PROPPEN

Controlling benthic release of phosphorus in different Baltic Sea scales

Final Report on the result of the PROPPEN Project (802-0301-08) to the Swedish Environmental Protection Agency, Formas and VINNOVA

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Summary

The general aim of the PROPPEN project was to study whether it is possible to counteract near-bottom anoxia and excess benthic nutrient release ("internal loading") in the Baltic Sea by artificial oxygenation in cost-efficient and socio-economically beneficial ways.

Two pilot sites were selected for the study: a coastal basin of Sandöfjärden in the outer archipelago of the western Gulf of Finland and a relatively small sub-basin of Lännerstasundet in the inner archipelago off Stockholm. Both areas are subject to anoxia, but they differ from each other both regarding to physical dimensions and to flow and mixing conditions due to differences in stratification of the water masses. Artificial bottom water ventilation by oxygenation pumping was chosen as the test method to study the possibilities to counteract anoxia and benthic release of nutrients in coastal marine conditions in the Baltic Sea. The method is energy effective compared with pumping of oxygen or air, and has been used in Finnish lakes since the 1980s.

In Lännerstasundet pumping oxygenation clearly improved oxygen conditions and decreased nutrient concentrations in near-bottom waters, while oxygenation with the applied effectiveness could not prevent the formation of anoxia in late summer in Sandöfjärden. The coastal results indicate that oxygenation pumping is able to improve near-bottom oxygen conditions and decrease nutrient concentrations in certain kind of coastal water areas via both direct and indirect effects. The factors which evidently favor positive results of oxygenation pumping are:

1. Sufficient relative pumping efficiency compared to deep water volume of a basin
2. Favorable basin topography (deep sills, high deep water volume / sediment area –ratio)
3. Sill topography and density stratification which allow inflows of oxygen-rich water into the deep basin affected by pumping

The model simulations of PROPPEN suggest that oxygenation pumping could improve oxygen conditions of deep waters in open sea areas, where the pumped water could be taken from the cold intermediate layer between the thermocline and halocline. According to model simulations flow dynamics around the oxygenation sites in general increases the bottom water oxygen concentration and reduces oxygen concentration higher up in the water column below the halocline. The simulated reduction of hypoxic near-bottom water area does not transfer directly to a reduction of anoxic sediment area and the amount of "internal loading" of nutrients because of the complex physical and biogeochemical processes at the sediment-water interface which are not considered in the model simulations.

Artificial oxygenation may offer an applicable and cost-efficient method to counteract oxygen deficiency and its consequences especially for sheltered coastal water areas. Particularly water areas, where local eutrophying load is small, or reduced to such a low level that reducing external loading is not cost-efficient anymore, may benefit from oxygenation. Local morphological and hydrodynamic conditions largely govern the applicability of the method, and need to be studied before practical actions are plausible. Additionally, at least during pilot phases of oxygenation, intensive monitoring is needed to study its effects both on oxygen conditions and factors indicating the status of the ecosystem under restoration.

Oxygenation pumping in offshore coastal waters and the open sea would require large investments both regarding development of proper technology and the construction and maintenance of facilities in practice. Our present knowledge on ecological, socio-economic and

technical prerequisites and consequences is not sufficient for the implementation of such investments even in a larger coastal scale. More scientific information is needed in the first place on physical and ecological factors, but also on technical, political, and socio-economic questions related to artificial oxygenation of the Baltic Sea.

1 Introduction

Heikki Pitkänen, Jouni Lehtoranta

1.1 Eutrophication in different Baltic Sea scales

Eutrophication with its consequences has changed the status and functioning of both open sea and coastal ecosystems of the Baltic Sea considerably (HELCOM 2007). External nutrient loading has been considered as the main factor that has caused the changes. Per receiving water area and volume of the Baltic Sea and its main basins external loading is not particularly high as such. However, together with the estuarine density stratification with relatively small deep water volume, and limited water exchange with the North Sea, the Baltic Sea is sensitive to excess nutrients causing accelerated production of oxygen consuming organic matter sedimenting into the deeper water layers and the bottom with very limited replenishment of oxygen reserves. In addition to physical conditions, the composition of bottom sediment – high concentration of sulphides and low concentrations of iron - makes most parts of Baltic Sea sensitive to benthic nutrient release compared with freshwater systems.

Although trends in factors indicating eutrophication – increase in phosphorus, nitrogen and chlorophyll-*a* concentrations – have settled and in most sub-basins turned towards decrease along with decreased external nutrient loading in recent decades, the general status of the Baltic Sea is far below good according to classification made by HELCOM (2007). The only sub-basin that has been classified to show good environmental status (GES) compared with reference conditions, is the most lake-like part of the Baltic Sea, the Bothnian Bay. Less than good status is valid also for most of the coastal water areas, where nutrient loading from local external sources is the principal factor causing eutrophication. However, also in coastal waters sediment release of nutrients – either locally or indirectly via exchange of water with neighboring open sea – may be the principal factor causing eutrophication. In coastal waters the original aim of EU's Water Framework Directive is to reach GES in 2015, while in the open sea the corresponding target year of EU's Marine Strategy Framework Directive (MSFD) is 2021.

HELCOM has in the Baltic Sea Action Plan (BSAP) given quantitative targets for nutrient load reductions to achieve GES for the main sub-basins of the Baltic Sea. In most areas the targets years of the EU Directives can't be reached in given schedules even if the most ambiguous reduction targets could be reached, because of the poor sediment retention capacity and long residence times of nutrients, especially phosphorus, in water-sediment system of the Baltic Sea.

Deep waters and sediments of the Baltic Proper are generally anoxic, and oxygen consumption rate easily exceeds the transport of oxygen from major saltwater pulses which have occurred occasionally in intervals of 1 to 4 years, but since the 1980's the average length of the interval has been about 10 years (Matthäus 2006, Myrberg et al 2006). The lack of oxygen results in enhanced sediment phosphorus release and increased water phosphorus (P) concentration. The studies of Kahru et al. (2000), Conley et al. (2002), Kiirikki et al. 2006, Vahtera et al. (2007) and Wulff et al. (2007) demonstrate that in large scale spatial cycling and in temporal scales of less than about 10 years, variations in phosphorus release from sediments play a much more important role in eutrophication and the production of nitrogen-fixing cyanobacteria than even strong inter-annual changes in external loading from the catchment area. Paleological studies have proven that cyanobacterial blooms, induced by strong salinity stratification and sediment phosphorus release, existed already 7000-4000 years ago (Bianchi et al. 2000).

Although a tight negative correlation between measured deep-water oxygen and phosphorus is evident, there is no direct relationship between these factors (Lehtoranta *et al.* 2008). It is the iron (Fe) cycle (i.e. iron reduction and re-oxidation) and microbial processes that combines the cycles of oxygen and phosphorus. According to the 'classical model' ferric oxides are reduced to dissolved ferrous iron in anaerobic sediments, while the phosphorus bound to iron is released into sediment pore water. When soluble ferrous iron is diffused to oxic sediment surface, it is oxidized into ferric iron oxides preventing phosphorus to 'escape' into free water above the sediment.

Basically the same processes control sediment binding and release of nutrients in both open and coastal waters. The big differences come from physical conditions. Due to long term stagnation periods in the open sea, especially in the Baltic Proper, also anoxic periods are long-term. Thus, oxygen will be gradually consumed, unless a new inflow does not take place within 1-2 years. In the coastal waters hypoxic/anoxic conditions are in most cases seasonal because of the thermocline which prevents the replenishment oxygen reserves of deep and near-bottom waters is broken in autumn. On the other hand, in eutrophied coastal waters oxygen depletion may develop easily due to small sub-pycnocline water volume and high sedimentation of organic matter. Although being quite short term in late summer and early autumn, coastal anoxia is detrimental for higher benthic life. Once benthic fauna has been lost, also nutrient release happens more easily, because the burrowing fauna does not anymore 'aerate' the sediment surface. Also in coastal waters there are areas of long-term anoxia in estuarine waters where high enough and constant river water inflow creates a halocline.

