EUROPEAN UNION
European Regional
Development Fund

Interreg
Central Baltic

SEABASED
SEABASED MEASURES IN
BALTIC SEA NUTRIENT MANAGEMENT

Potential for improving water quality in the Baltic Sea by sediment removal

SEABASED Project report

WP T5 Sediment removal

Introduction

Dredging has been used for decades in freshwater lakes to remove nutrients and decrease internal phosphorus loading (Peterson, 1982, Jeppesen et al., 2009). Marine environment, however, presents different challenges. We started this project to find out if and how we could overcome these challenges. Conventional dredging would encompass environmental problems. Dredging causes increasing water turbidity, particularly when the sediment is fine-grained, as the settling of particles takes a long time. Extensive or uncontrolled excavation of the seafloor alters local hydrography. Clay particles and organic material can drift in suspension load far from the dredging area when local currents are changing and strengthening. Increasing turbidity hinders feeding and reproduction of marine animals and can even destroy entire benthic colonies. This can affect to the whole food web through so-called bottom-up control, *i.e.,* changes in a lower level in the wood web have a cascade effect to higher levels by diminished food sources. Thus, avoiding turbidity is very important to achieve the desired outcome as improved water quality.

There has been recent development of low flow suction dredging techniques in small inland lakes in Sweden and Norway. Thin sediment surface layer removal can reduce the harmful consequences of dredging to the environment. To our knowledge, sediment removal has not been previously used as a restoration method in the Baltic Sea. Therefore, we explored thoroughly the available techniques for sediment removal in such way that the thickness of the sediment to be removed can be controlled and the sediment could be recycled or deposited in a sustainable way.

Aim

The SEABASED project was started to test selected sea-based measures to reduce nutrients and improve water quality in coastal areas of the Baltic Sea. The aim of the Sediment Removal pilot in the SEABASED project was to test removal of approximately 10 cm thick, loose sediment surface layer with low-flow suction in a small scale and assess the feasibility, cost-effectivity, and sustainability as a new sea-based measure to remove nutrients from the sea, reduce internal phosphorus loading and mitigate the harmful consequences of eutrophication. To gain information about feasible ways to apply sediment removal as a potential method for water quality improvement in marine coastal areas, we aimed to obtain comprehensive information of all phases of the measure. Thus, the sediment removal pilot included thorough exploration of available techniques and methods for the pilot implementation.

Theoretical effect of sediment surface layer removal

Autochthonous, fresh organic material degrades quickly, and the degradation of organic matter consumes oxygen. In the archipelago areas, seasonal oxygen deficiency is common in many places where fine-grained, organic-rich sediment deposition takes place, and the water circulation is restricted. Hence, when the fresh, newly deposited organic material is removed, the oxygen demand can be expected to decrease. The decrease in oxygen demand can lead to higher oxygen concentration in the water above the sediment. When oxygen is present on the seafloor, formation of hydrogen sulphide discontinues, and bottom fauna can recolonize the seafloor areas that have formerly been dead. Bottom fauna oxygenates the sediment by burrowing into the sediment (bioturbation). Consequent iron oxidation allows formation of iron oxides that bind phosphorus. The hypothesis is that if the fresh organic matter could be removed after spring bloom during several years repeatedly, the water quality might improve by higher oxygen concentrations, stronger phosphorus binding into iron oxides and reduced organic matter degradation.

Possibilities for sediment recycling

The dredged, dewatered sediments can be used, for example, for topsoils in farming, landscaping in parks and recreation, capping or protecting waste landfills, flow or flood control structures, erosion control, creating and restoring habitats. The possibilities for beneficial use of dredged materials are manifold (Welch et al., 2016). However, the coasts along the Archipelago Sea are often steep cliffs, and the transportation of the sediment from the dredging site can be costly.

Risk assessment of the pilot activities

We identified different types of potential risks in this pilot project. These risks should be considered, and appropriate actions should be taken when similar activities are implemented later in marine environments. The following chapters present identified risks, as well as suggestions for actions to avoid any harm and detriment caused by planning and implementing sediment removal works.

Ecological risks/impacts (literature, expert assessment)

Organisms (species composition, sensitive/endangered/directive species)

- Mapping and preliminary research of potential pilot sites, including plans for evaluating possible risks. Risk assessment and planning of specific actions minimise risks throughout the project.

- Sediment samples for zoobenthos analyses at the preliminary stage of the selection of the pilot sites. The pilot sites will include locations where oxygen depletion is either permanent or annual, which has already diminished the number and abundance of benthic species. Although there is a risk of harm to existing zoobenthos, implementation of the pilots – both sediment surface removal and phosphorus binding into the sediment – is likely to facilitate recolonization, as the oxygen concentration at the sediment surface is expected to increase.

Water (quality - nutrients, turbidity, oxygen, pH)

- Water samples from potential pilot locations, analyses of nutrients (phosphorus and nitrogen), oxygen, pH, turbidity, and chlorophyll-a, Sechhi disk transparency and temperature measurements *in situ* to assess the water quality.
- Monitoring changes in algal species dominance or cyanobacterial growth is difficult, as marine bays are subject to water exchange between adjacent basins. Furthermore, several other factors can control the occurrence of cyanobacteria and the productivity in the water.
- In a shallow sub-basin removal of near-bottom water may destabilize the water column by altering the density stratification.

Soil (sediment removal, removal of pollutants, changes in agricultural soil quality)

Hazardous/harmful substances

- Use of available data from previous investigations to estimate if any harmful substances could be detected in the sediments. Pilot site selection in areas where the risk for release of pollutants is low or non-existent
- Laboratory analyses for harmful substances in sediment samples

The level of risk can be controlled by sediment analyses. Sediment removal can only be implemented on the condition that the concentration of any harmful substances does not exceed national or international standards.

Social risks

Landowners, local people

- Information letters to the primary owners of the waters in potential pilot sites before or during preliminary investigation of the most potential pilot sites.
- Information meetings for local stakeholders and other interested.

