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## NUTRIENT LODING AND REDUCTION FROM SOURCE-LAKE TO SEA

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### Abstract

So far, the processes behind the eutrophication of coastal waters are poorly understood. As a consequence of this, efforts to counteract this phenomenon have failed. In this study ecological valuations are used in comparisons of nutrient utilization in different types of lakes and watercourses in parts of the drainage basin of the River Göta älv from a source-lake to the river estuary and the Sea. The abundance of nitrogen and phosphorus and especially their reciprocal proportions, the N/P-ratio, necessary for primary production, constitute the important parameters utilized. A high N/P-ratio is initiated at higher levels by atmospheric input of nitrogen. However, this nitrogen concentration is low when compared to the input from wastewater treatment plants. A high N/P-ratio is then reinforced in lakes, which become oligotrophicated. Reduced primary production impoverish the food chains, including fish production. Abundant nutrients from agriculture, close to an optimal N/P-ratio, are rapidly transformed to biomass causing oxygen deficiency. A similar process obviously happens when nitrogen-rich river water is mixed with phosphorus-rich coastal water. New ecological methods are required to transform nitrogen to biomass before it reaches the Sea. Such methods have to re-use the finite phosphorus resources.

### Sammanfattning

Hittills har processerna bakom övergödningen av kustvattnen varit bristfälligt kända. Som en följd av detta har ansträngningarna att motverka detta fenomen misslyckats. I denna studie har ekologiska värderingar gjorts för att jämföra utnyttjandet av närsalter i olika typer av sjöar och vattendrag i delar av Göta älvs tillrinningsområde från en källsjö till älvens estuarium och havet. Mängden av kväve och fosfor och i synnerhet deras inbördes proportioner, N/P-kvoten, nödvändig för primärproduktionen, utgör de viktiga parametrar som utnyttjats. En hög N/P-kvot inleds på höga nivåer genom tillförsel av kväve från luften. Men denna koncentration är låg vid jämförelse med tillförseln från reningsverk. En hög N/P-kvot förstärkes sedan i sjöar som blir näringsfattigare. Minskad primärproduktion utarmar näringskedjorna inklusive produktionen av fisk. Rikligt med närsalter från jordbruket, nära en optimal N/P-kvot, överföres snabbt till biomassa som ger upphov till syrebrist. En liknande process inträffar uppenbarligen när kväverikt älvvatten blandas med fosforrikt kustvatten. Nya ekologiska metoder erfordras för att överföra kväve till biomassa innan det når havet. Sådana metoder erfordras för att återanvända en ändlig fosfortillgång.

### 1. Introduction

In spite of comprehensive establishment and upgrading of sewage-treatment plants, eutrophication of coastal waters has been steadily increasing during the last decades of the 20<sup>th</sup> century. Today it is generally admitted that excessive nitrogen loading is the principal factor causing algal blooms and oxygen deficiency resulting in bottom death in the marine environments in southern Sweden. Although the phosphorus (P) reduction in purifying plants

is much more effective than the nitrogen (N) reduction, the processes resulting in high and increasing N/P-ratio in lakes and streams has primarily been searched for in agricultural nitrogen fertilizing and from air-borne nitrogen originating from traffic and industrial processes. It is stated that anthropogenic phosphorus mainly originates from households and industry, while nitrogen mainly stems from wash out of excess fertilizer from agricultural soils (*Hansen et al., 2001*).

Every successful farmer knows that a good harvest depends on the mutual composition of the nutrients N, P and potassium (K), and, consequently, that if one of these components is lacking, then the harvest will be reduced. A limiting nutrient may restrict the growth. This imports that optimal nutrient conditions are prevailing close to an N/P-weight ratio of 7. Successful reduction of P in the purification plants has increased the N/P-ratio in lakes and, as a result of this, reduced eutrophication in limnic environments. However, the increased ratio means that because of P deficiency a lot of N remains in the water volume. This surplus of nitrogen can not be utilized, neither in primary production nor in denitrification, at least in oxygen-rich water. Instead it may be transported to the sea through the watercourses. The remaining problem is still how to handle this.

In freshwater, eutrophication has been limited through wastewater treatment plants. Their effective reduction of P, in comparison with N, transformed P to the limiting factor in freshwater. However, in saline water, N is considered to be the limiting factor for a primary production causing eutrophication. This change seems to have confused the conceptions behind the different processes. In both cases, however, high concentrations of the non-limiting nutrient may be insignificantly reduced or utilized in primary production.

Results from the Swedish Environmental Agency research program *Wetlands and Lakes as Nitrogen Traps*, aimed at a reduction of the nitrogen transport in the farmland streams to the sea, is summarized in 1994 (*Jansson et al., 1994*). It is argued (i) that nitrogen removal must rely on denitrification, (ii) that lakes are the most efficient nitrogen traps and (iii) that ponds are the best alternative for nitrogen removal. In this research program aimed to halt nitrogen loading, the attention was only focused on the nitrogen loading without regard to the importance of the prevailing phosphorus concentration. This may explain some uncertainties in a clear understanding of the processes involved (*Kessler & Jansson, 1994*) and especially the conclusion that denitrification is the principal process in nitrogen traps.

In this study, the aim has been to reveal further knowledge from collected – but so far too sparsely worked up – sampling data. A new approach has been to establish the importance of the N/P-ratio in the explanation of optimal primary production conditions giving rise to algal blooms. Thus, the prerequisite, both in limnic and saline environments, is that high algal primary production may enter when neither N nor P is limiting (N/P weight ratio ~ 7 or the corresponding atomic ratio ~ 16), but when both are abundant. Since the society has failed to counteract the eutrophication problems by chemical and technical methods, the idea has been that a more detailed penetration into the ecological processes behind should facilitate the discovering of a corresponding solution. This should contemporaneously make it possible, not only to eliminate harmful effects in one ecosystem without destroying another, but it should also render it possible to make use of the available nutrients in both.

## 2. Study area and methods

Available data from monthly sampling by Göta Älvs vattenvårdsförbund (*Göta älvs Vattenvårdsförbund, 1995-2002*) at a number of sampling stations in parts of the catchment area of the River Göta Älv (Fig. 1) are studied. Samples were taken in the river water of Göta Älv (A-E), in rivulets running into Lake Hullsjön (a-b) and into the River Göta Älv (c-g) and in running water from in- and outlets to lakes and other parts of the River Sävån (1-16). The

figures are put together as mean values during the two 4 year-periods 1994-1997 and 1998-2001 on total N and total P concentrations (Fig. 2-3). Published data (*Selmer & Rydberg, 1993*) are used to evaluate the processes in the estuarine environments from the central city of Göteborg out to the Dana Fjord (Fig. 1: F-I).

Available data are utilized to evaluate processes affecting nutrient status and the mutual relations (N/P-ratio) between these two indispensable components in the primary production of organic matter created by photosynthesis. More knowledge about the ecological processes along the watercourses with different types of human influence is necessary to comprehend processes in the sea. In such comparisons, momentary concentrations (e.g.  $\text{mg L}^{-1}$  or  $\mu\text{mol L}^{-1}$ ) give more valuable information than annual removal, transport and deposition (e.g.  $\text{tonnes yr}^{-1}$ ), especially when the watercourses reach the sea.