1.2 Possible eco-engineering solutions to counteract eutrophication

There has been an active debate in recent years especially in Sweden and Finland about the chances to speed-up the recovery of the Baltic Sea by using different kind of engineering solutions – in addition to improved waste water management. The possibilities to either prevent the saline water inflow or make it easier in the Danish Sounds in order to make the halocline weaker, and thus improve vertical mixing conditions, have been studied with modeling (Conley et al. 2009). In both cases the expected improvement would not necessarily happen. Additionally, the natural physical conditions of the Baltic Sea would change drastically.

An engineering approach that has been widely used in freshwater basins is oxygenation pumping. In these bottom water ventilation applications air, oxygen gas or (naturally or artificially) oxygenated water is pumped into the deep water layers suffering from anoxia (Lappalainen and Lakso 2005). The application where oxygen containing surface water is pumped through pycnocline benefits from density differences between the surface and deep water layers, because the lighter surface water efficiently mixes with deep water at the same time when it flows upwards. Additionally, energy requirements per pumped weight unit of oxygen are very small compared with the pumping of air or oxygen.

In the Baltic Sea enhanced sediment release of nutrients could be counteracted by bringing oxygen rich surface layer water onto the sediment surface and by this way creating a continuous iron cycling (re-oxidation of Fe), which would maintain the coupled sediment cycling of iron and phosphorus. According to Stigebrand and Gustafsson (2007) and Gustafsson *et al*. (2008), it might be possible to improve deep water oxygen conditions and sediment phosphorus retention in large Baltic Sea scales with relatively small energy needs by utilizing the existing vertical density gradient in water. According to the Recommendations given by Daniel Conley and the Hypoxia Project Working Group halocline ventilation (by pumping) is the only engineering solution that cannot be ruled out. The pumping oxygenation method has been widely used in the inland lakes in Finland for about 25 years (Lappalainen 1994, Lappalainen and Lakso 2005). It has also been tested in the brackish waters in the estuarine Pojo Bay in 1995 and 1996 (Malve et al. 2000). In those experiments bottom water oxygen concentration was assessed to have increased by 1-2 mg l-1 as a result of the pumping. At the moment three larger experiments studying oxygenation of the Baltic Sea are going on. In the program launched by the Swedish EPA in 2009 the projects PROPPEN and BOX and by EU-funding the WEBAB Project are all studying ventilation oxygenation in different study sites locating in coastal waters. WEBAB is studying the direct use of wave energy, while PROPPEN and BOX are using electric power as energy source of the pumps transferring surface water to deeper depths.

1.3 Potential ecological, economic and technical risks related to artificial oxygenation

There are several ecological, economic and technical risks related to artificial (pumping) oxygenation. In addition to the basic question about the functioning of artificial oxygenation in marine conditions, the potential ecological risks are related to unwanted effects in the manipulated ecosystems, such as changed physical regimes, warming of deep water and upwelling of nutrients. Economic risks concern cost-efficiency and cost-benefits of oxygenation, and technical risks all the different aspects related to the used equipment, its assembly and maintenance including arrangements related to the management of the needed energy. The risks increase along with increased physical dimensions of oxygenation. Studying these risks in a laboratory and small experimental scale is one of the tasks of PROPPEN, giving also valuable information for large scale analyses. The risks are in detail assessed in Chapter 6 of the present report.

The basic ecological (and also economic-technical) risk concerns the question of sediment surface oxygenation. Even if increased oxygen concentration – which is favorable as such – can be reached in deep waters, this would not necessarily lead to decreased benthic nutrient release. It is possible that artificial oxygenation cannot be targeted sufficiently to the oxidation of iron and binding of phosphorus in the surface sediment due to the formation of iron sulphides and blocking of the iron cycle (Caraco et al. 1989, Gächter and Muller 2003). The coupled sediment iron-phosphorus cycling seems not to follow the classical model in eutrophied regions of the Baltic Sea, where organic matter sedimentation is high (Lehtoranta et al. 2008). Results from the Gulf of Finland show that in summer conditions even modest oxygen concentrations in near-bottom waters cannot maintain the sediment surface oxidized (Lehtoranta 2003). On then other hand, the throughout mixing of oxygen rich water with deep water in late autumn and winter is able to do that.

It is also possible that despite oxygen-rich water can be pumped into the vicinity of sediment surface, enough oxygen cannot be transferred through the diffusive boundary layer (DBL) to maintain coupled iron-phosphorus cycling there. In the case of the pumping of oxygen-rich water from the upper thermocline into near-bottom layers, the penetration of oxygen into the sediment is based on diffusion, which is much slower process than advective transport. Thus, in artificial oxygenation the increase of near-bottom oxygen concentration should be high enough to induce a sufficient transport of oxygen through the diffusive boundary layer.

In case oxygenation of the sediment surface happens, this may have positive influence also to other biogeochemical processes than coupled iron-phosphorus cycling in sediments. Toxic reduced sulphur compounds can be oxidized via artificial oxygenation and it may affect nitrogen cycling at the sediment-water interface by increasing coupled nitrification-denitrification, i.e. permanent removal of nitrogen into the atmosphere. This phenomenon counteracts eutrophication. In addition, artificial oxygenation might help to enhance the re-colonization of bottom by animals which would further improve the cycling of iron in sediments (Canfield et al. 2005) and also enhance denitrification (*Info Box 1-1*).

Info Box 1-1 : Removal of nitrogen by denitrification

Denitrification and anammox processes together with the burial of nitrogen remove nitrogen from the aquatic systems. Denitrification and anammox processes requiring oxidized forms of nitrogen produce nitrogen gases, which are transported into water and then to the atmosphere. The oxidized forms of nitrogen can be reduced in three microbial processes: a) in denitrification, b) in anammox-process or c) in ammonification or in dissimilatory nitrate reduction to ammonium. In denitrification nitrate is consumed by the heterotrophic bacteria and nitrate is reduced to nitrogen gas (N_2O or N_2). The nitrate can also be used for the oxidation of hydrogen sulfides when nitrate is reduced by chemolithoautorophs to N_2 gas and sulfides are oxidized to sulfate (Canfield et al. 2005). In anammox process ammonium is oxidized anaerobically by chemolithoautotrophic bacteria and oxidized nitrogen is reduced to N_2 gas. In ammonification oxidized nitrogen is used to detoxify NO_2 or as an electron sink during fermentation or as in true respiration (Welsh et al. 2001). The ammonification processes occur under the same conditions as denitrification (especially if there are free sulfides), but on the contrary to denitrification, it keeps the inorganic nitrogen in the aquatic system.

In the absence or near absence of oxygen denitrification is based on the nitrate, which is rapidly depleted if there is no transport of "new" nitrate to anoxic water layers. However, the presence of oxygen enables nitrification and the continuous renewal of nitrate pool for denitrification. The process is named "coupled nitrification-denitrification", which is one of the key processes maintaining the nitrogen removal in the Baltic Sea (Tuominen et al. 1998, Hietanen and Kuparinen 2008). Theoretically, although denitrification is mainly an anaerobic process, it may be favored by the oxic conditions forming the electron acceptor (i.e. nitrate) for denitrification. Therefore, bottom water ventilation may enhance nitrogen removal.

1.4 The PROPPEN Project

1.4.1 Objectives of the study

The general aim of PROPPEN is to study *whether it is possible to counteract near-bottom anoxia and excess benthic nutrient release ("internal loading") in the Baltic Sea in cost-efficient and socio-economically beneficial ways*.