Keeping local landowners informed and discussion with them active lowers the risk.

Economical/financial risks

This pilot project gives a good estimation of how the total costs will be comprised. The price of sediment removal depends on several factors, such as the techniques used for sediment removal and the deposition of the sediment, scale of the measure, the location and reachability of the dredging site, the distance of the sediment deposition site from the dredging site, available infrastructure and required constructions at the work site. However, it is wise to be prepared for some unexpected extra costs.

Administrative risks

Permitting procedure can be time consuming. Furthermore, the time required for the authorities to assess the permit application is case-dependant, and the process is different in different countries.

The permitting process for the sediment removal pilot in Finland from submitting the application to the final decision took nine months and 24 days. We asked the authorities to expedite the permit decision, invoking the limited time of the project. It remains unknown whether it speeded up the decision or not. This falls within average processing time. Clear, detailed, and complete permit application, together with open information spreading helps minimizing the risk of delays in the permit process. In addition, the current workload of the permit authority affects the processing time.

Despite of informing locals and allowing discussion, there is always a risk of appeal within the permitting process. Open discussion and information spreading are likely to lower the risk, or at least will make the permit applicant better aware of possible resistance or issues that should be worked out for smooth processing of the permit application.

Legislative risks

Public procurement is subject to national procurement legislation. There is a very good general guidance to public procurement in Finland provided at the website www.publicprocurement.fi. Furthermore, we used the services of our own legislative advisor at the ELY Centre and had all legal procurement documents proof-read before publication. This was important to minimize the risk of a lawsuit, which would be costly and markedly hinder and delay the procurement process.

In public procurement there is always a risk that someone takes the decision to market court. Sometimes the purpose can be as simple as hindering the works. The risk can be lowered, although not definitely prevented, by careful preparation of procurement documents and decisions. We recommend consultation of a skilled procurement expert. Open discussion from the beginning of planning works, continuing actively throughout the process lowers the risk of complaints and opposition. These pilot activities are well justified, which lowers legislative risks, as does the thorough risk assessment.

Methods

Preconditions for the pilot site

A pilot site for the implementation of the sediment removal pilot must be a semi-enclosed bay, where the water exchange between adjacent basins is restricted. Sedimentary environments must be calm, and almost continuous accumulation of fine-grained, organic-rich sediment must be present. There should exist no currents that would cause sediment resuspension, erosion, or exchange of water. The sediment should be anoxic, preferably throughout the year, and the near-bottom water should experience at least seasonal anoxia.

A threshold at the mouth of a bay hinders water exchange and thus contributes to development of seasonal oxygen deficiency in the near-bottom water. In the summer, the water column is temperature-stratified, and a thermocline prevents oxygen-rich surface water to reach the bottom. Low energy in the bottom due to the absence of waves and currents facilitates organic-rich sediment accumulation. Intensive degradation of organic matter increases oxygen demand, leading to hypoxia in the bottom.

Alternatively, an anoxic depression could serve as a pilot site, if it can be logistically reachable, and applicable technique for removing sediment and transporting it to deposition is available.

The sediment should be free from vegetation, and there should be none or very limited bottom fauna, i.e., the bottom should be dead. Sediment removal from a dead bottom ensures minimising ecological risks.

The pilot area must be outside conservation areas and away from any known underwater cultural heritage. The register of underwater cultural heritage was utilised in selecting the pilot sites to meet this precondition.

The pilot implementation must not cause any direct or indirect threat to the fauna or flora in the area. Therefore, a pilot site must be selected outside of known habitats of red-listed species, and the pilot must be implemented outside of the breeding season of birds.

High phosphate concentrations in the near-bottom water as an indication of internal loading of phosphorus should be measured at least in July–August. The possible impact of sediment removal can be observable in a place where consequences of eutrophication are locally evident.

Water samples must be taken at the surface layer at one-meter depth, and another one as close to the seafloor as possible, without causing turbulence by the sampling equipment. The following analyses must be included: temperature, Secchi depth, chlorophyll-a, total phosphorus (P), PO_4-P, total nitrogen (N), $NO_{2,3}$-N, NH_4-N, turbidity, conductivity, pH, and oxygen concentration.

Sediment analyses must include sediment water content, LOI (loss-on-ignition), bulk density, total and organic carbon, total nitrogen, phosphorus, sulphur, and iron. Moreover, zoobenthos analysis, as well as analyses for harmful substances are needed.

The harmful substances in the sediment must be analysed according to the sediment dredging and deposition guide, set by the Ministry of the Environment in Finland.

The sediment removal should only be implemented at a sea area free from harmful substances. The concentration limits are the same as for sediment deposition in the sea, set by the Ministry for the Environment in Finland. the potential pilot locations should be selected in areas where there is a low risk for harmful substances in the sediment, based on available background data in the Archipelago Sea area. This ensures that the sediment removal will not cause mobility of pollutants from the sediment in the sea or on land at the sediment deposition site. Polluted sediment needs special treatment for depositing on land, which is out of the focus of this project.

Recycling of the nutrients in the sediment and water should be included in the process to make it sustainable, cost-efficient, and justified in future sediment removal as a measure to counteract eutrophication.

Research for finding pilot sites

Searching for potential pilot sites started by gathering background information about physical, chemical, and ecological conditions on coastal bays and depressions in the Archipelago Sea. We concentrated on areas nearby

Field work

We carried out preliminary field work during May and September 2018 to find potential pilot sites for closer study. We visited altogether 67 bays and depression in the Archipelago Sea, taking water samples, looking at the sediment and other visible conditions of the sea (Fig. 1).