### 3. Atmospheric input of nitrogen

**Lake Säven** (Fig. 1: 1), the source-lake of the **Rivulet Säveån**, lies in an oligotrophic and less populated area 155 m above sea level. Thus, this lake is expected to be less affected by both agricultural and municipal effluents, which is evident from the low P-content (0,009 and 0,011  $\text{mg L}^{-1}$ , ranging between 0,006 and 0,017, Fig. 3c: 1). Although the N/P-ratio is high (74 and 61, Fig. 3a: 1), the N-content (0,582 and 0,591  $\text{mg L}^{-1}$ , Fig. 3b: 1) is the lowest noted for this watercourse on its continued way to the sea (Figs. 1: 1-16, E-F, 3b: 1-16 and 2b: E-F). This may indicate that air-borne nitrogen is of minor importance when compared with sampling stations at lower levels affected by agriculture and discharge from sewer purifying plants in more densely populated communities. In this comparison it is provided that air-borne N is evenly deposited over large land areas, where a certain part of it is utilized in biological primary production, whereas N from the other two origins usually are swiftly transported in culverts and water courses to lakes and to the sea. However, that part of the air-borne N that reaches the source-lake constitutes an almost tenfold surplus of which only 1/10 can be used in the oligotrophic and P-poor lake water. In this way, the N-transport to the sea has started – already in the source-lake.

This may be compared with three ultra-oligotrophic – oligotrophic lakes in a sparsely populated mountain and heathland area in southwestern Norway (*Berge et al., 1997*) where the P-concentration ranged from 0,002 to 0,006  $\text{mg L}^{-1}$  and the N-concentration from 0,324 to 0,441  $\text{mg L}^{-1}$ . The corresponding N/P-ratio varied between 183 and 74. The authors conclude that high nitrogen retention is not to be expected unless the N/P-ratio is close to the proportional needs for the aquatic plants.

### 4. Nutrients from agriculture

**The Rivulet Mellbyån** is a branch of the Rivulet Säveån (Fig. 1: 6) and opens into Lake Anten together with **the Rivulet Lobäcken** (Fig. 1: 7). Both originate from agricultural areas, which is obvious from the high contents of P (0,094  $\text{mg L}^{-1}$ , both periods, Fig. 3c: 6; 0,073 and 0,110  $\text{mg L}^{-1}$ , Fig. 3c: 7). Even the N-content is high (1,921 and 1,888  $\text{mg L}^{-1}$ , Fig. 3b: 6; 1,672 and 1,972  $\text{mg L}^{-1}$ , Fig. 3b: 7). The low N/P-ratios (21 and 20, Fig. 3a: 6; 25 and 18, Fig. 3a: 7) indicate a strong influence from agricultural runoff.

In **Lake Anten** (18  $\text{km}^2$ , 66 m above sea level, Fig. 1: 8), a considerable reduction of both P (0,017 and 0,022  $\text{mg L}^{-1}$ , Fig. 3c: 8) and N (0,669 and 0,726  $\text{mg L}^{-1}$ , Fig. 3b: 8) has occurred. This process may be explained as a result of high primary production. This is made possible by high concentration of both nutrients at almost optimal ratios. The increased N/P-ratio (to

39 and 33, Fig. 3a: 8) indicates that proportionally more P than N of the available nutrients is used up, which may be expected in the production of planktonic biomass. When this is sinking to the bottom, bacterial decomposition is reducing the oxygen, creating an oxygen deficiency at the bottom of this 26 m deep lake. This rather big lake constitutes as a nutrient trap that has still the capacity to store more nutrients in its sediments, but at the expense of hypolimnetic oxygen deficit in the deeper parts. So far, abundant oxygen production through phytoplanktonic assimilation in the euphotic zone in combination with exposition from dominating southwesterly winds preventing thermal stratification may supply conditions that neither release P nor favour denitrification. If the mean contents of the two inflows (6 and 7) during both periods are compared with the corresponding values in the outflow, the N-contents is reduced by 62,6 % and the P-contents by 79,0 %.

The small **Lake Ålandasjön** (depth 18 m) downstream Lake Anten (Fig. 1: between 8 and 9) has totally collapsed since many years. The nutrient trap is filled. Released P from the sediments (from 0,017 to 0,023 and from 0,022 to 0,025 mg L<sup>-1</sup>, Fig. 3c: 8→9,) is leaving the lake with the water in the outflow to the next lake. The insignificant N-reduction (from 0,669 to 0,652 and from 0,726 to 0,717 mg L<sup>-1</sup>, Fig. 3b: 8 and 9) could possibly be a combination of denitrification and primary production, where some of the released P from the sediments is reused and the remainder is leaving the lake in the outflow. The present conditions with oxygen deficit below 4-5 m and with hypolimnetic oxygen depletion below 14 m (*Göta älvs Vattenvårdsförbund, 2001*) constitute the presumption for both processes. The fairly low N/P-ratios may allow some nutrient uptake, but this is negligible when compared with Lake Anten, where the initial concentrations were much higher.

**Lake Hullsjön** (88 m above sea level) is another newly collapsed lake in an agriculture area. This shallow lake had earlier a rich bird life. However, a comprehensive supply of both P and N with a favourable N/P-ratio in two inflows (Fig. 1 a and b) has caused a heavy primary production with accompanying oxygen deficiency and reduction of both fish and invertebrate populations that were earlier used by birds. The increased outflow of P (maximum 0,355 mg L<sup>-1</sup> in 1998, Fig. 4c: c) through the Rivulet Stallbackå (Fig. 1: c) compared with the maximal input year 2001 (0,226 mg L<sup>-1</sup>, Fig. 4c: b) indicates an extensive release of P from the sediments. When mean values of the two inflows (a and b) are compared with the outflow (c) in which the P-concentration increased with 78,0 %, the N-concentration was reduced by only 3,4 %. This indicates that this overfilled nutrient trap, from which P is leaching, in addition, is a negligible nitrogen trap, since the reduced N/P-ratio (-46,4 %) is primarily a result of increased P-output.

Input of both nitrogen and phosphorus into rivulets from agriculture areas show peaks in early spring and in autumn (Fig. 5). This tendency is less pronounced in areas with restricted cattle breeding (Fig. 1: f and g), when compared with the agricultural region around Lake Hullsjön. This coincides in time with periods when liquid manure is usually spread on the fields in quantities that the vegetation may have restricted possibilities to absorb before the nutrients are washed out by rain. This exemplifies how restrictions and recommendations to counteract eutrophication may get the opposite function.

## 5. Municipal nutrients

The sampling stations 2-5 in the River Sävån (Fig. 1) are influenced by water from wastewater treatment plants in built-up areas like Vårgårda and Alingsås. When compared with the oligotrophic water from the up-stream source-lake Säven, this water, affected by municipal nutrients, is characterized by much higher N-loading (up to 2,1 mg L<sup>-1</sup>, Fig. 3b). But, the P-loading is lower than in pure agriculture areas (Fig. 3c). This is a result of P-reduction in the purifying plants.

In Fig. 6, it is shown how a complementary establishment of chemical precipitation in the Rya waste water purifying plant, situated just down-stream the sampling station F (Fig. 1), has changed the N/P-ratio. During the early period 1975-1983, the mean N-content ( $18,478 \text{ mg L}^{-1}$ ) and P-content ( $3,256 \text{ mg L}^{-1}$ ) gave the N/P-ratio 5,7. After chemical treatment, during the period 1988-1999, the P-content was reduced with 87 % to  $0,434 \text{ mg L}^{-1}$ , whereas the N-content only was lowered with 1,2 % to  $18,258 \text{ mg L}^{-1}$ . This increased the N/P-ratio from 5,7 to 42,1. This rough level, half between air polluted (Fig. 3a: 1) and agriculture polluted (Fig. 3a: 6 and 7) water, may indicate strong influence from municipal nutrients.