The Project has the following specific aims:

A. To critically test in laboratory and under real coastal conditions whether seasonal anoxia/hypoxia and enhanced sediment phosphorus release can be counteracted by artificial oxidation.

B. To extrapolate and assess the results obtained in A to larger coastal and open sea scales by physical-biogeochemical modelling.

C. To estimate the socio-economic implications through the use of cost efficiency (CE) and cost benefit (CBA) analyses of the applied restoration procedures compared with effects of decreased external nutrient loading. The analyses will take place in different spatial scales by using the results of A and B, as well as state-of-the art monetary valuation techniques on the willingness to pay (WTP) for improved water quality in the Baltic Sea area.

D. To make a throughout technical, socio-economic and ecological risk analysis on the use of the method in the full Baltic Sea scale.

E. To make proposals on the applicability of the studied restoration methods, and to compare their effectiveness with those effected by cuttings in external nutrient loading, at different temporal and spatial scales.

1.4.2 Research plan, a short overview

The study is strongly based on the experimental work in the two coastal test basins Sandöfjärden in the coastal western Gulf of Finland and Lännerstasundet in the inner Stockholm archipelago, where oxygen-rich surface water was artificially pumped with the Mixox-oxygenator technology into near-bottom waters (bottom water ventilation). Laboratory experiments were made to simulate the effects of oxygenation pumping in a Baltic Sea –like stratified system. Laboratory studies on the role of mixing caused by oxygenation pumping were made in co-operation with the University of Helsinki (Magnus Lindström).

The project included intensive physic-chemical and biological monitoring programs for the both study areas. Changes in temperature, salinity, currents, turbidity and oxygen concentration were followed by automatic devices in order to monitor short term (minutes-hours) dynamics of the basins both during pumping periods and between them.

Data from the laboratory and coastal scale experiments, as well as open sea monitoring data were used in 1D and 3D model applications to simulate effects of oxygenation on the main physical and biogeochemical processes affecting oxygen conditions.

The socio-economic analyses included cost-efficiency (CE) and cost-benefit (CBA) analyses in different temporal and spatial scales from the small scale *in situ* experiments to large coastal and open sea scale simulated manipulations based on measured data and modeling. Cost-efficiency properties of the studied oxygenation method were compared with those of reducing external loading by nutrient removal in waste water treatment plants. A willingness to pay –analysis (WTP) was made in co-operation with the BOX-Project to study how much people living by the Baltic Sea are ready to pay for a better marine environment.

A throughout risk analysis was made to survey the potential ecological, economic and technical risks of oxygenation in various Baltic Sea scales from coastal small scale to full open sea scale. A project risk analysis was performed to help to survey and take into account the potential risks during project's run.

1.4.3 Projects participants and structure

The PROPPEN Project is participated by eight research institutes, universities and companies from the Nordic Countries:

- Finnish Environment Institute (SYKE), coordinator
- National Environment Research Institute, Aarhus University (NERI)
- Pöyry A/S, Norway
- Pöyry Finland Oy
- Stockholm Vatten
- University of Helsinki, Department of Environmental Economics (UH/DEE) and Tvärminne Zoological Station (UH/TZS)
- Vituslab, Denmark
- Water-Eco Ltd, Finland

The Project consists of the following five Work Packages (responsible scientist(s) and partner institute(s) in brackets):

The research float in Sandöfjärden, the western Gulf of Finland.

WP1. Coastal pilot studies and laboratory experiments (Water-Eco/Erkki Saarijärvi, SYKE/Jouni Lehtoranta)

- laboratory experiments (SYKE, UH/TZS)
- coastal scale pumping oxygenation experiments (Water-Eco, SYKE, Stockholm Water)
- coastal tracer experiments (Water-Eco, Vituslab, SYKE)

WP2. Physical and chemical monitoring of the pilot test areas (Jouni Lehtoranta, SYKE, Christer Lännergren, Stockholm Vatten, Marko Reinikainen, UH/TZS)

- physical (temperature, salinity, currents, oxygen) and chemical (nutrients, chloropyll-a) monitoring of the Finnish case area (SYKE, UH/TZS)
- physical (temperature, salinity, currents, oxygen) and chemical (nutrients, chloropyll-a) monitoring of the Swedish case area (Stockholm Vatten)
- assessment of ecological effects of the manipulations in the coastal scale experiments (SYKE, Stockholm Vatten, UH/TZS)

WP3. Modeling the effects of oxidation in different spatio-temporal scales (Jørgen Bendtsen, Vituslab)

- 1D hydrodynamic modeling of the effects of pumping oxygenation (Vituslab, NERI, SYKE)
- 3D simulations on the effects of oxygenation in the case areas (Vituslab, NERI, SYKE)
- 3D simulations on the effects of oxygenation in larger coastal and open sea areas (Vituslab, NERI, SYKE)

WP4. Economic analyses and risk assessment (Markku Ollikainen, UH/DEE, Marianne Zandersen, Pöyry A/S, Juhani Anhava, Pöyry Finland Oy)

- cost-efficiency analyses (UH/DEE)
- cost-benefit analyses (UH/DEE, Pöyry A/S)
- monetary estimates for water quality improvement in the Baltic Sea (Pöyry A/S)
- risk assessment in different spatio-temporal scales (Pöyry Finland Oy)
- project risk assessment (Pöyry Finland Oy)

WP5. Management, overall conclusions and final reporting (Heikki Pitkänen, SYKE)

- financial management (SYKE)
- agreements, permission applications (SYKE)
- follow-up of the project work plan (SYKE)
- internal (between WPs) and external co-operation (SYKE, all partner institutions)
- compilation and edition of the final report (SYKE, all partner institutions)
- external communication, dissemination of project's results (SYKE, all partner institutions)

1.4.3 Financing

The Swedish Environment Protection Agency (SEPA) is the main external funder of PROPPEN, being responsible for about 1.1 million euro funding in 2009-2011. Additionally, Formas and VINNOVA participated in project's financing. The total Swedish contribution is about 1.3 million euro. The own contribution of the participating research institutes, universities and companies is about 0.8 million euro.

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2 Description of the coastal pilot sites

Jouni Lehtoranta, Christer Lännergren

The coastal pilot sites for artificial oxygenation are located in two coastal areas of the Baltic Sea: In the eastern sub-basin of Lännerstasundet, near Stockholm, in Sweden and in a semi-enclosed basin of Sandöfjärden in the north-west coast of the Gulf of Finland (*Figure 2-1*).

Figure 2-1. The location of coastal pilot sites Lännerstasundet and Sandöfjärden in the Baltic Sea.

Sandöfjärden, Finland

Sandöfjärden is a semi-enclosed basin in the coastal Gulf of Finland belonging to the municipality of Raasepori (*Figure 2-1, Table 2-1*). Sandöfjärden is one of the most intensively monitored basins in the Finnish coastal areas giving sufficient background data to assess the general effects of the oxygenation pumping of surface water into the near-bottom water layers. Sandöfjärden suffers annually from late summer oxygen depletion with subsequent high release of phosphorus from the bottom sediment into water. The reason for the continuous anoxia after the late 1990's is not clear, but it may be related to the overall eutrophication of the Gulf of Finland. The observed anoxia is partly related to the geomorphological features of the area which restricts the bottom water exchange of the basin after formation of thermocline. On the basis of echo-soundings the cross-section area of the two deepest sounds (western and eastern sounds) restricting the water exchange in Sandöfjärden are 1390 m^2 and 1500m^2, respectively (*Figures 2-2-1, 2-2-2, Table 2-1*).

