



UNIVERSITY OF
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Oxygen profiles and phosphorus content in two Ice-covered Lakes in Sweden



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Sammanfattning

Vintern 2010 var kall och ett lager av is och snö täckte sjöar även i delar av södra Sverige. Två grunda och näringsrika sjöar; Ellenösjön och Viksjön undersöktes i Färgelanda kommun i södra Sverige. Syre och fosforhalter mättes under isen i början av mars. Mätningar gjordes i sjöarnas djuphåla samt 5 mätpunkter längs en transekt på sjöarnas grundare delar.. Vattenprov i inlopp och utlopp togs i början och slutet av mars för analys av vattenkemi.

Borttaget: .

Is och speciellt ett tidigt snölager påverkar syrekoncentrationen negativt då algers fotosyntes stannar av utan ljus. Isen fungerar som barriär för diffusion av syre från atmosfären. Syrebrist är särskild uttalad i djuphålan av sjön och kan leda till att fosfor frigges från sedimenten med en försämring av sjöarnas näringsstatus till följd.

I början av mars hade sjöarna syrebrist och höga fosforhalter i djuphålan. Syrehalten var lite bättre i 5 mätpunkter längs en transekt på den grunda delen av sjöarna, men var fortfarande låga. Fosforhalter i inlopp och utlopp var också höga.

Fosforhalterna var extremt höga och sjöarna klassades som hypereutrofa. I Ellenösjön frigavs fosfor, medan Viksjön fungerar som fosforsänka. Ett samband med vinterns is- och snölager på sjön med låga syre- och fosforhalterna kan troligen existera.

Analys av halterna i Ellenösjön från 2000 – 2008 visade att Ellenösjön varit en fosforkälla i de flesta månader över åren. En neråtgående trend existerar för fosfor koncentrationen i Ellenösjön från 2000 – 2008 vilket indikerar att rådgivningsprojektet ”Greppa näringen” har haft positiv verkning och bör fortsättas. Denna nedåtgående trenden är något större för inloppet än för utloppet och Ellenösjön fungerar troligen som en fosforkälla och åtgärder för att minska den interna källan behövs för att minska läckaget av fosfor från Ellenösjön nedströms.

Abstract

In Sweden the winter of 2010 was unusual cold with a prolonged ice and snow cover on lakes and rivers. This could lead to diminishing oxygen content in shallow eutrophic lakes, especially in the deep areas and subsequently to release of phosphorus. Two lakes in Southern Sweden, Lake Ellenösjön and Lake Viksjön were examined in midwinter (beginning of March) for their oxygen and phosphorus content under the ice cover in their deep areas and along a transect in their shallower part. Samples from inflow and outflow for phosphorus analysis were taken in the beginning and in the end of March. Both lakes were anoxic in the deep areas and hypoxic in the five sample sites along a transect on the shallow part of the lakes. The ice and snow cover had probably resulted in the anoxic condition in the deep areas and hypoxic conditions in some of sample sites in transects. Analysis of water chemistry revealed high phosphorus content in the inflow and outflow and in the deep areas in the beginning of March. In the end of March only the inflow and outflow were sampled. The later samples showed extremely high phosphorus levels and the lakes are hyper-eutrophic.

Overall it seems like Ellenösjön has the biggest problems with eutrophication with high amount of phosphorus, leaching phosphorus from the sediment and in the end of March Ellenösjön greater values of color, turbidity and phosphate-phosphorus in outflow than inflow indicating an internal loading. Ellenösjön is leaking phosphorus and Viksjön sediment phosphorus. It is likely that the snow and ice cover has resulted in the oxygen depletion and high phosphorus contents of the lakes.

Analysis of the inflow and outflow of Ellenösjön (2000 - 2008) revealed that Ellenösjön has acted as a phosphorus source in most months over the years. There has been a diminishing trend in the phosphorus content in Ellenösjön. This trend is higher in the inflow than in the outflow indicating that Ellenösjön has been acting as a phosphorus source over the years, but this trend is diminishing. Advisory programs such as "Focus on nutrients" seems to have had a positive impact on the external loading, but more actions needs to be taken for reducing the internal loading of Ellenösjön to reduce the consequences of nutrients further downstream.

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Introduction

Under a prolonged ice and snow cover oxygen from the atmosphere cannot penetrate and mix with the water. The light to the underlying water is attenuated or absent and results in reduced or no algal photosynthesis under the ice and snow. The lack of oxygen and photosynthesis together with respiratory oxygen consumption results in diminishing oxygen content and eventually can lead to mass mortalities of fish also called winterkill. Furthermore oxygen depletion can lead to phosphorus release and augment nutrient contamination to the already nutrient loaded lakes.

The winter of 2010 has been unusual cold with a prolonged ice- and snow cover on lakes and rivers in Southern Sweden. In Gothenburg the period with snow cover has been the longest for 40 years (SMHI). The hypothesis is then that because of the prolonged ice and snow layer in 2010, the oxygen content will diminish in those already nutrient loaded lakes with a following release of phosphorus from the sediment.

Ellenösjön is part of a bigger monitoring program:SRK (Samordnad Recipient Kontroll), where a range of different measurements has been done over the years. Among other parameters, the amount of total phosphorus has been measured for the inflow (V9) and the outflow (V12). This can give a rough idea about the phosphorus retention over the years and for different month during the seasons.

I have examined the phosphorus content in V9 and V12 in the period 2000 to 2008 for temporal trends, and to evaluate whether the lake use to function as a sink or source of phosphorus. Modelled data exist from SMED (Samordnad Miljö- och Emissions Data) and SMHI where expected amount of phosphorus is calculated due to catchment area, flow and runoff. A comparison has been done on the phosphorus content of Lake Ellenösjön over the years from existing and modelled measurements from 2000 to 2008.

The aim of this Thesis is to sample the oxygen levels and analyse the phosphorus levels under the ice in two shallow nutrient rich lakes in the winter 2010, and to examine Lake Ellenösjön for temporal trends in phosphorus in the period 2000 - 2008.

The Catchment area

Örekilsälvens catchment has an area of 1340 km². It is situated in Västra Götaland in south west Sweden, see figure 2 (Enebjörk et al. 2006). The two lakes Ellenösjön and Viksjön are situated in the southern part of the catchment area of Örekilsälven, which runs into Gullmarn. The two lakes are part of waterways running east west towards the Fjord of Gullmarn (figure 1). North-south run the two biggest watercourses (rivers) in the system, Örekilsälven and Valboån.

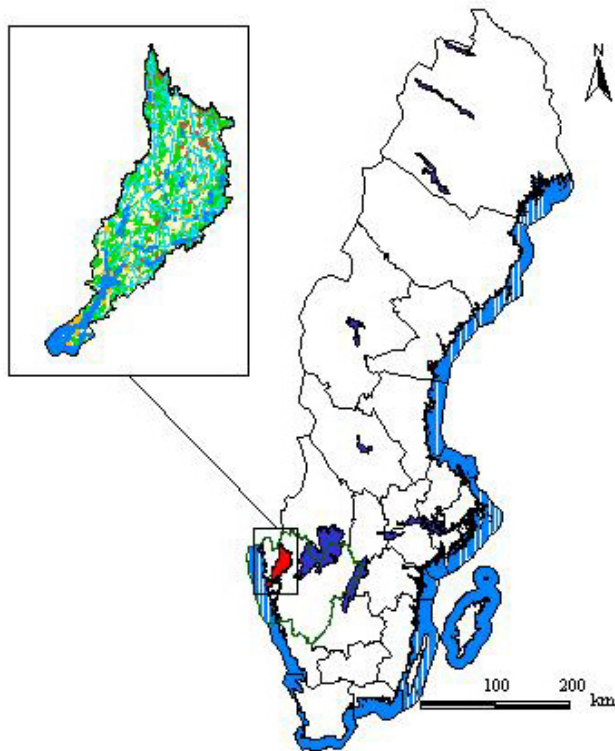


Figure 1. The river basin of Gullmarn in South-West of Sweden (Enebjörk & Fränne 2006)

The catchment area of Örekilsälven and Gullmarn are exposed to human impacts. Especially nutrients leaking from farms and rural areas are problems. Also the increase in population during summer time is a problem. The population increases 10 fold because it is a recreation area. The two biggest point sources are the paper industry; Arctic paper Munkedals AB and Munkedals municipal wastewater treatment plant.

Earlier the area was a wetland and has been drained in order to obtain arable land. Also lowering of Lake Ellenösjön has occurred and straightening of watercourses for better transportation has been done. This has led to problems with eutrophication (Enebjörk & Fränne 2006).

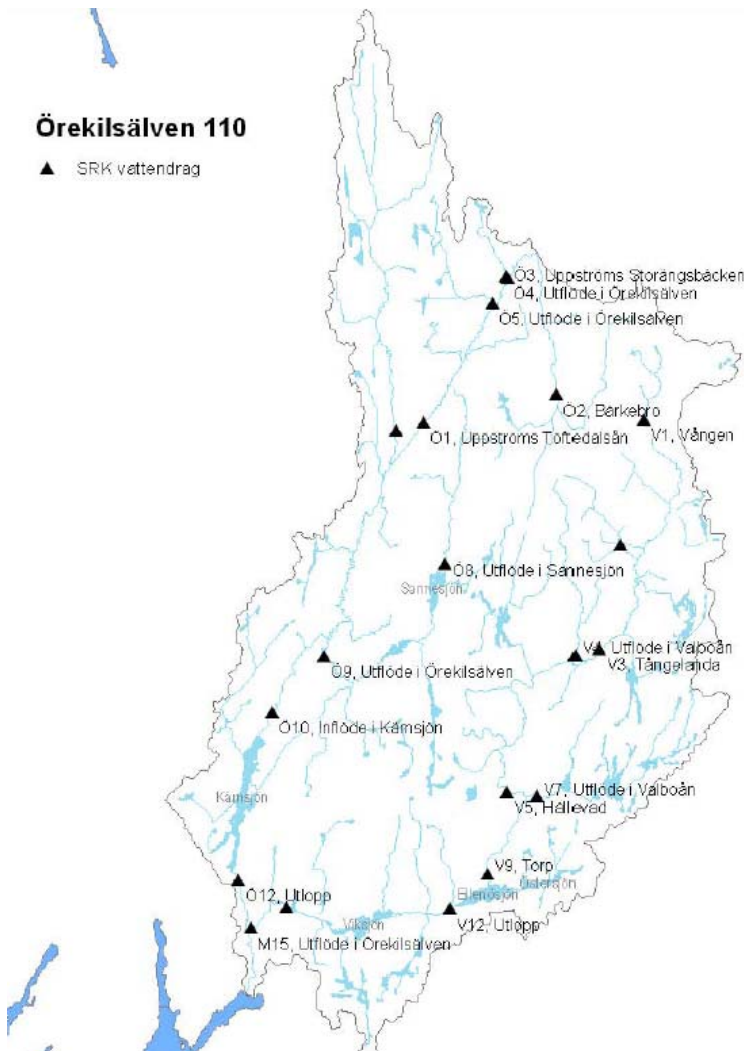


Figure 1A. Catchment area of Örekilsälven.

Four bigger lakes are connected in the area from east toward west: Lake Östersjön, lake Ellenösjön, lake Viksjön and Lake Vassbotten. This route has been used as a waterway to transport tree logs for the paper industry (Arctic Paper Munkedals AB)

until 1965. The lake Vassbotten was often covered with tree logs at that time. (<http://www.friluft.se/munkedal>)

Lake Viksjön

Lake Viksjön is located west of Lake Ellenösjön (see figure 2). It is a relative small lake with an area of 2.76 km². It is a shallow lake with a mean depth less than 4 meters. The deepest area of the lake is situated in the southern part with a depth of 7 meters. The ecological status has been classified as bad. This is based on phytoplankton algae and cyprinid fishes. This is probably due to a high input of nutrients that lead to eutrophication.

There has been a test fishing in 1988, which revealed many cyprinid fishes, which means it probably has the same problem as Ellenösjön due to bioturbation (see under Ellenösjön). Based on other tests in the lake and other lakes in the system, the ecological status of the lake is still classified as bad. The humic substances have been measured to exceed 50 mg Pt/l.

The chemical status except mercury is classified as good. In Sweden today all waters exceed the allowed level of mercury because of aerial downfall (Viksjön VISS 2010).

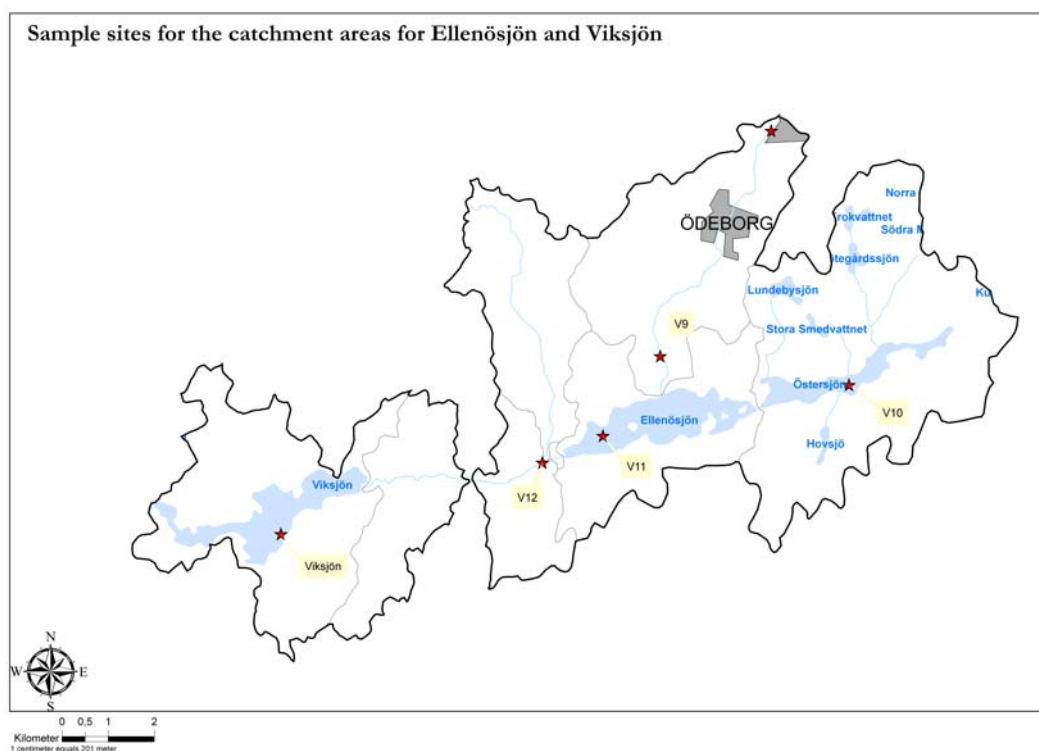


Figure 2 Lake Ellenösjön and Viksjön showing the sample sites for SRK. V9 inflow, V11 deep area, V12 outflow of Ellenösjön (Data from SRK. ArcMap)

Lake Ellenösjön

Lake Ellenösjön (figure 2) is located in the southern part of the municipality of Färgelanda, which is a part of the province Dalsland in Southern Sweden. It is a shallow and nutrient rich lake with an area of 3.1 km². The deepest area of the lake is 8 meters and the average depth is around 4 meters.