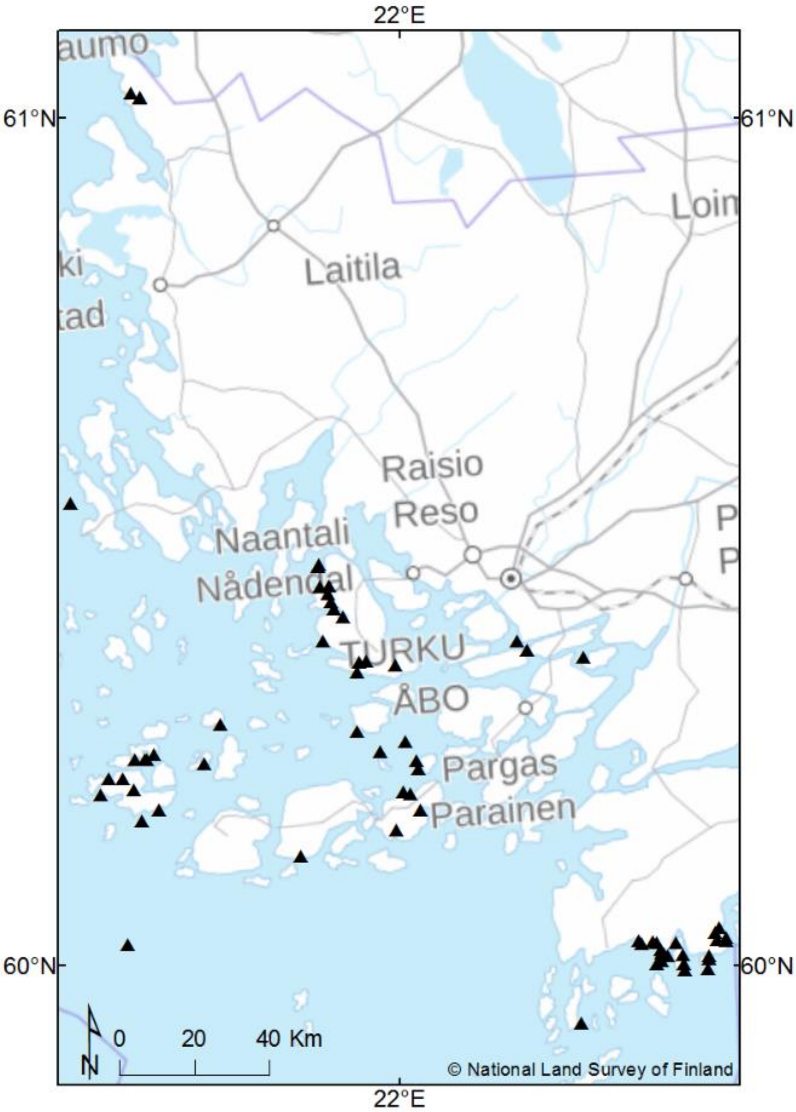
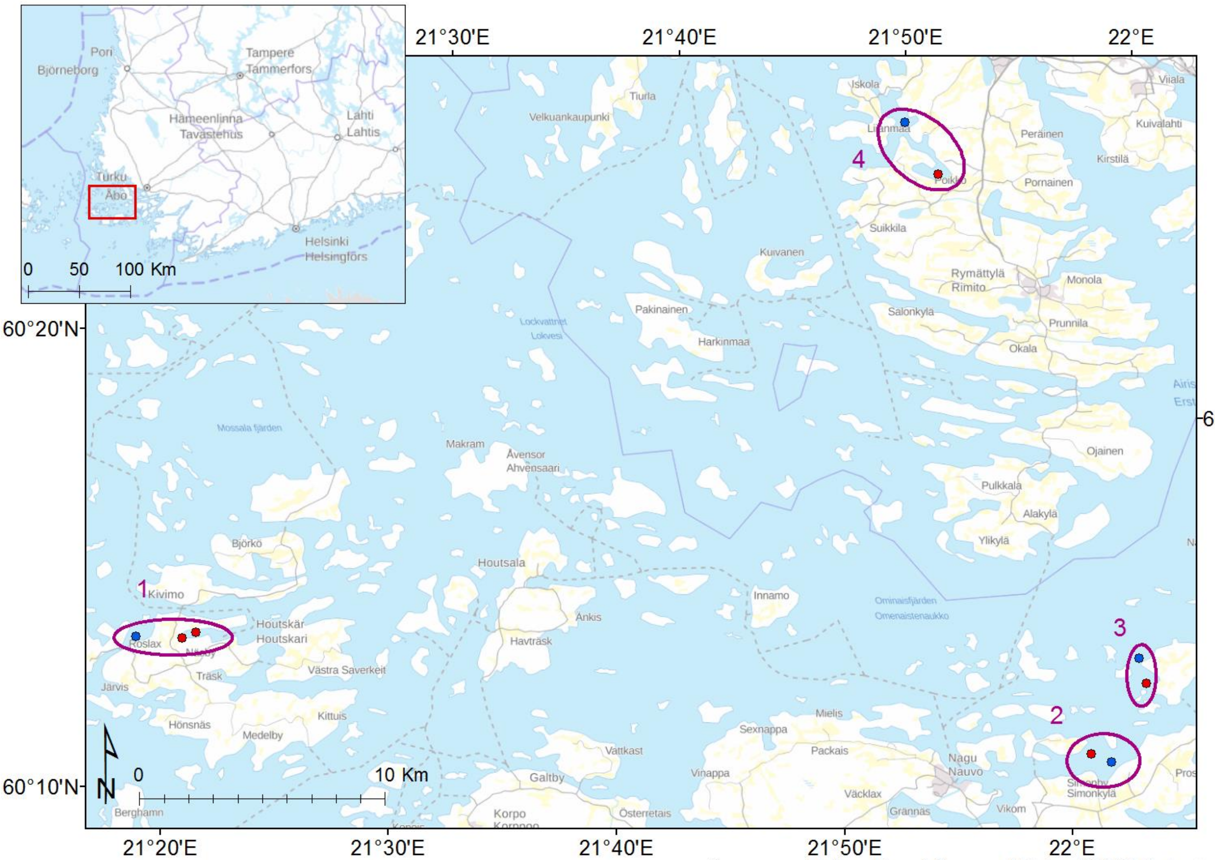


Figure 1. Altogether 67 locations were explored for potential pilot sites in the Archipelago Sea.