## 6. Lakes as nutrient traps

Lake Mjörn ( $55 \text{ km}^2$ , 58 m above sea level, depth 48 m, Fig. 1) receives water from two inflows. Water from the River Sävån (Fig. 1:5) has high contents of N ( $1,942$  and  $1,470 \text{ mg L}^{-1}$ , Fig. 3b: 5), but reduced levels of P ( $0,041$  and  $0,033 \text{ mg L}^{-1}$ , Fig. 3c: 5). This gives high N/P-ratios (48 and 46, Fig. 3a: 5) characteristic of influence from wastewater purifying plants. Water from the rivulet Mellbyån (Fig. 1: 9) has passed the nutrient traps Lake Anten and Lake Ålandasjön. Though the latter is leaching nutrients, the affluent to Lake Mjörn has low contents of both N ( $0,652$  and  $0,717 \text{ mg L}^{-1}$ , Fig. 3b: 9) and P ( $0,023$  and  $0,025 \text{ mg L}^{-1}$ , Fig. 3c: 9). The increasing N/P-ratio after Lake Anten (39 and 33, Fig. 3a: 8) is reduced in Lake Ålandasjön (29 and 30, Fig. 3a: 9), probably as a result from P-leaching from the sediments.

The big Lake Mjörn seems to be an efficient nutrient trap of both N ( $0,898$  and  $0,958 \text{ mg L}^{-1}$ , Fig. 3b: 10) and P ( $0,010$  and  $0,011 \text{ mg L}^{-1}$ , Fig. 3c: 10). However, if the mean contents of the affluents during both periods are compared with the corresponding values in the outflow, the P-content is more effectively reduced (65,6 %) than the N-contents (22,4 %). This comparison is complicated because of the different types of nutrient content and without information about the hydraulic load. In Fig. 7, the two inflows to Lake Mjörn (Fig. 1:5 and 9) are treated separately but with the same outflow from the lake. This also illustrates a more efficient uptake of P than of N, the high levels of which are maintained until the Rivulet Sävån enters the River Göta Älv (Fig. 3: 10-16). This explains the increased N/P-ratio (91 in both periods, Fig. 3a: 10). The effective uptake of P, whether a result from a long water renewal time or from high N- concentration, results in a P-concentration similar to that in the oligotrophic source-lake Säven.

**Lake Sävelången** and **Lake Aspen** (Fig. 1, between 12 and 13) show small deviations from Lake Mjörn with regard to N, P and N/P in the outflow (Fig. 7a-b, d). Otherwise, Lake Sävelången shows some conformity with Lake Ålandasjön by release of P in some years, which indicates that even this lake is a nutrient trap that may be filled in a near future. Lake Sävelången also corresponds to Lake Ålandasjön through a tendency towards restricted uptake of both N and P when compared with other lakes (Fig. 7c). Lake Aspen is supplied with some nutrients, in particular P (Fig. 3c: 12) which increased with 45,7 % during the 8 year-period, in the water flow between the sampling stations 11 and 12. According to the low N/P-ratio (13,2), this may be deduced from agricultural influence. However, Lake Aspen, which is lacking signs of oxygen deficiency, still has capacity to reduce the P-content (Fig. 7c) down to the levels ( $0,008$ - $0,013 \text{ mg L}^{-1}$ ) obtained in Lake Mjörn ( $0,008$ - $0,015 \text{ mg L}^{-1}$ ) through uptake (Fig. 7c) in primary production. In this way the N/P-ratio is restored.

**Lake Vänern** ( $5425 \text{ km}^2$ , 46 m above sea level, depth 98 m, Fig. 1), the biggest lake in Sweden and the 3<sup>rd</sup> biggest in Europe, shows the same character as a nutrient trap (Fig. 2A) as is shown by Lake Mjörn and Lake Aspen. The mean N-concentration in the outlet from Lake Vänern during the 8-year period ( $0,811 \text{ mg L}^{-1}$ , range  $0,754$ - $0,861$ ) is lower than that of Lake Mjörn ( $0,928 \text{ mg L}^{-1}$ , range  $0,857$ - $0,992$ ) and Lake Aspen ( $0,951 \text{ mg L}^{-1}$ , range  $0,855$ - $1,007$ ).

Moreover, this level is decreasing in Lake Vänern (Fig. 2b: A) but increasing in the other two lakes (Fig. 3b: 10 and 13). The corresponding P-concentration in Lake Vänern (0,012 mg L<sup>-1</sup>, range 0,009-0,015) is insignificantly higher than that of Lake Mjörn (0,011 mg L<sup>-1</sup>, range 0,008-0,015) and Lake Aspen (0,011 mg L<sup>-1</sup>, range 0,008-0,013). The levels are declining in Lake Vänern (Fig. 2c: A) and are stable (0,011 mg L<sup>-1</sup>) in the other lakes (Fig. 3c: 10 and 13). As a consequence of this, the N/P-ratio is rising in Lake Vänern (from 62 to 76, Fig. 2a: A). The present N- and P-concentration in the principal part of Lake Vänern (0,8 and 0,006-0,008 mg L<sup>-1</sup> [6]) gives the much higher N/P-ratio 100-133. This indicates that P from the effluents surrounding the big lake is reduced to a higher extent than N. This may also be compared with Lake Vättern, the second largest lake in Sweden (1900 km<sup>2</sup>, 88 m above sea level, depth 128 m), where the N- and P-concentrations (0,7-0,8 respectively 0,004 mg L<sup>-1</sup> (Bengtsson & Hallerstig, 2003) give the N/P-ratios 175-200.

The oligotrophication of lakes through an increasing N/P-ratio imports a reduced primary production. This was also the primary aim in order to reduce overgrowth and eutrophication of lakes. However, reduced planktonic primary production entails reduced food abundance to primary consumers. This is exemplified by the glacial relict amphipod *Monoporeia affinis*, which has shown large population fluctuations in both Lake Vänern and Lake Vättern in relation to phytoplankton biovolume at a 1-yr-lag (Goedkoop & Johnson, 2001). A reduction of primary consumers also affects the next step in the food chain, the secondary consumers, e.g. fish.

## 7. Nutrients in water courses

In the lower parts of the River Göta Älv (Fig. 2c: C-E) and the Rivulet Sävån (Fig. 3c: 13-16), the P-concentration is increasing towards the river mouth, whereas the N-concentration is more stable. This can neither be explained as an effect from air pollution nor from municipal nutrients. The municipal sewage from the communities all round about the city of Göteborg is brought to the common Rya purifying plant (Fig. 6). Nor can agricultural discharge have caused this supply from densely populated areas (Fig. 5: f-g compared with a-d). The diverging concentrations during the second period at station F (Fig. 2: year 98-01) close to the discharge from the Rya wastewater treatment plant may be explained by increased efficiency in the treatment processes (Fig. 6).

There are at least two possible explanations of this increase of P in the two watercourses. One is the release of P from filled nutrient traps. Another is release of P from digested sludge, whether utilized as fertilizer or as loading material when mixed with soil, sand or peat. The N/P-ratio of digested sludge is ~ 1,8, which imports that a surplus of P may be released at rainfall as leaching because it is not used in primary production as a result of N-deficit.

## 8. The estuary

Four different water currents affect the outlet of the River Göta Älv and its estuary from the bridge Göta Älvbron (Fig. 1: F and Fig. 8) out to the Dana Fjord (Fig. 1: I). At station Göta Älvbron (Fig. 8) and station E (Fig. 2) up-stream station Lindholmen (Fig. 8), the surface water is still almost pure freshwater, unaffected by saline water at the sampling period about year 1990 (Selmer & Rydberg, 1993). This river freshwater is characterized by a high N/P-ratio (=37), which, however, is only half of that registered at the outflow from Lake Vänern (Fig. 2a: A). The reduced N/P-ratio in the river freshwater is entirely a result of the increased supply of P along the river (Fig. 2c: B-D).