The ecological status of the lake has been classified as poor because of eutrophication. This is probably due to a high nutrient load and a high number of cyprinid fishes (see below). The fish fauna has been evaluated on three occasions during 2001-2005, using standardized test fishing. Furthermore the water level has been lowered. The aim is to get good ecological and chemical status, but now only chemical status is good with exception of mercury. 2021 is the deadline for attaining good ecological status (Ellenösjön VISS, 2010).

Ellenösjön is famous for pike-perch (gös) fishing. Pike-perch has been bred and released in the lake, but now they reproduce naturally. The pike-perch thrives in warm and moderately nutrient rich lakes and waters and has a high oxygen demand: more than 3.5–4.5 mg O₂/l. The species flees already at concentrations at 5–6 mg O₂/l to more oxygen rich waters if possible (Berglund, 2004).



Figure 3 Pike Perch (*Sander Lucioperca*) (Drawing: Tommy Gustavsson)

Different fish species have different oxygen requirements. Salmonids are more demanding and needs concentration between 8-10 mg O₂/l. Levels below 3 mg O₂/l will make them suffocate. Cyprinid fishes are less demanding. They like concentrations between 6-8 mg O₂/l. Suffocation signs occur when levels drop to 1.5 – 2 mg O₂/l (Svobodová et al. 1993).

Table 1 shows the species found at the two test fishing occasions done in 2005 and 2007 compared with a mean from a number of Swedish lakes.

Table 1 Species found in Ellenösjön at two test fishing compared with the mean number in a number of lakes with bottom net. (Swedish names in brackets). (Modified after Fiskeriverket 2010. Vattenkartan 2010. Ljung 2004)

Species	Number/net 2007	Number/net 2005	Number/net Mean	Number Lakes for mean
Perch (Abborre)	6.17	6.50	16.4	1804
White Bream (Björkna)	13.92	34.88	5.8	152
Bream (Braxen)	14.58	19.00	3.0	560
Burbot (Gers)	3.83	6.13	3.9	600
Pike (Gädda)	0.08	0.13	0.3	1410
Pike Perch (Gös)	1.54	3.38	1.4	121
Bone Bleak (Benlöja)	21.42	15.54	2.5	353
Common Roach (Mört)	31.33	34.75	17.8	1361
European Smelt (Nors)	0.04	0.13	0.7	186
Crusian Carp (Ruda)	0.08	-	4.2	107
Common Rudd (Sarv)	0.33	0.08	1.5	330
Tench (Sutare)	0.04	-	0.4	328

The table reveals that cyprinid fishes like White Bream, Bream, Bone Bleak and Common Roach are abundant. Some of them (especially bream and white bream) are disturbing the bottom, while searching for burrowed worms and larvae, thereby releasing phosphorus from the anoxic sediment (bioturbation) and in that way worsening the eutrophic state of the lake (Kalff, 2002).

Phosphorus sources in the lakes

In figure 4 and table 2 underneath, the different sources of total phosphorus and their relative contribution to Phosphorus for the catchment areas of the lakes are shown. The figure only shows the catchment area of the outflow of Ellenösjön. The same figures for the inflow of Ellenösjön and Viksjön and the outflow catchment areas are not shown, but those changes are more visible in table 2 and 3. Agriculture contributes most with phosphorus with three quarter share of the total. Next biggest contributor is open land and forest with approximately one tenth each. Other contributors are not mentioned because their contribution is minor (for example industry and road and paved area run off).

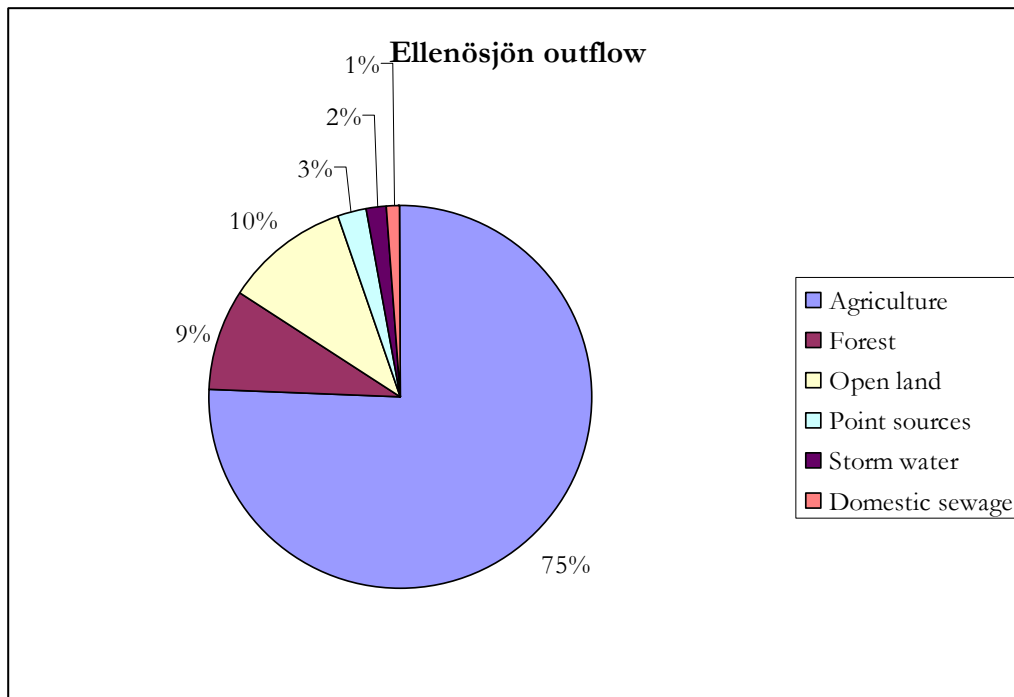


Figure 4 Different sources of the phosphorus contribution (kg/year) in the catchment area of the outflow of Ellenösjön (Data modified after SMED; Samordnad Miljö- och Emissions Data).

Table 2 Different sources of the phosphorus contributions (kg/year) in the catchment areas. (Data modified after SMED; Samordnad Miljö- och Emissions Data).

P kg/year	Agriculture	Forest	Open land	Point sources	Storm water	Domestic sewage	Total (Ton)
Ellenösjön infl	11754	1234	1554	405	271	159	15.50
Ellenösjön outfl	12111	1377	1664	433	271	163	16.20
Viksjön inflow	12663	1582	1842	455	271	163	17.16
Viksjön outflow	13232	1794	2038	485	271	163	18.19

Table 3 Phosphorus (ton/year) in the catchment areas. Area. Hectares and Load. Load (kg/km²) = 1000 * Total (ton)/Hectares (km²) (Data modified after SMED; Samordnad Miljö- och Emissions Data).

P kg/year	Total (Ton)	Area km ²	Hectares	Load kg/km ²
Ellenösjön in	15.50	410	41140	37.8
Ellenösjön out	16.20	451	45132	35.9
Viksjön in	17.16	501	50060	34.3
Viksjön Out	18.19	555	55494	32.8

Table 3 shows that the calculated amount of phosphorus, due to size and type of the catchment area, are increasing throughout the system. The catchment areas are increasing as well so the load are supposed to diminish on the way down the

system. The expected amount of retention can be calculated from table 3. Due to the modeled data from SMED the amount of retention from Ellenösjön is expected to be $1.9\text{kg}/\text{km}^2 * 451 \text{ km}^2 = 857\text{kg}$ and the amount of retention for Viksjön should be $1.5\text{kg}/\text{km}^2 * 555 \text{ km}^2 = 832.5 \text{ kg}$.

Survey of monitored parameters

Following is a brief survey of the theories behind the parameters, which have been measured in this report.

Oxygen

Oxygen is the most fundamental parameter for the life in running waters and lakes. Therefore it is essential to understand the dynamics and solubility of oxygen in inland waters. Approximately 20 % of the air is oxygen and almost all the rest is nitrogen. Oxygen is more soluble in water than nitrogen. The solubility increases with decreasing temperatures and increasing pressure and decreases with salinity.

Diffusion of oxygen in the lake water is a slow process, which mostly happens when the water circulate rigorously as in the storm periods of spring and fall turnover. At spring and fall circulation the oxygen concentration of the lake water becomes near or above 100 % saturation. This is between 12 to 13 mg O₂/liter at 4°C at sea level. This will result in an **orthograde oxygen profile** (100% oxygen saturation with depth; decreasing temperatures and increasing pressure with depth → increasing O₂ concentration) (Wetzel, 2001).

Clinograde oxygen Profile

In an eutrophic lake with a great load of nutrients and high organic production in the form of algae, bacteria and cyprinid fishes there will be a large oxygen demand for respiration and decomposing. This can lead to oxygen depletion especially in summer with high temperatures, high production and lower solubility of O₂. The water will stratify and diffusion of oxygen will only occur in the upper strata, whereas in the hypolimnion mostly O₂ consumption occurs. Also in winter O₂ concentration can diminish due to little water circulation and especially with an ice cover, which inhibits diffusion of O₂ with the water. The oxygen profile with diminishing O₂ concentration with depth is called a **Clinograde oxygen profile** (see figure 5 and 7) (Wetzel, 2001).

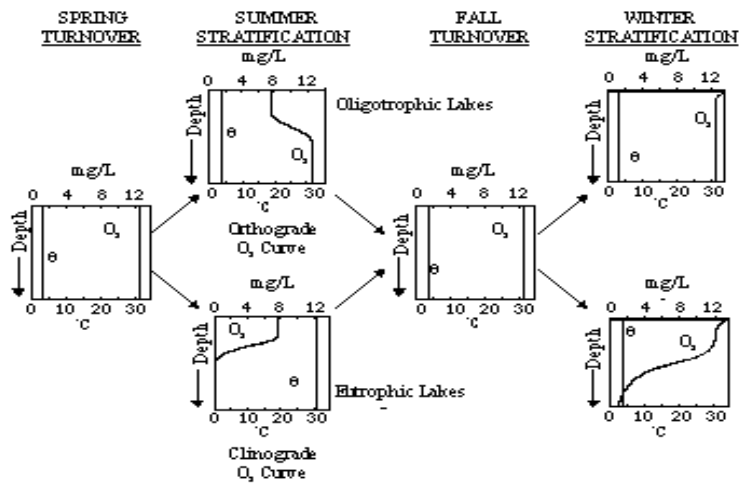


Figure 5. Idealized vertical distribution of oxygen concentrations and temperature during the four main seasonal phases of an oligotrophic and an eutrophic dimictic lake (Source: Wetzel, 2001)

Shallow lakes often receive large inputs of organic matter from the catchment areas in relation to their lake area (see figure 5 and 7) and decomposition of this allochthonously derived matter dominates the oxygen consumption. This will create an anaerobic hypolimnion and eventually lead to extinction of life in the lake. A shift will occur from aerobic to anaerobic bacterial metabolism and efficiency of decomposition will decrease (Wetzel, 2001).

Oxygen status is defined as hypoxic with DO between 1 and 2 mg/l, and anoxic with DO concentrations under 1 mg/l (Horne and Goldman, 1994).

Moderate tolerant fish species requires at least 2-5 mg O₂/l and 5-9 mg O₂/l are necessary for cold water species (Salmonids) (Kalff, 2002). In table 4 is the Swedish status classification.

Table 4. Status classification off oxygen concentration for lakes based on the fish fauna; "common" warm water fish and more oxygen requiring Salmonids in Sweden (for example salmon, trout, char, steelhead and grayling) (Naturvårdsverket, Bilaga A, Handbok 2007:4 Bedömningsgrunder för sjöar och vattendrag)

Status	Temp(°C)	Oxygen mg/l Warm water fish	Oxygen mg/l Salmonids
High		≥ 8	≥9
Good	0 - 5	≥ 7 and < 8	≥8 and < 9
Good	5 - 15	≥6 and < 7	≥7 and < 8
Good	> 15	≥5 and < 6	≥6 and < 7
moderate		≥4 and < 5	≥5 and < 6
Unsatisfactory		≥3 and < 4	≥3 and < 5
Poor		< 3	< 3

Ice-covered lakes

When ice forms on the lakes diffusion of oxygen to the water ceases. In eutrophic lakes the production and respiration continues to consume oxygen and oxygen concentration diminishes with depth. Oxygen production from photosynthesis still occurs in the photic zone in the upper layer as long as light can penetrate. But with a snow cover light is attenuated so photosynthesis ceases and only respiration occurs. This results in increased oxygen consumption. The oxygen levels will diminish and be insufficient to support life in the lake. This can cause a condition with winterkill. Such conditions are common in temperate, shallow eutrophic lakes; especially with a mean depth less than 4 meters (Mathias & Barica 1980, Wetzel, 2001).

Several factors have a negative influence on the concentration of dissolved oxygen in lakes. These are “*absence of inflowing water, high elevation, extensive ice and snow, small surface area, and abundant aquatic macrophytes*” (Guenther and Hubert, 1991). Marszelewski et al (2006) found a strong relationship ($R_2 = 0.78$) between the duration of the ice cover on the lakes and diminishing oxygen content in the deep area of three examined lakes.