Bottom sediment is soft mud and the areas of recent sedimentation are found from the middle of the basin where water depth exceeds 15m (*Figures 2-2-1, 2-2-2*). Characteristically for the other coastal basins in the Gulf of Finland, the sediment is reduced and colored black by iron sulphides, and there is a strong smell of gaseous hydrogen sulphide. The previous studies have confirmed a significant efflux of phosphate from the bottom sediment (Lehtoranta 2003) which explains the increase in concentration of phosphate below thermocline. The Sandöfjärden basin was considered as a suitable experiment area for the pumping because it has an enclosed bottom water area, and that the internal vertical exchange of water is free because there are no considerable internal sills restricting quasi-horizontal movements of bottom water. The exchange of deep water is restricted, but that of surface water occurs rather freely through the several openings around the basin. The deepest sounds are found from the SW and SE corners of the basin (*Figures 2-2-1, 2-2-2*). The local external nutrient loading can be considered insignificant, because there are no significant nutrient sources (large rivers or point sources) in the catchment of Sandöfjärden.

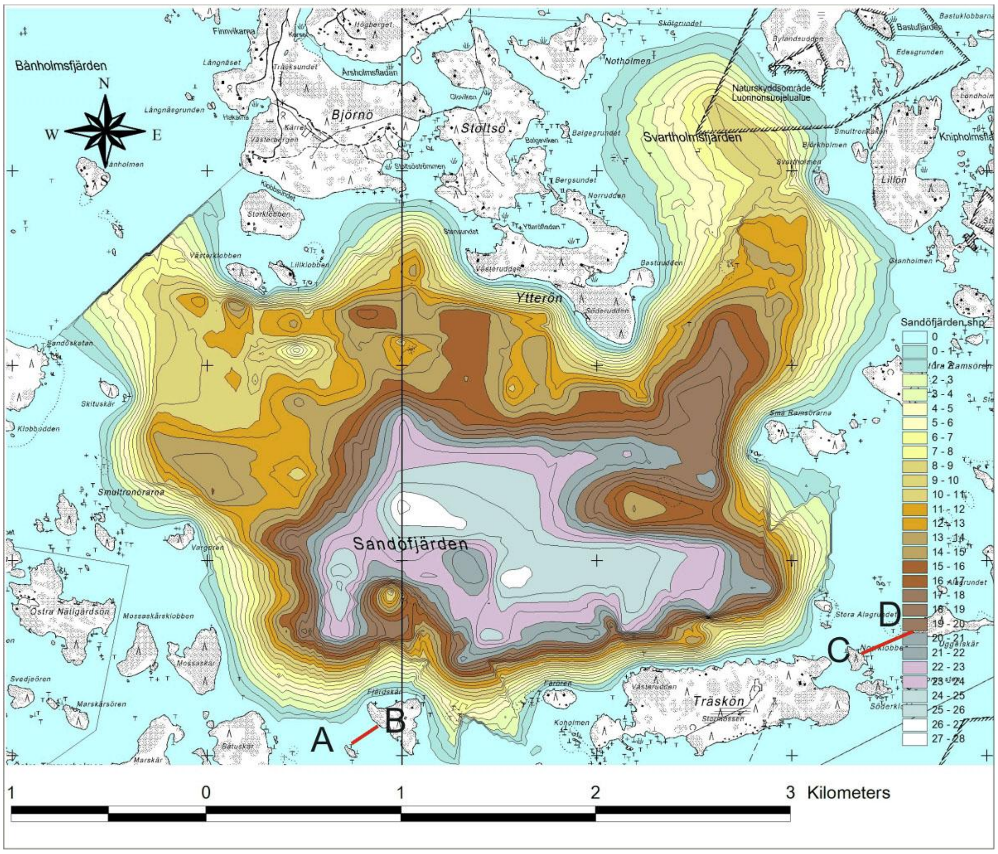


Figure 2-2-1. Bottom topography of Sandöfjärden. The two cross sections measured separately in two major deepest sounds entering Sandöfljärden basin are also marked (A-B, C-D). Note that the echo sounding data of the topography map does not cover all the area, thus depths towards the sounds are described shallower than they actually are. The actual sill depths are presented in Figure 2.2-2.

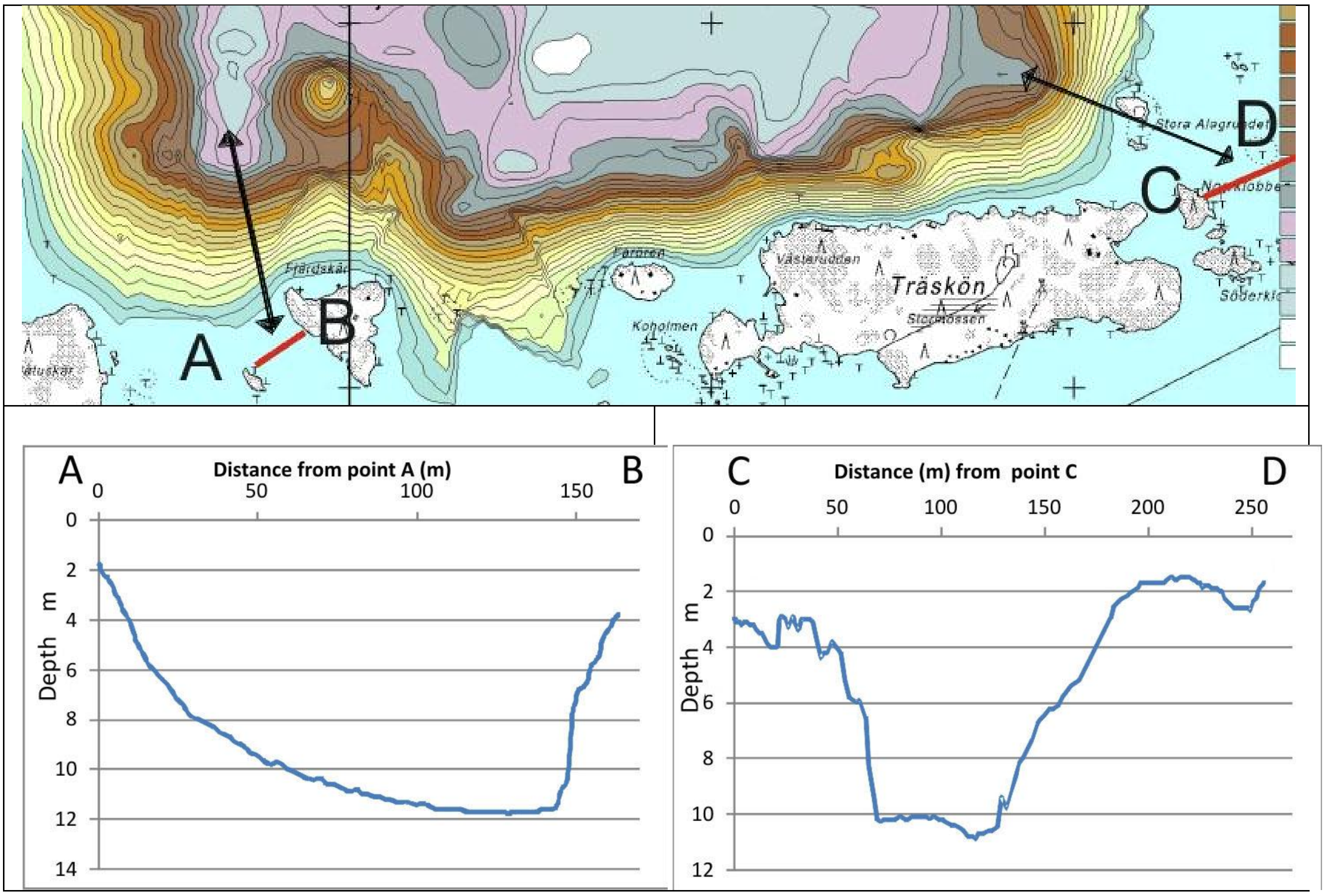


Figure 2-2-2. Bottom topography of Sandöfjärden and the cross sections, showing the actual sill depths, of two major deepest sounds (A-B (left) and C-D (right)) entering Sandöfjärden basin.