The second current is a saline compensation or reaction current running along the bottom up-stream the river. This saline current has a low N- but a high P-concentration resulting in a low atomic N/P-ratio (Fig. 8). The atomic ratio, close to the optimal level (N/P=16), should favour phytoplanktonic primary production, but this is impeded by light deficiency through the turbid surface freshwater. The saline bottom water is gradually mixed with the freshwater outflow, which in this way successively gets a higher salt content but also a higher P-concentration on its way out into the archipelago.

After station F (Fig. 1) the N/P-ratio is rising again as a result of the third current, from the Rya wastewater treatment plant (Fig. 6). This water has a high N-concentration, which affects the surface water from station F to station H. This is obvious through a higher concentration of ammonia-N that reaches its highest level at station G. Reduced eutrophication conditions reported from the Älvsborg Fjord (between stations F and G) may thus be explained by reduced production of filamentous macroalgae as a result of lowered output of P from the wastewater treatment plant (Fig. 2c: F).

Similar results are reported from the Stockholm archipelago, where the water quality now appears to be better than 100 years earlier (*Johansson & Wallström, 2001*). In both cases an estuarine oligotrophication seems to give rise to reduced eutrophication, which, however, is removed towards the Sea. In the city of Malmö, a solution of the local problem was obtained through a discharge of the wastewater into the Sound of Öresund (*Olsson, 2001*), and consequently to the Baltic Current. The high N/P-ratio and a high ammonia/nitrate-ratio (*Selmer & Rydberg, 1993*) in the Göta Älv estuary may be maintained through a low phytoplanktonic primary production of oxygen. The skewed N/P-ratio that strengthens the prevailing P-limitation both in Norwegian oligotrophic lakes and in riverine runoff in nearshore marine areas (*Hessen et al., 1997*) has its analogy in Sweden and imports a development towards oligotrophication.

## 9. The sea

The Baltic surface current running northwards along the Swedish West Coast is the fourth current that affects the river water. This brings the N-rich surface water in Dana Fjord (I) further, north together with the same type of water from the Nordre Älv Fjord (Fig. 1), which, moreover, has a three times higher hydraulic load. The present high N/P-ratio 40 in the Göta Älv outflow (Fig. 2a: F, year 98-01) corresponds to the landbased estimated mean nutrient load in the 1990s to the upper layer of the Skagerrak from Sweden (ratio 39,0, from tonnes yr<sup>-1</sup> (*Hansen et al., 2001*: Figure 2.2)). This is the highest ratio level given around the Skagerrak but close to the value from the Oslo Fjord area (ratio 37,4), which thus indicate that both are affected primarily by municipal wastewater treatment plants. The corresponding ratios from the inflow from Kattegat (ratio 20,3) and northern Jutland (ratio 16,9) should, in consequence of the given results, indicate a higher influence from agricultural runoff.

It is reasonable to assume that the lowering of the N/P-ratio, started in the two river estuaries, as a result of mixing with P-rich bottom water, is proceeding as the water currents are running northwards both in and outside the archipelago. Especially in the archipelago and the fjords, where P may leach from oxygen depleted bottoms, just as in filled freshwater nutrient traps, this process may be favoured. When the N/P-ratio is approaching the optimal level in the euphotic zone further northwards, then production of phytoplankton and filamentous algae will possibly increase. This is confirmed by noted chlorophyll *a* maxima in the fjords inside the islands Orust and Tjörn (*Hansen et al., 2001*: Figure 2:10). Even planktonic and floating filamentous macroalgae produced near the estuaries are brought northwards, before they sink and give rise to new or add force to existing bottoms. In this way

the oxygen deficit (*Hansen et al., 2001*: Figure 2:19) allows organic P to be reverted to inorganic P. A reinforced P-circuit is growing up. This may maintain the eutrophication, just as in the freshwater nutrient traps.

## 10. Discussion

The results obtained do not prove that nitrogen removal must rely on denitrification (*Jansson et al., 1994*). The most efficient nitrogen uptake is noted in Lake Anten, and this happens when the N/P-ratio is low and makes high phytoplankton production possible. The increasing N/P-ratio in the outlet, indicating that P is more effectively utilized than N, also supports the assumption that denitrification is of minor importance.

The second postulate (*Jansson et al., 1994*), still generally accepted in Sweden (*Steineck et al., 2000*:17), that lakes are the most efficient nitrogen traps, may also be disputed. Both smaller (Aspen, between 12 and 13) and bigger lakes (Mjörn, Vänern and probably Vättern) are inefficient nitrogen traps. And they are all characterized by a high N/P-ratio. Once a lake has obtained a high N/P-ratio, large quantities of P are required to reduce this ratio, and consequently to reduce the N-transport to The Sea. Though the River Göta Älv obtains a lot of P along its flow between Lake Vänern and The Sea resulting in increasing P-contents and a declining N/P-ratio, the N-content is still insignificantly reduced. Neither primary production nor denitrification is obviously efficient in the turbid river water.

The third postulate (*Jansson et al., 1994*) that ponds are the best alternative for nitrogen removal, may be considered in comparison with the small collapsed lakes (Hullsjön and Ålandasjön) but also with bigger lakes (Anten and Sävelången) that show earlier stages of cultural eutrophication. When the balance between the trophic levels in a lake or a pond is broken, then a collapse may rapidly enter. The pond/lake is supplied with both plant tissues (phytoplankton in the first trophic level) and oxygen in the euphotic zone. But, when the grazers in the consumer level are not longer able to make use of an abundant rain of organic material from the first level, then their consumer rôle is taken over by bacteria, which utilize oxygen and may cause oxygen depletion. In a shallow lake/pond the oxygen content is more rapidly reduced than in a deeper lake of the same size and with the same depth of the trophogenic zones (*Wetzel, 1975*:138). The capacity of the lake ecosystem to handle the added vegetative biomass depends on lake size and consequently on the water renewal time. However, it also depends on the possibilities of the secondary production in the food chains.

The comparisons performed in this study prove that it is necessary to take both nitrogen and phosphorus into consideration when trying to explain the factors that govern eutrophication. This is still more important when trying to find methods to counteract these processes both in limnic and saline environments. However, the simple parameter N/P necessitates that at least total N and total P are sampled. Ammonia-N, nitrate-N and phosphate-P are also valuable parameters when trying to confer the water quality. When supplied with these parameters it is possible to distinguish between three principal types of water: (i) source-lake water affected by atmospheric input, (ii) input from agriculture and (iii) municipal input. Though decision-makers are well aware of the stated bad situations, they have, so far, failed to find effective solutions when trying to take consideration even to other economic interests. As a consequence of this, effects from domestic effluents are usually considered to be of less importance than agricultural runoff and atmospheric input.

Although it is admitted that the supply of nitrogen is the principal factor behind eutrophication in the marine environment, no effective restrictions are prescribed concerning the concentration of nitrogen in the discharge from small, municipal wastewater treatment plants. However, the Swedish Parliament has assumed 15 new environmental quality goals,

one of which prescribes that the present marine eutrophication should be eliminated at 2027 through reestablishment of conditions prevailing in the 1940s (*Naturvårdsverket*). In order to achieve these conditions, regional authorities (*Bengtsson & Hallerstig, 2003*) have suggested a maximum concentration of 15 mg N and 0,3 mg P L<sup>-1</sup> in effluents from wastewater treatment plants. This maintains the skewed N/P-ratio 50, but, nevertheless, the N-concentration in Lake Vänern is expected to be reduced by 25%.