Prowse and Stephenson (1986) have examined the impact of ice and snow cover of temperate lakes on their levels of light and oxygen depletion. The ice and snow cover eliminates oxygen diffusion from the atmosphere and the snow inhibits light from reaching the water with ceased photosynthesis as a consequence. They found that especially the first snowfall on the ice cover reduces the radiation to almost zero and a linear decrease in oxygen occurs.

The lakes transparency to radiation, which is crucial for photosynthesis and oxygen production, can be measured in different ways. The penetration of the light through water or ice is reduced by the **albedo**; the surface reflection to the atmosphere.

It is also reduced by the **attenuation**; the weakening in strength of the light when it travels through matter such as water or ice. Attenuation is normally measured by an extinction coefficient I_d .

Snow and ice layers can be divided into three layers

1. Black ice forms when lake water freezes. It is highly transparent and has an albedo about 0.1 almost similar to the albedo of open water.
2. White ice forms when snow and water refreezes and forms smaller and less organized grains. White ice have an albedo somewhere between 0.3 - 0.45.
3. Snow has the greatest reflection with an albedo on 0.95. Almost no light are penetrating to the underlying water under a snow cover.

When the water surface freezes to ice it is initially black ice and the transparency is still moderate and photosynthesis can occur. When it snows, the transparency ceases and no photosynthesis can occur. Later in winter, white ice forms by refreezing and packing of snow and water and a little irradiation can reach the water and some photosynthesis can occur again. So the rate of oxygen from photosynthesis is highly dependent on the timing and duration of snow cover. The longer period with snowfall and the longer the winter, the greater oxygen depletion.

Prowse and Stephenson (1986) gave an equation of the oxygen content of an ice-covered lake:

Equation 1 Oxygen content of an ice covered lake: (Source: Prowse and Stephenson 1986)

$$D = (C + P + F + Q) - (B + R + S + L), \text{ where}$$

D = Total dissolved oxygen

C = Initial O₂ content at freeze up

P = Photosynthetic production of O₂

F = Freeze out of oxygen in the formation of black ice

Q = Contribution of oxygen by inflowing water

B = Benthic sediment respiration

R = Water column respiration

S = Loss of oxygen to slushing

L = Loss of oxygen in out flowing water"

This gives a good picture of the sources and sinks of oxygen in an ice-covered lake. The benthic respiration is normally the greatest O₂ consuming part (Prowse and Stephenson, 1986).

Phosphorus

Phosphorus plays a major role for the life in freshwater. It is a fundamental nutrient and a major cellular constituent. Only a small amount of phosphorus is available from the hydrosphere. Phosphorus is the least abundant of the major components and is often limiting biological productivity. Most of the phosphorus (90%) found in inland waters occur as organic phosphates and is bound in the biota. The inorganic soluble form of phosphorus is most often in the form of ionic orthophosphate also called phosphate phosphorus (PO₄³⁻). It only constitutes a few percent of total phosphorus and is utilized very quickly. The ratio to other forms of phosphorus is 1:20 or less than 5%.

The inorganic soluble orthophosphate ions PO₄³⁻ are important for biological life. This is the source of phosphorus that plants, algae and animals are able to utilize in the water and is often limiting to growth.

The phosphate anions PO_4^{3-} will have a tendency to bind into complex formations with metal cations such as ferric and aluminum cations. The solubility of aluminum phosphate (AlPO_4) and ferric phosphate (FePO_4) is minimal at pH 6 (Wetzel, 2001). The availability of phosphate ions is often very low because they bind to either iron oxy hydroxide aggregates (FeOOH) or precipitate as FePO_4 under aerobic conditions. The aggregates continue to absorb phosphorus ions at the sediment surface and act as an effective barrier to phosphate diffusion from the sediment to the free water column (Kalff, 2002).

The classical theory

The classical theory of phosphorus cycling suggested that the binding and thus release of phosphate ions to iron and the aggregates depends upon the oxygenation and redox potential. The redox boundary of 200 mV and presence of oxygen create oxidizing conditions (Fe^{3+} and insoluble PO_4), which binds phosphate ions strongly to Fe (Kalff, 2002).

Internal loading

If the environment becomes anoxic (oxygen free at the bottom) and the redox potential exceeds 200 mV the condition becomes reducing instead. Iron (Fe^{3+}) will be reduced to Fe^{2+} and can thereby not bond with PO_4^{3-} . The oxy hydroxide aggregates (example FeOOHPO_4) dissolve and PO_4^{3-} can diffuse into the hypolimnion. This is known as internal loading (phosphorus released from the sediment) (Boström et al. 1982, Kalff, 2002).

Release of phosphorus from the sediment is generally favored under anaerobic conditions. Stratifications of deep lakes or micro stratifications in shallow lakes can result in anoxic zones where internal P will be released (Christophoridis & Fytianos 2006) Anoxic conditions can also arise by an extensive ice- and snow cover (Mathias & Barica 1980).

Historically there has been focus on “external loading” of phosphorus, which comes from sources outside the water body. Many studies have shown no improvement in phosphorus content in lakes even though reductions have been made in external loading. This indicates that a counteracting release of phosphorus occurs from the sediment (Steinman et al. 2004). Wetzel (2001) states that recovery rates for lakes of average size require 2 – 10 years after reduction of phosphorus loading. A shallow lake with a long history of eutrophication has a high “internal loading” of phosphorus from the sediments and has lost its resilience. This results in a slow rate of lake recovery after reductions of external phosphorus loadings.

The classical theory of phosphorus cycling was later refined when scientists (add reference(s)!) found that phosphorus release also depended on the presence of sulfur.

Sulfate (SO_4^{2-}) after reduction by microbes yields sulfide (S^{2-}). Sulfate then binds to iron as FeS or FeS_2 . If the amount of sulfur compared to phosphorus is big enough, there will be less iron to trap phosphorus. This is mostly applicable in calcareous lakes.

Another finding indicated, if the Fe:P ratio is less than 10, phosphorus will be released even under oxic conditions, probably because there is too little iron to bind P (Kalff 2002).

Soluble Reactive Phosphorus (SRP)

Newer models have been considered because some lakes didn't fit the old models. More recent research indicates that not only chemical (oxygen, redox potential) but also biological mechanisms (microbial respiration and decay) are involved in the phosphorus cycle. Biological release happens when bacteria die and decompose (cell lysis). The amount of soluble reactive phosphorus they release can be quite big (10 – 75 % of potentially soluble sediment phosphorus) (Boström et al. 1988, Prairie et al. 2001).

“Sinks” or “sources” of phosphorus

Generally, bigger and deeper lakes with a thick hypolimnion are able to hold a larger mass of oxygen and they often have an oxic hypolimnion. They have a longer water residence time (**WRT**) due to their bigger volume and a smaller catchment-nutrient loading than smaller lakes. Deep lakes with long WRT (more than 10 years) retain 70-90 % of the incoming phosphorus, which binds with cations (for example Fe, Al) and sediment. If the phosphorus load and the influx of organic matter from the catchment are not too big, the algae production remains low and the lake act as a phosphorus **sink**. Those lakes are termed **oligotrophic**.

Shallow and unstratified lakes usually have a shorter water residence time and often have an anoxic hypolimnion. This results in a poor sedimentation and retention of organic matter and nutrients (phosphorus). The phosphorus input is retained longer in the epilimnia and is available for algal production. This can lead to elevated turbidity and fish production. There is a great chance that the lake has an anoxic hypolimnion if the mean depth is less than 10 meters and the WRT is less than 2 years. If the lake has high external phosphorus loading the lake will act as a phosphorus **source** with the poor sedimentation and retention. Those lakes are **eutrophic**. Phosphorus can even be released in oxic conditions for example by natural turbulence, which removes released, dissolved phosphorus from the sediment-water interface. Phosphorus can also be released by a continuous supply of phosphorus and by bioturbation (Kalff, 2002).

Sources of phosphorus

The major sources of nutrients' pollution of waters are from sewage treatment plants, untreated sewage, farming and precipitation. Urban sources are domestic sewage, industrial wastes and storm drainage. Rural sources include leaching by water percolating the soil, run off of animal manure, fertilizers and by erosion (Kalff 2001). Urbanization increases the phosphorus discharge to surface waters in proportion to population densities (Wetzel, 2001).

Wetzel (2001) adds that nutrients accumulate on snow during winter and can be released in great amounts during spring thaw. Phosphorus in precipitation is normally quite low but can constitute up to 40 % of annual loading. When accumulated it can easily exceed 0.07 g/m²/year. This amount has been estimated as the permissible amount of phosphorus loading rate for lakes. Values above 0.13 g/m²/year are considered bad for lakes under 5 meters mean depth due to eutrophication (Wetzel, 2001 p.270).

Table 5 General relationships of lake productivity and average concentrations of epilimnetic total phosphorus (Source: Wetzel, 2001)

Lake productivity classification	Total Phosphorus mg/L
Ultra-oligotrophic	<0.005
Oligotrophic	0.005-0.010
Mesotrophic	0.010-0.030
Eutrophic	0.030-0.100
Hyper-eutrophic	>0.100

The Swedish classification is a little different and can be seen in the following table.

Table 6 Condition due to total phosphorus in limnic water (Bedömningsgrunder för miljö kvalitet - Sjöar och vattendrag". Naturvårdsverket Rapport 4913).

Total Phosphorus concentration. mg/ l	Class	Condition of concentration
≤ 0.0125	1	Low
0.0125 -0.0 25	2	Moderate
0.025 – 0.050	3	High
0.050 – 0.100	4	Very high
>0.100	5	Extremely high

Color and Turbidity

Color and turbidity are both quality measures of the transparency of the water. Humic substances in the water can cause an increase in color and algal biomass an increase in turbidity. These are relevant measures because the less transparent a lake is; the more of the irradiance converts into heat. The solar energy will be absorbed in the surface layer and the lake will stratify earlier in the spring and have a shallower epilimnia. These factors increase the possibility of anoxia (Kalff, 2002).

Color

Color gives an indication on the amount of humic substances in the water. Humic substances are organic acids more or less degraded. Especially coniferous forests (needles from spruce and fir are slowly degradable) are a big source of humic substance that reaches the waterways. Humic acids are a source of phosphorus and therefore add to the primary production. Bacteria and zooplankton can utilize humus as a carbon source. Also iron and manganese adds to color, which is measured in milligram platinum per liter mg Pt/l.

- 1 mg humus per liter gives a color value 6-11 mg Pt/l
- 1 mg iron per liter gives a color value 20 mg Pt/l
- 1 mg manganese per liter gives a color value 150 mg Pt/l

The normal value for Swedish lakes is between 10 – 80 mg Pt/l (Bydén et al. 2003).

Table 7 Condition of Color according to Swedish standards (Bedömningsgrunder för miljökalitet - Sjöar och vattendrag. Naturvårdsverket Rapport 4913).

<i>Color mg Pt/l</i>	<i>Class</i>	<i>Condition</i>
≤ 10	1	not colored
10 - 25	2	slightly colored
25 - 60	3	moderate colored
60 - 100	4	considerable colored
> 100	5	highly colored

Turbidity

Turbidity is a measure of particulate matter in the water and a way to describe water quality. Particulate matter can consist of clay, phyto- and zooplankton, bacteria and so on. For measuring turbidity a turbid meter measures the amount of scattering of the materials. The water scatters light in proportion to the amount of suspended materials in the water sample. The most widely used unit for measuring turbidity is FTU (Formazine Turbidity Units) or FNU (Formazine Nephelometric Units) (Bydén et al. 2003). The threshold of turbidity for drinking water in Sweden is 0.5 FTU.

Table 8 Condition of Turbidity according to Swedish standards (Bedömningsgrunder för miljö kvalitet - Sjöar och vattendrag, Naturvårdsverket Rapport 4913).

Turbidity (FNU)	Class	Condition
≤ 0.5	1	Not turbid
0.5 - 1.0	2	Slightly turbid
1.0 - 2.5	3	Moderate turbid
2.5 - 7.0	4	Considerable turbid
> 7.0	5	Highly turbid

Focus on Nutrients

It is obvious that in the pursuit of improving the quality of the limnic waterways and the seashores it is necessary to focus on nutrients, especially phosphorus, as this is often the limiting factor to algal growth.

In Sweden an advisory and information project (*Greppa näringen; Focus on Nutrients*) was introduced in 2001 to reduce the loss of nutrients from agriculture. This project is a joint venture between the Swedish Board of Agriculture, the County Administration Boards and the Federation of Swedish Farmers (LRF). The goal is to reduce losses of phosphorus and nitrogen from agriculture. This is obtained by giving information on knowledge and tools. The measures for preventing phosphorus losses include:

- *“Decreasing amount of phosphorus that can be lost*
- *Decreasing the risk of phosphorus leaving the field*
- *Capturing the phosphorus leaving the fields”*

(www.greppa.nu)

By avoiding excessive feeding of the animals, a smaller amount of phosphorus will be found in the manure. Spreading phosphorus rich manure more evenly will spread the phosphorus better. Decreasing or refining the phosphorus fertilization and careful tillage will also have effect. Creation of riparian zones along waterways and lakes and creation of wetlands will trap nutrients and prevent it from leaching out in watercourses (www.greppa.nu)

Methods

Oxygen profiles and water samples for water chemistry

The two lakes Ellenösjön and Viksjön were visited several times over two periods with 3 weeks in between. The first time they were covered with a thick layer of ice approximately a meter deep. The second time a thaw period made it impossible to go out on the ice and measure the deep areas, which had initially been the idea so only inflow and outflow were sampled. The first monitoring was done in the end of February and beginning of March 2010. The second monitoring was taken in the end of March. Holes were drilled in order to take water samples for water chemistry analysis and oxygen measurements and samples were taken from inflow and outflow.