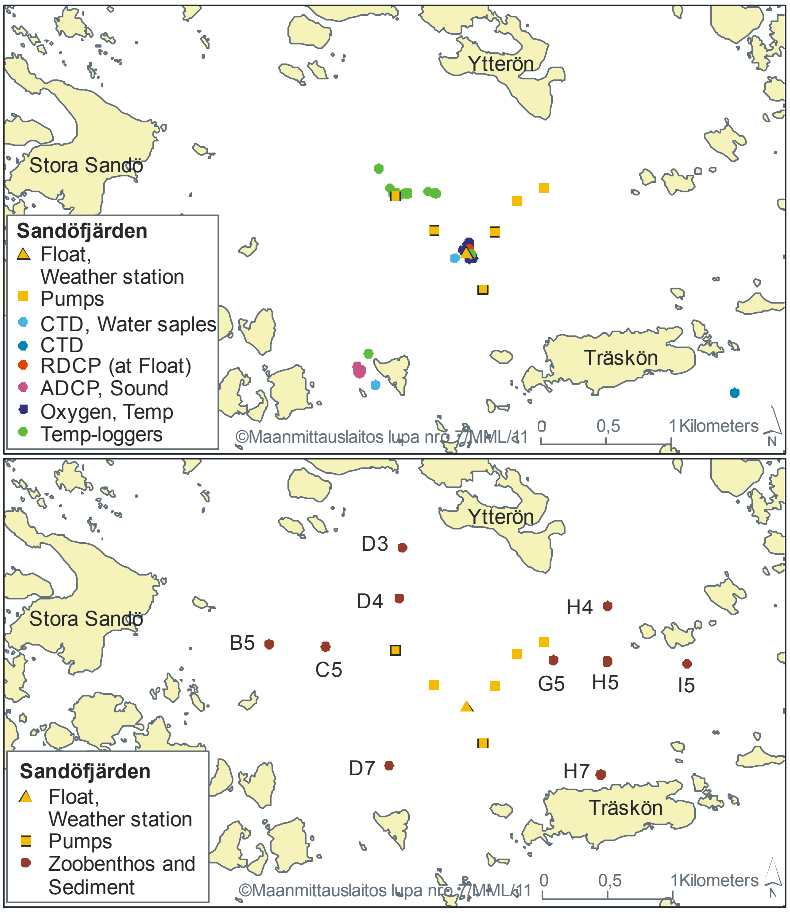


Figure 2-3. The locations of monitoring stations, automatic devices (above), and sampling sites on benthic fauna and sediments (below) in Sandöfjärden.

Lännerstasundet, Sweden

The Sound of Lännerstasundet locates in the municipality of Nacka and it connects the inner part of the Stockholm archipelago to the southern middle archipelago (*Figure 2-4, Table 2-1*). The surface water is influenced by the out-flowing water from L. Mälaren, by storm waters and discharges from the sewage treatment plants. The loading of nutrients from the catchment is estimated to be 2 400 kg y^{-1} for nitrogen and 130 kg y^{-1} for phosphorus, the main sources being sparsely built-up areas and forests. Lännerstasundet itself consists of two basins of which the westernmost one has been monitored since 1992 (Lännergren and Eriksson 2009, *Figure 2-4*).

Stagnant and anoxic periods caused by the stratification preventing vertical mixing may prevail from one up to four years, while oxic conditions in bottom water are exceptional and short (*Figure 2-7*). These conditions form a steep chemocline (i.e. a difference in oxidized and reduced forms of substances) between the oxic and anoxic water layers. During the stagnant periods the concentrations of phosphate-P and nitrogen-N increase in bottom water layers and reach very high levels up to 680 µg P l^{-1} and 4 900 µg N l^{-1}, respectively (*Figure 2-8*). Concentrations of hydrogen sulphide have increased after 2008 and have reached over 30 mg l^{-1} in 2010 and 2011, which is explained by the shortage of saline water intrusions into Lännerstasundet. The regularly monitored westernmost basin reflects well the conditions in the entire Lännerstasundet (*Figure 2-8*) serving, thus, good background and reference data for the easternmost basin where pumping campaigns were carried out in 2009-2011.

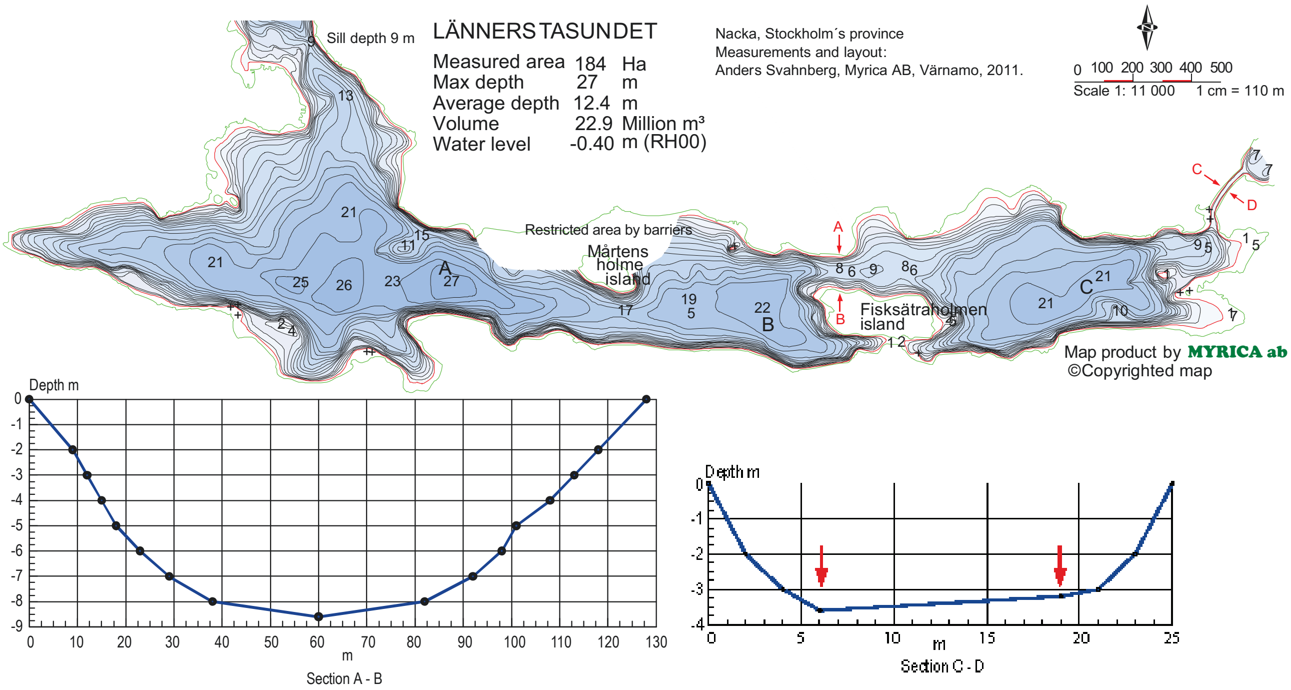
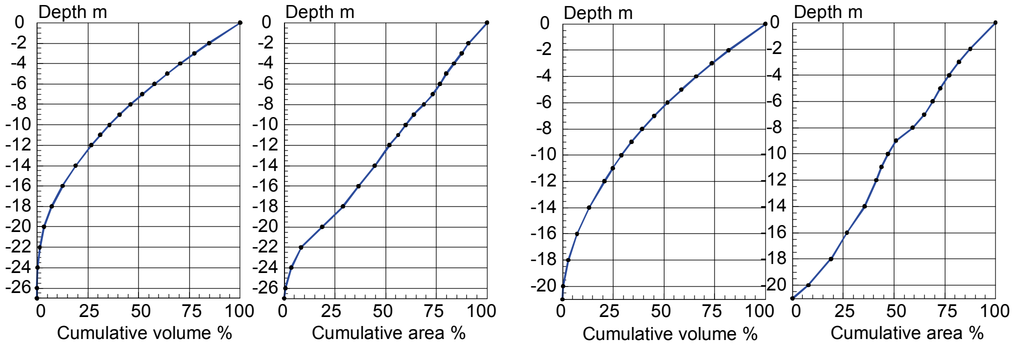


Figure 2-4. Bottom topography of Lännerstasundet. The cross section A-B is for the sill between the easternmost basin and reference basin and C-D between easternmost basin and adjacent sea area. A, B and C denote the sampling sites in the basins.