We scaled down the number of potential pilot sites by excluding the ones that did not meet the preconditions we had set in advance (Fig. 2). Then we revisited a few of the most promising sites. We took water samples again.



Base map: National Land Survey of Finland/ESRI Finland

Figure 2. Four locations were selected as pilot sites for sediment removal pilot and binding phosphorus into the sediment. The red dots on the map show the locations of pilot site monitoring stations. The blue dots are control stations.

Before the final selection of the pilot sites, we did some monitoring at several potential sites in the Archipelago Sea. First, we searched for the deepest part of the area in question. Then we looked at the sediment surface. We were looking for fine-grained, containing a lot of organic material, with no underwater plant growth, and black at the surface, indicating oxygen depletion. If the sediment seemingly met our criteria, we took further water samples for analyses. This was necessary to assess critically the potential pilot sites which ones of them meet the predefined criteria, and, thus, are suitable for sediment removal pilot. Subsequently, we selected four pilot sites, including a control monitoring station for each. The idea of the control station is to exclude the effect of variability within a year and between years. The control stations were selected in a nearby location, where the sediment and environmental conditions were like those in the pilot area in question. Although, according to the original project plan, we only needed two pilot sites for sediment removal and one for binding phosphorus to the sediment, we decided to monitor one extra area, in case we had to reject some of the selected for an unexpected reason.

The pilot site Haverö (No. 3, Fig 2) was later rejected, due to the reluctance of the owner.

Two depressions in Hålax vik, Houtskari, were selected as pilot sites for the sediment removal pilot. In Hålax vik, there are two depressions that are deeper than the surrounding bottom. The anoxic bottom sediment of each depression covers ca. one hectare, and the depth in both is approximately 12 metres.

Phosphorus Binding into Sediment pilot (marl pilot) was decided to implement in Kolkka, Naantali (No. 4 in fig. 2). After the final selection of the pilot sites was done, no further monitoring was caried out at the monitoring stations 2 and 3 (Fig. 2).

Two monitoring stations at the pilot site in Hålax vik, Houtskari, and the control station Roslax länsi remained for sediment and water quality monitoring for the sediment removal pilot. The coordinates (WGS 84) of the monitoring stations are

Hålax vik 1:	60.22382° N, 21.33775° E
Hålax vik 2:	60.22641° N, 21.34746° E
Roslax länsi:	60.22309° N, 21.30449° E

Sediment monitoring

We planned to collect and analyse sediments at the two monitoring stations in Hålax vik and the control station three times: in May 2019, autumn 2019, and once again after the implementation of the sediment removal pilot (Table 1).

Table 1. Sediment monitoring plan for the sediment removal pilot. The planned analyses are defined in the text after the table.

Sample site	Sub-sample Depth in the sediment	May 2019		Oct-Nov 2019	2020
		Basic analyses[1]	Harmful substances[2]	Basic analyses[1]	Basic analyses[1]
1–Hålax vik 1	0–2 cm	X	X	X	X
	2–5 cm	X	X	X	X
	5–10 cm	X	X	X	X
1b–Roslax länsi	0–2 cm	X		X	X
	2–5 cm	X		X	X
	5–10 cm	X		X	X
2–Hålax vik 2	0–2 cm	X	X	X	X
	2–5 cm	X	X	X	X
	5–10 cm	X	X	X	X

[1] Basic analyses include following analyses

- Sediment water content, loss-on-ignition, grain-size (as clay-content ø < 0.002 mm), bulk density
- Total Carbon (TC), organic carbon (TOC), total nitrogen (TN), total phosphorus (TP)
- Sulphur (S), iron (Fe)

The analysis of [2]harmful substances in the sediment follows the guidelines for sediment dredging and deposition published by the Finnish Ministry for the Environment (2015). The analyses include following substances:

<u>Metals and metalloids</u>

- mercury (Hg)
- cadmium (Cd)
- chrome (Cr)
- copper (Cu)
- lead (Pb)
- nickel (Ni)
- zinc (Zn)
- arsenic (As)

PAH-compounds (polycyclic aromatic hydrocarbons)

- naphthalene
- anthracene
- phenanthrene
- fluoranthene
- benzo(a)anthracene
- chrysene
- pyrene
- benzo(k)fluoranthene
- benzo(a)pyrene
- benzo(ghi)perylene
- indeno(123-cd)pyrene

Total Petroleum Hydrocarbons C10-C40

PCB compounds (IUPAC-numbers)

- 28
- 52
- 101
- 118
- 138
- 153
- 180

Organotins

- Tributyltin (TBT)
- Triphenyltin (TPhT)

Dioxins and furans (PCDD and PCDF)

Analyses for harmful substances were done at 0–2 cm, 2–5 cm and 5–10 cm depth in the sediments following the Finnish Ministry for the Environment guide for dredging and deposition of sediments.

Furthermore, zoobenthos analyses were planned to be carried out twice: once before the pilot implementation, in May 2019, and once afterwards in 2020, to see possible change in zoobenthos communities after the pilot implementation.

According to our sediment-monitoring plan, the sediment samples were to be collected and analysed again after the pilot measure. Since it later turned out, that the costs of the planned sediment removal would be markedly higher than expected and what our budget allowed, we decided to interrupt the monitoring plan. Despite that, we have gained valuable information of the sediment as well as the water quality in Hålax vik. The obtained data can be used to see if there are any noticeable changes since the previous investigations during the years 2008–2015 within the project Pro Hålax vik.

Water quality monitoring

Water samples were collected every two weeks from June to October from the two monitoring stations in Hålax vik, and once a month at the control station Roslax länsi (Fig 2, No 1). The water sample depths were 1 m, 8 m, and 0.5 m above the seafloor. Temperature was measured from each sample on the field, and

Secchi depth was determined at each visit at the sampling station. Samples for a-chlorophyll analysis was aggregated from samples down to the depth corresponding twice the Secchi depth. Total and phosphate phosphorus (TP and PO_4-P, respectively), total nitrogen (TN), the sum of nitrate and nitrite nitrogen ($NO_{2,3}$-N), ammonia nitrogen (NH_4-N), turbidity, conductivity, pH, oxygen concentration and oxygen saturation were analysed from all samples.