Field-sampling

Three kinds of samples were collected

1. A transect perpendicular to the shore with five samples approximately 50 meters apart were drilled in order to examine the oxygen profile on the shallower part of the lakes (figure 6). Water samples were also taken here. With a multiparameter (HI 98280. Hanna Instruments) we took measure of dissolved oxygen in percentage saturation (DO %), dissolved oxygen in concentration (DO mg/l), temperature (°C) and pH (the pH meter didn't work for Viksjön). This was done for every half-meter depth and the GPS-data (WGS 84) was taken. This was done for Viksjön February 25th and for Ellenösjön March 2nd 2010.
2. At two periods water samples were taken in the inflow and outflow of both lakes half a meter beneath the surface. The water samples were frozen until analysis. The first time this was done for Viksjön was February 25th and for Ellenösjön March 2nd 2010. The second time it was done for both lakes March 25th 2010.
3. Oxygen profiles and water samples (for phosphorus analysis) were made in the deep areas of both lakes. The deep areas in both lakes were located with GPS and echo sounders. Geographical positioning points for the deep areas already existed and were obtained from SRK (see explanation below). Holes

were drilled in the ice. Oxygen profiles were made by measuring every half-meter. PH and temperature were also measured. Two double water samples for later analysis were taken from a half-meter from the top and one meter from the bottom with a Ruttner water sampler (Swedish equipment for taking water samples from different depth). This was done March 5th 2010.

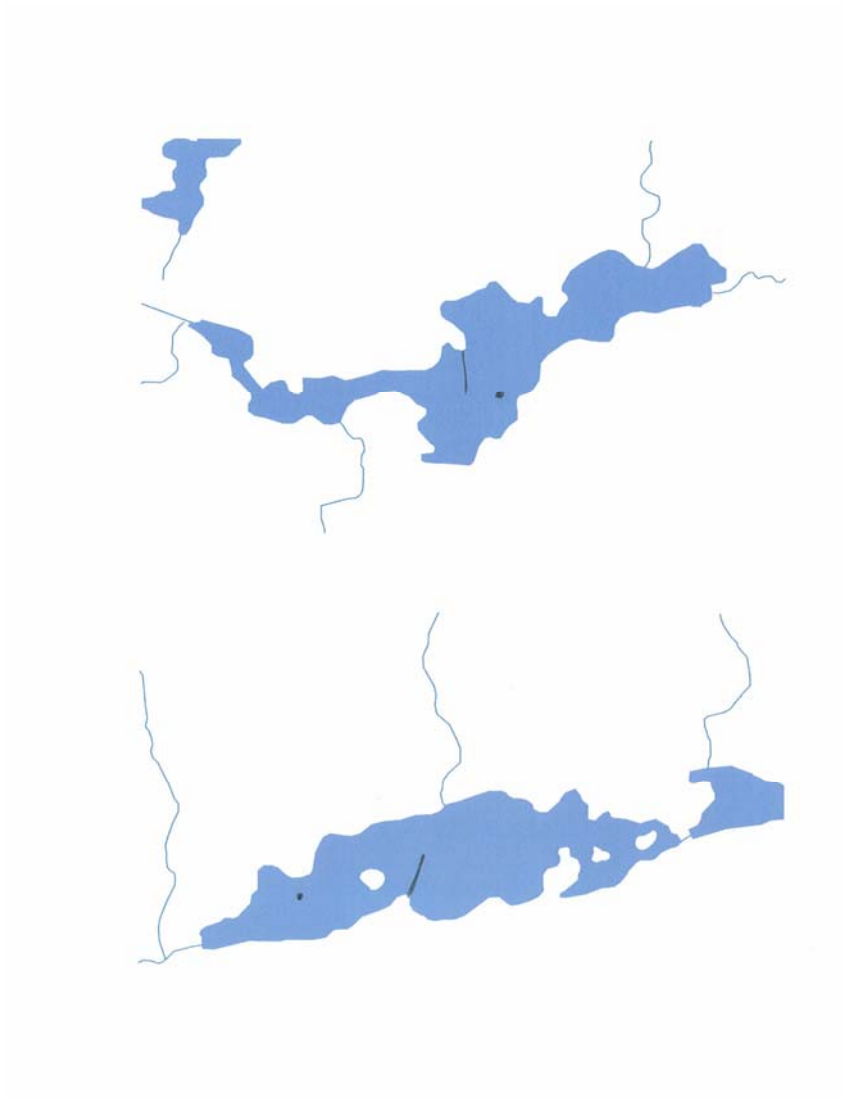


Figure 6. Viksjön (top), and Ellenösjön with location of deep areas and transects, each marked by a dot and a line, respectively.

Laboratory analysis

Laboratory analyses were done in the beginning of April. In the laboratory analysis measurements were taken of total phosphorus, ortho phosphate, color, turbidity and pH. The chemical analysis of **total** phosphorus is based on its reactivity with molybdate after hydrolysis. The complex forms of phosphorus are converted to ortho-phosphate during enzymatic and acidic hydrolysis. This is done with Lange Cuvette Test LCS 349, which can detect phosphorus in the range of 0.05 – 1.50 mg/l $\text{PO}_4\text{-P}$ and 0.15 – 4.50 mg/l PO_4 .

3.5 ml samples are prepared and heated for an hour then transferred to a 50 mm semi-micro cuvette and analyzed in a spectrophotometer.

Ortho-phosphate (or phosphate phosphorus) was also measured with Lange Cuvette Test LCS 349. 3.5 ml samples were prepared, then transferred to a 50 mm semi-micro cuvette and analyzed in a spectrophotometer.

Turbidity and color were measured with a HACH 2100N turbid meter and pH with a pH-meter.

Analysis of Existing data for Ellenösjön

SRK

Ellenösjön has been part of a measuring program called **SRK** (Samordnad Recipient Kontroll; coordinated recipient control). This is a control system for the water system of Örekilsälven, which collects data from the water systems from bigger rivers to the coastlines. Three sample sites exist for Ellenösjön: The inflow (V9), the outflow (V12) and the deep area (V11). Especially the inflow and outflow have been extensively monitored. Water chemistry data exists for these sites with approximately two samples per month for many years back. I have examined the phosphorus content in V9 and V12 in the period 2000 to 2008 for temporal trends, and to evaluate whether the lake use to function as a sink or source of phosphorus.

Modeled data

The Swedish environment and emission data (SMED) have modeled data on the amount of phosphorus (and other nutrients) that should be expected due to the size and type of the catchment area. This is shown in the part about phosphorus sources. The Swedish Meteorological Institute (SMHI) has also modeled phosphorus content due to the flow and runoff in the area. A distribution in percent over the month from 2000 - 2008 is shown later.

SMHI also have modeled data for the expected phosphorus content in inflow and outflow of Ellenösjön. From this modeled data I have calculated the Tot P

difference between the inflow and outflow (I call it retention. which is a bit misleading. but it shows the magnitude of the retention). The retention is calculated for all Januaries 2000 – 2008, all Februaries and so on.

$$100 * (\text{Tot-P V9} - \text{Tot-P V12}) / \text{tot-P V12}.$$

Where monthly mean content of Total Phosphorus:

$$(\text{Tot-P}) = (1000000 / (1000 * 3600 * 24 * \text{days/month})) * \text{P-Transport (ton/month)} / \text{mean flow/month (m}^3)$$

Results

Oxygen Profiles in the deep areas

The oxygen profiles in the deep areas of both lakes revealed that there was very little oxygen present. In both lakes it was under 2 mg/l even in the top, which is the critical level even for cyprinid fishes. In the bottom it was as low as 0.19 in Ellenösjön and 0.15 in Viksjön (Table 9 and figure 8). Figure 8 reveals that in Viksjön there was a big drop in oxygen at 2 meters depth. As seen from table 9 it drops from 1.24 to 0.63 mg/l from 2 to 2.5 meters depth. It is only in the top two meters that there is some oxygen left in Viksjön. In Ellenösjön it looks like there is a more graduated or subtle decrease in oxygen. The oxygen status is classified as poor when under 3 mg/l (table 4) which are all the measures in the deep areas. In both lakes the surface temperature is very low and increases towards the bottom to around 5 °C. GPS-coordinates, depths, pH and atmospheric pressure of the deep areas can be seen in table 1, appendix B.

Table 9 Oxygen profiles in the deepest areas. DO: Dissolved Oxygen March 5th 2010.

Dept m	Ellenösjön DO mg/l	Viksjön DO mg/l
0.5	1.72	1.49
1.0	1.7	1.47
1.5	1.63	1.44
2.0	1.54	1.24
2.5	1.37	0.63
3.0	1.26	0.42
3.5	1.2	0.3
4.0	1.17	0.22
4.5	1.09	0.18
5.0	0.83	0.15
5.5	0.56	0.14
6.0	0.39	0.15
6.5	0.23	
7.0	0.19	

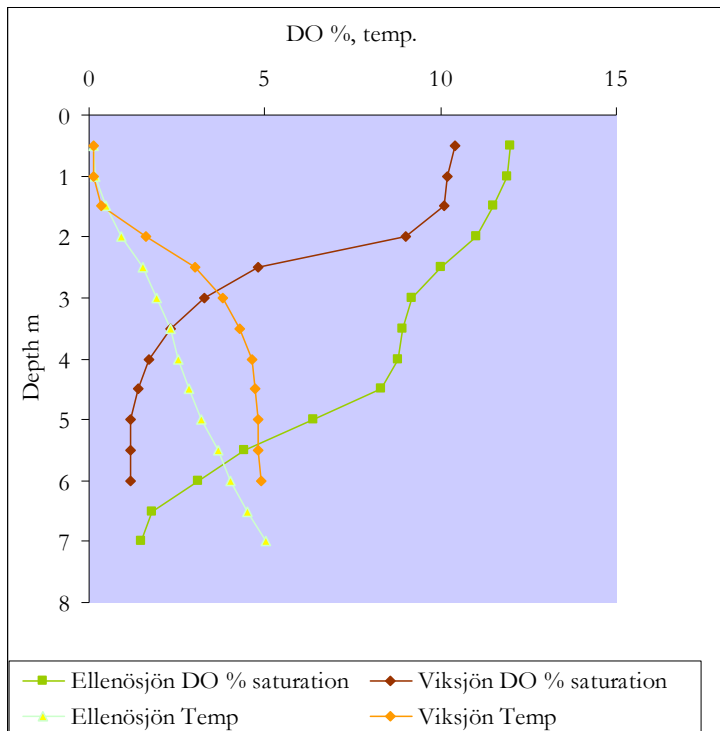


Figure 7 Oxygen profiles and temperatures in the deep areas of Ellenösjön and Viksjön. DO %: percent Dissolved Oxygen. March 5th 2010.

Oxygen profiles in the transects of the lakes

Two transects (one in each lake) were made on the shallow part of the lake in an attempted straight line perpendicular to the shore (see figure 6). Each transect consisted of 5 sampling sites with approximately 50 meters in between each sampling site. Over all both lakes were very shallow with a thick layer of ice on top. Only one meter of depth was reached in Ellenösjön and 2.5 meter in the last sampling site on the transect of Viksjön.

The two transects revealed higher oxygen content in the shallower part of the lakes than was found in the deep areas. Especially Ellenösjön had a tendency of increasing oxygen levels the further out on the lake, with values from 3.28 - 5.35 mg/l. This is classified as unsatisfactory to good (>5) according to standards (table 4). Viksjön showed a tendency to have decreasing oxygen content further out on the lake, with oxygen content ranging from 3.39 in the first sampling site to 1.61 mg/l in the fifth site (unsatisfactory to poor).

PH was only measured for Ellenösjön and ranged between 7.5 – 7.9. (The pH-meter didn't work when Viksjön were visited). Figures 8 and 9 show the oxygen contents in the two transects. The GPS-coordinates for the sample sites of each transect are shown in appendix B.

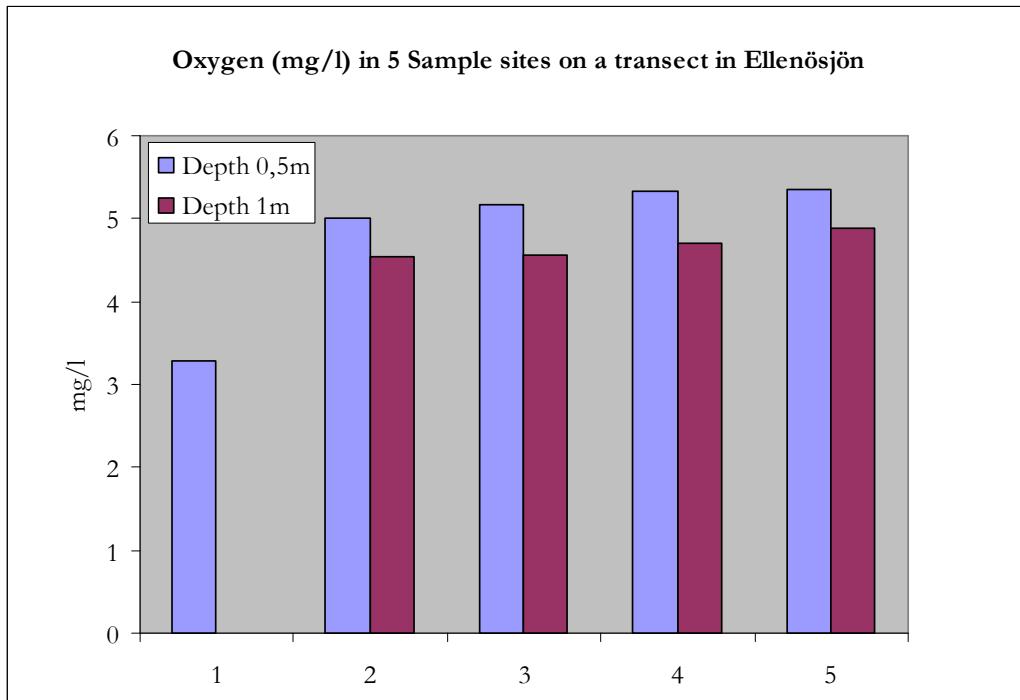


Figure 8 Oxygen contents (mg/l) along the transect with 5 sample sites in Ellenösjön March 2nd 2010.

