Article

Role of Internal Phosphorus Loading in the Archipelago Sea Ecological Status

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Role of Internal Phosphorus Loading in the Archipelago Sea Ecological Status

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Abstract: In eutrophic aquatic ecosystems like the Archipelago Sea, in the northern Baltic, the role of the sediment as a sink and source of nutrients is especially important. Based on previous research in the Archipelago Sea, it can be concluded that the store of phosphorus that can be released with time from the sediments is large, and that internal phosphorus recycling processes thus may play a key role in phosphorus fluxes in the coastal zone. The release of nutrients from the sediment has been suggested as an explanation for the fact that a substantial reduction in external nutrient load does not always result in a corresponding reduction in nutrient concentrations and phytoplankton biomass in the recipient waters. However, the magnitude of the actual internal phosphorus load in the Archipelago Sea has not been successfully estimated, or the estimates have been evidently too high. In this study, I perform calculations based on measured water quality data to estimate how much phosphorus has been transported from the bottom water layer to the surface layers during the biological production season for use in algal production. In other words, what is the magnitude of the effective internal phosphorus load in the Archipelago Sea. Calculations have resulted in a summer internal net phosphorus load in surface layer of approximately 300 tons/5 months. The other total phosphorus load in the Archipelago Sea, which mainly (60 %) originates from the catchment area, is 575 t/a. A permanent way to mitigate internal loading has been thought to be to reduce external loading. However, the decrease in internal loading occurs with an unknown delay, making it impossible to predict the recovery rate.

Keywords: Baltic; Archipelago Sea; phosphorus; internal loading

1. Introduction

Bottom water hypoxia and anoxia are common eutrophication problems in coastal waters of the Baltic Sea, where root cause is excessive inputs of nutrients. As a result, there is increased settling of organic matter, which increases oxygen (O_2) consumption [1]. It is well known that release of phosphate-phosphorus from sediments can be drastically enhanced when bottom waters turn anoxic [2,3]. The phenomenon is called by internal phosphorus loading.

Over long-time scales, phosphorus can be considered the limiting nutrient of phytoplankton production in Baltic Sea, because atmospheric nitrogen is an endless source for N-fixing species [4,5] Nitrogen fixation brings more nitrogen to the system, turning it towards phosphorus limitation [6]. Enhanced internal loading of phosphorus and inorganic nitrogen removal with increased hypoxia leads to lower nitrogen to phosphorus ratios, which are one of the main factors promoting nitrogen-fixing cyanobacteria blooms [7].

The sediments in the rather shallow Baltic Sea play an important role for the transformation of organic to inorganic phosphorus and on long time scales for the removal of phosphorus from the biochemical cycling in the water column [8]. In the marine phosphorus (P) cycle, dissolved inorganic phosphorus (DIP), particulate inorganic (PIP) and organic phosphorus (POP) and dissolved organic phosphorus (DOP) are the main P pools [9]. Total phosphorus (TP) was in this study used as a proxy for nutrients available to the planktonic organisms. The basis for this assumption was that in a nutrient-constrained environment with significant turnover of N and P, like during the summer season in the northern Baltic Sea, inorganic nutrients are rapidly (within hours) assimilated by the organisms [10].

The chlorophyll-a concentration, which indicates algal production during the ecological classification period, can used as an indicator for water quality. The ecological classification of coastal waters is primarily based on phytoplankton chlorophyll-a, and some other biological factors. A comprehensive assessment of water quality is made by combining information from all quality factors to evaluate the state of the water. If total nutrients are classified differently, phosphorus results are given priority [11].

Although the eutrophication mechanisms of the Baltic Sea and the Archipelago Sea have been studied extensively e.g. [12–15], the assessment of internal phosphorus loading has received less attention. The magnitude of the actual internal phosphorus load in the Archipelago Sea has not been unambiguously estimated, or the estimates have appeared to be very high compared to other known nutrient loads [15–17]. For example, Puttonen *et al*. [17] estimated that the amount of internal phosphorus loading in the Archipelago Sea area would be 3 200 t/a, nearly ten times higher compared to river loading (350 t/a).

In this study, I perform statistical calculations based on measured water quality data from years 2000-2024 in different monitoring stations which are located across different parts of the Archipelago Sea. The aim is to assess how much phosphorus has been transported from the bottom water layer to the surface layers during the biological production season for use in algal production. In other words, what is the magnitude of the effective internal phosphorus load in the Archipelago Sea.

The article also analyzes how the ecological status of the Archipelago Sea varies across its different parts, using surface water chlorophyll-a concentration, which reflects algal production, as an indicator during the ecological classification period. The seasonal dynamics of phosphorus are described using representative data from the intensive monitoring station at Seili, located in the middle archipelago.

2. Material and Methods

2.1. Study Areas

The Archipelago Sea is located between the Baltic proper and the Bothnian Bay (Figure 1). It is characterized by an enormous topographic complexity, including about 30,000 islands. The average water depth is only 23 m, and the deepest trench reaches 146 m. The total coastal drainage area is about 8 900 km^2 (of which lakes cover under 2% and fields cover 28%). The total area of the Archipelago Sea is about 9 500 km^2, and the water volume is 213 km^3. The combined surface area of the mainland-side water bodies of the Archipelago Sea is 6 191 km^2, covering 65% of the entire region. The remainder lies on the Åland side. The sea is non-tidal and characterized by a strong seasonality, including high summer temperatures and a more than 90% probability of annual ice cover during winter. Eight rivers run into the Archipelago Sea. The amount of water brought to the sea by the rivers is approximately 2.2 km^3/a. The mosaic morphology and the environmental gradients (e.g., salinity, temperature, exposure) create several biotopes and complicated ecological webs [18,19]. As the topography is complex and the water shallow, the area acts as a buffer or filter between the coastline and the open sea and also between the Baltic proper and the Bothnian Bay [20].

According to statistics from the Finnish Environment Institute, the total phosphorus load to the Archipelago Sea (6191 km^2) has averaged 493 tons per year (t/a) between 2000 and 2023 (Table 1). Based on river water measurements, 27.6% of the total phosphorus is in dissolved form (DIP). The DIP load brought to the sea by the rivers is therefore 97 tons per year (t/a). Atmospheric deposition has been estimated based on literature data [21] at 15 kg of phosphorus per square kilometer per year (kg P/km^2/a). It is often assumed that there the proportion of dissolved phosphorus in total phosphorus is 100%. According to Helminen and Inkala [20], from 2000 to 2014, the net background phosphorus load averaged about 465 t/a, of which 120 t occurred during the summer. But starting in 2015 the surface currents and phosphorus flows made a U-turn and the annual outflow of phosphorus in 2015–2021 was estimated to be 182 t, of which 162 t occurred during the summer.

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Finnish Environment Institute has e.g. estimated using the so-called FICOS model [16] that the internal phosphorus load of the Archipelago Sea could be as high as 2826 tons per year (t/a). However, this estimate should be approached with caution.

Table 1. The total phosphorus load from various sources into the mainland water bodies of the Archipelago Sea (6191 km^2).

Source	Load (t/a)
diffuse load	350
natural leaching	97
point source	35
atmospheirc deposition	93

Water Quality Data

The water quality of the Archipelago Sea has been monitored long with standard methods, and the results are available from the open data service of Finnish Environment Institute (https://www.syke.fi/avoindata). The water quality analysis here based on total phosphorus concentrations and on algae production-related chlorophyll a concentration in the surface water during the ecological classification period (1 July–7 September). The Seili intensive monitoring station (*Nau 2361 Seili intens*) in the middle archipelago provides a detailed example of the seasonal variations in phosphorus concentrations, total (TP) and dissolved inorganic phosphorus (DIP) concentrations, and oxygen conditions in the Archipelago Sea. These changes are influenced by seasonal cycles, such as temperature stratification, biological activity, and external nutrient inputs.