Additionally, an automated water quality station was moored close to the monitoring station Hålax vik 1. Coordinates of the station (WGS 84) are 60.22386° N, 21.33813° E. The probes were moored at one meter above the seafloor, and they produced data of temperature, conductivity, and PO_4-P. The data were transmitted online from the instruments via internet.

After pilot implementation

According to our original plan, the sediment analyses were to be repeated after the sediment surface layer removal (Table 1). In the south-western Finland Archipelago Sea sediments in areas of continuous accumulation of fine-grained, organic-rich sediment, phosphorus is commonly enriched at the top of the sediment (Puttonen et al., 2014). Mobile phosphorus migrates upwards by diffusion in the pore water from deep sediment layers. When the sediment surface is oxic, soluble phosphorus iron oxides trap phosphorus. However, when the sediment remains anoxic up to the surface, diffusive dissolved phosphorus flows to the near-bottom water, and further to the entire water column. At our pilot site in Hålax vik, the total phosphorus content at the sediment surface was 0.9–1.2 mg/g dry weight (dw). The water column was hypoxic up to at least 2 m above the sediment surface during the summer 2019, when there was a continuous water quality monitoring equipment moored at the pilot site. Furthermore, sediment surface was black, and it had a strong smell of hydrogen sulphide. These observations together imply that iron is in reduced bivalent form in the sediment, and phosphorus binding into iron oxides is non-existent.

Sediment surface layer removal

Sediment removal

The project workplan defined framework conditions for the sediment removal. The sediment removal should be carried on by a method, that can remove 10 cm thick layer of the fluffy, fine-grained, and organic-rich sediment surface. The dredging method must avoid causing cloudiness in the water. Large amounts of water will come up along with the removed sediment. Therefore, the sediment needs dewatering before placing on land. The excess water must be cleaned from phosphorus and nitrogen to a certain, acceptable concentration, before it can be led back to the sea. The concentrations of total phosphorus and nitrogen in the water should not exceed the target threshold levels defined by HELCOM.

Sediment dewatering and deposition/recycling

We explored thoroughly available technical solutions to implement the sediment removal pilot as planned. Before starting the public procurement process, we published a market consultation. However, we failed to gain any information about the price of the works before the public procurement. That led to two subsequent procurement processes. In the first one we defined the preconditions for the works. We received three tenders that all exceeded the pilot budget. We then decided to suspend the process and start it again in a different manner. In the second procurement, we defined the price at 200 000 euros, and failed to receive any tenders.

Theoretical removal of phosphorus

Although the implementation of the sediment removal pilot as planned turned out too expensive, we can use the monitoring results to calculate a theoretical estimate of phosphorus removal from the system by removing the sediment surface.

We estimated that by removing 10 cm of the top sediment in an area of 2 hectares Hålax vik deepest parts we could remove altogether 300 kilos of phosphorus. Thirteen kilos of the total amount would be phosphate in the pore water and the water column above the sediment. Phosphate in the water is readily bioavailable, whereas sediment phosphorus is partly in refractory form, i.e., it cannot be transformed into bioavailable phosphorus. Based on earlier studies, approximately half of the total phosphorus in the sediments will circulate back to the water column. Thus, we can estimate to remove 75–80 kg potentially bioavailable phosphorus per hectare by removing the topmost ten centimetres of sediment.

The estimations are based on the average total phosphorus content in the topmost ten centimetres of sediment, total phosphorus concentration determined in Hålax vik during 2018–2020 in all measured depths in the water column, and phosphate-phosphorus concentration in the pore water determined earlier in the Archipelago sediments nearby.

The phosphorus concentration in the water is likely an underestimation, as the surface water low phosphorus concentrations are included in the average. Suction dredging would take water near the sediment surface. Additionally, along with the sediment, 1150 kg nitrogen and 7900 kg carbon would be removed per hectare.

Sediment incubation experiment

Methods

In this report, the methods are described briefly, and the main results with conclusions are presented here. The complete report of the sediment incubation experiment (in Finnish) was delivered separately in the electronic project report for period 6.

The experiment was designed by PhD Jouni Lehtoranta, a senior scientist at the Finnish Environment Institute SYKE. Lehtoranta belongs to the steering group of the SEABASED project.

The implementation of the marine sediment incubation experiment was based on the experimental design that was included in the tender document. Some modifications were necessary to apply to the original experimental design in the early stage of the test. Incubation times were shortened since the oxygen demand was remarkably high. Additionally, the set-up was modified in the beginning of the experiment due to observed oxygen leakage. However, this experiment provides new information about the effect of sediment removal on the oxygen demand of the collected sediments, as well as nutrient fluxes between the sediment and water.

The sediment and water samples were collected at 12 m depth in Hålax vik, where the sediment removal pilot was planned.

Before and after each incubation, samples were taken from the supernatant, and following variables were analysed:

- Ammonium-nitrogen, NH_4^+-N
- Nitrate-nitrogen, NO_3^- -N
- Nitrite-nitrogen, NO_2^- -N
- Total nitrogen, Tot-N
- Dissolved total phosphorus, DTP
- Dissolved inorganic phosphorus, DIP
- Total iron, Fe
- Total manganese, Mn
- Dissolved oxygen, DO

When sediment layers were removed prior to the second and third incubations, sediment samples were collected for following analyses:

- Dry matter content
- Bulk density
- Total phosphorus, Tot-P
- Total nitrogen, Tot-N
- Total iron, Fe
- Biogeochemical oxygen demand, BOD_7

The sediment incubation test consisted of five sequential incubations. Three test units — S1–S3, S4–S6, and S7–S8 — consisted of three test tubes each. The test tubes in each test unit were treated as parallel tests, where each test tube was treated similarly (Table 1).