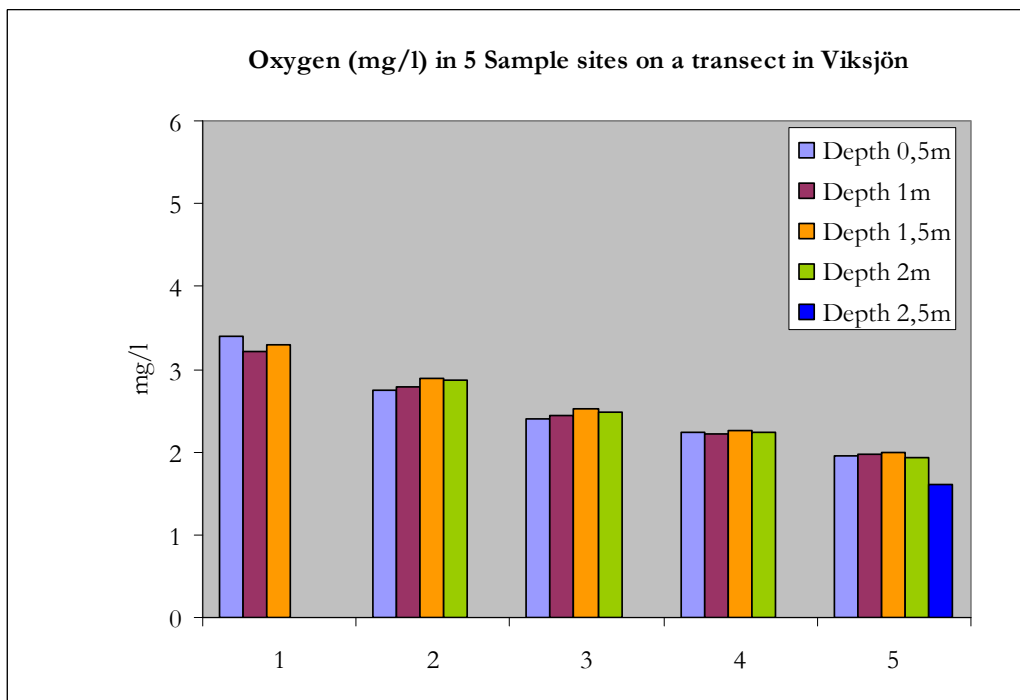


Figure 9 Oxygen contents (mg/l) along the transect with 5 sample sites in Viksjön. February 25th 2010

Phosphorus, color and turbidity in the two lakes

Samples from the first period (March 2nd and 5th 2010)

Surprisingly phosphate-phosphor showed to take up a large part of total phosphor, which is unusual. Especially in the inflow and outflow March 5th was the share of phosphate phosphorus high, above 90 %. In general all the samples taken in the first period showed very high phosphate contents due to the Swedish rating system (50 - 100µg/ l (see table 6). In the first period it is a little higher in Ellenösjön. In Viksjön the inflow equaled the outflow. In Ellenösjön the outflow exceeded the inflow indicating a negative retention or a small phosphorus leak. It seems like the phosphor content is a little higher at the bottom of the deep area than in the top especially in Ellenösjön (figure 10 and 11).

For detecting any major differences between midwinter conditions at the beginning of March and the thaw period in the end of March table 12 shows the mean values for inflow, outflow and deep areas for the two periods. Color is around 70 in Viksjön and around 60 mg Pt/l in Ellenösjön (table 10 and 11) classified as considerable due to Swedish standards (see table 7). Turbidity is a bit higher in Ellenösjön. Mean turbidity is 3.5 for Viksjön and 5.5 for Ellenösjön. This is classified as considerable humic (table 8).

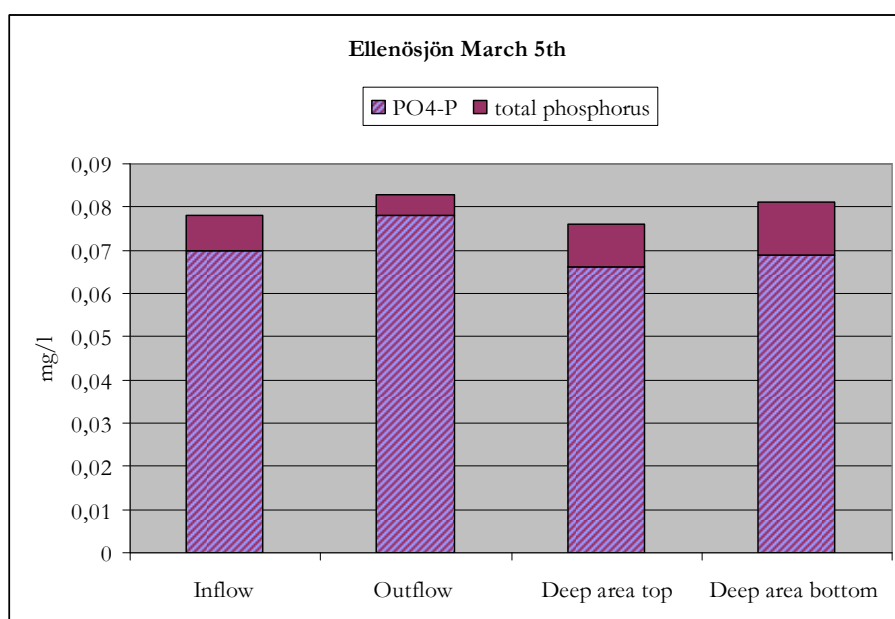


Figure 10 Phosphorus (mg/l) in Ellenösjön March 5th 2010.

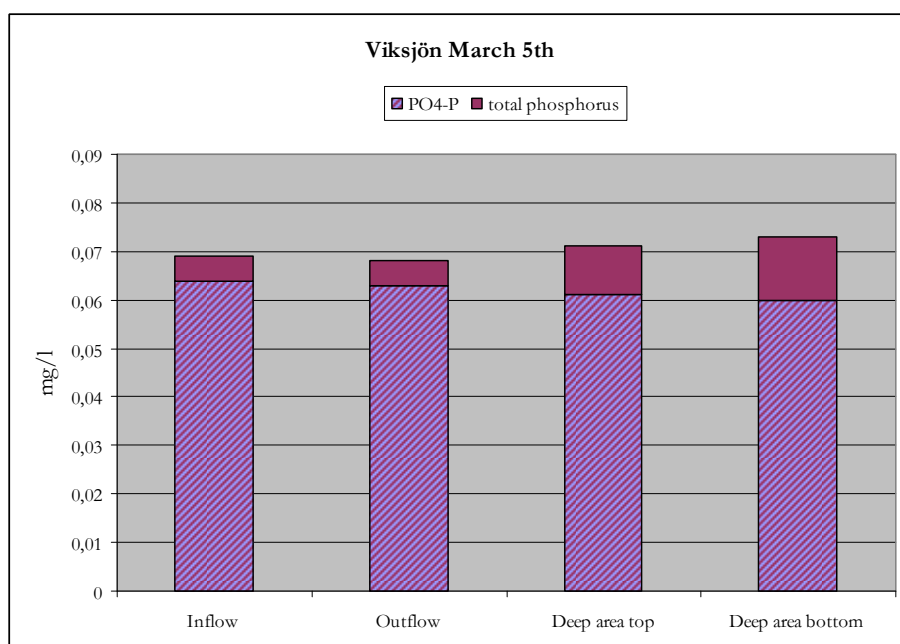


Figure 11. Phosphorus (mg/l) in Viksjön March 5th 2010.

Table 10. Viksjön inflow, outflow February 25th. Deep area March 5th 2010.

Viksjön	Inflow	Outflow	Deep area top	Deep area bottom
Color (Pt/l)	70	76	71	69
Turbidity (FTU)	3.89	3.97	2.62	3.56
pH	7.17	7.29	7.84	7.54

Table 11 Ellenösjön Inflow, outflow March 2nd. Deep area March 5th 2010.

Ellenösjön	Inflow	Outflow	Deep area top	Deep area bottom
Color (Pt/l)	64	62	63	64
Turbidity (FTU)	4.57	5.17	6.08	6.24
pH	7.75	7.80	7.64	7.09

Table 12 Mean between the lakes.

Mean of inflow, outflow and deep areas	Mars 5 th		March 25 th	
	Viksjön	Ellenösjön	Viksjön	Ellenösjön
Total Phosphor mg/l	0.070	0.080	0.1145	0.114
Phosphate phosphor mg/l	0.062	0.071	0.09	0.098
Color (Pt/l)	71.5	63.25	158	162.5
Turbidity (FTU)	3.51	5.515	2.665	4.88
pH	7.46	7.57	7.3	7.13

Samples from the last period (March 25th 2010)

When looking at the phosphorus contents of the two sample dates March 5th and March 25th; an increase in phosphorus content in both lakes is seen on the later date. Viksjön has the greatest total phosphor content of 0.129 mg/l in the inflow and 0.100 mg/l in the outflow indicating retention on March 25th (figure 12 and Appendix C). Ellenösjön balances inflow and outflow on 0.114 mg/l of total phosphorus but have a small leak of phosphate-phosphorus. Still the share of phosphate-phosphorus is very high (around 90%). According to table 6 the phosphorus contents are classified as extremely high or hyper-eutrophic (table 5).

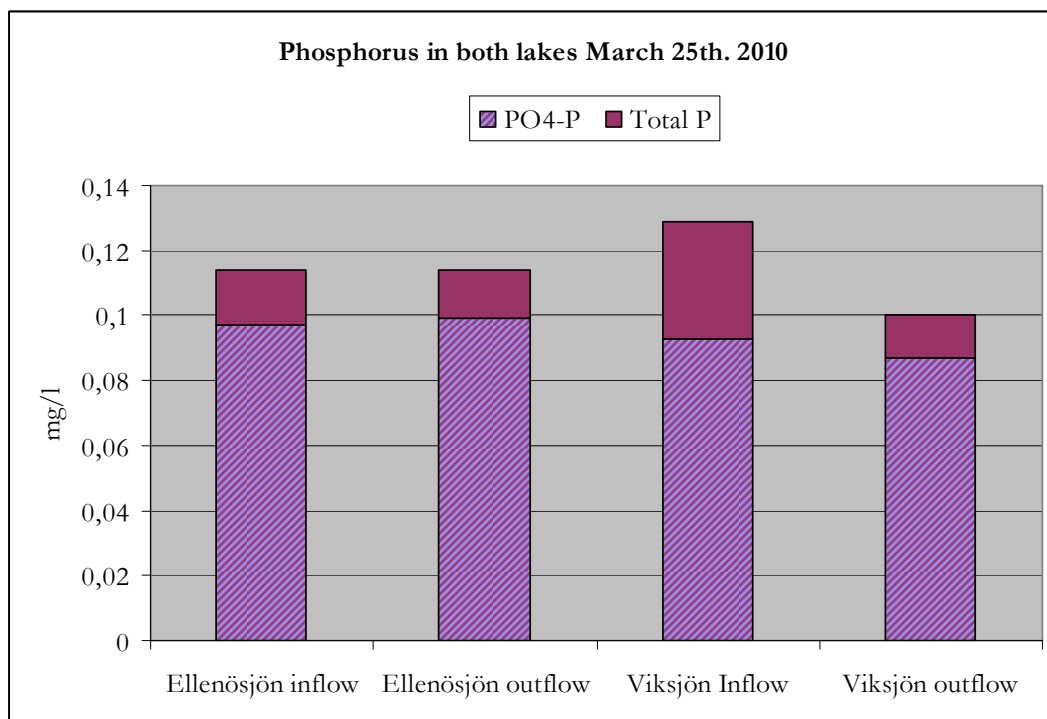


Figure 12 Phosphorus in inflow and outflow of both lakes, March 25th 2010.

In the beginning of March, pH and color are fairly constant but turbidity is a little smaller in the deep area of Viksjön and a little bigger in the deep area of Ellenösjön than in the inflow and outflow. The values of color are more than twice the size than earlier. This is shown visually in appendix C. In the last monitoring (March 25th) the amount is bigger in the outflow than in the inflow of Ellenösjön and vice versa for Viksjön (Table 13). They are classified as highly colored by the Swedish standard (table 7). On the other hand turbidity has decreased a bit in the end of March but is still classified as considerable humic. In Ellenösjön turbidity is a bit bigger in the outflow than previous.

Table 13 Ellenösjön and Viksjön. March 25th 2010.

	Inflow Viksjön	Outflow Viksjön	Inflow Ellenösjön	Outflow Ellenösjön
Color (Pt/l)	184	132	144	181
Turbidity (FTU)	2.60	2.73	3.61	6.15
pH	7.45	7.15	7.09	7.17

Data from the monitoring program (SRK)

Phosphorus in Ellenösjön 2000 – 2008.

Three monitoring sites exist for Ellenösjön where a range of different measurements has been done from the monitoring program (SRK), a kind of recipient control system. Among other parameters, the amount of total phosphorus has been measured for the inflow (V9) and the outflow (V12). This can give a rough idea about the phosphorus retention over the years and for different month during the seasons. In table 14 and figures 13 and 14 the yearly transport, flow and weighted mean are shown.

Table 14 Phosphorus: transport (ton) per year. Flow dependent mean content (weighted mean) ($\mu\text{g/l}$) per year and flow (m^3) per year. Data from SRK.

