 and 8%, respectively. Taken together the change in occurrence of nitrogen fixers seems to be larger than expected from the subtle changes in chemical indices given in Figure 5 and Table 4. This supports the idea that in a close-to-balance situation between N and P, as judged by chemical indices, the balanced situation is the result of a balanced input or due to a strong activity by N-fixing organisms. This is best revealed by phytoplankton analyses or direct measurements of nitrogen fixation.

EXCESS OF NITROGEN AND NITROGEN STORAGE

While N-deficiency, or slight excess, with no or little concentration change during the latest decades has been the rule in the Mälaren and Hjälmaren basins, marked concentration increases have been noted in Vättern and Vänern. In L. Vättern a rapid and significant increase in nitrate concentration occurred from the start of the monitoring in 1966 and onwards. The increase, confined to nitrate, was approximately linear during the first 20 years, but somewhat retarded during the last decade (Fig. 6). It led to a doubling of the N-content of the lake's water mass within 25 yrs. The mass balance presented by Persson et al. (8) gives an overview of the fate of N-input (Table 5). It suffers from

Figure 6. Time series of inorganic N-concentrations in Vänern and Vättern.

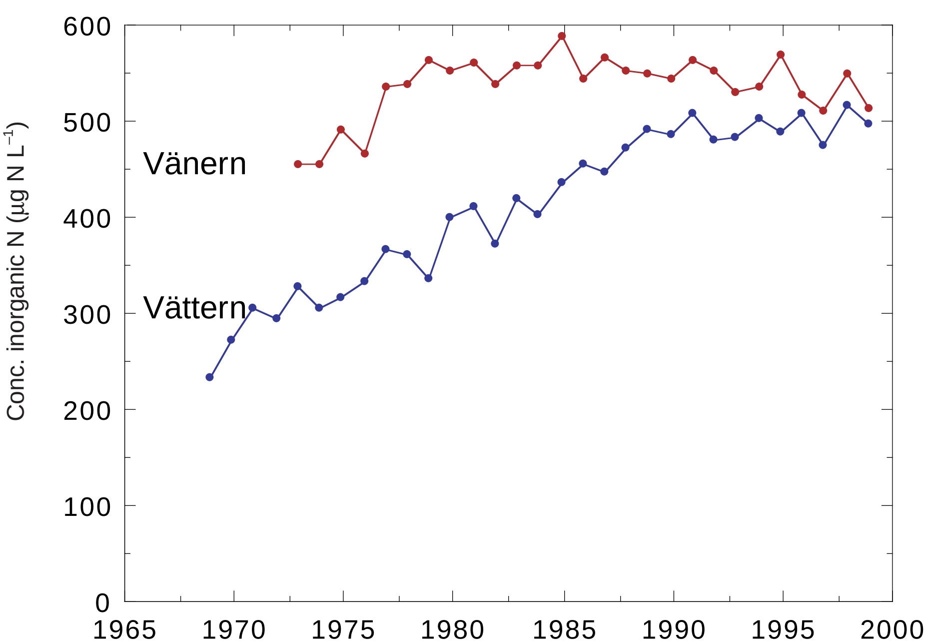


Table 5. Nitrogen balance for L. Vättern (8).

Source	Nitrogen t yr⁻¹	Fate	Nitrogen t yr⁻¹
Deposition on lake	1300	Accumulation in water	950
Drainage area	1400	Burial in sediment	300
Sewage-treatment plants	500	Denitrification	1200
Total input	3200	Outlet loss	750

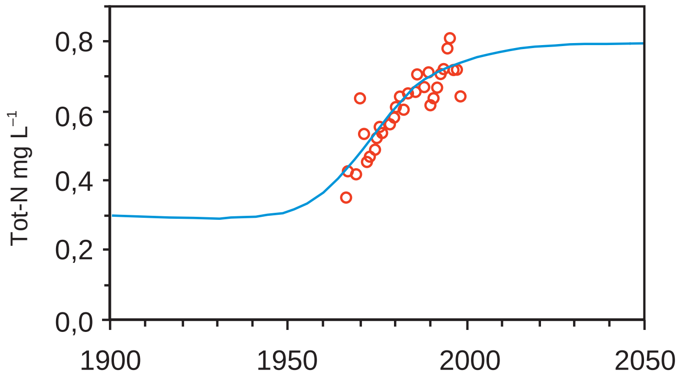


Figure 7. Modeled (using N-limitation) concentrations of total-N in L. Vättern for the period 1900–2050 according to Olsson (20) and measured concentrations.