Table 1. Treatments of each test unit in the sequence of incubations. The test unit S6–S9 was a control unit with the natural sediment surface throughout all incubations.

	Treatment prior to incubation				
	water aeration			water deoxygenation by N_2 gas sparging	water aeration
Test unit	1st incubation	2nd incubation	3rd incubation	4th incubation	5th incubation
S1-S3	Natural sediment surface	5 cm sediment surface removal	15 cm sediment surface removal		
S4-S6		15 cm sediment surface removal	25 cm sediment surface removal		
S7-S9		Natural sediment surface			

The aim of the first incubation was to determine oxygen consumption and the initial level of nutrient concentrations in the supernatant.

After the five incubations with sediment surface layer removals according to the experimental design, two oxygen demand incubations were carried out. The duration of these additional incubations was four hours each, and only the oxygen concentration was determined from the water before and after each incubation. The sediment surface depth in the additional incubations compared with the original sediment surface were as in the fourth incubation, i.e., 15 cm for the test unit S1–S3, 25 cm for the test unit S4–S6 and 0 cm for the control test unit S7–S9.

Additionally, a continuous measurement of oxygen concentration was carried out after the five incubations to study how much time is required until all oxygen is exhausted from the supernatant. The measurement was done.

Results

Sediment removal

Implementation of sediment surface layer removal using slow flow technique, or comparable, to avoid sediment resuspension and turbulence, was beyond the SEABASED project budget. Therefore, we decided to carry out an experiment in a laboratory to study probable effects of sediment removal to sediment oxygen demand and nutrient fluxes between the sediment and the overlying water. Although we could not implement sediment removal in practise, the experiment provides theoretical information of the potential effect of the measure, bearing on mind that the results only apply to the place where the sediment and water samples were collected. Phosphorus content across the Archipelago Sea vary markedly.

Monitoring results

Sediment

All studied sediments were classified as muds (grain-size Ø < 0.063 mm), containing 15.1–43.3 % clay fraction (Ø < 0.002 mm, Table 2). Contents of harmful substances in the sediment were very low. None of the observed values exceeded the critical values for sediment deposition on land or sea (App. 1).

Table 2. Range of determined key variables of the sediments in Hålax vik and the control station. Dw = dry weight.

	Water content %	Clay % dw	LOI % dw	TOC g/kg dw	TP g/kg dw	TN g/kg dw	Fe g/kg dw	S g/kg dw
Hålax vik 1	84–89	16.9–35.6	12–13	50–58	0.92–1.1	7.4–8.8	39–43	12–14
Hålax vik 2	84–88	15.1–43.3	11–13	48–55	0.92–1.1	6.8–8.7	40–43	12–13
Roslax l.		16.6–21.6	12–14	47–56	1.0–1.5	7.0–8.8	45–46	8.4–14

Total phosphorus, nitrogen, and organic carbon contents in the sediment were typical to accumulation sediments in eutrophied coastal areas.

Total Fe:P ratio in the sediments was 36–47, which is considered high enough for the sediments ability to retain phosphorus in iron oxides under constant oxic conditions (Jensen et al., 1992). Sulphur content could be used to estimate the need of liming to prevent acidification, in case of placing the sediments directly on farmland.

Water

Oxygen concentration dropped to zero in late June 2019, followed by rapid rise of phosphate concentration in the near-bottom water (Fig. 3). Phosphate concentration kept rising to extreme values during the summer. The near-bottom water below thermocline was reoxygenated only after mixing of the water column by surface water cooling in October. Phosphate concentration decreased shortly after water column mixing.

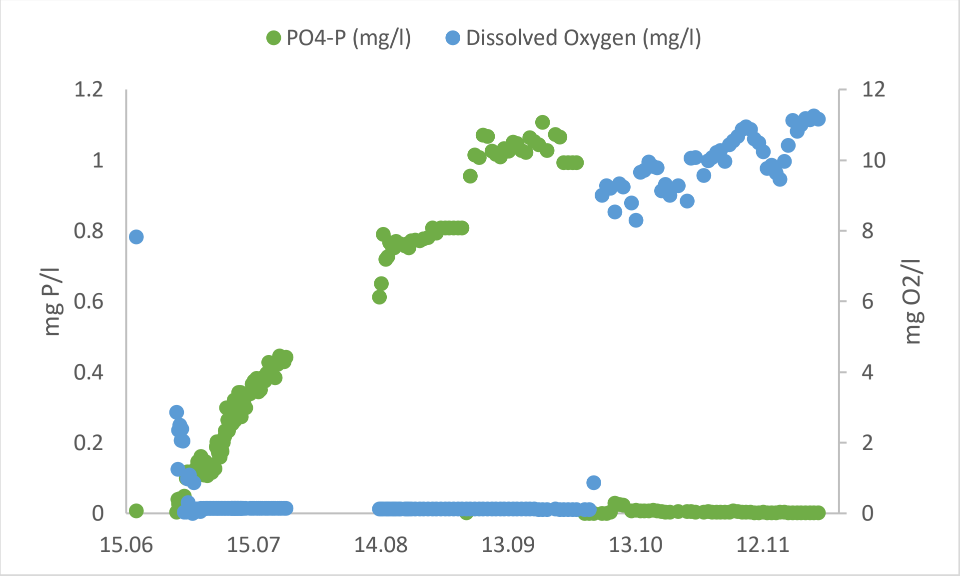


Figure 3. Phosphate and oxygen concentrations in the near-bottom water at Hålax vik automated water quality monitoring station.

Results of the Sediment incubation experiment

In all results, the values below the detection limit are replaced by half of the detection limit.

First incubation: the original sediment surface

The changes in the analysed DTP and DIP concentrations were negligible, and the direction of the change in all test units (Table 2). Oxygen concentration was low already in the beginning of the incubation, although the water phase was aerated prior to the incubation. Oxygen concentration increased in all test units during the first incubation.