	Year	Flow year (m^3)	Transport (ton)	Weighted mean $\mu\text{g/l}$
V9 Inflow	2000	371738592	24.6	66
	2001	210958560	11.6	55
	2002	223293888	11.7	52
	2003	166629312	10.4	62
	2004	241882848	14.4	60
	2005	180205098	9.3	52
	2006	291588112	9.9	34
	2007	234697495	8.2	35
	2008	307425364	13.9	45
V12 Outflow	2000	411468768	23.2	56
	2001	234185472	13.1	56
	2002	244522368	11.2	46
	2003	173661408	12.1	70
	2004	268439616	16.5	62
	2005	199705091	9.6	48
	2006	317058331	13.2	42
	2007	254251548	11.3	44
	2008	342447166	15.0	44

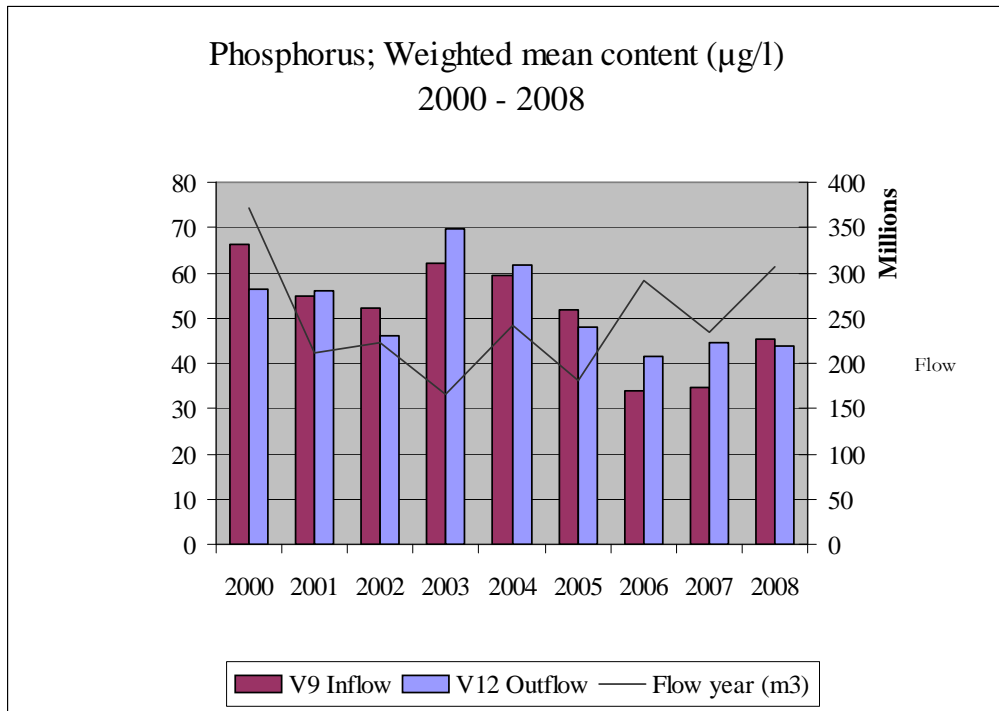


Figure 13 Total Phosphorus in Ellenösjön 2000 – 2008. Flow dependent mean content (weighted mean) ($\mu\text{g/l}$) per year and flow (m^3) (Source SRK)

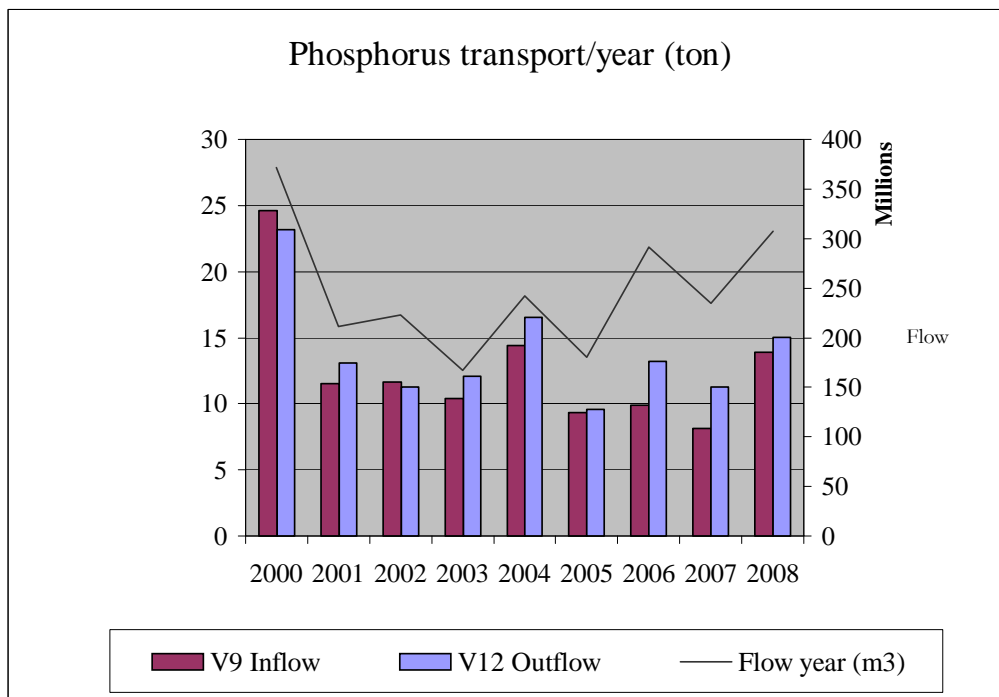


Figure 14. Total Phosphorus in Ellenösjön 2000 – 2008. Transport (ton/year) and flow (m^3/year). (Source SRK)

ANOVA

Following is shown an ANOVA regression analysis of all SRK data from 2000 to 2008 on total phosphorus plotted against the dates. Figures 15 and 16 show, that there is a diminishing trend of phosphorus over the years. There is a particular strong connection in the inflow (Inflow: $F=12.6$. $p<0.001$; ANOVA) (Fig. 15). In the outflow it is still significant but not as clear (Outflow: $F=6.4$. $p<0.05$; ANOVA) (Fig.16). The R^2 values are very low though, due to the huge spread of values with a lot of extreme values.

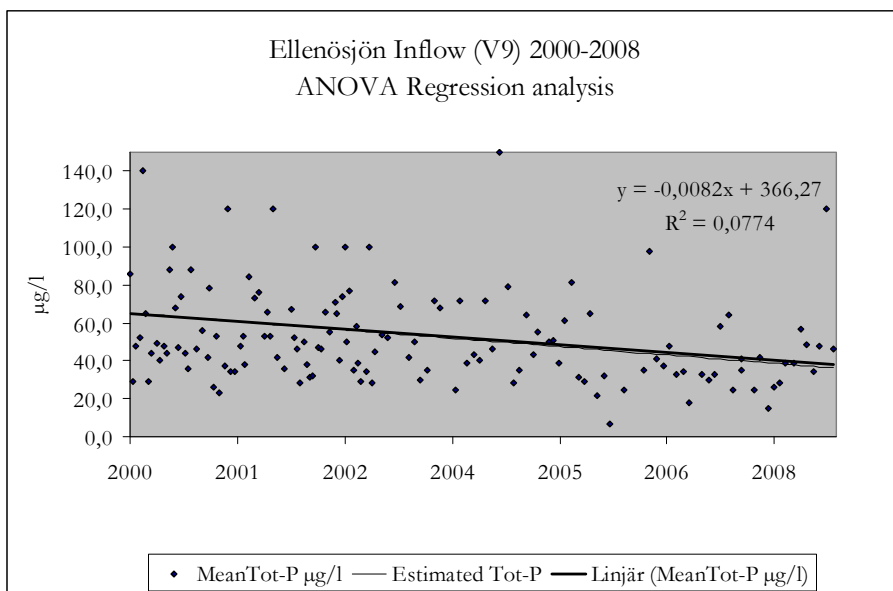


Figure 15 Regression line for phosphorus content in the inflow of Ellenösjön in 2000 - 2008

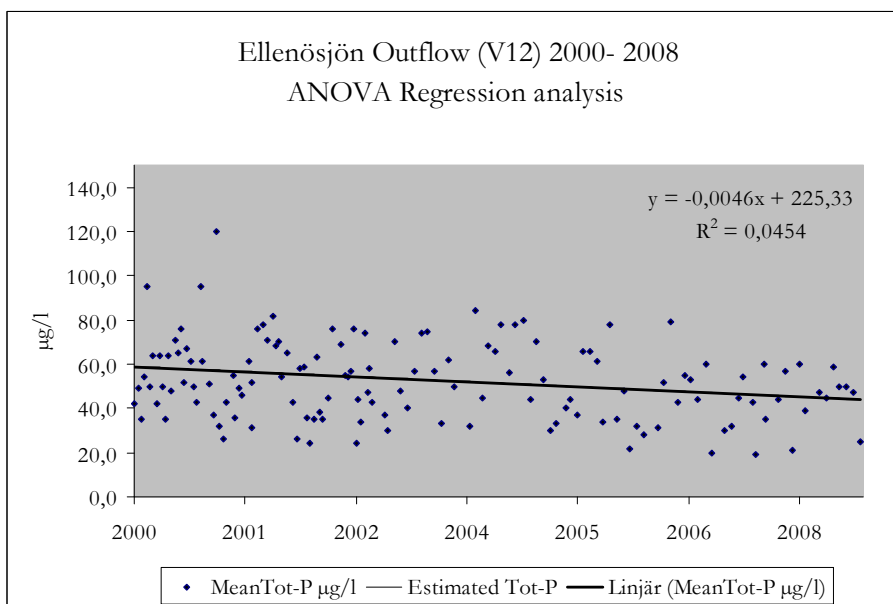


Figure 16 Regression line for phosphorus content in the outflow of Ellenösjön in 2000 – 2008

From the equations of the regression line it is seen diminishing trend of phosphorus is bigger in the inflow than in the outflow. This indicates a net release of phosphorus. If the lake should have been a phosphorus sink, the (negative) slope of the trend should have been greater for the outflow than the inflow. It is possible to calculate the diminishing trend in percentage by the equations. This is done by calculate a value for the first date (2000) and divide with a calculated value of the latest date (2008). ANOVA puts a value in place of the dates, that is for the minimum (January 3rd 2000) 36527 and maximum (December 19th 2008) 39815. Putting those numbers in the equation gives for inflow (V9) $39.79/66.75 * 100\% = 60\%$. This means that **the phosphorus concentration diminished with 40% in the inflow**. For the outflow (V12) it is $42.18/57.31 * 100\% = 74\%$. **The diminishing trend for the outflow is then only 26%.**

Seasonal phosphorus in Ellenösjön

To see if there is any seasonal or monthly connection, a monthly median of phosphorus in the years 2000 – 2008 is calculated. That is, median for all Januaries, all Februaries and so on has been calculated to see if there is a “sink or source” trend connected to a period or month. The standard error shows huge variations in the values. With means of variables that fluctuates that much it is difficult to say any generalizations or show any patterns. Also the mean flows during the years 2000-2008 is shown to see if there is a connection. Table 15 and figure 17 shows the monthly means and medians.

Table 15 Ellenösjön. Mean and median of phosphorus differences ($\mu\text{g/l}$) (inflow – outflow (retention)) for all month 2000 – 2008. That is; mean of all Januaries, all Februaries and so on. SD: Standard Deviation (Spread of actual data values around the mean).

SE: Standard Error (Spread of multiple sample means around the true mean) = SD/\sqrt{n} . Mean flow m^3/s . (Data from SRK)

<i>Month</i>	<i>Mean</i>	<i>Median</i>	<i>SD</i>	<i>SE</i>	<i>Mean flow</i>
1	-11,64	-11	32,52	9,80	16,04
2	3,23	-2	18,17	5,04	11,20
3	-6,56	-12	21,41	7,14	9,59
4	12,42	-3	44,91	12,96	9,21
5	1,20	1	17,60	5,57	5,24
6	-11,92	-13	22,59	6,52	3,71
7	-0,55	-5	18,35	5,53	5,32
8	2,15	6	14,19	3,94	3,73
9	-6,91	-15	28,64	8,64	4,34
10	15,93	0	32,78	8,46	7,54
11	-3,60	-14	30,74	9,72	13,50
12	-5,00	-9	17,28	5,46	13,93

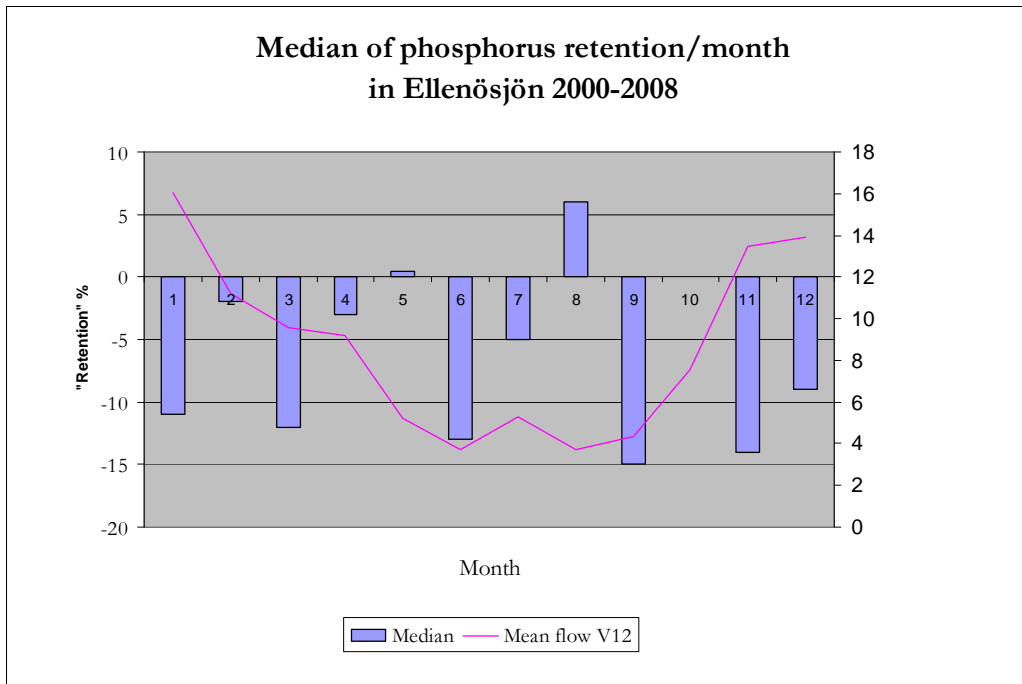


Figure 17 Monthly median of phosphorus retention ($\mu\text{g/l}$) and mean flow (m^3/s) in Ellenösjön 2000 – 2008. Data from SRK. Confidence limit: $r=3$ ($n=12$) for p approx. 95% (Barnard et al. 2007)

The choice of using the median as well is partly because the values examined aren't necessary normal distributed as assumed when using means, SD and SE. Using medians avoids these assumptions (Barnard et al. 2007). The median shows the central value and is therefore chosen to eliminate extreme values.