shortcomings, especially regarding the unusually large input from atmospheric deposition (c. 1300 t N yr^{-1}), but since only small input increases occurred during the monitoring period, explanations for the accumulation of more than 900 t N yr^{-1} were sought. It was discussed whether during the period a decrease in denitrification could have taken place due to reduced organic production (20), through reduced P-input (Fig. 3a), or reduced input of organic substances *per se* (34).

Both lowered N sedimentation and a lower supply of organic material for the denitrification process itself, and for creating the close-to-anaerobic conditions for the process, may result from reduced production in the lake (35). A numerical model for these kinds of effects is not available, however. Emissions of biodegradable organic matter (mainly from the pulp and paper industry) decreased from c. 10 000 t BOD yr^{-1} in 1970 to 1700 t yr^{-1} at the beginning of the 1980s (36). If it is assumed that BOD is exclusively the energy source for denitrification then 1 t BOD will be equivalent to 0.35 t of nitrate N denitrified. Consequently, the annual capacity for denitrification would be 2900 t N yr^{-1} lower at the end of the period. This is a high figure, higher than the total N-retention in the lake (Table 5). Of course the bulk of BOD is oxidized using dissolved oxygen. The decrease in discharged BOD is accompanied by a similar decrease in total organic matter (37). Diminished discharge of organic matter may thus indirectly support nitrate accumulation (34, 38), but it would be premature to state to what extent.

The extremely long water residence time (56 yrs) creates special problems when looking for nitrate accumulation explanations. As a matter of fact the combination of a long water residence time and fairly low N-retention offers yet another possible explanation. With a retention coefficient of 0.2–0.5 (8) and a water turnover time of 56 yrs, the 95% equilibration time will be 80–130 yrs (Eq. 1). The increase in nitrate concentration to a new heightened level during the monitoring period therefore was suggested to be an effect of escalated nutrient input during an earlier period. Thus, the atmospheric deposition increased from 1955 to 1980 by a factor c. 2 (39) and the general use of commercial fertilizers increased eightfold during this period.

The delayed-response explanation was tested by Olsson (20) using a simple mass-balance model and an assumption of slightly more than doubled N-input 1950–1970. In 2 alternative calculations he then assumed the retention to be proportional to the in-lake concentration of either N or P. The result indicates a more rapid equilibration at a lower concentration level for the N-governed model (Fig. 7) as compared to the P-governed. At equilibrium, N-retention was calculated to 70% and 30% for the N- and P-governed models, respectively. Equilibrium was estimated to be reached by 2050 and 2200, respectively. In the latter case, at a much higher concentration level. As stated by Olsson, the models offer no explanation for the observed concentration rise, but they certainly underline the slow pace by which lakes of this type adapt to changes, whether they are found in input alterations or changed within-lake processes. In order to fully understand this behavior, more directed research as well as long-term monitoring will be needed.