Table 3. Average concentrations before and after the first incubation in the test units, and the change as a percentage.

	Test unit	Tot-N µg/l	NO$_2$-N µg/l	NO$_3$-N µg/l	NH$_4$-N µg/l	DTP µg/l	DIP µg/l	Fe µg/l	Mn µg/l	DO mg/l
Before	S1-S3	2733	4	9	2067	713	683	153	353	4.8
	S4-S6	2233	3	6	1733	543	537	147	267	5.1
	S7-S9	2567	3	6	2000	647	653	150	337	4.9
After	S1-S3	2467	3	7	1867	700	710	105	347	6.7
	S4-S6	2167	3	3	1700	537	550	73	260	6.4
	S7-S9	2467	3	3	1967	647	657	84	323	5.9
Change %	S1-S3	-10	-9	-21	-10	-2	4	-32	-2	39
	S4-S6	-3	0	-55	-2	-1	2	-50	-3	26
	S7-S9	-4	-20	-56	-2	0	1	-44	-4	20

Second incubation

The aim of the second incubation was to determine the change in oxygen demand and nutrient fluxes between the sediment and water after five cm or fifteen cm sediment removal in test units S1–S3 and S4–S6, respectively. Concentrations of measured variables were markedly lower in the beginning of the incubation than in the first incubation. The concentrations decreased during the second incubation throughout the test units (Table 4). Manganese was an exception: its concentration increased slightly during the second incubation. The most noticeable decrease in phosphorus concentration was observed in test unit S4–S6, from which 15 cm sediment was removed. Oxygen concentration deceased markedly in all test units.

Table 4. Average concentrations in the test units before and after the second incubation.

	Test unit	Tot-N µg/l	NO_2-N µg/l	NO_3-N µg/l	NH_4-N µg/l	DTP µg/l	DIP µg/l	Fe µg/l	Mn µg/l	DO mg/l
Before	S1-S3	1367	5	6	707	143	113	200	82	8.1
	S4-S6	1400	7	11	830	140	103	280	62	8.2
	S7-S9	1113	5	9	590	163	118	297	87	7.9
After	S1-S3	1030	3	3	293	123	91	69	88	0.5
	S4-S6	937	6	3	264	40	13	38	36	0.7
	S7-S9	1087	3	3	503	133	117	108	94	0.9
Change %	S1-S3	-25	-33	-57	-58	-14	-19	-66	8	-94
	S4-S6	-33	-5	-77	-68	-71	-87	-87	-42	-92
	S7-S9	-2	-38	-71	-15	-18	-1	-64	9	-89

Third incubation

The third incubation was started after 10 cm sediment removal from test units S1–S3 and S4–S6. Thus, compared with the original, natural sediment surface, the sediment surface was at 15 cm in the test unit S1–S3, and at 25 cm in the test unit S4–S6. Concentrations of DTP and DIP in the water were lower in the beginning of the third incubation than in the beginning of the second incubation. The concentrations of DTP and DIP increased during the third incubation (Table 5). Oxygen concentration was exhausted in the end of the incubation.

Table 5. Concentrations in the supernatant before and after the third incubation, and the change percentage.

	Test unit	Tot-N µg/l	NO_2-N µg/l	NO_3-N µg/l	NH_4-N µg/l	DTP µg/l	DIP µg/l	Fe µg/l	Mn µg/l	DO mg/l
Before	S1-S3	1073	4	3	14	71	22	139	25	7
	S4-S6	977	4	3	2	61	5	109	22	6.8
	S7-S9	940	3	3	2	81	30	38	69	6.4
After	S1-S3	1133	3	3	2	126	29	187	39	0.6
	S4-S6	1267	4	3	2	96	9	153	37	0.4
	S7-S9	1060	3	3	2	130	75	113	89	0.4
Change %	S1-S3	6	-25	0	-89	78	30	35	57	-92
	S4-S6	30	-8	0	0	57	75	41	68	-94
	S7-S9	13	11	0	0	61	151	197	28	-94

Fourth incubation

The fourth incubation was carried out with the same sediments as the third incubation, i.e., with no further sediment removal. The supernatant was deoxygenated by nitrogen sparging before the incubation. The aim was to investigate nutrient fluxes between the sediment and water under anoxic conditions. Iron concentration was particularly high in the beginning of the incubation, decreasing markedly during the incubation (Table 6). A minor increase in oxygen concentration was observed, which was interpreted to imply oxygen leak to the incubation system. Concentrations of all other measured substances decreased during the incubation.

Table 6. concentrations of the measured substances before and after the 4th incubation.

	Test unit	Tot-N µg/l	NO_2-N µg/l	NO_3-N µg/l	NH_4-N µg/l	DTP µg/l	DIP µg/l	Fe µg/l	Mn µg/l	DO mg/l
Before	S1-S3	973	9	12	140	110	99	2753	39	0.4
	S4-S6	1007	9	13	143	115	95	3233	38	0.4
	S7-S9	867	10	13	163	117	102	420	23	0.4
After	S1-S3	630	3	3	2	81	57	94	11	1.5
	S4-S6	610	3	3	2	70	42	105	12	2.2
	S7-S9	567	3	3	2	117	82	126	22	0.5
Change %	S1-S3	-35	-67	-79	-99	-26	-42	-97	-71	256
	S4-S6	-39	-68	-80	-99	-40	-55	-97	-70	411
	S7-S9	-35	-69	-81	-99	0	-20	-70	-7	18

Fifth incubation

The fifth incubation was started by aeration of the supernatant. No further sediment was removed from the test tubes. Oxygen concentration declined extremely low in all test units (Table 7).

Table 7. Results of the 5th incubation.