Eastern basin

Area	53	Ha
Max depth	21	m
Average depth	10.3	m
Volume	5.46	Million m³



Volume

Depth m	Volume Million m³
0 - 2	0.9934
2 - 3	0.4491
3 - 4	0.4215
4 - 5	0.3972
5 - 6	0.3760
6 - 7	0.3553
7 - 8	0.3290
8 - 9	0.2918
9 - 10	0.2592
10 - 11	0.2400
11 - 12	0.2249
12 - 14	0.4061
14 - 16	0.3291
16 - 18	0.2407
18 - 20	0.1374
20 - 21	0.0139

Figure 2-5. (Left) Cumulative volume and area for the overall Lännerstasundet basin and (right) for the easternmost pumping area. Volume figures for various depths on the right are for the pumping area.

Table 2.-1. Geomorphological and hydrographical features of the easternmost sub-basin of Lännerstasundet and Sandöfjärden. Values for area and volume are for water depths >4 m in Sändöfjärden.

Basin	**Area, km^2**	**Max. depth (m)**	**Mean depth (m)**	**Volume 10^6 m^3**	**Drainage area, km^2**	**Sill depth (m)**	**Cross-section areas of sounds (m^2)**
Lännerstasundet	0.53	19	10.3	5.5	11	8.6	A-B=740/C-D70
Sandöfjärden	7.7	31	14.5	112	10	11	A-B = 1390 C-D=1500

Basin	**Surface and deep water salinity, psu**	**Type and length of anoxia**	**Estimated area of anoxic bottom, km^2**	**H_2S in deep water**	**Number of pumps**
Lännerstasundet	1-4 3-5	Semi-permanent	0.26; below 9m	yes	1
Sandöfjärden	5-6 5-6	seasonal, 2-4 months	4.75; below 12m	not measured	6

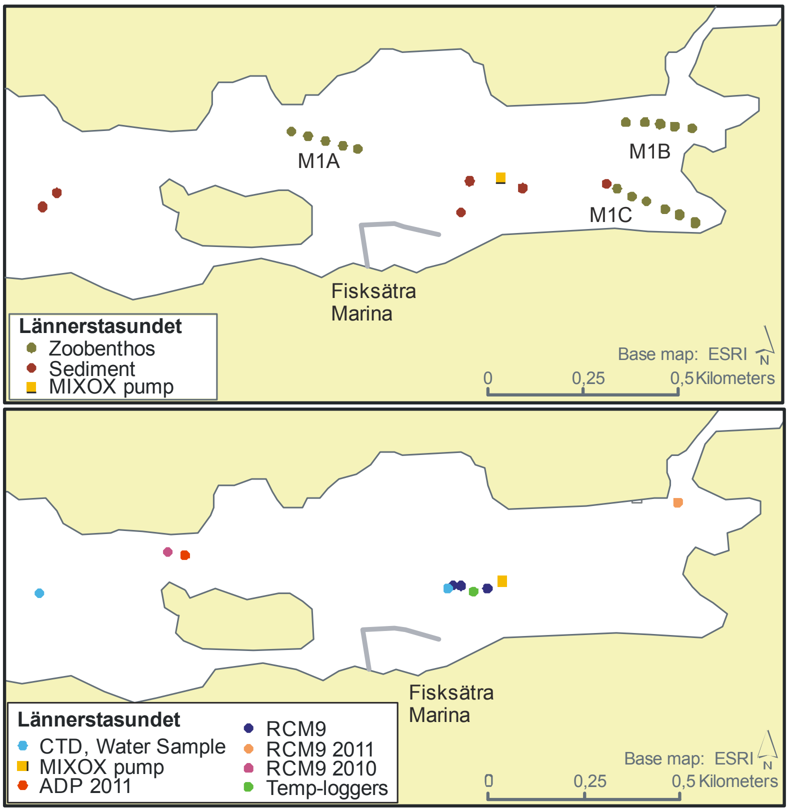


Figure 2-6. The locations of sampling sites on benthic fauna and sediments (above) and monitoring stations, automatic devices (below) in ***Lännerstasundet***.

The eastern sub-basin, in which the pumping device was installed, has not been regularly monitored previously. The basin was chosen for pumping because the water exchange is limited by two opposing sills (8.6 m and 3 m) and the water volume of the basin can be estimated accurately. Additionally, the basins separated by sills have fairly similar geomorphological, hydrographical and mixing characteristics and the sheltered location limits the effects of winds on water circulation. Recent sedimentation bottoms, i.e. mud with high water content, are found from areas where water depth exceeds 9 m. As in Sandöfjärden, sediment is reduced and colored black by iron sulphides and there is a strong smell of gaseous hydrogen sulphide.

From geomorphologic perspective the sounds of Lännerstasundet serve a rather similar pair of basins for the present research project with the eastern sub-basin being manipulated by pumping oxygenation and with the western sub-basin serving as a reference area.

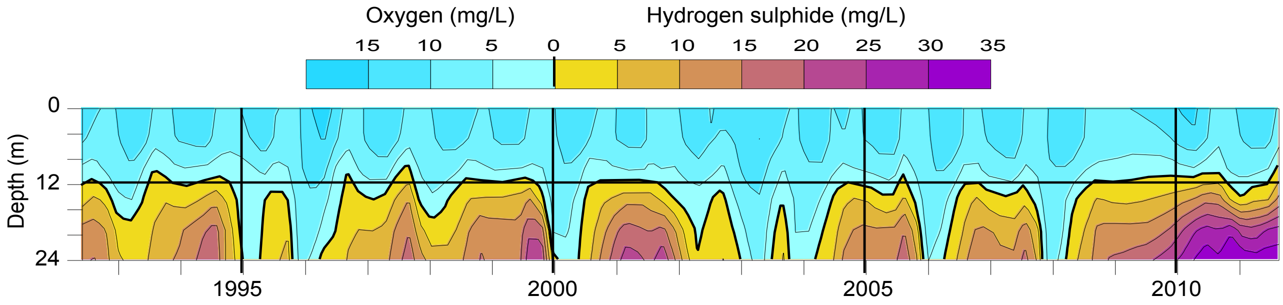


Figure 2-7. ***Lännerstasundet***. Distribution of oxygen and hydrogen sulphide at 0-24 m depth in regularly monitored western basin 1992-2011 (Data partly from Lännergren and Eriksson 2009).