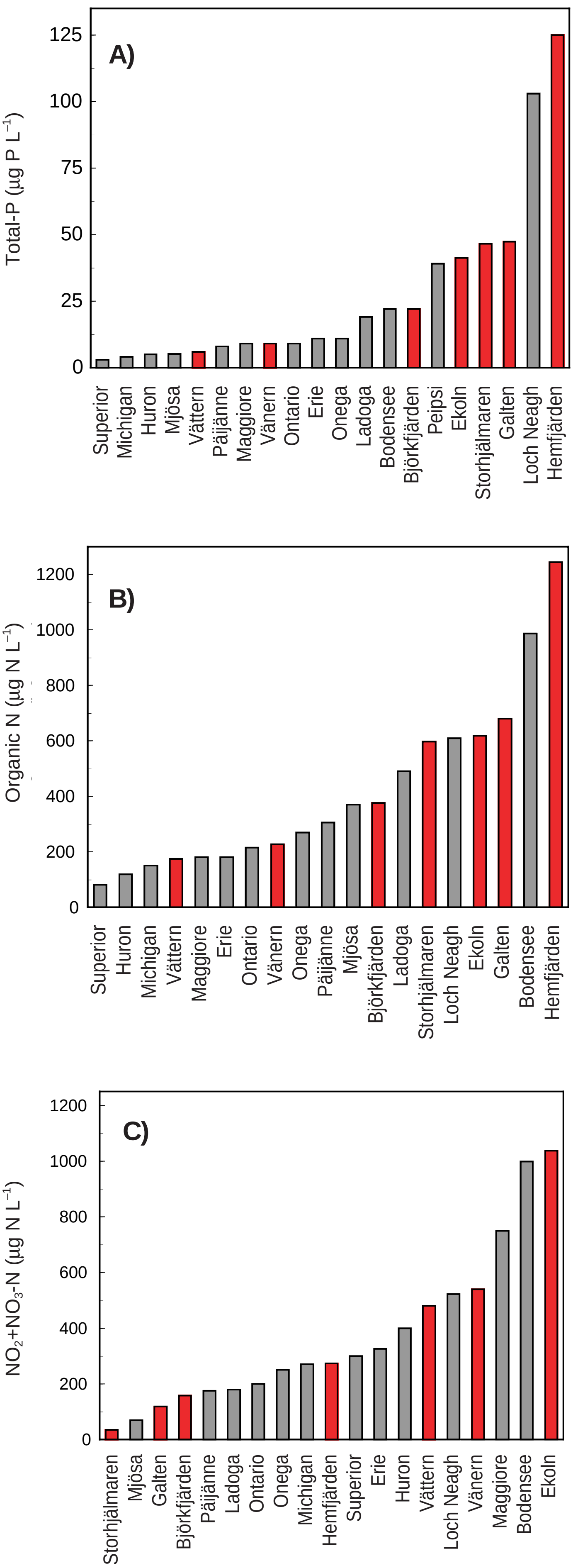
In L. Vänern there was an increasing in-lake concentration of inorganic N similar to that in L. Vättern during the initial 10 yrs (Fig. 6). But after 10 yrs the positive concentration trend was smoothly turned into a significant linear decrease ($p = 0.006$). Two calculations of N-retention in the lake arrived at 30–40% for the period 1982–1992 and 25–40% for the period 1970–1989 (21, 40). Olsson (21) also reported a lowered retention coinciding with reduced P-input and rising in-lake concentration. Clearly, the reduced P-input during the initial period (Fig. 3b) could have contributed to the nitrate increase due to a lower phytoplankton production, leading to a prolonged nitrate increase or at least a final constant concentration.

In L. Vänern, as in L. Vättern, the anthropogenic discharge of BOD also fell prior to and during the monitoring period. From 1969 to 1995, emissions fell by c. 100 000 t to 7000 t BOD yr^{-1} and the annual denitrification could presently theoretically be c. 32 600 t N yr^{-1} lower corresponding to an annual accumulation of 230 μg N $L^{-1}yr^{-1}$. The actual accumulation, mainly occurring before 1980, was 100 μg N L^{-1} (from about 450 to 550 μg L^{-1}). A potentially reduced denitrification of this size clearly could contribute to the observed accumulation of inorganic N in the water mass. Since the BOD reduction was confined almost entirely to the period up to 1970 a reduced denitrification, attributed to reduced BOD input, would fit into the pattern of increased nitrate concentration. In L. Vänern, the 95% equilibration time was calculated to about 17 yrs, which indicates that the concentrations found up to the 1980s could also be due to an input increase mainly before the monitored period in the same way as has been hypothesized for L. Vättern. The following slow concentration decline would then merely mirror the diminishing N-input seen during the monitoring period.

PRESENT AND FUTURE LAKE STATUS

Nowadays, the water quality of the four Swedish large lakes spans over a broad scale as compared to 13 other large lakes (Fig. 8). The lowest concentration of tot-P is found in the upper three Laurentian Great Lakes (Fig. 1) followed in increasing order by the Norwegian Lake Mjösa and L. Vättern. Hemfjärden, and Loch Neagh rank highest as regards P followed at less than half the concentration by three other Swedish basins. Low organic

Figure 8. Nutrient concentrations in the Swedish large lakes and basins as compared to some selected large lakes in other countries. Nutrients: A) Total P; B) Organic N; and C) dissolved inorganic N.