Even large treatment plants with long waste pipes become ineffective when the effluent is diluted through leakage. The comparison between domestic effluents and agricultural runoff in the Rivulet Sävån shows that as soon as the natural/optimal N/P-ratio is skewed through P-deficit, then it is difficult to restore. Neither healthy nor collapsed lakes are effective nitrogen traps in such situations. The oxygen deficit in collapsed lakes is even hampering denitrification.

Agricultural runoff with optimal N/P-ratio is rapidly converted to primary production, and both nitrogen and phosphorus are effectively reduced, when entering open water with sufficient renewal time (Lake Anten). However, if the discharge is heavy, if the water surface is restricted and if the euphotic zone is narrow (Lake Hullsjön), then – sooner or later – eutrophication is rapidly converting the water body to a filled nutrient trap. Then the nutrient trap has to be dredged. This is possible with settling basins after a wastewater treatment plant but hardly with a lake. Then another problem is arising. The dredged material, just as the digested sludge, has a low N/P-ratio and may be leaching P towards the sea.

As recommended (*Jansson et al., 1994*), lots of ponds and minor lakes, denominated wetlands, have been built (*Svenland, 1998-2001*) according to the earlier perceptions. They are usually constructed through banking up rivulets down-stream agriculture areas where nutrients are diluted to diffuse non-point sources that are expected to require large water bodies to reduce nutrients. Future sampling and valuation of their efficiency are expected but not planned.

## 11. Conclusion

A preconceived opinion that the eutrophication along our coasts is caused by sea currents from far (*Steineck et al., 2000; Bengtsson & Hallerstig, 2003*) must now be rejected. Nutrients in coastal surface currents are swiftly used up, and saline estuarine compensation currents (including to the Baltic current) may also contain phosphorus from adjacent dead bottoms.

New ecologically adapted methods are required to counteract the gradual progression of the cultural eutrophication in our coastal areas. Our efforts to re-use phosphorus that is a finite resource have not been successful. This eutrophication element is inflexibly finding its way to the sea, where it is brought together again with the nitrogen that we succeeded to separate in our wastewater treatment plants.

It is time to find methods without separation of the two nutrients. We have to utilize the possibilities of growth-limiting nutrients to be swiftly used up at an optimal N/P-ratio through photosynthetic activity before they are diluted and before they reach the Sea. Where possible, we have to prevent point sources to be diluted into non-point sources, when it is too late to get effective results.

At present, fish populations are reduced through oligotrophication of freshwater lakes (e.g. *Fall, 2002*) and through eutrophication of coastal waters, both as effects from increased N/P-ratios originating from municipal wastewater treatment plants. We have to find levels of an adaptation of nutrient reduction to the capacity of the receiving lakes in a drainage basin to furnish food chains for increasing fish populations. In the same way we have to restore the

effective nutrient-reducing ecosystems in estuarine environments. In the estuary of the River Göta Älv a series of basins is suggested to convert nutrients to waterfowl food in a Natura 2000-area (Pehrsson, 2001). The high productivity of such brackish and shallow environments imports a high nutrient reduction capacity. Similarly, we have to restore the ecosystems with rich fish populations in the fjords and in the archipelago that are now almost empty of fish when compared with earlier times. These suggested methods, considered to restore lakes and coastal areas, also make it possible to re-use the finite resource phosphorus in human fish food.

A new artificial wetland has been designed and checked (Pehrsson *in prep.*) during a 10-year period. It is effectively (> 90 %) transferring both municipal and agricultural nutrients to a biomass of food chains, through which both nitrogen and phosphorus may be dispersed to the surroundings. No nutrient rich sediments, as obtained through retention in a nutrient trap, have to be taken care of, but the created ecosystem has to be kept in an early succession stage. In this way few inorganic nutrient compounds are brought to the sea.

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**Key words:** Eutrophication, oligotrophication, nitrogen, phosphorus, N/P-ratio, lakes, water courses, estuary, sea.

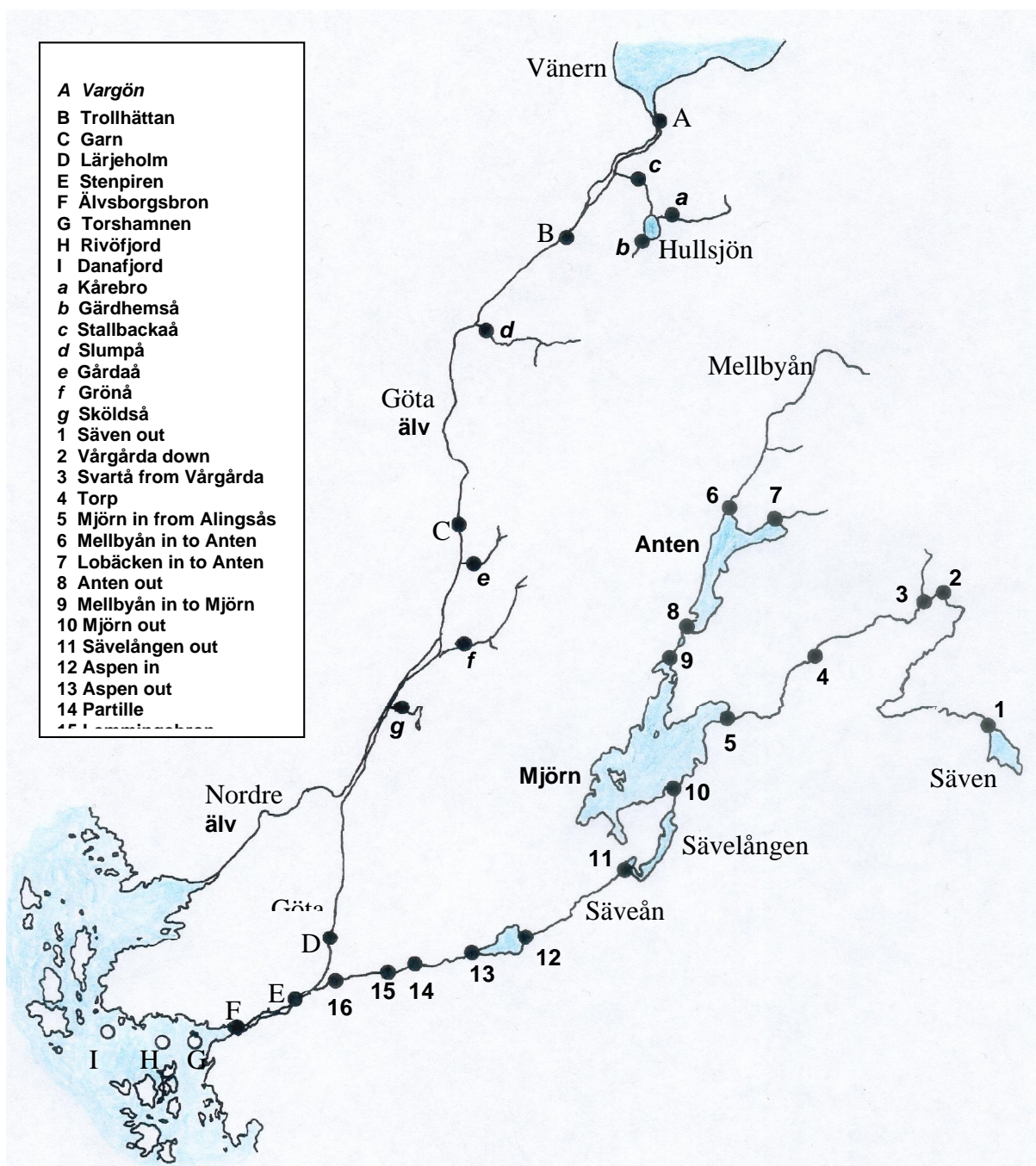


Figure 1. The study area with sampling stations in the River Göta älv between Lake Vänern and the Göteborg archipelago (capital letters), in the outflow to the River Göta älv from minor tributaries (small italic letters) and in the River Sävån (figures).