Figure 18 shows the proportion of dates with negative differences. This is calculated by number of dates with negative difference divided by number of dates with positive differences. By differences is meant inflow minus outflow of mean phosphorus $\mu\text{g/l}$ for each month. In that way a proportion above 0.5 indicates a net negative retention in the particular month, which means that more phosphorus has left the lake than the lake has received. For example in the 10 Septembers the proportion of negative differences is 0.82. This indicates that a lot of phosphorus is leaving the systems in general in Septembers. This makes sense when this is the end of the summer stratification, which probably is the time greatest oxygen deficiency. In most months the proportion exceeds 0.5. This means that the lake in general has negative retention or releases phosphorus.

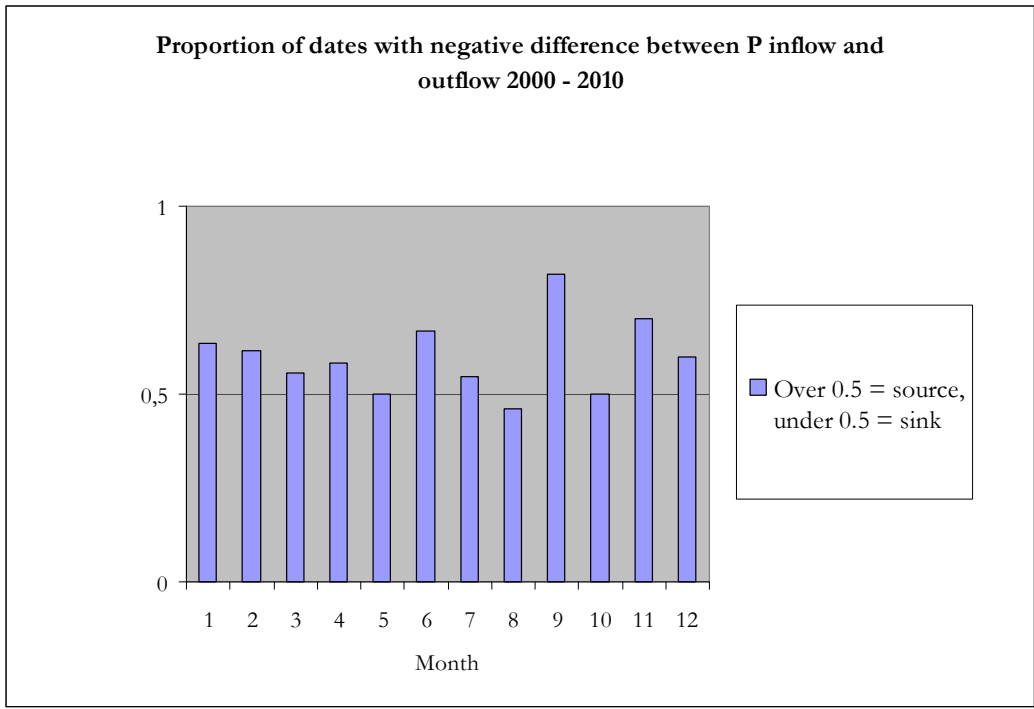


Figure 18 Ellenösjön. Proportion of dates with negative difference between inflow (V9) and outflow (V12) 2000 – 2010 (Source SRK)

Modeled data

SMHI has modeled data for the expected phosphorus content in inflow and outflow of Ellenösjön. From this modeled data I have calculated the Tot P difference between the inflow and outflow (alias retention). A distribution in percent over the month from 2000 - 2008 is calculated as the retention for all Januaries 2000 – 2008, all Februaries and so on.

From the modeled data it is clear that in the spring, phosphorus ought to be leaching, while in the late summer and autumn phosphorus ought to sediment and retention should occur. The actual situation looks different where Ellenösjön most often is leaking phosphorus. Only in May and October phosphorus retention occurs to some extent. Figure 19 shows the comparison between modeled and actual monthly retention in %. A table can be seen in appendix C.

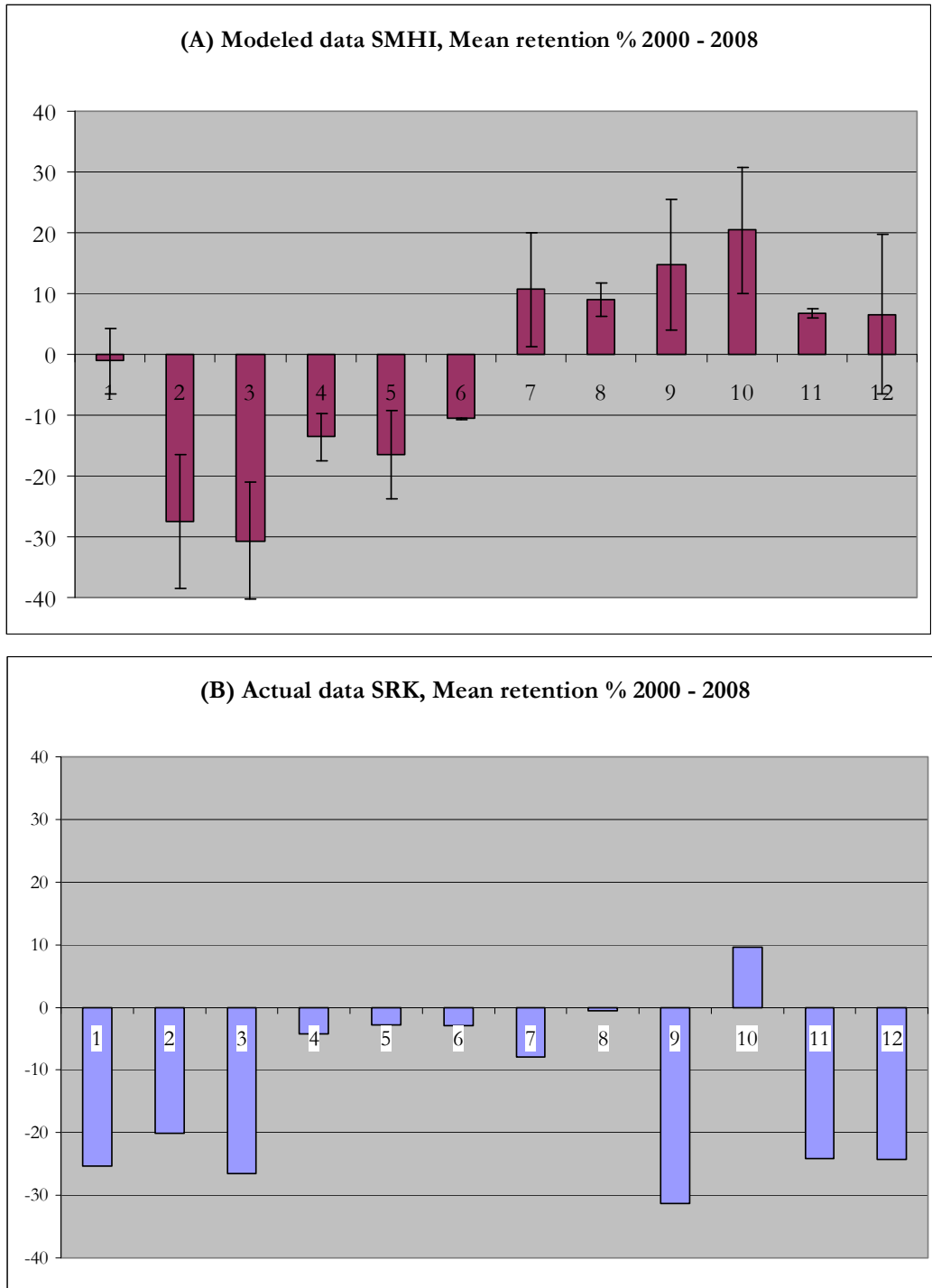


Figure 19 Modeled data from SMHI (panel A) compared to actual SRK data (panel B): Inflow minus outflow in percent for each month. Showing an expected monthly trend, compared to the actual trend. (Negative values indicate a phosphorus leak)

Discussion

Oxygen in the deep areas

In general, Ellenösjön has more oxygen and a more subtle decrease than Viksjön in the deep areas. The oxygen is still very low: under 2 mg/l for both lakes so it is critical for the life within these lakes. It is classified as poor conditions even for warm water fish according to the Swedish standards ($<3 \text{ mg/l O}_2$) (Naturvårdsverket Bilaga A. Handbok 2007:4 Bedömningsgrunder för sjöar och vattendrag). In Ellenösjön, one explanation to the less profound increase of oxygen with depth could be the location of the deep areas on the lakes. As seen on the maps of the lakes the deep area of Ellenösjön is situated between the inflow and outflow. If there is a flow through the lake, there will be some running water going through the deep areas, which is able to oxygenate the water, at least in the top.

The big drop from 1.24 to 0.63 mg O_2 /l from 2 to 2.5 meters depth in Viksjön indicates that it is only in the top two meters that there is some oxygen left in Viksjön and almost anoxic conditions exist in the deeper parts. Anoxic conditions exist for both lakes near hypolimnion and both lakes show a Clinograde oxygen curve (figure 7). This indicates the oxygen consumption exceeds the production and the lakes are highly eutrophic. The prolonged ice cover furthermore impairs the diffusion of oxygen and there have been several reports of snowing occasions, which have resulted in increased albedo and ceased photosynthesis. The presences of large quantities of cyprinid fishes as indicated by the test fishing are all factors that aggravate the eutrophic condition and lead to anoxia.

Oxygen in the transects

The oxygen contents in the sample sites of the two transect on the shallow areas of the lakes indicate a better oxygen status for Ellenösjön. One conspicuous observation is that, in Ellenösjön the oxygen content increases the further out on the lake, whereas for Viksjön the case was opposite. Lake Ellenösjön is situated upstream Viksjön, and adjacent to Ellenösjön is Östersjön, which is a less eutrophic lake. The nutrient loading of Ellenösjön could possibly be smaller than for Viksjön because the nutrient load is diluted with the water from Östersjön. The location of the transects of Ellenösjön is also adjacent to Östersjön. The oxygen content in

Ellenösjön is between 3.28 to 5.35 mg/L, a low value for the pike-perch which generally needs more than 3.5–4.5 mg O₂/l. The species has been reported to move to more oxygen rich waters if concentrations decrease 5–6 mg O₂/l (Berglund, 2004).

In Viksjön the oxygen contents of the transects are even lower; from 1.61 - 3.39 mg O₂/l at the bottom of transect 5. Even cyprinid fishes have a hard time surviving here.

It is assumed that the oxygen conditions will not improve as long as the ice layer prevails and the anoxic conditions will precede through out the winter till the melting of ice will increase the water flow and oxygen can diffuse naturally at the atmosphere – water surface. This could lead to conditions with winterkill and an alteration of life in the lakes.

Unfortunately we were not able to measure the oxygen content in the end of March when taking the last samples of inflow and outflow, because of the ice thaw. It looked like there were a very high flow in the inflow and outflow, which was also ice-free. And even on the lakes there were large patches with ice-free water so it can be assumed that the oxygen status has improved.

Phosphorus

Ortho phosphate

Phosphorus is an unpredictable nutrient to estimate, especially ortho phosphate, because it easily reacts with other metals and the amounts alter from the original water sample when stored. Therefore, I have mostly examined the results of total phosphorus. However, some remarks should be said about the ortho phosphate results. In table 16 below the amount (in percentage) phosphate phosphorus relative total Phosphorus is shown. In the beginning of March almost all of phosphorus is phosphate phosphorus (more than 90% in inflow and outflow). Why was then the share of ortho-phosphorus (PO₄³⁻) so big (between 72 – 94%)? As noted in the chapter on phosphorus, generally (PO₄³⁻) only constitutes a few percent of total phosphorus and is the source of phosphorus that generally utilize very quickly. Perhaps during winter conditions, there might be a restricted amount of biological activity and hence fewer amount ortho-phosphates will be utilized.

Another complimentary explanation could be that the iron oxy hydroxide aggregates (FeOOH) that normally absorb phosphorus ions at the sediment surface continually (acting as a barrier to phosphate diffusion from the sediment to the free water column) doesn't absorb iron but releases it because of anoxic conditions.

This could be due to the time of year and the weather conditions; it was a very cold winter with a thick layer of ice on top of the lakes with probably little or none production. Hence no utilization of ortho phosphate as usually will be consumed very rapidly. In Ellenösjön it also seems like there is more phosphorus and phosphate phosphorus in the outflow than inflow, which indicates no production/utilization in the lake and even a release of phosphorus from the sediments. It wasn't possible to analyze the water samples on the same day as they were taken and this could have influenced the result because ortho phosphate is very reactive and thereby more difficult to estimate. However, this should have given a smaller amount of ortho phosphate than total phosphate, which it didn't so this is unlikely because the results are so far above the normal.

Table 16 Share of phosphate-Phosphorus. Viksjön. Beginning of March.

<i>Viksjön.</i>	<i>Inflow</i>	<i>Outflow</i>	<i>Deep area</i>	<i>Deep area</i>
<i>Beginning of March</i>			<i>top</i>	<i>bottom</i>
Total Phosphor mg/l	0.069	0.068	0.071	0.073
Phosphate phosphor mg/l	0.064	0.063	0.061	0.06
Share of Phosphate P	93%	93%	86%	82%

Table 17 Share of phosphate-Phosphorus. Ellenösjön. Beginning of March.

<i>Ellenösjön.</i>	<i>Inflow</i>	<i>Outflow</i>	<i>Deep area</i>	<i>Deep area</i>
<i>Beginning of March</i>			<i>top</i>	<i>bottom</i>
Total Phosphor mg/l	0.078	0.083	0.076	0.081
Phosphate phosphor mg/l	0.07	0.078	0.066	0.069
Share of Phosphate P	90%	94%	87%	85%

Table 18 Share of phosphate-Phosphorus. Both lakes. End of March.