N-concentrations are again found in the upper Laurentian Great Lakes accompanied by L. Vättern and Lago Maggiore and this more or less mirrors lake productivity. The highest concentrations occur in Hemfjärden and Lake Bodensee accompanied at a somewhat lower level by Loch Neagh and three Swedish basins. Storhjälmaren has the lowest nitrate concentration, lower than Lake Mjösa and then increasing concentrations are found in Galten and Björkfjärden. The highest nitrate concentration is found in Ekoln with Bodensee, Lago Maggiore, Vänern, Loch Neagh and Vättern a bit lower.

This brief review indicates that among these selected lakes the shallow basins of the Swedish large lakes, and maybe also the deep basin Ekoln, are at the extreme end as regards productivity indicators.

Programs to fight eutrophication are generally in operation for many lakes with P-concentrations exceeding 10 µg P L^{-1}, at times even lower. This is interesting, since strong eutrophication effects—worthy of addressing as problems—usually do not appear until P-levels above 25–30 µg P L^{-1} are attained (17, 41). Abatement plans and targets are instead frequently based on some acceptable deviation from original or virgin conditions with a general principle that the P-concentration should not exceed, e.g. twice the "background" or "reference concentration"(42). The Swedish National Water Quality Criteria (31) contains both a scale relative to "reference" concentrations (calculated in a standardized manner or otherwise estimated) and an absolute scale related to P-concentration. Specified P-targets for the four Swedish large lakes were set up, bearing these two kinds of criteria in mind (Table 6). For N there is, nowadays, pronounced excess except for Hjälmaren and the basins Galten and Björkfjärden in Mälaren. The N-excess is not considered to cause problems in these basins. However, since production of the sea areas bordering southern and central Sweden is considered regulated by N, downstream effects of inorganic nitrogen output may be severe (31, 43). Concern for downstream areas (seas) therefore is reflected in N-targets for the lakes (Table 6).

The goal for P in L. Vänern is that the present concentration of 8–10 µg L^{-1} should not be exceeded in the open part of the lake (44). The long-term goal for N is a 50% reduction of the anthropogenic contribution of N-input to the lake. This is anticipated to reduce the total N-concentration in the lake from 800 to about 600 µg L^{-1}. In the latter half of the 1990s the P-concentration was about 7 µg L^{-1} and the tot-N was roughly 800 µg L^{-1} of which about 500 in the form of nitrate. Thus the quality goal for P is achieved, while for tot-N the level is still too high.

The environmental goal for Vättern (45) from 1990, states that the tot-P concentration should not increase from present level, about 6 µg L^{-1} and that the tot-N concentration should decrease from the present 600–700 µg L^{-1} to below 450 µg L^{-1}. Similar to Vänern the goal is reached for tot-P but not for tot-N. Even in this case the bulk of N is in the form of nitrate. The high input portion of N from atmospheric deposition is here an abatement obstacle as in Vänern.