Figure 2. Nutrient concentration ( $\text{mg L}^{-1}$  of N and P) in the River Göta älv during the periods 1994-1997 and 1998-2001 at the sampling stations A-F.

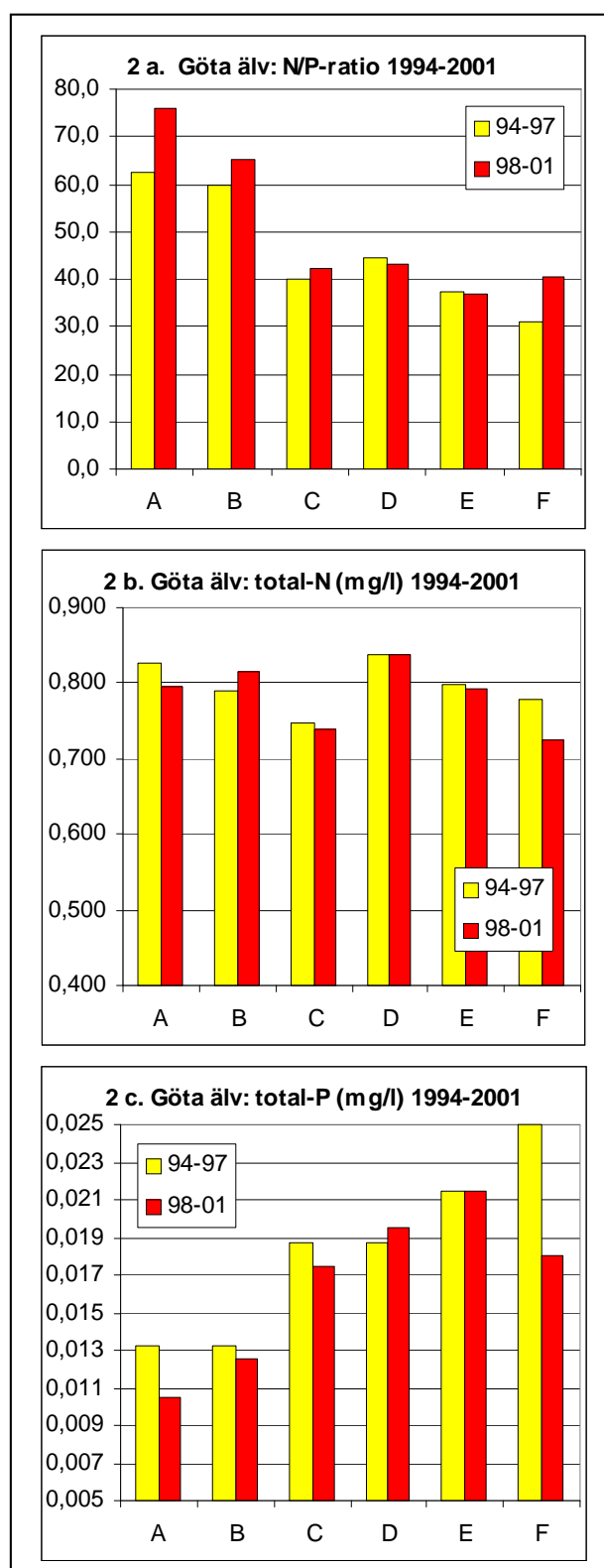


Figure 3. Nutrient concentration (mg N and  $P L^{-1}$ ) at sampling stations in the Rivulet Säveån (1-16) and in the River Göta älv (E) during the periods 1994-1997 and 1998-2001.

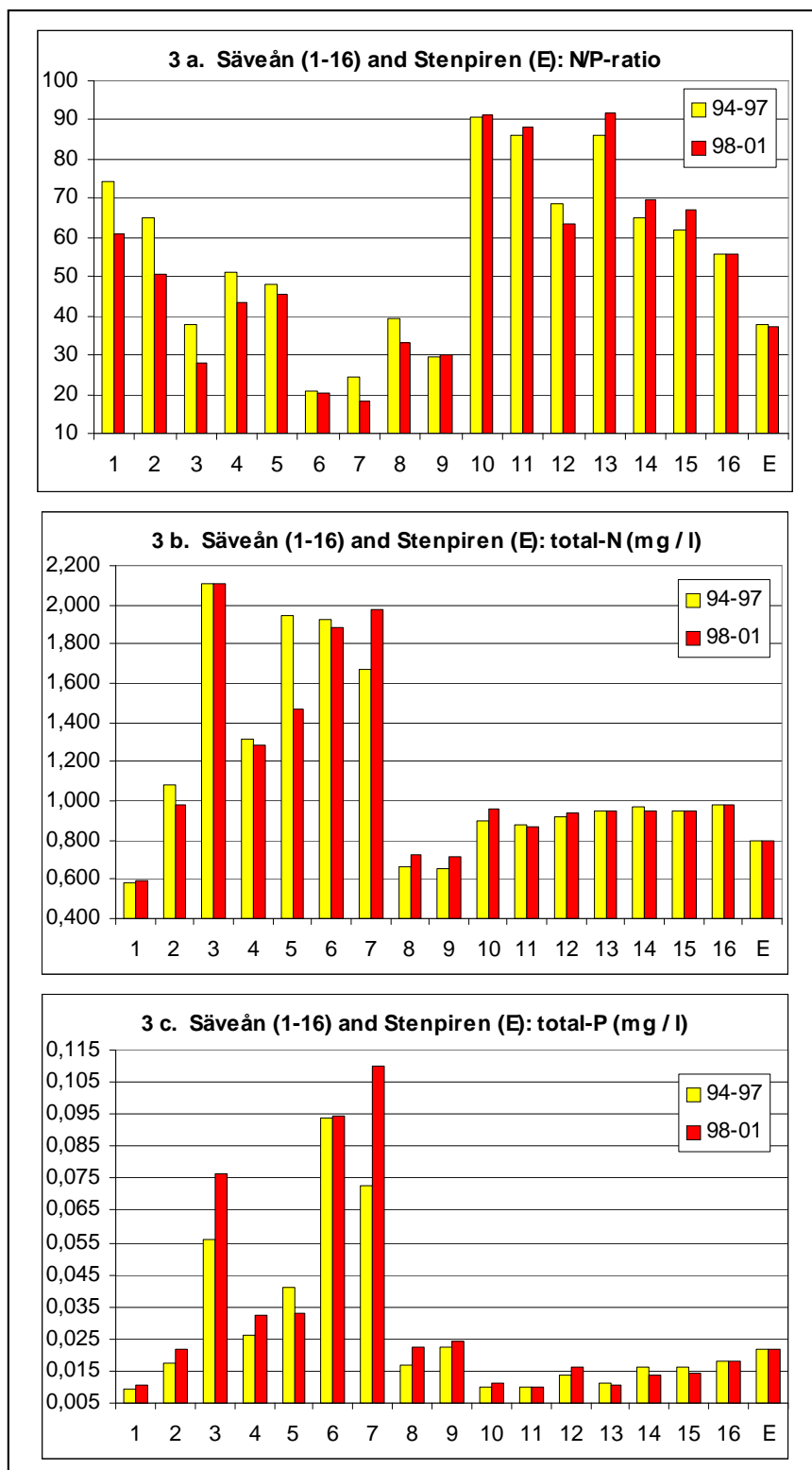


Figure 4. Nutrient concentration (mg N and  $P L^{-1}$ ) at sampling stations into (a and b) and out from (c) Lake Hullsjön into the River Göta älv from 1995 to 2001.