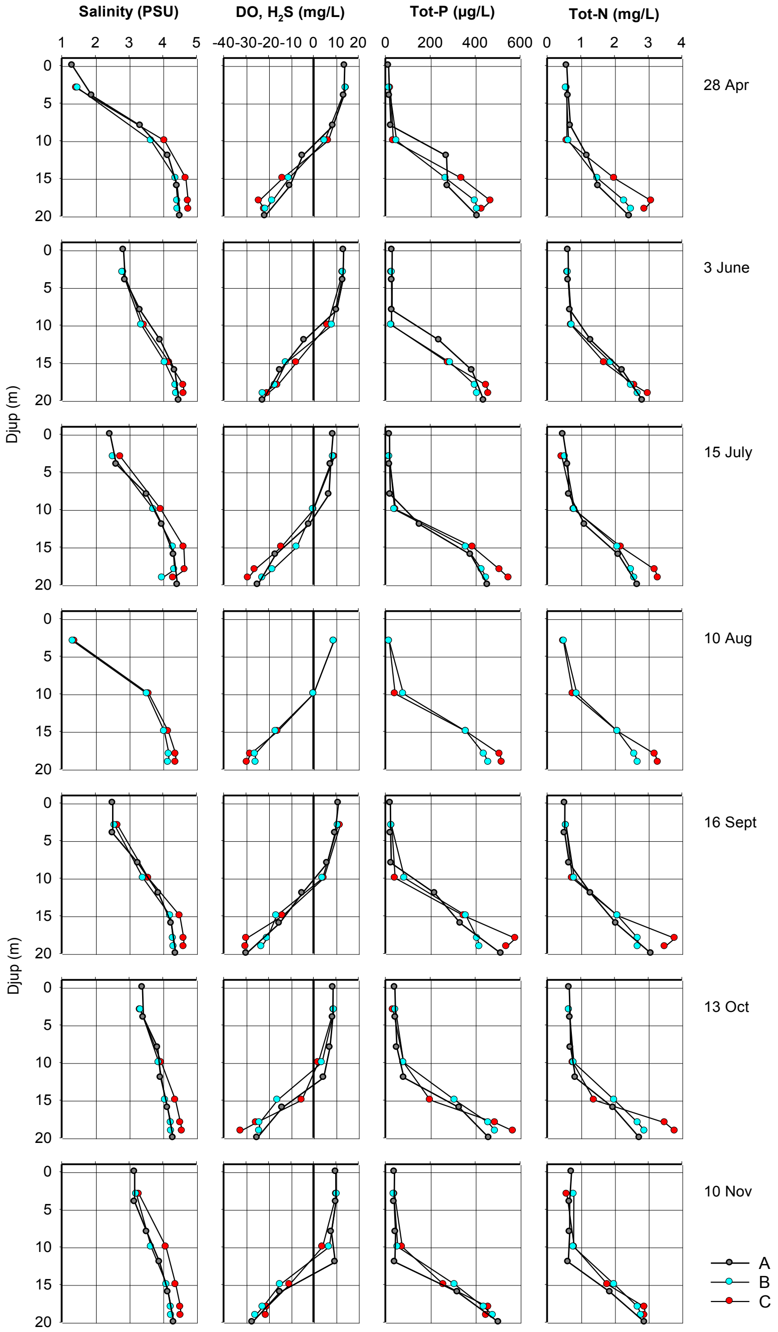


Figure 2-8. Vertical profiles of salinity, oxygen and hydrogen sulphide, total phosphorus and total nitrogen at the (A) western basin, (B) reference site, and (C) eastern basin (pumping area) before pumping in 2009 (see Fig. 2-6 for sampling sites).

2.1 Comparison between the pilot sites

The chosen experimental areas serve us an opportunity to study the effects of bottom water oxygenation in various stratification conditions: in ***Sandöfjärden*** thermocline restricts the vertical mixing and exchange of water with the adjacent sea areas in summer, whereas in ***Lännerstasundet*** water mixing and exchange is restricted by the semi-permanent halocline more or less all year round. Consequently, *Sandöfjärden suffers from seasonal and Lännerstasundet from semi-permanent anoxia.*

In ***Sandöfjärden*** the circulation of water after the autumn overturn is efficient (*i.e.* sufficient transport of oxygen to bottom water), and there is a need for pumping only for the period of temperature stratification. In ***Lännerstasundet***, in contrast, the pumping would be reasonable throughout the year.

In ***Sandöfjärden*** the aim of the study was to find out whether oxygenation is able to maintain oxic conditions and nutrient retention capacity after the formation of thermocline, whereas in ***Lännerstasundet*** the target is to study whether oxidized conditions of near-bottom water could be formed and the ability of the system to retain phosphorus could be returned.

References

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Lännergren, C. and Eriksson, B. 2009. Undersökningar i Stockholms skärgård 2008. Stockholm Vatten 2009-04-21, Dnr 09SV139. (in Swedish).

3. Coastal pilot studies and laboratory experiments

Erkki Saarijärvi, Jouni Lehtoranta, K. Matti Lappalainen

The pilot studies in *Sandöfjärden* (Finland) and *Lännerstasundet* (Sweden) were performed using **Mixox MC 1100 oxygenation pumps (diameter 1100 mm)**, which were moored with steel wires at the bottom. In order to protect the oxygenator from waves and ice, it is normally installed at 2-4 meters below the surface; only a buoy is above the water surface (*Figures 3-1, 3-2* and *table 3-1*).
In addition, in laboratory experiments, the effects of oxygen pumping on the sediment-water interface were studied detailed.

Figure 3-1. The Mixox MC 1100 oxygenation pump (diameter 1 100 mm).

Table 3-1. Technical details of Mixox-oxygenation pumps.

Pump	Mixox MC 1100	Mixox MD 1100 (Duplex)
Pumping capacity, m3 day-1	82 000	131 000
Electric power, kW	2.5	5.5
Weight, kg	185	220
Material	EN 1.4044	EN 1.4462
Diameter of the propeller, mm	1100	1100
Antifouling	Hempel Mille XTRA (copper-based) Mille Alu-Safe (copper free)	Hempel Mille XTRA

In ***Sandöfjärden*** six pumps were used in several periods during summer stratification 7/2009 – 10/2011. The maximum oxygen pumping capacity was in 2009 and in 2010 ~ 4400 kg day-1 and in 2011 ~ 5300 kg day-1. In ***Lännerstasundet*** only one pump was used in several relatively short campaigns 12/2009-10/2011. The maximum oxygen pumping capacity was ~ 740 kg day-1.

Because severe corrosion problems observed on the pumps the original stainless steel (EN 1.4404) were replaced by Duplex steel alloy (EN 1.4462) in part of them. The Duplex steel did not get corrosion damages during the four-month pumping period in 2011. In order to prevent fouling of bay barnacles and filamentous algae, which can block the water intake as well as anchoring mechanism, the pumps were painted with antifouling paint.