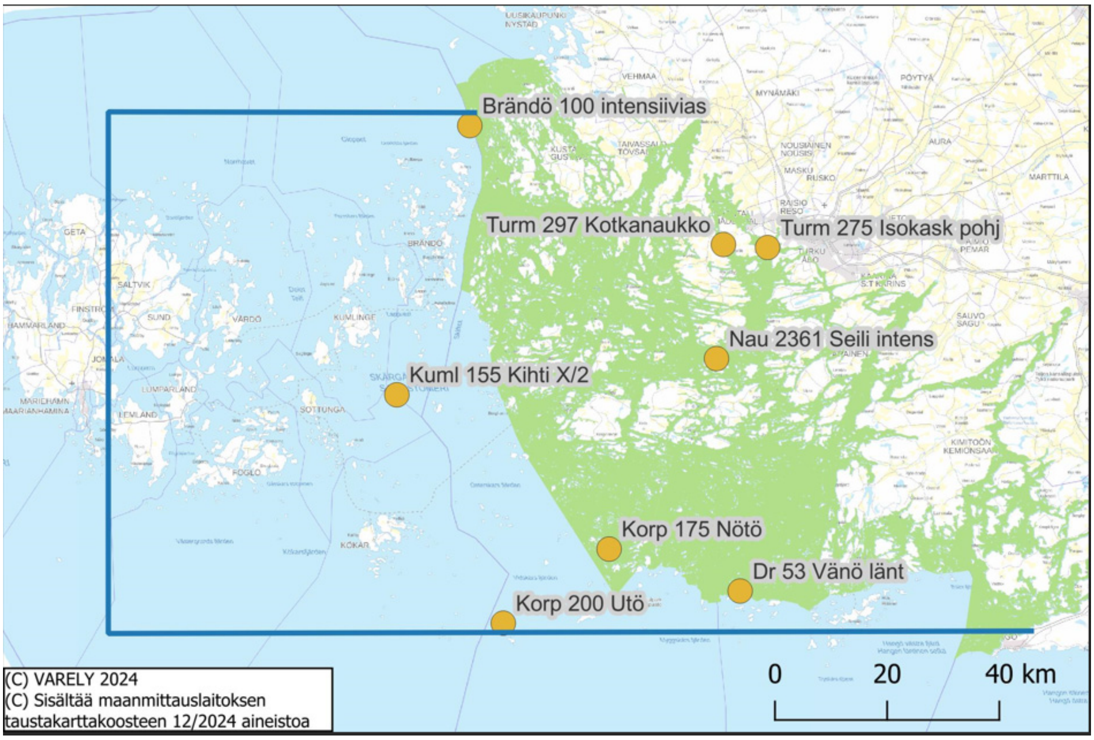

Figure 1. Map of the Archipelago Sea and the locations of water quality monitoring stations. The blue line indicates the boundary of the Archipelago Sea, and green marks represent those mainland-side water bodies or parts of water bodies where internal loading is assumed to occur.

Calculations for Internal Phosphorus Loading

The assessment of internal loading was conducted separately for the inner, middle, and outer archipelago zones of the Archipelago Sea. The water column was divided vertically into layers of 0–10 m, 10–20 m, 20–50 m and 50-100 m. Their volumes were estimated based on Traficom map data (Table 1). Based on this data, the surface area of the Archipelago Sea was calculated to be 9 558 km², and its boundaries are shown in the Figure 1.

Table 1. Estimated volumes (km³) of the Archipelago Sea water layers (0–10 m, 10–20 m, 20–50 m and 50-100 m) based on Traficom map data. https://creativecommons.org/licenses/by/4.0/deed.fi.

Layers (m)	Volume (km³)
0-10	80,2
10-20	51,3
20-50	67,57
50-100	21,32

The calculation was limited to the biological production season, which in this context was defined as the period from May 15 to October 15. In the Archipelago Sea, the spring bloom typically ends by mid-May, and the autumn turnover usually begins around mid-October. During this period, nutrient loading from rivers draining the catchment area is minimal. In Figure 2 is the total phosphorus load (t/month) from the Aurajoki (98 t/a) and Uskelanjoki (39 t/a) rivers into the Archipelago Sea during different months: less than 6 % of the annual load enters the sea between June 1 and September 30. For example, diffuse DIP load to the Archipelago Sea would thus be 1,4 t/kk during summer. Therefore, it can be assumed that virtually all observed increases in phosphorus concentrations in the water column originate from internal processes within the Archipelago Sea, primarily internal loading and its transport. The same approach has often been applied when estimating the magnitude of internal loading during the production season based on lake data [22,23].

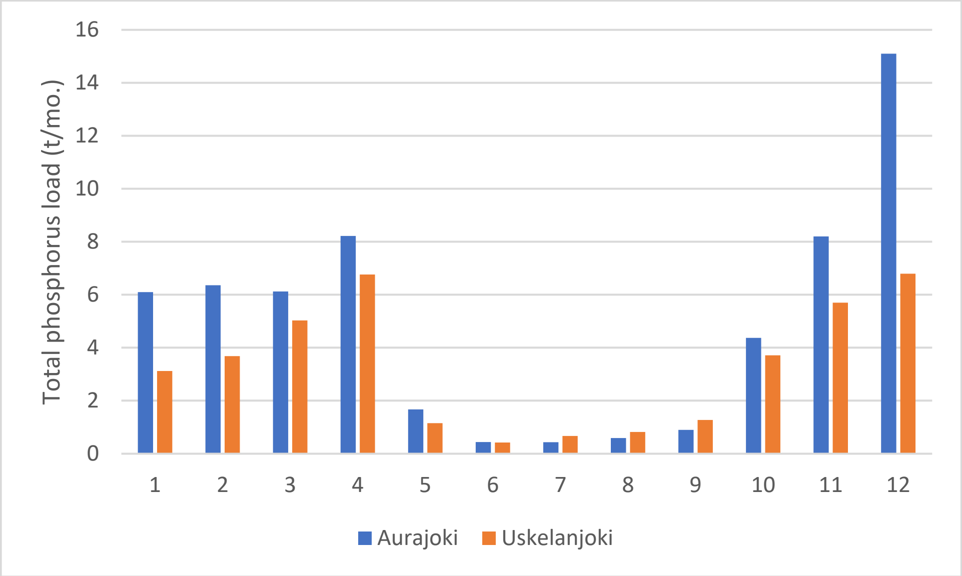

Figure 2. The total phosphorus load (t/month) from the Aurajoki and Uskelanjoki rivers into the Archipelago Sea during different months (1-12).

The addition of phosphorus (t) in each archipelago type (inner, middle, and outer) and in their every depth layer (0-10 m, 10-20 m and 20-50 m) was calculated using regression equations, where x = time (months) and y = measured total phosphorus concentration (µg/l) at the time of observation.

The monthly phosphorus addition (t/km^3) in the period from May 15 to October 15 is then the *slope* of the regression equation.

The estimated monthly phosphorus addition obtained in this way was then multiplied by the volume of each water layer (table) and the ratio of the surface area of the water body type (Table 2) to the total surface area of all water bodies (6191 km^2).

As background information for the annual phosphorus cycle, this study also calculated how much phosphorus is removed from the surface layer (0–10 m) to deeper layers during or immediately after the spring bloom of phytoplankton, carried by sinking planktonic organisms. For this purpose, regression equations for total phosphorus concentrations as a function of time were calculated for different observation stations during the period April 1–May 31. The calculation of the removed phosphorus amount was performed in the same manner as the estimation of internal loading for the surface layer.

Table 2. Surface areas of different water body types (inner, middle and outer) in the Archipelago Sea. Proportion (%) refers to the portion of the water body where internal loading is estimated to occur.

Zone	Total surface area (km^2)	Proportion (%)
Inner	679	100
Middle	1280	100
Outer	4232	39

Results

Ecological Status of the Archipelago Sea

The a-chlorophyll concentration used as an indicator of ecological status in this study varies significantly across different zones of the Archipelago Sea. The highest concentration was measured in the inner Archipelago at the *Turm 275* station in 2004, with a maximum of 18.5 µg/L (Figure 3). The average concentration there for the period 2000-2024 was 10.2 µg/L, which corresponds to a *poor* ecological status in the classification. At the *Turm 297* station, which is also located in the inner archipelago, the a-chlorophyll concentration was lower: the average for the period 2000-2024 was 6.0 µg/L, which falls into the *moderate* ecological class (Figure 4). In the years 2022–2024, the average concentration (7.3 µg/l) has already been in the *poor* category.

At the Seili intensive monitoring station in the middle archipelago, the average concentration of chlorophyll-a between 2000 and 2024 has been 4.2 µg/L, which corresponds to the *moderate* status in classification (Figure 5). But in recent years concentration has reached a level of 5 µg/L, which is close to the poor status threshold (5.8 µg/L).

In the southeastern part of the Archipelago Sea, at observation stations *Korp 175 Nötö* and *Dr 53 Vänö* located in the outer archipelago water bodies, chlorophyll-a concentrations have averaged the same level, 4.1 µg/L, as at the Seili station (Figure 6). However, in the years 2022–2024, concentrations there have been lower than in previous years, with an average of 2.8 µg/L.

The ecological status appears to have improved based on chlorophyll measurements at the Kuml 155 observation station, which is located in the southern part of Kihti in the middle of the Archipelago Sea (Figure 7). The decrease observed from was statistically significant ($p = 0.02$). From 2017 to 2024, the average was 2.2 µg/L, indicating a *good* status had been achieved.