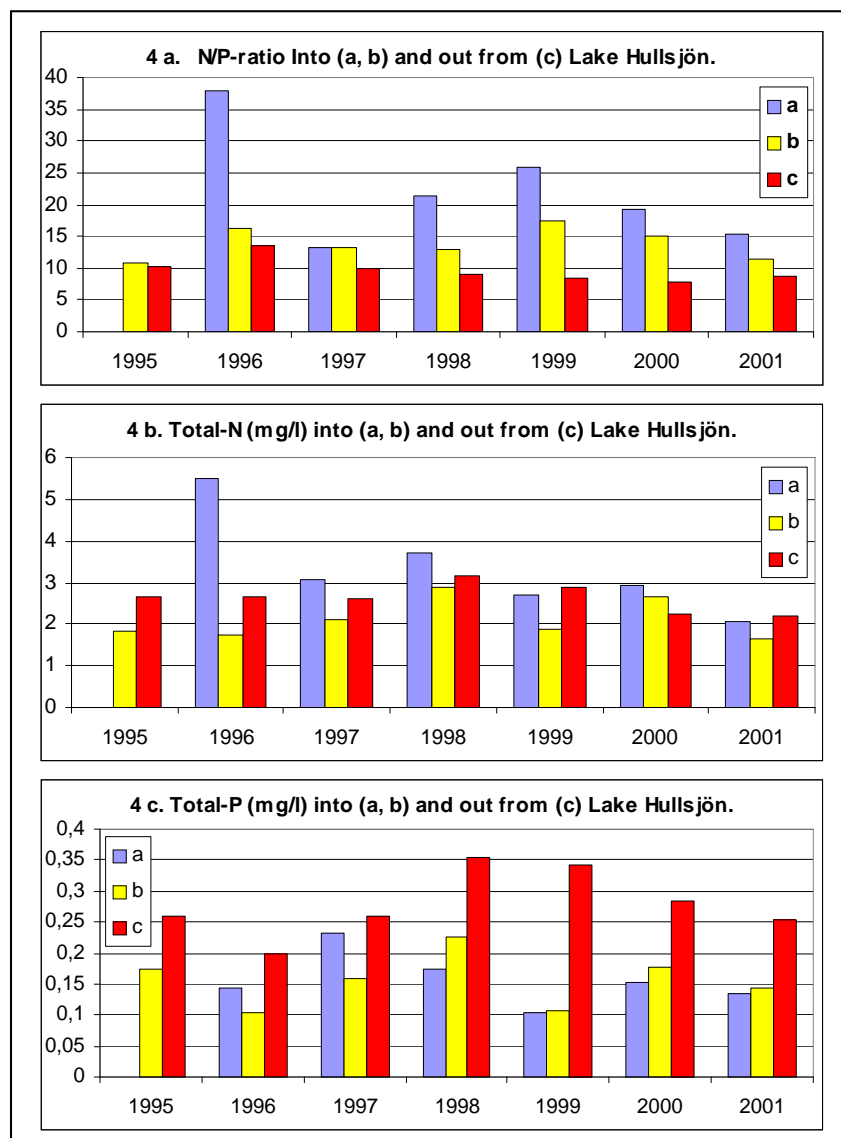


Figure 5. Nutrient concentration (mg N and P L<sup>-1</sup>) during a year (2001) in the outflow from the minor tributaries (a-g) showing higher values in spring and autumn.

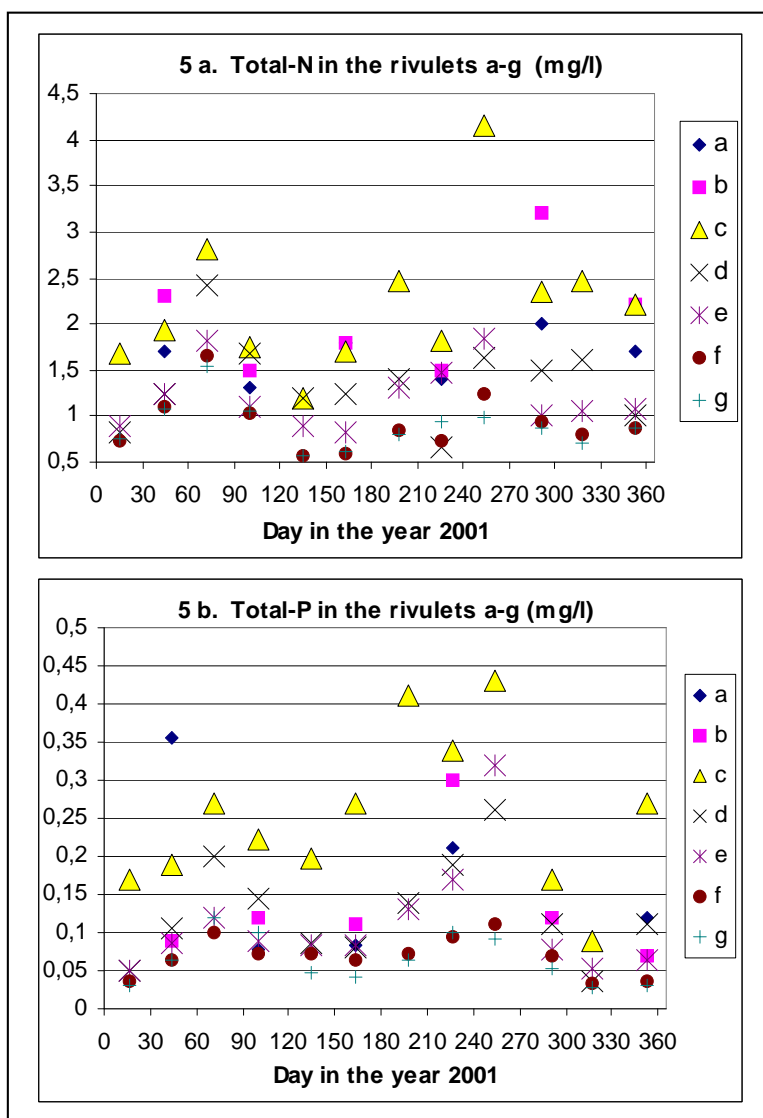
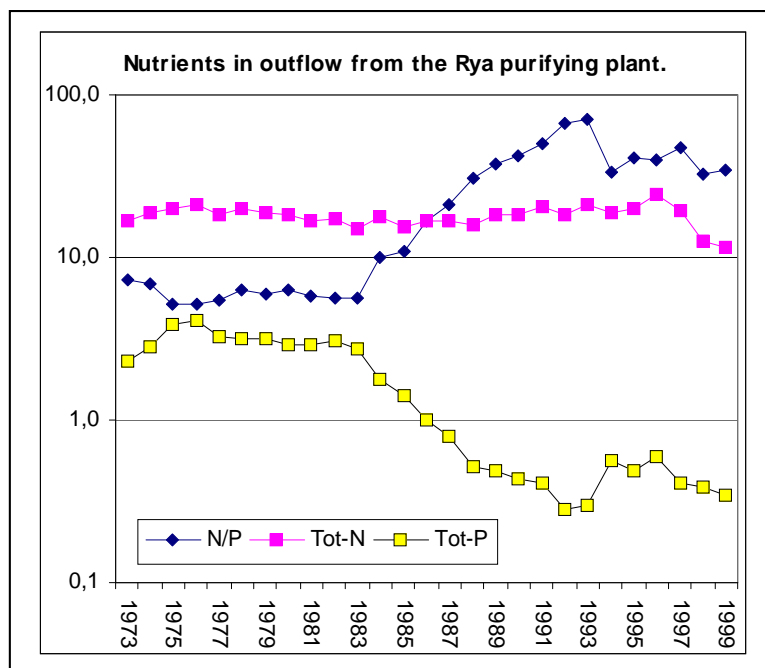