<i>Both lakes</i>	<i>Inflow</i>	<i>Outflow</i>	<i>Inflow</i>	<i>Outflow</i>
<i>End of March</i>	<i>Viksjön</i>	<i>Viksjön</i>	<i>Ellenösjön</i>	<i>Ellenösjön</i>
Total Phosphor mg/l	0.129	0.1	0.114	0.114
Phosphate phosphor mg/l	0.093	0.087	0.097	0.099
Share of Phosphate P	72%	87%	85%	87%

Total Phosphorus

Total phosphorus in both lakes is very high and both lakes are classified as eutrophic in the beginning of March and in the end of March they are hyper-eutrophic (table 5). Ellenösjön is releasing phosphorus (5 µg/l tot-P) in the beginning of March whereas Viksjön actually has retention in the last period (29 µg/l Tot-P).

Unfortunately it wasn't possible to monitor the deep areas in the end of March due to the sudden thaw.

As seen under the phosphorus chapter anoxic conditions can arise by an extensive ice- and snow cover. This can lead to a reducing environment, which means that iron (Fe^{3+}) will be reduced to Fe^{2+} and cannot bond with PO_4^{3-} . The oxy hydroxide

aggregates dissolve and PO_4^{3-} can diffuse into the hypolimnion, thus phosphorus releases from the sediment, which is known as internal loading. It is plausible to assume there occurs an internal loading in Ellenösjön. Hence, if there is a counteracting release of phosphorus from the sediments it is important not only to focus on reducing the external loading from the catchment area and the surrounding environment.

It is noteworthy that the phosphorus content are extremely high in the end of March where the snow melt has begun and the flow of the water has increased and thereby the oxygen content assumes to increase as well (thereby decreasing the internal loading). It could be a result of an increased flow and thereby an increased external load from the environment. The increased flow also creates natural turbulence, which removes released, dissolved phosphorus from the sediment-water interface. With the thaw there might be considerable erosion from the riparian zone. This is also supported by the change in watercolor (See below). Also an increase of nutrients accumulated on snow during winter that can be released in great amounts during spring thaw can add up. In Ellenösjön it could also arise from an internal source because of anoxia in hypolimnion (outflow exceeds inflow) and by bioturbation from the high quantity of cyprinid fishes.

Color and Turbidity

The overall biggest change is in color, which increases almost three times from March 5th to March 25th. This indicates that the water contains more humic matter probably reflecting the big thaw and increased flow in the rivers and lakes. The increased water flow is carrying large quantities of humic matter and will increase erosion, which will add to the pollution. The increased amount of humus will add to the problem with eutrophication. While humic acids are a source of phosphorus the primary production increases. The transparency of the water will decrease and the irradiance from the sun will convert into heat and the top layer of the water will increase in temperature, which in turn will increase eutrophication and the possibility of anoxia (Kalff, 2002)

Both lakes are classified as considerable turbid, Ellenösjön more than Viksjön, especially in the deep areas and in the outflow in the end of March. This could indicate some increased algal activity in Ellenösjön. Turbidity in Viksjön is somewhat unchanged and indicates no increased algal production.

Overall it seems like Ellenösjön has the biggest problem with eutrophication with high amount of phosphorus, leaching phosphorus from the sediment and in the end of March Ellenösjön had greater values of phosphate-phosphorus, color and turbidity in outflow than inflow indicating an internal loading. Even Viksjön had poor oxygen conditions and were hyper-eutrophic with extremely high phosphorus content in the end of March. Viksjön still acted as a sink of phosphorus with a

higher amount of phosphorus in the inflow than outflow. It is very likely that the ice and snow cover has acted as a barrier for oxygen diffusion and photosynthetic oxygen production by alga. This is likely to have led to phosphorus release from the sediment hence the extremely high amount of both phosphate phosphorus and total phosphorus.

Data analyzed from SRK. Phosphorus in Ellenösjön during 2000 - 2008

In figure 18 (median) it becomes obvious that there is a net release of phosphorus in the most months during the years. Only in May and August is there a net positive retention of phosphorus. According to figures 5 and 6 the phosphorus situation ought to be due to the area and type of the catchment areas. Those figures show that phosphorus contents increase during the systems in tons, but the load (kg/km^2) decreases because of a bigger catchment area downstream. Figure 18 (median) shows that Ellenösjön is releasing phosphorus in the most months. This will lead to increasing phosphorus throughout the system instead of diminishing with increasing catchment areas. Also SMHI's model shows there ought to be a net retention in the summer and autumn month and a phosphorous leak only in spring and early summer. The ANOVA analysis shows a diminishing trend over the years, but it becomes evident that the trend is bigger in the inflow than the outflow of Ellenösjön (14% difference). It is obvious that Ellenösjön are releasing phosphorus and is highly eutrophic.

The diminishing trend of phosphorus over the years indicates that there has been a reduction of the load from the catchment areas. This could be due to climate changes, with milder winters. Also, this could well indicate that the advisory and information project "Focus on nutrients" (www.greppa.nu) had had an effect, This is positive and should continue to go on in the pursuit of reducing the nutrient loading of the waterways. This will eventually slow down the problems with eutrophication and its complications further downstream. Ellenösjön is however still releasing phosphorus from the sediment and it is a long process to reduce the impacts of eutrophication because the amount of phosphorus stored in the sediment can be huge. As earlier noted this could take another ten or twenty years to see an effect on reduction of external loads. For that reason it could be necessary to reduce the internal loading with methods such as aeration of the water or reducing the amount of cyprinid fishes.

Conclusion

- Oxygen conditions were poor in both lakes. Anoxic conditions existed in the deep areas and even poor conditions were found in the shallower part.
- Both lakes had very high phosphorus contents in the beginning of March and extremely high content in the end of March, so it is likely that the ice and snow cover have had an influence on the low oxygen content and the very high phosphorus content.
- According to modeled data the lakes should act like a sink in parts of the year, but Ellenösjön acts as a source and Viksjön acts as a sink.
- According to data from SRK on phosphorus content, there has been a down going trend over the years (from 2000 – 2008), but this trend is bigger in the inflow than the outflow of Ellenösjön, indicating that Ellenösjön is a phosphorus source.
- Ellenösjön is highly eutrophic and releases phosphorus in the most months and years.

Limitations and Sources of errors

Quantification of the relationship between ice and snow cover, oxygen content and phosphorus proved difficult because

- Only one measurement of oxygen and phosphorus were made in the deep area due to the sudden melting. It is difficult to say anything about the duration of the low oxygen content. If it was temporary or more prolonged
- Monitoring and samples of oxygen and phosphorus were only done at one time a day. This may be a source of error because diurnal fluctuations of oxygen may happen due to respiration at night and photosynthesis during day.
- The flow is not taken into account. It's hard to know how much flow is under the ice and how this is affecting the oxygen and phosphorus concentration.

- Only single measurements were done due to time, economic and practical limitations. This makes it impossible to make any statistical analyzes of the monitoring results. (Though this was done for existing data)

To have had a better scientific result it would have been necessary to have investigated more lakes with similarly features (catchment areas, depths and so on) and compared with lakes of different features (for example lakes that are expected to be oligotrophic).

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Link to Sander: http://en.wikipedia.org/wiki/Sander_lucioperca

Fiskeriverket 2010: ([Länk till Fiskeriverkets databas om provfiske NORS. Ellenösjön](#))

Appendices

Appendix A

The Catchment Area

Örekilsälven and eventually the lakes Ellenösjön and Viksjön run into the Fjord of Gullmarn. The fjord has a unique marine fauna and is classified as Natura 2000-area. See figure 1. The Fjord of Gullmarn is formed partly by a fault hollowed out by water and ice and partly during the last ice age, carved by a glacier cutting a U shape during its course. This makes it very deep at some points (118 meters) ((Molander 1964) in Enebjörk & Fränne 2006, Norling & Sköld 2002). The Fjord is called a sill fjord because it has a rise or sill at its mouth caused by the glacier's terminal moraine (<http://en.wikipedia.org/wiki/Fjord>). Gullmarn is the only sill fjord in Sweden and is 25 kilometer long. The depth of the sill is 42 meters. The sill and the salinity stratification complicate the exchange of the water. The water is normally exchanged once a year with oxygenated seawater but some years no exchange occurs (as in 1997). This caused oxygen depletion and bottom death. Because of its special features Gullmarn is very vulnerable to pollutants. Too much nutrients will lead to alga blooms and subsequently to oxygen deficiency in the bottom water (Enebjörk & Fränne 2006). Gullmarn has been part of a pilot project in the North Sea countries: NOLIMP-WFD (North Sea Regional and Local Implementation of the Water Framework Directive) aiming to improve collaboration between the countries around the North Sea and improving ecological status in pilot areas (Enebjörk & Fränne 2006).

Appendix B

Table 19 GPS-coordinates for the deep areas (from SRK)

	Viksjön	Ellenösjön
GPS coordinates for the	582343.4 N	583005.2 N
Deep areas (WGS 84)	114855.3 E	115556.7 E
Depth (m)	6.2	7
pH	7.87	8.3
Atmospheric pressure (mmHg)	997	997

Table 20 GPS-coordinates for the 5 sample sites in Ellenösjön.

<i>Sample number</i>	<i>Ellenösjön GPS</i>	<i>(WGS 84)</i>
1 (Depth 1m)	583005.8 N	115708.6 E
2 (1m)	583007.1 N	115709.4 E
3 (1m)	583008.5 N	115710.8 E
4 (0.9m)	583009.1 N	115711.9 E
5 (1m)	583010.5 N	115713.8 E

Table 21 GPS-coordinates for the 5 sample sites in Viksjön

<i>Sample number</i>	<i>Viksjön GPS</i>	<i>(WGS 84)</i>
1 (Depth 1.8m)	582913.1 N	119852.9 E
2 (2.1m)	582911.8 N	114851.4 E
3 (2.4m)	582910.9 N	114850.5 E
4 (2.4m)	592909.8 N	119849.8 E
5 (2.8m)	582908.4 N	114849.1 E

Appendix C

Phosphorus in the two lakes.

Table 22 Viksjön inflow, outflow February 25th. Deep area March 5th 2010.

Viksjön	Inflow	Outflow	Deep area top	Deep area bottom
Total Phosphor mg/l	0.069	0.068	0.071	0.073
Phosphate phosphor mg/l	0.064	0.063	0.061	0.060

Table 23 Ellenösjön Inflow, outflow March 2nd. Deep area March 5th 2010.

Ellenösjön	Inflow	Outflow	Deep area top	Deep area bottom
Total Phosphor mg/l	0.078	0.083	0.076	0.081
Phosphate phosphor mg/l	0.070	0.078	0.066	0.069

Table 24 Ellenösjön and Viksjön. March 25th 2010.

	Inflow Viksjön	Outflow Viksjön	Inflow Ellenösjön	Outflow Ellenösjön
Total Phosphor mg/l	0.129	0.100	0.114	0.114
Phosphate phosphor mg/l	0.093	0.087	0.097	0.099

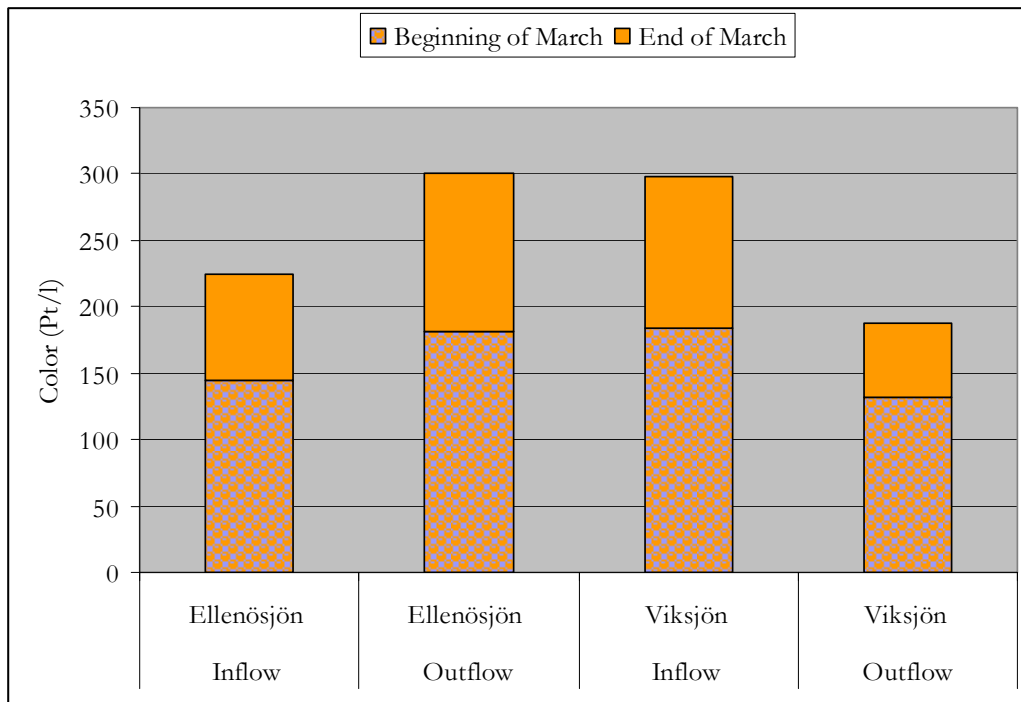


Figure 20 Color in the beginning and end of March.

Table 25 Retention as inflow – outflow in percent 2000 – 2008. Modeled after SMHI's HYPE model and compared to the actual values from SRK.

Month	SMHI Mean Retention %	SE	SRK Mean Retention%
January	-1.1	5.3	-25,4
February	-27.5	11.0	-20,1
March	-30.7	9.6	-26,6
April	-13.5	3.9	-4,2
May	-16.5	7.3	-2,8
June	-10.6	0.0	-2,9
July	10.6	9.4	-7,9
August	9.0	2.8	-0,5
September	14.8	10.7	-31,3
October	20.4	10.4	9,6
November	6.7	0.7	-24,1
December	6.6	13.1	-24,3
Sum	-31.9/12		
Average	=-2.7		-13,4