At the Brändö station on the northern edge of the Archipelago Sea, the chlorophyll-a concentration has been quite stable throughout the monitoring period (Figure 8). The average concentration has been 2.5 µg/L, which is classified as *moderate*, but the threshold for *good* status has not been far off, and in some years, it has fallen below. At the Utö station on the southern edge of the Archipelago Sea, the chlorophyll-a concentration has been approximately 50% higher than in the north, with an average of 3.8 µg/L (*moderate*) (Figure 9).

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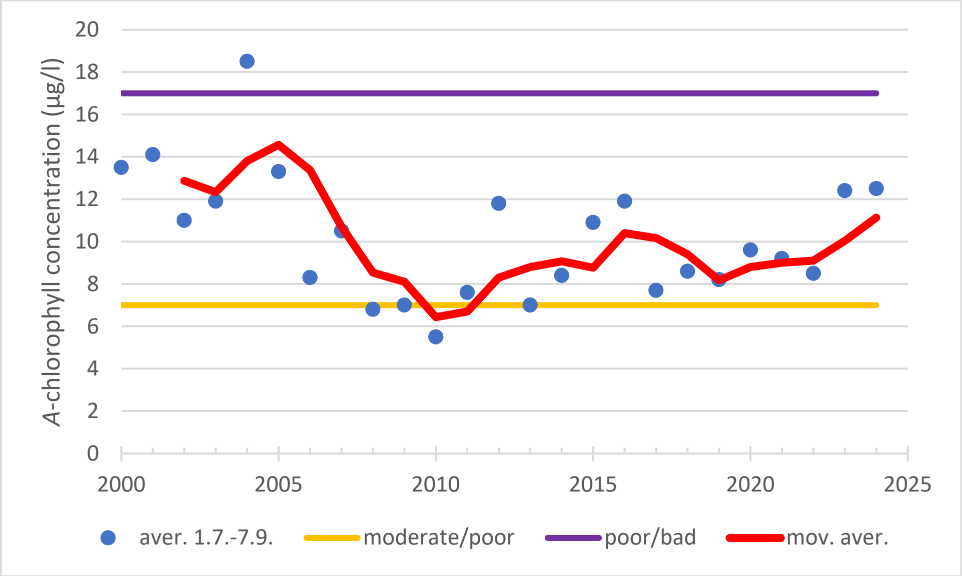

Figure 3. The concentration of chlorophyll a (µg/L) in surface water (0–10 m) at observation station *Turm 275* during the ecological classification period (1 July–7 September) from 2000 to 2024. The poor status lower threshold (moderate/poor) is 7.0 µg/L and upper (poor/bad) 17.0 µg/l. The red line indicates the moving average in the chlorophyll a concentration over the entire period under review.

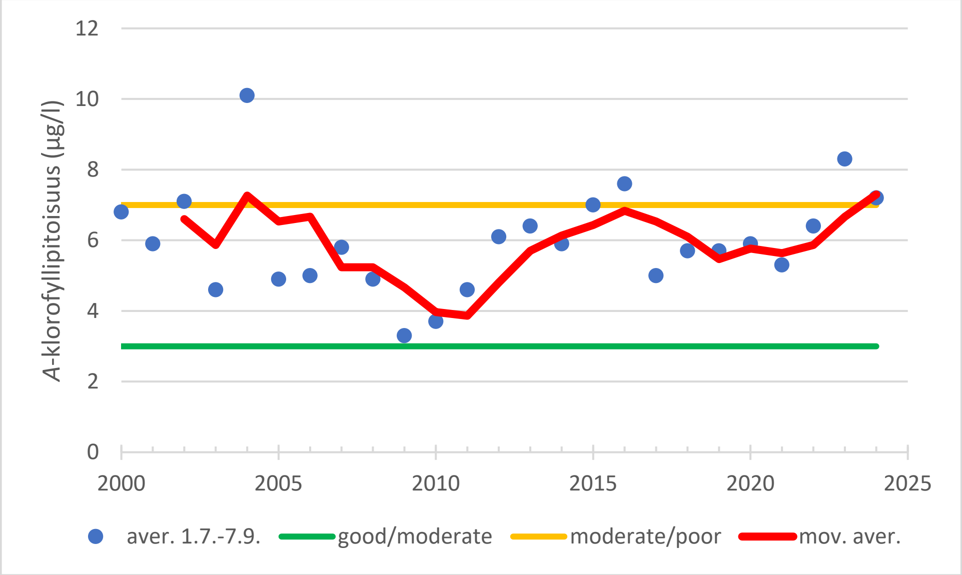

Figure 4. The concentration of chlorophyll a (µg/L) in surface water (0–10 m) at observation station *Turm 297* during the ecological classification period (1 July–7 September) from 2000 to 2024. The moderate status lower threshold (good/moderate) is 3.0 µg/L and upper (moderate/poor) 7.0 µg/l. The red line indicates the moving average in the chlorophyll a concentration over the entire period under review.

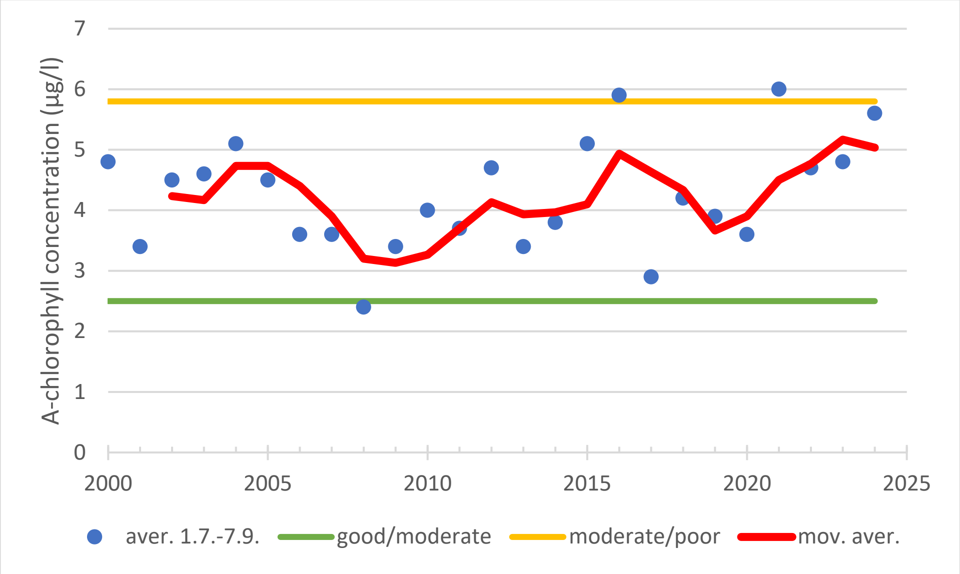

Figure 5. The concentration of chlorophyll a (µg/L) in surface water (0–10 m) at observation station *Seili* during the ecological classification period (1 July–7 September) from 2000 to 2024. The good status lower threshold (good/moderate) is 2.5 µg/L, and upper (moderate/poor) one is 5.8 µg/L. The red line indicates the moving average in the chlorophyll a concentration over the entire period under review.

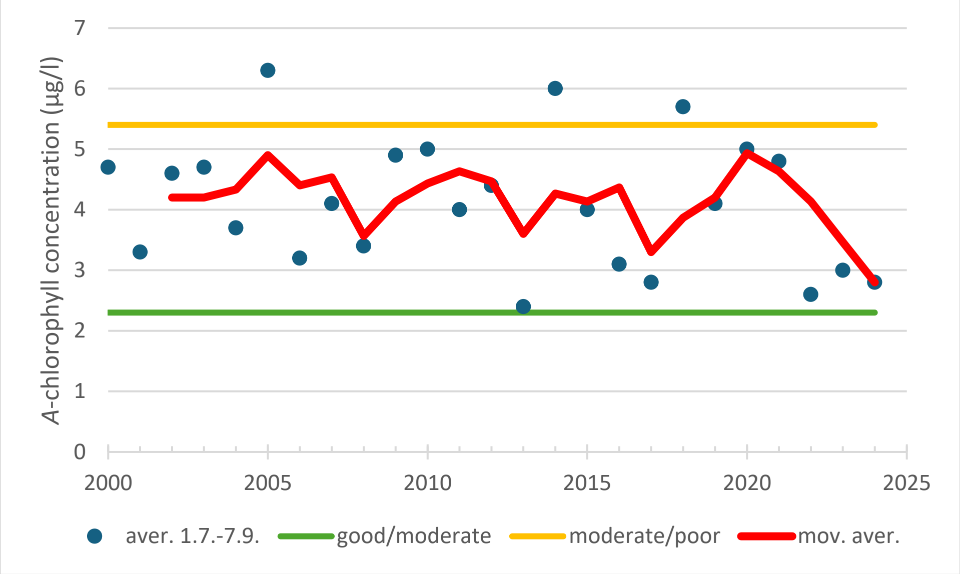

Figure 6. The concentration of chlorophyll a (µg/L) in surface water (0–10 m) in combined data of observation stations *Korp 175 Nötö* and *Dr 53 Vänö* during the ecological classification period (1 July–7 September) from 2000 to 2024. The good status lower threshold (good/moderate) is 2.3 µg/L, and upper (moderate/poor) one is 5.4 µg/L. The red line indicates the moving average in the chlorophyll a concentration over the entire period under review.