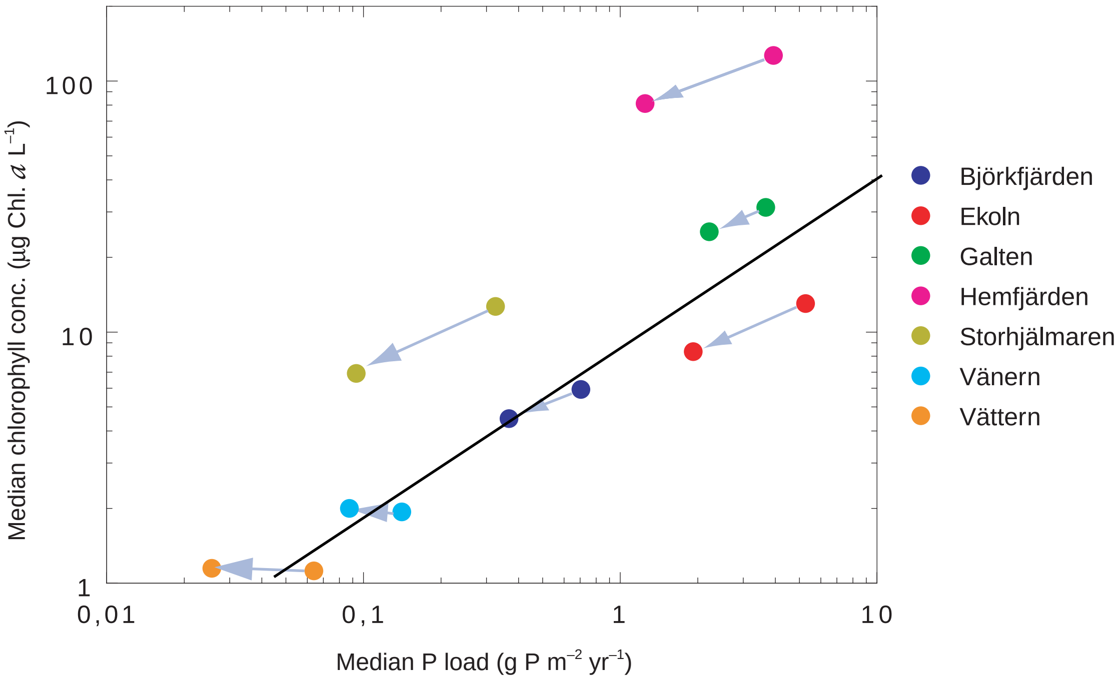
The long-term goal for Mälaren (46) is a tot-P concentration at most twice the background concentration. For N, the long-

Table 6. Water quality targets for the largest Swedish lakes.

Lake	P-target	N-target	Reference
Vänern	< 8–10 µg tot-P L^{-1}	50% reduction of anthropogenic input	(44)
Vättern	< 6 µg tot-P L^{-1}	< 450 µg tot-N L^{-1}	(45)
Mälaren	< 2* "background" conc.	< 2*outlet "background" transport	(46)
Hjälmaren	< 25 µg tot–P L^{-1}	–	*

* Provincial Authority of Örebro Council. (Pers. comm.).

Figure 9. Annual area specific phosphorus loading and corresponding chlorophyll concentrations in the large Swedish lakes and basins. Data for two 5-yr periods (one before P reduction and the second at the end of the monitoring period) are presented. The regression line found by Ahl (14) is inserted (cf. Fig. 1), although an exact comparison to Ahl's material is not possible due to a modification of basin borders to fit the present sampling program.



term goal is to reduce the N-transport through the outlet to the sea to less than twice the background transport.

These targets call for estimates of background or reference values, which may not be easily achieved. For Björkfjärden in L. Mälaren, between 6.4 and 40 µg P L^{-1} has been suggested as discussed by Renberg et al. (47). With these values in mind, and in-lake concentrations of 17 µg P L^{-1} today, Wallin et al. (48) selected a concentration of 11 µg P L^{-1} as a realistic background concentration. The corresponding values given for Ekoln and Galten were 26 and 25 µg P L^{-1}, respectively, which can be compared to older background estimates of c. 15 µg P L^{-1} in both basins (9, 46). A comparison between in-lake concentrations in the three Mälaren basins 1991–1995 and the new background values indicate that the P-targets are fulfilled at present (deviation quotients = 1.5, 1.6, and 1.9, respectively), whereas much remains to be done to reach the goal if the old lower background levels are applied. The issue of choosing adequate "background" or reference conditions as well as goals is presently under study, while a program revision for Mälaren is prepared.

In L. Hjälmaren, for the largest basin Storhjälmaren, an environmental goal for tot-P is set to less than 25 µg P L^{-1}. For this basin the present evaluation shows the most worrying development; with increasing or stable P-concentrations and a gradually lowered P-retention. Despite a substantial reduction in P-input, the heavy burden of nutrients in the sediment seems to strongly dampen recovery. Only through increased retention towards former levels will the desired target be reached at present day input. The reasons for the present development are, however, poorly understood and deserve further study.

In conclusion, for the studied lakes the goal with regard to tot-P is reached, with the single exception of L. Hjälmaren, where sediment deposits will drastically delay any recovery.