	Test unit	Tot-N µg/l	NO_2-N µg/l	NO_3-N µg/l	NH_4-N µg/l	DTP µg/l	DIP µg/l	Fe µg/l	Mn µg/l	DO mg/l
Before	S1-S3	667	3	4	6	65	43	623	15	7.1
	S4-S6	843	3	3	2	63	31	558	14	7.2
	S7-S9	667	2	3	2	67	40	90	20	6.2
After	S1-S3	613	3	3	2	72	45	83	11	0.6
	S4-S6	790	3	3	2	70	40	77	11	0.7
	S7-S9	743	2	3	2	97	69	108	27	0.3
Change %	S1-S3	-8	-20	-38	-76	11	5	-87	-25	-92
	S4-S6	-6	-11	0	0	11	28	-86	-21	-91
	S7-S9	12	-14	0	0	44	72	20	37	-95

Additional tests for oxygen demand

In the additional tests for oxygen demand, the oxygen concentration in the water declined down to 4.5 mg/l in four hours incubation time.

Conclusions

The increase in oxygen concentration during the first incubation implies to a leak in the system. Therefore, the silicon hoses were replaced with air-tight ones, and the lids of the test tubes were sealed after the first incubation to prevent oxygen diffusion from the atmosphere into the incubation system. Although the incubation time was short, particularly high oxygen demand was observed in room temperature, and the test units were almost entirely exhausted of oxygen during the incubation. Oxygen demand would probably be lower in situ due to lower temperature in the near-bottom water. During the tests, the oxygen demand varied widely between the test units. The highest values of oxygen demand were observed in the test units with the original sediment surface (i.e., no sediment was removed). Thus, these additional tests suggest that sediment removal can moderate sediment oxygen demand.

The magnitude and direction of phosphorus flux between the sediment and water varied in the incubations. Moreover, the initial concentrations of DTP and DIP were different between incubations. These results together make the conclusions ambiguous. The results from the sediment incubation test suggest that sediment surface layer removal might slightly lower oxygen demand temporarily. However, the small decrease in oxygen demand would probably not be enough to maintain high oxygen concentration in the near bottom water. In the studied place, surface water warming in the summer creates a thermocline, which hinders mixing of water and oxygen-rich surface water penetration to the bottom. Furthermore, each year a new layer of decaying organic matter will sink to the seafloor, increasing the oxygen demand again to the preceding level. Sediment surface layer removal should be repeated annually to achieve lower oxygen demand at the sediment surface and in the near-bottom water. The decrease in oxygen demand might still be insufficient to enhance iron oxide formation and consequent binding of phosphorus at the sediment surface.

The determined BOD_7 decreased slightly towards deeper layers in the sediments. The thickness of the organic-rich sediment in the test samples was 25–30 cm. According to the results presented above, removal of 25 cm thick sediment layer could lower oxygen demand and phosphate concentrate in the near-bottom water.

To confirm the hypothesis that sediment surface layer removal will decrease phosphorus release from the sediments to the water, and the oxygen concentration in the water will increase, we should have seen clear indications in the incubation experiment. Such indications could be: 1) clear and consistent decline in the concentrations of DIP and DTP after sediment removal, 2) Clear and constant decline in BOD_7 with sediment depth, 3) at the end of the second, third, fourth and fifth incubations, higher oxygen concentration in the test tubes from which sediment had been removed (S1–S3 and S4–S6), compared with the control test tubes S7–S9. Concentration of DIP in the water phase in incubation test tubes was highest in the tubes where no sediment was removed, and lowest in the tubes where 25 cm of sediment was removed. Furthermore, if oxygen concentration was assumed to control the phosphorus release from the sediments by iron oxide formation, iron concentration in the supernatant should have decreased with the decline of the oxygen concentration in the supernatant. However, none of the abovementioned were obvious in the experiment. The concentration change of DIP and DTP during the incubations were various, and no trend was observed. BOD_7 did decline with sediment depth, but it was still considerable at the 25 cm sediment layer, but the measured decline in oxygen concentration during the incubations was rapid in all incubations and test units. Hence, oxygen consumption for organic matter breakdown would probably lead to hypoxia in the near-bottom water below thermocline, even if 25 cm of the sediment surface was removed. Therefore, we conclude, that reducing phosphate concentrations in the water by sediment surface layer removal is uncertain.

All things considered, sediment removal appeared to be a costly measure in marine environment, with several challenges. Furthermore, the measure should be repeated annually or almost all the organic-rich sediment with high phosphorus content should be removed to achieve anticipated effects. Notwithstanding, the outcome would be uncertain.

References

Jensen, H.S., Kristensen, P., Jeppesen, E. *et al.* Iron:phosphorus ratio in surface sediment as an indicator of phosphate release from aerobic sediments in shallow lakes. *Hydrobiologia* **235,** 731–743 (1992). https://doi.org/10.1007/BF00026261

Jeppesen E., Søndergaard M., Jensen H.S., Ventäla A.-M., 2009, Lake and Reservoir Management. Editor(s): Gene E. Likens, Encyclopedia of Inland Waters, Academic Press. Pages 295-309, ISBN 9780123706263, https://doi.org/10.1016/B978-012370626-3.00245-3.

Peterson, S.A. (1982), LAKE RESTORATION BY SEDIMENT REMOVAL1. JAWRA Journal of the American Water Resources Association, 18: 423-436. https://doi.org/10.1111/j.1752-1688.1982.tb00009.x

Puttonen I., Mattila J., Jonsson P., Karlsson O. M., Kohonen T., Kotilainen A., Lukkari K., J. Malmaeus M., Rydin E., Distribution and estimated release of sediment phosphorus in the northern Baltic Sea archipelagos, Estuarine, Coastal and Shelf Science, Volume 145, 2014, Pages 9-21, ISSN 0272-7714. https://doi.org/10.1016/j.ecss.2014.04.010.

Welch, Michelle; Mogren, Eric Thomas; and Beeney, Lauren, "A Literature Review of the Beneficial Use of Dredged Material and Sediment Management Plans and Strategies" (2016). Center for Public Service Publications and Reports. 34. Portland State University. Hatfield School of Government. Center for Public Service. https://pdxscholar.library.pdx.edu/publicservice_pub/34