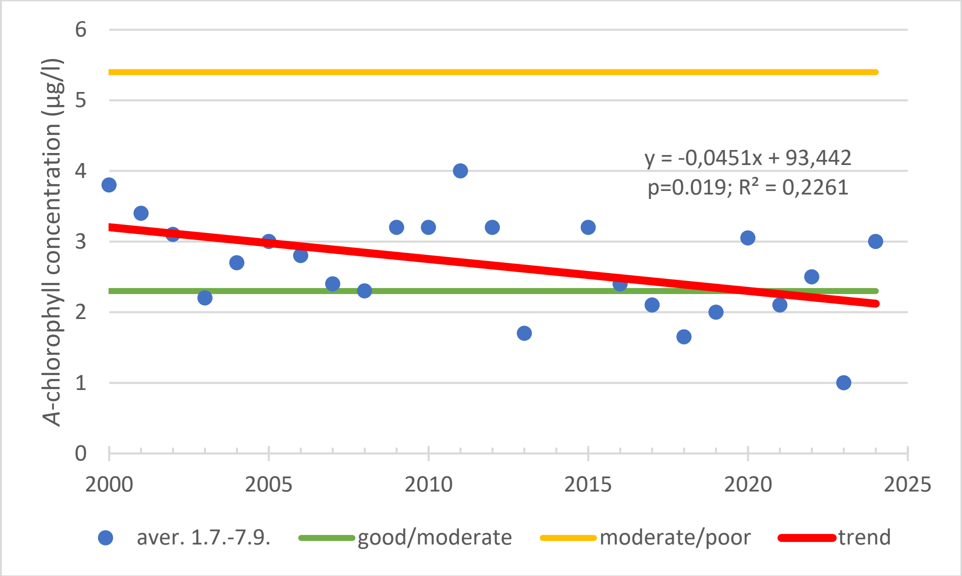

Figure 7. The concentration of chlorophyll a (µg/L) in surface water (0–10 m) at observation station *Kuml 155* during the ecological classification period (1 July–7 September) from 2000 to 2024. The good status lower threshold (good/moderate) is 2.3 µg/L, and upper (moderate/poor) one is 5.4 µg/L. The red line indicates the decrease in the chlorophyll concentration over the entire period under review (p = 0.02; R^2 = 0.23).

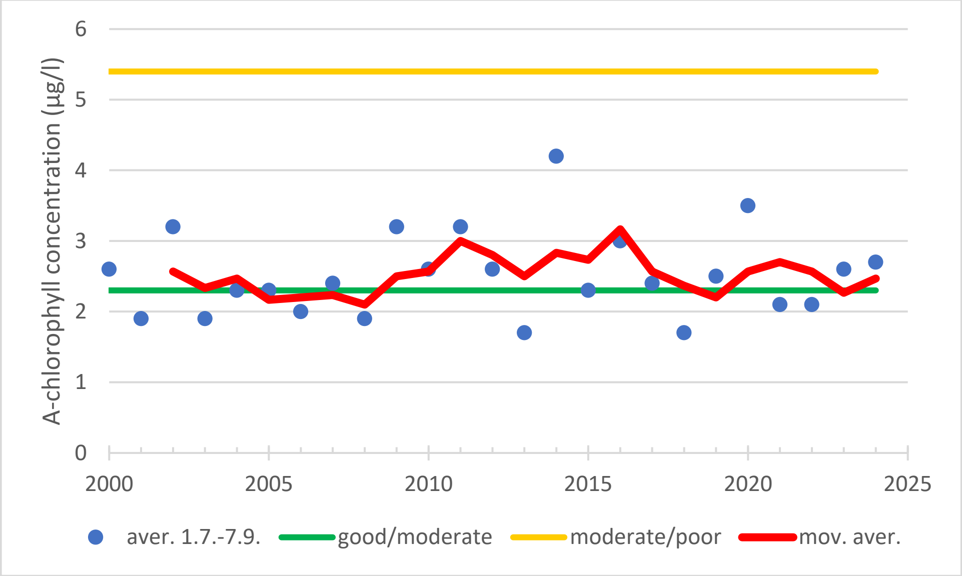

Figure 8. The concentration of chlorophyll a (µg/L) in surface water (0–10 m) at observation station *Brändö* during the ecological classification period (1 July–7 September) from 2000 to 2024. The good status lower threshold (good/moderate) is 2.3 µg/L, and upper (moderate/poor) one is 5.4 µg/L. The red line indicates the moving average in the chlorophyll a concentration over the entire period under review.

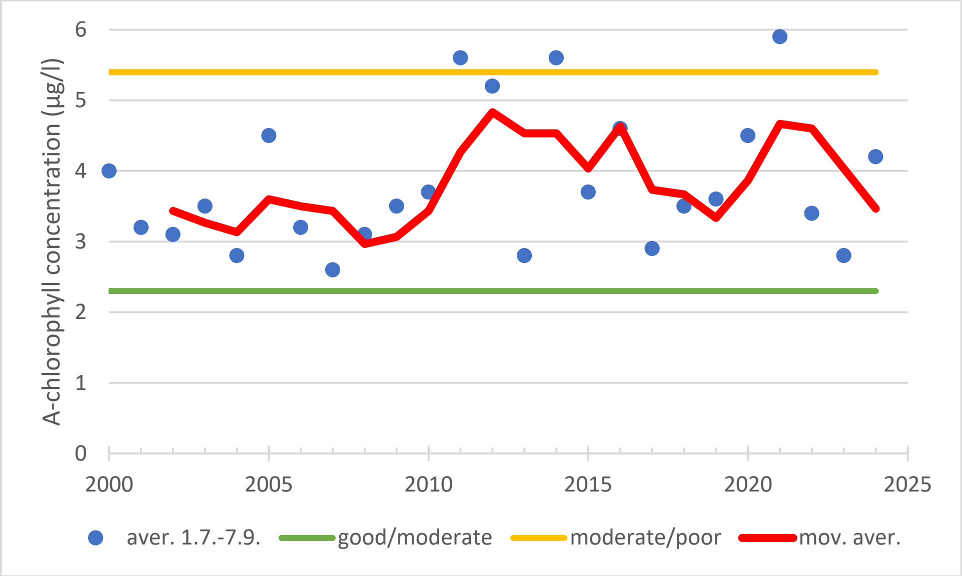

Figure 9. The concentration of chlorophyll a (µg/L) in surface water (0–10 m) at observation station *Utö* during the ecological classification period (1 July–7 September) from 2000 to 2024. The good status lower threshold (good/moderate) is 2.3 µg/L, and upper (moderate/poor) one is 5.4 µg/L. The red line indicates the moving average in the chlorophyll a concentration over the entire period under review.

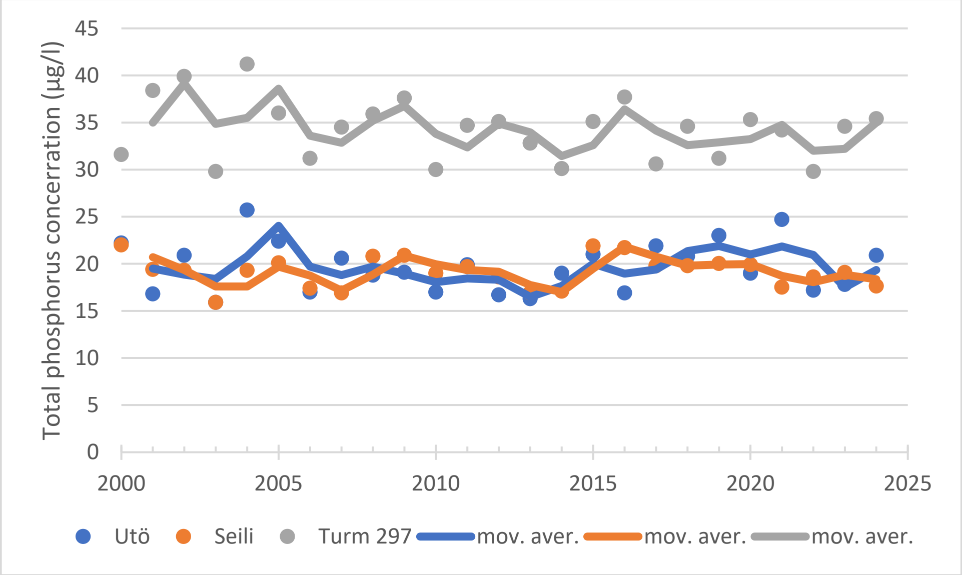

Figure 10. The concentration of total phosphorus (µg/L) in surface water (0–10 m) at observation stations *Utö, Seili and Turm 297* during the ecological classification period (1 July–7 September) from 2000 to 2024. The lines indicate the moving average in TP concentration over the entire period under review.