In contrast, the goals for N are not yet attained. For L. Vättern, and possibly Vänern, strong reductions in N-deposition (at present about 38% and 23% of the total input, respectively) have to be made and this is a task requiring actions on national as well as international levels. However, the loss from agriculture is considerable; for Vänern 23% and Vättern 28%, and measures have to be taken to reduce these N losses. Future N decreases in Mälaren have to depend on actions taken at both point sources and changed agricultural practices, here the atmospheric contribution is low, about 5% (9, 48).

So far, there are no specified biological goals for the Swedish large lakes. However, biological changes are expected, parallel to or delayed, in relation to nutrient changes and both chemical and biological reversibility have been assumed. Based on a 10-yr study of the lakes, Ahl (4) prepared an equation relating algal biomass (as chlorophyll) to area load of P (Fig. 1). Now data are available for a period of about 30 yrs to follow further development after decreasing loads (Fig. 9). It is obvious that immediate and complete reversibility are rarely seen. The trajectories from the initial conditions to the present-day situation, together with the pre- and posttreatment analyses of the IMSA-model, sums the 2 steps (subsystems) in treatment responses: *i*) decrease in P-concentration in response to reduced P-input; and *ii*) decrease in chlorophyll concentration in response to reduced P-concentration (25, 26).

As discussed above a complete reversibility (exponent = 1) was not predicted by Equation 2 or by Equation 3, at least not over the fairly modest time-scale used. Incomplete reversibility and/or delayed response are the main reasons for the deviations of trajectories for individual lakes from the general between-lakes relationship given by Ahl in his Vollenweider-type approach to the problem (Fig. 1). Among the deep basins, only Ekoln deviated from predicted lake P-concentrations relative to P-load where P-concentrations so far have come out lower than expected from P-loading. Measured chlorophyll concentrations for all these basins were as predicted by Equation 3 (chlorophyll response to P-concentration).

Among the shallow basins, phosphorus concentration in Galten agreed with that predicted but chlorophyll concentration responded more like that predicted for a deep basin. When it came to the Hjälmaren basins, the internal loading still gave higher than predicted P-concentrations. However, the two basins differed in predicted chlorophyll based on P-concentration; Hemfjärden had a lower-than-predicted concentration while Storhjälmaren had a higher. Since a continuously decreasing P-retention in Storhjälmaren is also seen, these basins can be pointed out as deserving most future attention; both as regards directed research and monitoring.

CONCLUSIONS

Data from long-term monitoring of the four largest lakes in Sweden efficiently demonstrated effects of a reduction in phosphorus inputs by c. 50–60%, and at the same time demonstrated influences from other time-dependent factors, mainly meteorology.

Responses were different in the single waterbodies studied which was, however, mainly attributable to the widely different physical prerequisites of the lake- and drainage basins. Such influences are taken into account in the general IMSA-model for eutrophication recovery (25) which was applied to check the generality of the outcome.

A posttreatment relation between P-input, in-lake P-concentration and chlorophyll, identical to the pretreatment relation, was neither predicted nor found under the equilibrium conditions used for the model construction. We question whether the prescribed equilibration time is long enough and whether the criteria for attainment of equilibrium conditions based on P-release from sediments are strict enough.

The agreement between predicted and measured conditions was generally acceptable for deep basins. One unexpected deviation from modeled conditions was found for Ekoln in L. Mälaren, which recovered better than predicted. The recovery of the shallow L. Hjälmaren basins was poor due to unattained equilibrium. In general, model predictions for shallow basins were poorer than for deep basins.

In most cases, the measures undertaken to reduce P input have led to the fulfilment of formulated environmental goals as regards eutrophication (an exception was Hjälmaren). For nitrogen the targets were far from attained, however, and increasing nitrate levels in the least productive lakes and basins have been a problem, not in the lakes themselves, but in downstream N-sensitive sea areas.

The achievement of specific goals depends on the chosen targets, however, and a review of nutrient conditions among selected European and North American large lakes indicates that the shallow basins of the Swedish large lakes, and maybe also the deep Ekoln, are at the high extreme end as regards productivity indicators. Goals are now in the process of being revised and tuned to the demands that have arisen from the European Water Directive (49).

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