Figure 6. Total-nitrogen ( $\text{mg L}^{-1}$ ), total-phosphorus ( $\text{mg L}^{-1}$ ) and N/P-ratio in the outflow from the Rya purifying plant into the river water just downstream the bridge Älvsborgsbron (Fig. 1: F) from 1973 to 1999.



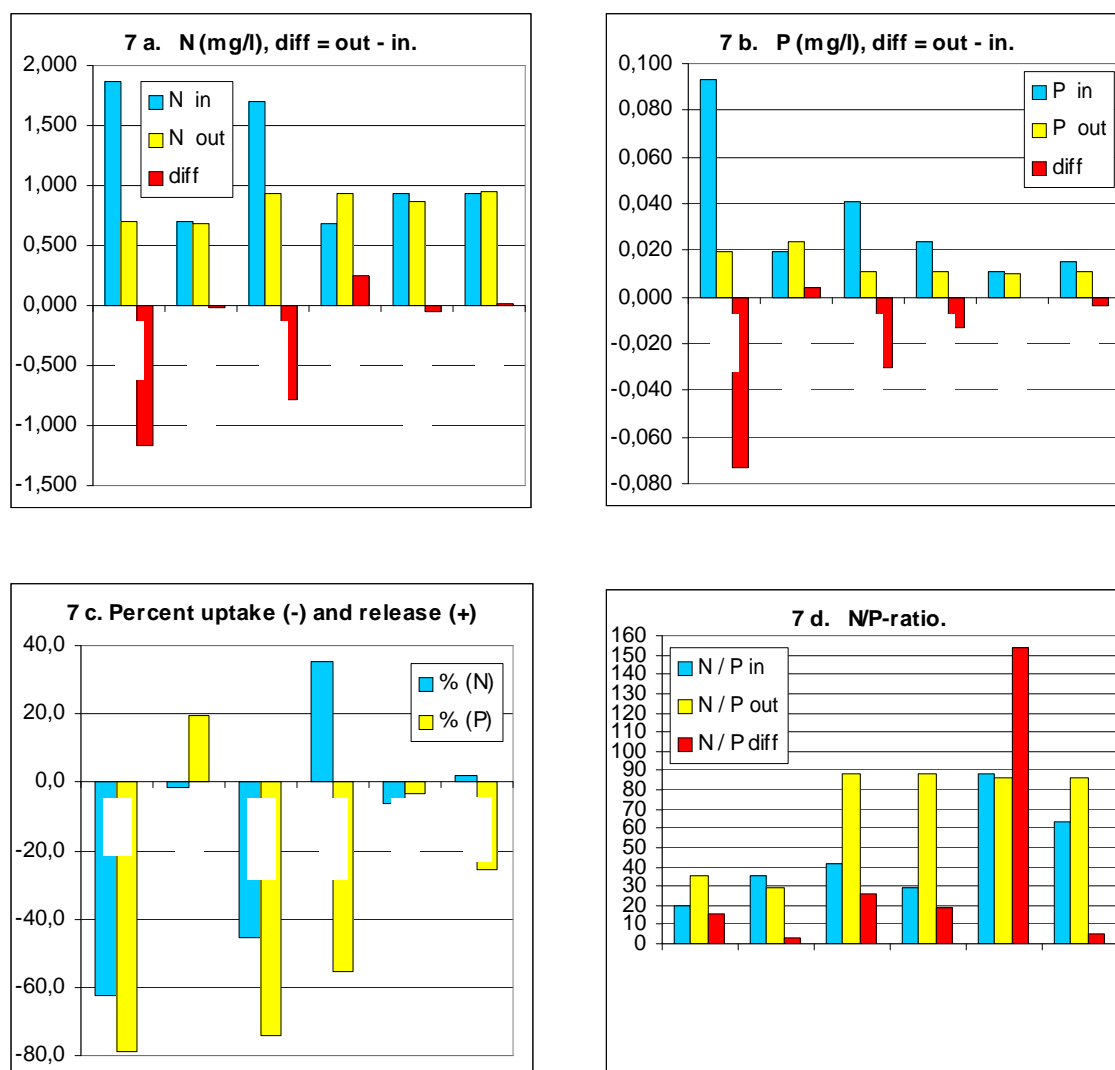
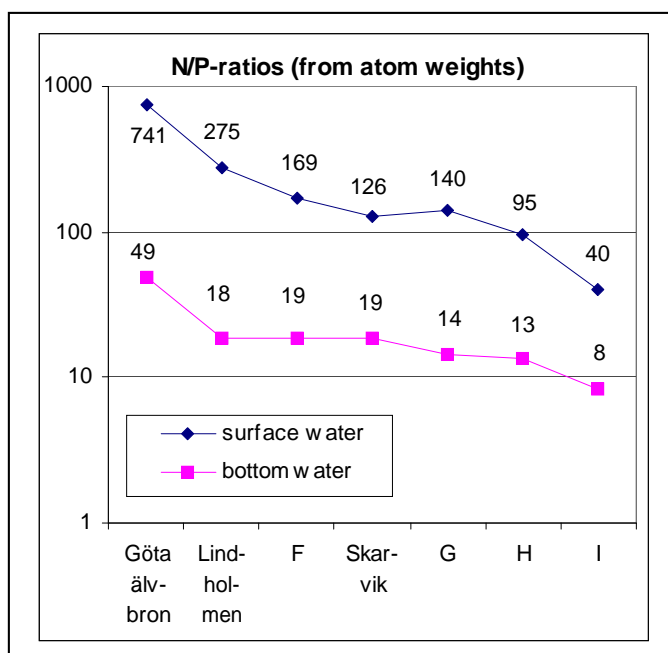


Figure 7. Total nitrogen ( $\text{mg N L}^{-1}$ ), total phosphorus ( $\text{mg P L}^{-1}$ ), N/P-ratio and the difference (diff) between out from and in to the lakes Anten, Ålandasjön (between 8 and 9), Mjörn, Sävelången and Aspen (between 12 and 13) in Fig. 1. The inflow values to Lake Anten are mean values of the two similar affluents 6 and 7, whereas the two qualitatively different affluents 5 and 9 to Lake Mjörn are shown separately but with the same outflow. Positive values of the difference between out- and inflow indicate an increase of both N and P in the water (release). Negative values may indicate an uptake of N through primary production and/or denitrification and of P through primary production and/or sedimentation.

Figure 8. N/P-ratios (atomic ratio) from measurements of  $\mu\text{mol L}^{-1}$  of ammonia-N + nitrate-N and phosphate-P in surface and bottom water (*Selmer & Rydberg, 1993*) on sampling stations down-stream E (Fig. 1) in the River Göta älv and its estuary. Optimal N/P-ratio = 16.



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