The average total phosphorus concentration at the *Utö* monitoring station on the southern edge of the Archipelago Sea was 19.8 µg/l during 2000–2024, which corresponds to a *moderate* status in classification (the upper limit for *good* is 18 µg/l). In the middle archipelago, the phosphorus concentration at *Seili* was 19.2 µg/l, classified as *good* (the upper limit for *good* is 20 µg/l). In the inner archipelago, at station *Turm 297*, the average concentration was 34.2 µg/l, classified as *poor* (the upper limit for *moderate* is 32 µg/l).

Annual Cycle of Phosphorus at the Seili Intensive Monitoring Station

Total phosphorus (TP) and dissolved inorganic phosphorus (DIP) concentrations are elevated in early spring due to winter mixing and nutrient-rich runoffs (Figure 11). TP concentrations of sea

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water (µg/L) in surface layer (0-10 m) have averaged 33.4 g/l during the period January 1–March 31, and DIP correspondingly 25.1 µg/l. Thus, the proportion of DIP in the total phosphorus concentration was 75%.

These levels then decrease as phytoplankton blooms (e.g., diatoms) take up nutrients during the spring bloom, which begins to sink to the bottom. The post-spring bloom minimum level of phosphorus concentrations (TP 15,7 µg/l and DIP 1,5 µg/l) is usually reached around mid-May, when the water temperature is approximately 8 °C. After that the TP (total phosphorus) concentration in surface water increases during the biological production season (May 15–October 15) at a rate of 1.4 µg/L per month, which is equivalent to 1.4 tons/km^3 per month (Figure 12). DIP (dissolved inorganic phosphorus) concentrations, on the other hand, remain low (below 2.5 µg/L) until the end of August, as the bioavailable portion of phosphorus is rapidly utilized in biological production. As the surface water temperature decreases in autumn, biological production in the surface layer slows down, leaving an increasing portion of phosphorus unused. This is reflected in a rise in DIP concentrations. Increased wind and cooling temperatures break down stratification, redistributing phosphorus throughout the water column. Typically, around mid-October, the so-called autumn turnover occurs, during which the water column mixes completely due to cooling surface temperatures and increased wind activity. This mixing redistributes nutrients, such as phosphorus, throughout the water column, equalizing concentrations between surface and bottom layers. This results in higher surface phosphorus concentrations compared to summer. In winter phosphorus concentrations are stable due to reduced biological activity and limited uptake.

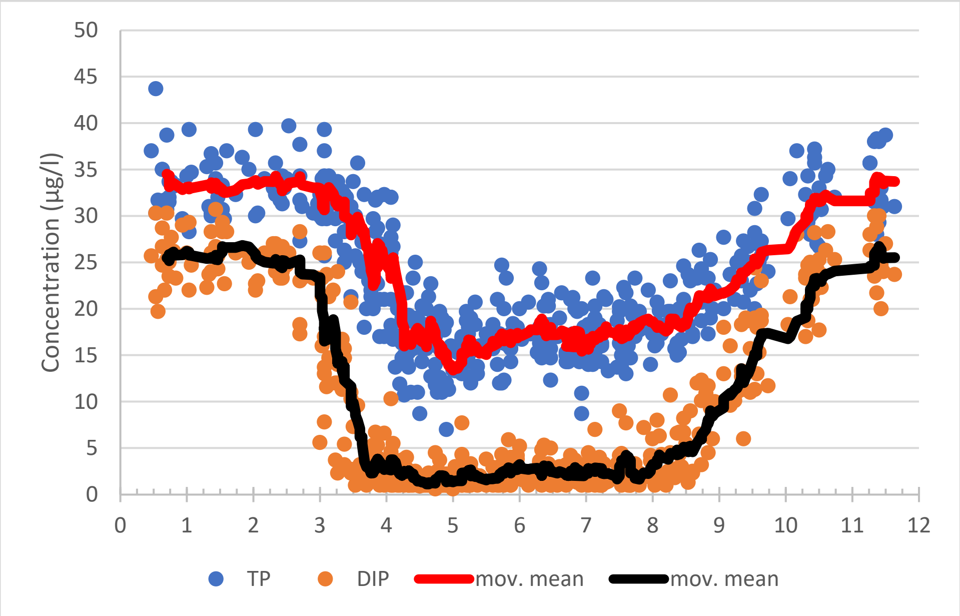

Figure 11. Total phosphorus (TP) and phosphate phosphorus (DIP) concentrations of sea water (µg/L) in observation station Seili in the Archipelago Sea in the surface layer (0-10 m) during the year (data from 2000-2024). The numbers on the x-axis refer to the months such that 0–1 represents January, and so on. 11-12 is December.

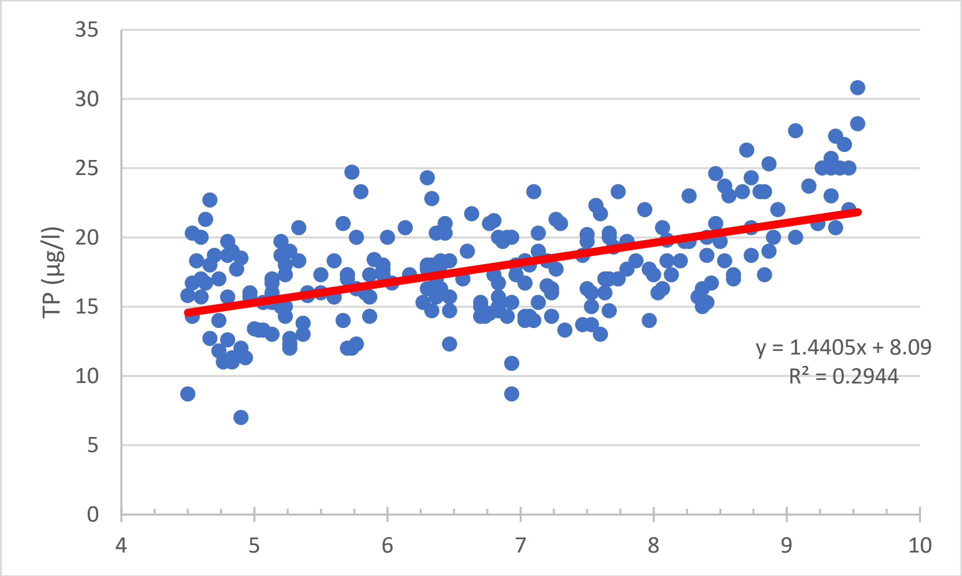

Figure 12. Total phosphorus (TP) concentrations of sea water (µg/L) in observation station Seili in the Archipelago Sea in the surface layer (0-10 m) during the period May 15–October 15 (data from 2000-2024). The numbers on the x-axis refer to the months such that 0–1 represents January, and so on. 11-12 is December. The red line indicates the increase in TP concentration over the entire period ($p < 0.001$; $R^2 = 0.29$).

At the Seili monitoring station, total phosphorus concentrations at a depth of 20 meters vary in a similar pattern to those in the surface layer (0–10 m) (Figure 13). However, during the biological production season, the increase in concentrations is more rapid at 20 meters. The TP concentration increases during May 15–October 15 at a rate of 2.4 µg/L per month, i.e. 2.4 tons/km³ per month (Table 3).

Table 3. Summary of the regression equations used in the calculation of internal loading in different part (inner, middle and outer) of the Archipelago Sea during the period May 15–October 15 for the years 2000–2024. The abbreviations of observation stations (e.g. *Turm275*) refer to Figure XX, which shows their locations. *Outer (out)* represents the part of the outer archipelago where internal loading is not expected to occur.

Layer (m)	***Inner***	***Middle***	***Outer (in)***	***Outer (out)***
	Turm275	*Seili*	*Korp175+Dr53*	*Korp200*
0–10	*1.65 x + 21.3 (p<0.001;R2=0.11)*	*1.44 x + 8.1 (p<0.001;R2=0.29)*	*0.84 x +14 (p=0.02;R2=0.03)*	*no significant*
0–20	*no data*	*2.38 x + 4.45 (p<0.001;R2=0.38)*	*no significant*	
20–50		*5.54 x + 1.56 (p<0.001;R2=0.13)*	*2.77 x + 6.8 (p<0.001;R2=0.20)*	
	Turm297		*Brändö*	
0–10	*1.15 x + 14.8 (p<0.001;R2=0.13)*		*2.0 x + 2.8 (p<0.001;R2=0.45)*	
0–20	*5.4 x - 5.42 (p<0.001;R2=0.48)*		*1.77 x + 6.3 (p<0.001;R2=0.25)*	
20–50			*1.48 x + 11.5 (p<0.01;R2=0.11)*	

Near bottom (at this station 44-50 m) the relative seasonal variation is smaller than in the surface layers, but the summer phosphorus release from the bottom sediments, i.e., internal loading, is clearly visible (Figure 14). The TP concentration increases during May 15–October 15 at a rate of 5.4 µg/L per month, i.e. 5.4 tons/km³ per month (Table 3) and correspondingly DIP concentration 8.0 µg/L per month, i.e. 8.0 tons/km³.

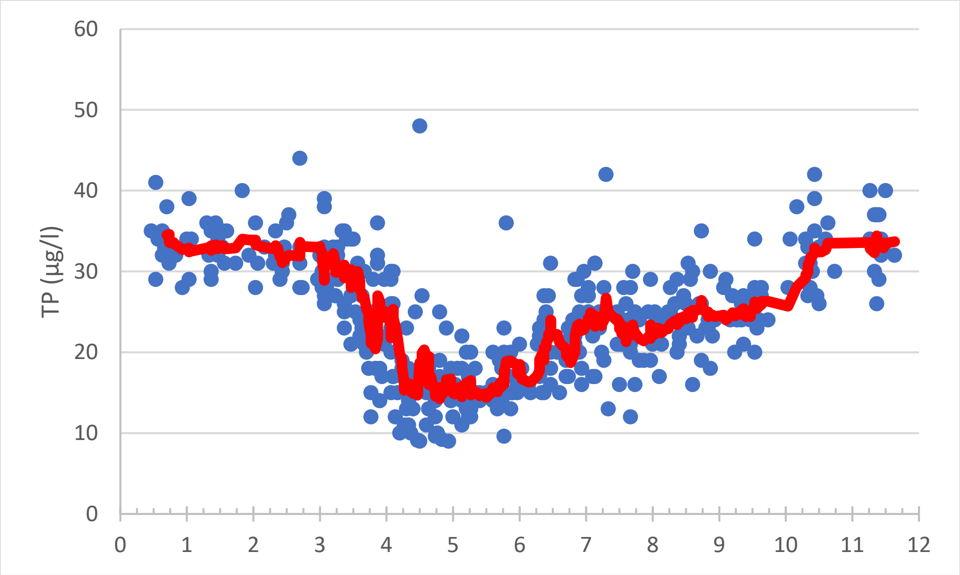

Figure 13. Total phosphorus (TP) concentrations of sea water (µg/L) in observation station Seili in the Archipelago Sea in the middle layer (10-20 m) during the period May 15–October 15 (data from 2000-2024).

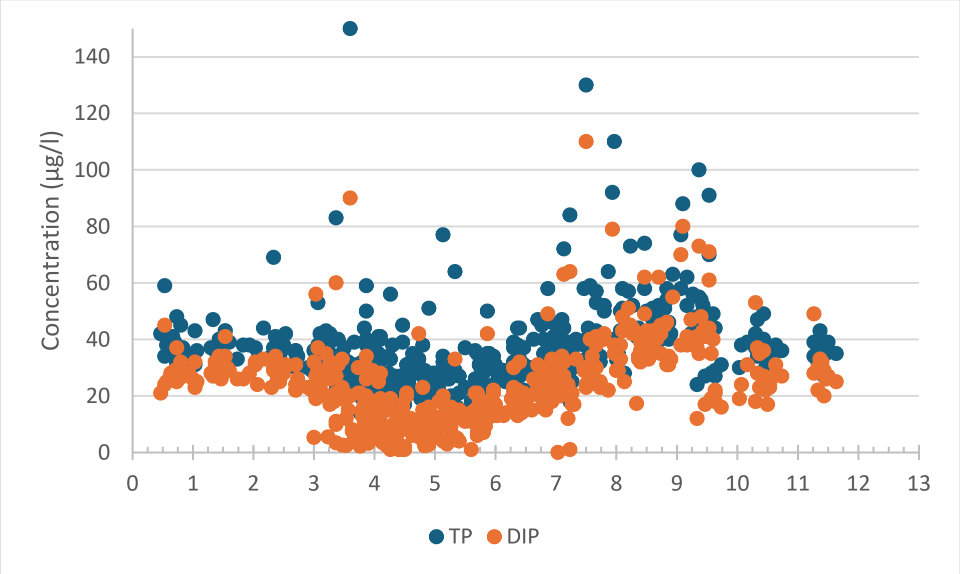

Figure 14. Total phosphorus (TP) and phosphate phosphorus (DIP) concentrations of sea water (µg/L) in observation station Seili in the Archipelago Sea near bottom (44-50 m) during the year (data from 2000-2024).

Before autumn circulation, during the period 1 September to 15 October, the total phosphorus concentration in the water column (0-48 m) has averaged 29.5 µg/l in the years 2000-2024. After autumn circulation, from 15 October to 31 December, it has averaged 32.7 µg/l. The phosphorus reservoir in the water column has thus increased by 3.2 t/km³.

In winter and spring (January 1–May 15), the water near the bottom at the Seili station is oxygen-rich (oxygen saturation 90%) (Figure 15). The oxygen conditions begin to deteriorate in early June, when the organic matter from the spring bloom starts to decompose. As the oxygen conditions deteriorate, dissolved inorganic phosphorus (DIP) begins to be released from the sediment, and internal loading is initiated.

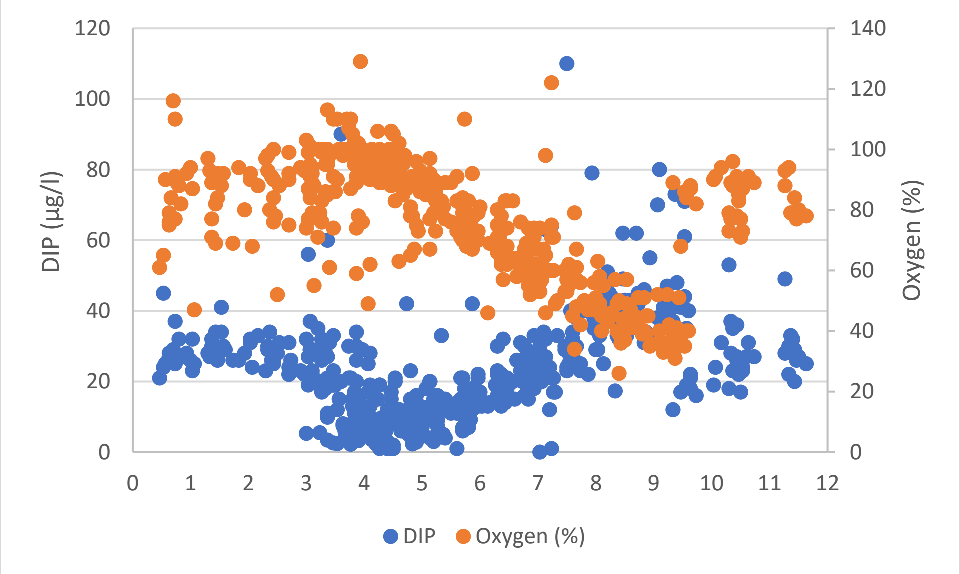

Figure 15. Phosphate phosphorus (DIP) concentrations of sea water (µg/L) and oxygen saturation rates (%) in observation station Seili in the Archipelago Sea near bottom (44-50 m) during the year (data from 2000-2024).

There is a statistically significant correlation between the oxygen saturation of the bottom water and DIP concentrations ($P < 0.001$, $R^2 = 0.28$): the less oxygen there is, the higher the concentration of dissolved inorganic phosphorus (Figure 16). The oxygen conditions improve significantly during the autumn turnover in mid-October, when the water temperature is around 4 ^{o}C, and the release of dissolved phosphorus from the bottom ceases.

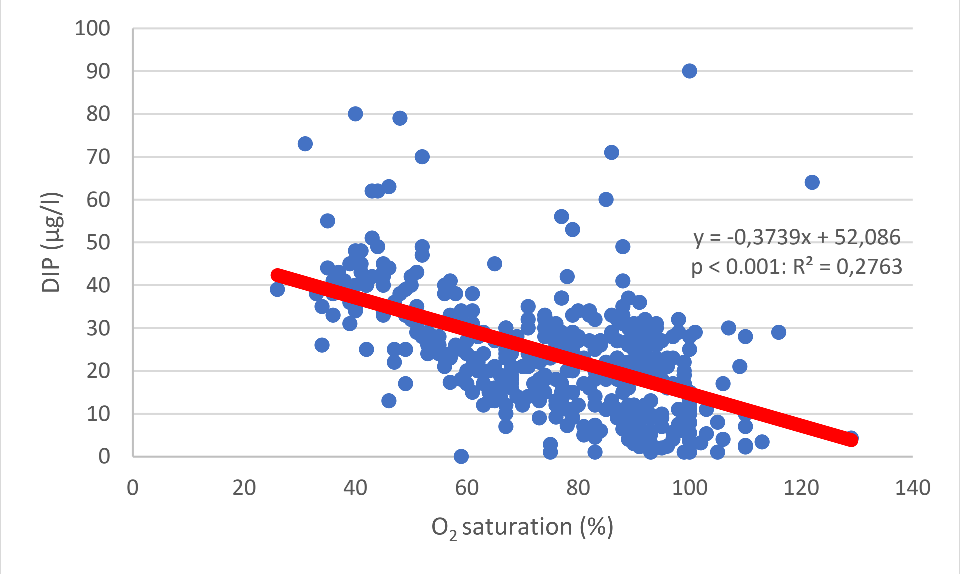

Figure 16. Relationhsip between phosphate phosphorus (DIP) concentrations of sea water (µg/L) and oxygen saturation rates (%) in observation station Seili in the Archipelago Sea near bottom (44-50 m) during the year (data from 2000-2024).

Regressions

The regression equations calculated based on the total phosphorus concentrations at observation stations in the Archipelago Sea during the period May 15–October 15 for the years 2000–2024 are compiled in Table X.

The regression equations used to estimate the amount of phosphorus removed during and after the spring bloom April 1-May 30 were: ***Seili*** **$y = -10.38x + 64.27$ ($p < 0.001$; $R^2 = 0.68$).** ***Korp175+Dr53*** **$y = -10.85x + 70.0$ ($p < 0.001$; $R^2 = 0.72$).** ***Brändö*** **$y = -7.06x + 44.7$ ($p < 0.001$; $R^2 = 0.46$).** ***Korp200*** **$y = -5.12x + 49.75$ ($p = 0.02$; $R^2 = 0.12$).**

Phosphorus Internal Loading

Based on changes in total phosphorus concentrations from May 15 to October 15, internal loading was estimated to occur in the inner archipelago and middle archipelago water bodies on the mainland side of the Archipelago Sea, as well as in some of the outer archipelago water bodies (Figure 1). The area covers a total of 3 617 km², which accounts for 58.4% of the entire surface area (6 191 km²).

The calculated internal phosphorus loads are summarized in Table 4. In the area of the Archipelago Sea defined in the study (3617.2 km²), the internal total phosphorus load reaching the surface layer (0-10 m) was estimated to be 194.8 tons, or 10.77 mg/m²/month. This accounts for 24.6% of the estimated total load of 791.6 tons, or 43.77 mg/m²/month. Relatively, the highest amount of internal loading occurs in the middle archipelago: 64.4 mg/m²/month. The corresponding estimate for the inner archipelago is 41.0 mg/m²/month and for the outer archipelago 20.8 mg/m²/month. However, if the relative loading is calculated based on the amount of phosphorus reaching the upper surface layers (0–20 m), it is highest in the inner archipelago, at 41 mg/m²/month. In the middle archipelago, the corresponding value is 25 mg/m²/month, and in the outer archipelago, it is 5.5 mg/m²/month.

Based on the estimates obtained above, it is possible to extrapolate the amount of internal phosphorus loading reaching the surface layer (0–10 m) and the total amount based on surface areas (estimated area 6 191 km² and the total Archipelago Sea area 9 500 km²). Calculated this way, the internal phosphorus loading in the Archipelago Sea region would amount to 1 215 tons during the period from May 15 to October 15. Of this, 299 tons, or 24.6%, reach the surface layer.

Table 4. The calculated internal phosphorus load from May 15 to October 15 in different zones of the Archipelago Sea (inner, middle, and outer archipelago) and in different water layers, which cover 87% of the total volume. In the "outer" section, the numbers in parentheses refer to the codes of the water bodies. The area included in the calculation is shown in Figure 1 with a green outline.

Layers	Inner	Middle	Outer (30-40)	Outer (10-70)	SUM
0-10 m	40.1	77.8	45.8	31.1	194.8
10-20 m	99.1	82.4	ns.	17.6	199.1
20-50 m		252.0	126.3	19.4	397.7
SUM	139.2	412.2	172.1	68.1	791.6

Phosphorus Dynamics in Spring Bloom

In the studied area of the Archipelago Sea (6 191 km²), a total of 989 tons of phosphorus is calculated to be removed from the surface layer (0–10 m) during the spring bloom as a result of the death of planktonic algae (e.g. Figure 10). The highest removal occurs in the outer archipelago, accounting for 670 tons, or 68% of the total. When this estimate is extrapolated to the entire Archipelago Sea area, the total amount is 1 518 tons.

Discussion

Concerns about the eutrophication of the Archipelago Sea have persisted for a long time [24,25], as the **Water Framework Directive** mandates that the goal of water management is to achieve **good ecological status** in all water bodies by **2027**. This directive underscores the urgency of addressing nutrient pollution and implementing effective measures to reduce eutrophication, particularly in areas where nutrient loads remain high and ecological recovery is slow. It is generally believed that **nutrient load reduction measures** implemented within the **catchment area** could achieve significant improvements in the condition of the **Archipelago Sea**.

However, previous model analyses of the Archipelago Sea [16] have concluded that that its good ecological status would be far from attainable in any sea area, nearby coastal region, or inner bay through unilateral local action conducted solely in the drainage basin. But according to [25] through coordinated load reductions (joint action) between all the Baltic Sea countries (BSAP or higher efforts), good ecological status can be achieved in the Archipelago Sea except for the inner archipelago, river mouths, and inner bays. According to BSAP [26] to reach good environmental status regarding eutrophication, the maximum input to the Baltic Sea that can be allowed is 792 209 tonnes of nitrogen and 21 716 tonnes of phosphorus annually. According to HELCOM reports, the total phosphorus load into the Baltic Sea has seen significant reductions over time. As of 2019, the load was 26 736 t/a, which still exceeds HELCOM's established Maximum Allowable Input (MAI) by 23%.

The reduction requirement for phosphorus inputs might seem modest when compared to the stringent good ecological status threshold set by HELCOM for the northern part of the Baltic Proper [27]. This threshold, at 0.38 µmol/L (equivalent to 11.8 µg/L), reflects the phosphorus concentration necessary to maintain a balanced ecosystem with minimized eutrophication. On the southern edge of the Archipelago Sea, at the northern boundary of the Baltic Sea's main basin, total phosphorus concentrations at the Utö monitoring station have averaged 19.8 µg/L in surface waters during ecological assessment periods in the 2000s. This is 68% above the HELCOM threshold. According to the ecological classification of coastal waters, the threshold for achieving good ecological status for total phosphorus in the **southwestern outer archipelago** is set at **15 µg/.** According to HELCOM average of total phosphorus concentrations in 2016-2021 in Northern Proper has been 0.74 µmol/L, equivalent to 22.9 µg/L.

In Hyytiäinen's article [25], the effects of nutrient load reductions were evaluated using the Finnish Environment Institute's FICOS model. This model has also been used to calculate area-specific load ceilings for achieving good ecological status in coastal waters [16]. Since summer algal abundance most commonly limits the ability to achieve good ecological status in coastal waters [28], the load ceilings are primarily based on achieving the threshold value of the indicator **chlorophyll-a concentration**. This indicator is a key measure of phytoplankton biomass and serves as a proxy for nutrient-induced eutrophication levels in aquatic ecosystems. When applying the FICOS model for calculating nutrient load ceilings, significant assumptions were made. According to the report [16], when calculating these ceilings, it was assumed that **airborne nutrient loads** and the **load from surrounding marine areas** would decrease by **50%.** This assumption of a 50% reduction means that, in practice, the total phosphorus concentrations of the water in the surrounding areas would be 50% lower than their current levels. In addition, the FICOS model also assumes that internal loading would decrease in proportion to reductions in catchment area and point source loads. According to the modeling results, when all the aforementioned assumptions are met, a further 68% reduction in nutrient loads is still required to achieve good ecological status in the coastal waters.

In practice, the nutrient load reduction requirements derived from the **FICOS model** to achieve good ecological status in the **Archipelago Sea** appear to be unattainable. The model's demand for a **68% reduction** in nutrient loads, combined with the additional assumptions on the reduction of internal and external loads, presents a challenge that is considered difficult to meet given current conditions. Therefore, it can indeed be somewhat perplexing to claim that certain parts of the Archipelago Sea have already reached **good ecological status**, especially considering that **no significant changes** in phosphorus concentrations of sea water or nutrient loads have occurred yet. Helminen and Inkala [20] found that in the southern part of Kihti in the middle of the Archipelago

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Sea since 2010 the chlorophyll a concentration began to decrease to its current values: from 2018 to 2023, the average was only 2.0 µg/L, indicating a good status had been achieved. The decrease observed from 2010 to 2022 was statistically significant. A similar trend was observed in this study from the observation station ***Kuml 155*** measurement data (Figures 1 and 7). From 2017 to 2024, the average of chlorophyll a concentration was 2.2 µg/L, indicating a *good* status had been achieved. According to **Helminen and Inkala [20]**, the reduction in algal production observed in the central Archipelago Sea was due to a change in the **background nutrient load** coming from the **Baltic Sea's main basin.** From 2015 to 2021, the net flow direction reversed, and water flowed from the Archipelago Sea to the Baltic proper in the surface layer. At the same time, the background loading of phosphorus entering the Archipelago Sea with the flows decreased significantly and the chlorophyll-a concentration decreased below the threshold for a good ecological status. Earlier in the 2000s, the net phosphorus load to the southern Archipelago Sea during the summer was around 120 t. According to modeling calculations, from 2015 to 2021, the net load had shifted to a phosphorus outflow of approximately 160 t during the summer [120].

In this study, no clear trend of change was observed in the surface water chlorophyll-a concentrations at the Seili station in the middle archipelago during the ecological assessment periods in the 2000s (Figure 5). In Helminen and Inkala's study [20], the time series for measurements began in 1983, when the monitoring at Seili station in the middle archipelago was first initiated. During the period from 1983 to 2023, the chlorophyll a concentration has steadily increased by approximately 0.6 µg/L per decade. In the inner archipelago, the ecological status of surface waters is classified as *poor*, as indicated by both chlorophyll-a and total phosphorus concentrations (Figures 3 and 10).

While changes in nutrient loads from the Baltic Sea’s main basin have contributed to a reduction in algal production in certain areas, such as the central Archipelago Sea, these improvements have not been as evident in the inland and middle archipelago regions. This disparity may be due to several factors, including internal nutrient cycling, where nutrients released from sediments continue to drive eutrophication, as well as diffuse loading that may have a greater impact on these areas. For example, the relative internal loading based on the amount of phosphorus reaching the upper surface layers (0–20 m), was highest in the inner archipelago, at 41 mg/m²/month. It was **1.6 times higher** than in the **middle archipelago** and **7.5 times higher** than in areas in the outer archipelago. In their modeling studies, researchers Miettunen *et al.* [29] have concluded that the middle archipelago is relatively sheltered and the water exchange with the outer archipelago is dependent on high wind events from the NW and SE directions. The inner archipelago is mostly sheltered and is under major influence from local riverine inputs. The FICOS model has also been used to estimate the relative contribution of different loading sources to water quality in various water bodies of the Archipelago Sea [26]. According to the estimates, in the inner archipelago, the share of total phosphorus loading from river inflows from the catchment area is 0.38, and for dissolved phosphorus loading, it is 0.23. In the middle archipelago (Seili), these ratios are 0.07 and 0.03, respectively, and in the outer archipelago (Utö), they are 0.02 and 0.01.

The amount of **internal loading in the Archipelago Sea** has previously been estimated primarily through **sediment quality studies** combined with modeling efforts. However, these results have significant **uncertainties**, especially when assessing the proportion of phosphorus that actually reaches the **biological production layer** of the water column. In the **FICOS model [15]**, the input for **internal phosphorus loading** was based on an assessment of the amount of phosphorus that could be released over time from the **surface layer of sediments** into the overlying water. This estimate was derived from **observational data** on the forms of phosphorus present in the sediments. Specifically, the focus was on calculating the quantity of **potentially mobile phosphorus**—phosphorus that could be released under certain conditions, such as low oxygen levels or changes in redox conditions. According to the **FICOS model**, the total amount of **internal phosphorus loading** during the growth seasons (April–September) from **2006 to 2014** was estimated at **2402 tons**. Of this, approximately half—**1220 tons**—was calculated to have reached the **surface layer** (0–10 meters). The **FICOS model** covers approximately the same **land-facing area** of the Archipelago Sea as examined in this study. However, the model assumes a **larger area**, with its total surface area being about **16% greater** (**7177**

km²) compared to the area used in this study. In any case, the **FICOS model** estimates **internal phosphorus loading** to be approximately **three times higher** than the values found in this study. Furthermore, the estimated portion of phosphorus that reaches the **surface layer** (0-10 meters) in the FICOS model is more than **six times greater** than the corresponding estimate in this study.

Puttonen et al. [17] present in their study O_2 status scenario, where the estimate of the potentially mobile P released from the reactive sediment surface of the soft, organic-rich sediments to the water resulted in an average release level of 0.56 g P m^{-2}, or an annual internal loading of 3200 t P from the entire 12 700 km² study area in the Archipelago Sea. The range of the internal P loading in the study area in this estimate was 0.01–3.7 g P m^{-2} yr^{-1}. Under different scenarios (better and worse), the minimum and maximum phosphorus release rates from sediments were estimated at 0.31 and 0.64 g P m^{-2}, respectively, According to Puttonen et al. [17], 78% of the annual internal nutrient loading occurs during the period from May 15 to October 15. This seasonal pattern is primarily driven by warmer water temperatures, which enhance biological activity and lead to increased release of phosphorus from sediments under low-oxygen conditions. In this study, the estimated internal phosphorus loading for the Archipelago Sea during the period from May 15 to October 15 was 0.219 g m² for the area from which phosphorus was assumed to be released (3617.2 km²). This corresponds to an annual loading estimate of 0.28 g m², which is close to the minimum estimate provided by Puttonen et al**.** [17], but only half of their average estimate. The annual internal loading estimate derived from this study is 1558 tons, which is about half the 3200 tons estimated by Puttonen et al. [17].

Our annual internal phosphorus loading estimate derived is notably like the calculated phosphorus loss from the surface layer during and after the spring bloom, 1 518 tons. On an annual basis, it could therefore be said that the net effect of internal loading on the phosphorus budget is approximately zero. Sediments are a P sink in spring and a P source in summer and autumn. Most of the deep-water P release from sediments in summer–autumn appears to be derived from the settled spring bloom. When comparing estimates of internal loading, it's crucial to clarify what exactly is meant by internal loading in each context. In this study, the focus was primarily on assessing how much phosphorus from internal loading ends up in the biological production layer of the water column, which is essential for understanding its role in eutrophication and algal growth. Puttonen et al. [17] emphasize that their estimates represent the amount of potentially mobile P stored in the sediments that can be released to the overlaying water in certain conditions and become (re)cycled at the sediment-water interface. They assume that only a part of it would eventually be mixed into the productive water layer, increasing algal production, while the rest is bound to (organic and inorganic) particulate material and deposited back to the sediment surface or transported horizontally to other areas.

Conclusions

The internal phosphorus load of the Archipelago Sea was estimated at 1 558 tons per year (t/a) in this study. During the biological production season, 299 tons, or 19%, of this load is transported to the surface layer (0-10 meters). During the spring bloom, an estimated 1 518 tons of phosphorus are removed from the surface layer with the sinking plankton mass. From the catchment area, an average of 350 tons of total phosphorus enters the Archipelago Sea annually via rivers, of which 97 tons is phosphate phosphorus (DIP) available for algae. Most of this is utilized during the spring bloom and sinks to the bottom along with it. Some portion of it returns to circulation during the summer.

These new assessments of the amounts of internal loading challenge the models applied in the Archipelago Sea and their conclusions regarding the need to reduce loading. Apparently, the model structures also need to be modified to account for the internal nutrient cycles of the marine ecosystem. Internal loading cannot simply be a static input.

At this point, it would be essential to investigate how much of the new phosphorus contributes to the internal cycling and whether reducing external loading can affect internal loading as commonly assumed. In Swedish coast Walve *et al.* [1] found that P release from historical deposits was apparently restricted to the first 10–20 years after the major P load reduction. Still, most of P release in summer and autumn is simply a recycling of P deposited by the sedimentation of the spring bloom.

Technical solutions to reduce internal loading in marine areas are practically limited and economically unfeasible. For example, bottom aeration or chemical treatment is not realistic because the seabed area to be treated in the Archipelago Sea spans 3,600 km². At best, internal loading has been successfully mitigated in lake environments, where the treated area has been around 1.5 km² [30].

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