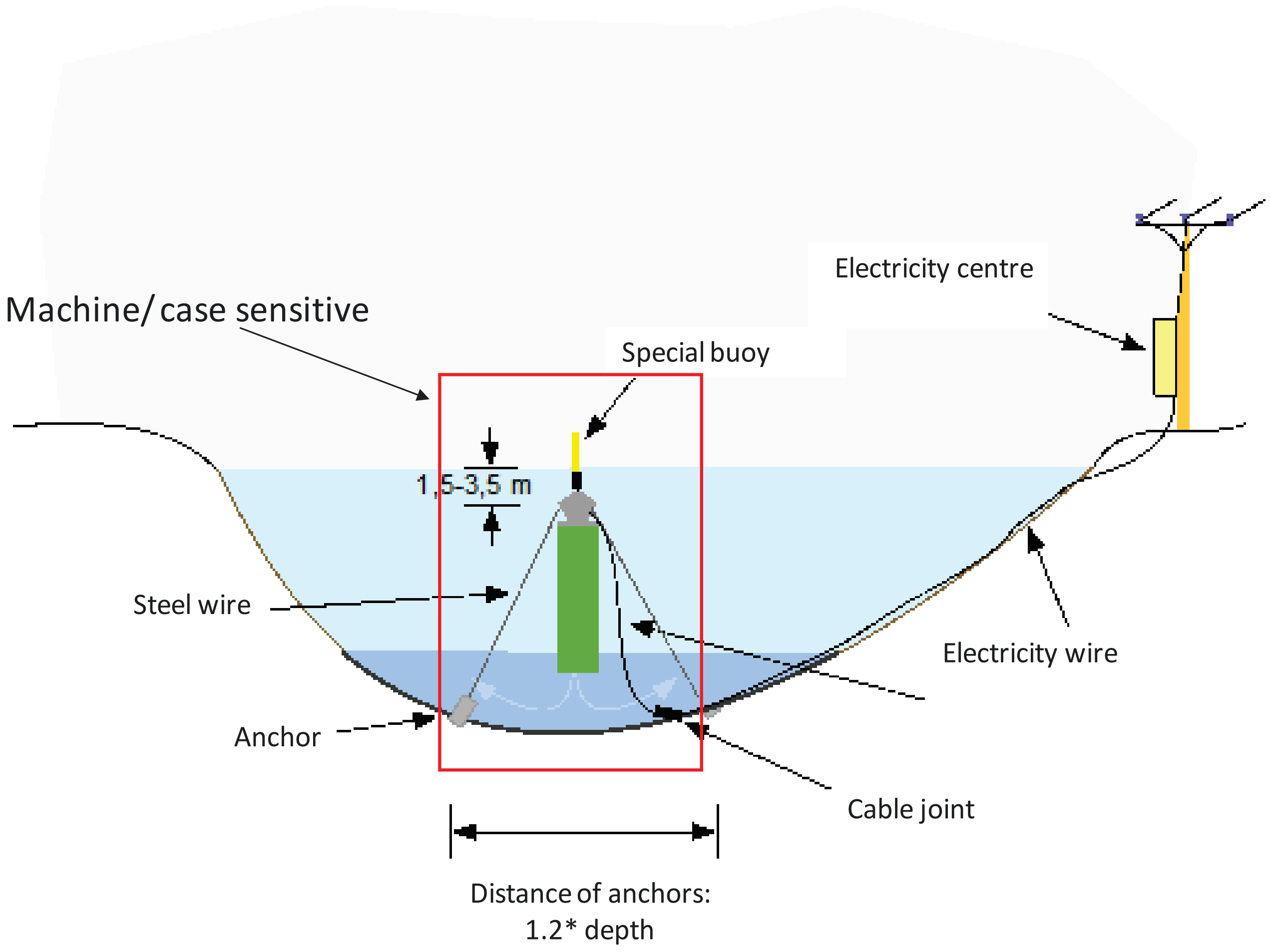

Fig. 3-2. Schematic presentation on the general arrangement of Mixox oxygenation.

3.1 Principle of oxygenation pumping and selection criteria of the method

Oxygenation pumping is one of many techniques aiming to improve oxygen conditions in bottom waters (Holdren et al. 2001, Cooke et al. 2005).

In aeration atmospheric oxygen is mixed into water. These techniques require a lot of energy because the oxygen must penetrate through the air-water surface film. Commonly the aeration efficiency is 0.5-1.5 kg O_2/ kWh (Lakso 1988).

In oxygenation pumping oxygen-rich water from the mixed surface layer (soluble oxygen) is pumped into bottom-water. This technique requires much less energy: 10-12 kg O_2/kWh aeration efficiencies have been achieved. Furthermore, some oxygenation systems use pure oxygen (Lake Hallwilersee, Switzerland, (http://www.ag.ch/umwelt/de/pub/themen/wasser/sanierung_hallwilersee/seebelueftung.php, 18.12.2011).

Artificial oxygenation technique by bottom-water ventilation is widely used in restoration in various size lakes in Finland (Lappalainen 1994, Meriläinen et al. 2003, Lappalainen & Lakso 2005, Saarijärvi & Lappalainen, 2005). Method has been used both in small and large lakes (from 0.07 km^2 to about 150 km^2 lakes). All lakes have summer and most winter thermal stratification.

In these projects the oxygenation pumping has improved quickly the quality of water (increased oxygen concentration, decreased phosphorus concentrations) if capacity of the pumps has been appropriate.

In the fjord-like brackish water Pojoviken Bay Mixox oxygenation increased bottom-water oxygen concentrations in 1995-1996 about 1-2 mg l-1 and no release of nutrients from bottom to surface layer was detected (Malve et al. 2000). In addition, it has been reported that the improvements in sediments can take several years: in lake Jyväsjärvi 20 year period of intensive pumping was needed to improved the quality of sediment (Meriläinen et al. 2003), in Lake Tuusulanjärvi it took ten years to reduce the capacity of ~4000 kg d-1 by ~ 30 % (Saarijärvi & Lappalainen 2005, Saarijärvi 2010 (unpublished).

In inner archipelago, like the Pojoviken Bay, the conditions are quite sheltered and a lake-like installation procedure of the pump could be used (Malve et al. 2000).

In this coastal Baltic Sea PROPPEN project the pumping method of surface water into anoxic bottom-water was selected to study the effects of artificial oxygenation. The selection was based on former experiences from the Pojoviken Bay as well as from many lakes.

The Mixox oxygenators pump oxygen rich water from the mixed surface layer into near-bottom depths. The primary water flow induces widespread secondary circulation in the experimental basins (*Figure 3-3*). Thus, oxygen is transported from upper, oxygen-rich (oxic) layers, into bottom anoxic/hypoxic water layers. Oxygen transport into near-bottom water layers is enhanced by inducing near-bottom density currents, which are supposed to transfer oxic water from shallower near-bottom layers to deeper areas.

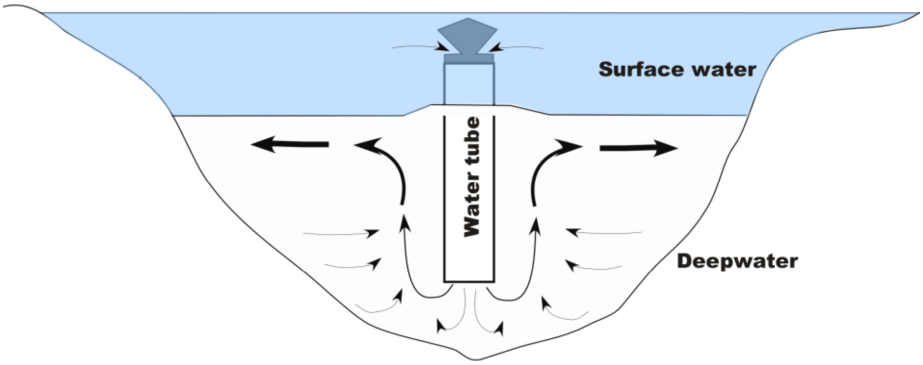

Figure 3-3. Schematic presentation on the effects of Mixox on currents. (For more detailed information, see chapter 5.)

3.2 Set-up and dimensioning of the devices at coastal sites

Set-up and dimensioning of the experiments were carried out according the standard procedures used in lake oxygenations by Water-Eco Ltd. At first, planning to select pump places was made using bathymetric maps. The needed pumping capacity and a rough estimate for the length of cables were calculated as well. After this preliminary work the exact places for the pumps were set using echo-sounding, and the installation of anchors and navigational buoys were performed. Finally, the cabling was done and the pumps were installed (*Figures 3-4 a,b*).

Figure 3-4. Set-up and removing of Mixox pumps in Sandöfjärden: a) anchoring (2009) b) cabeling and anhoring (2009) c) removing (2011).

In order to minimize the cable diameter in long cables (each ~800-1400 m) the voltage was increased from 400 V to 690 V on electric center (the island of Ytterö). Each pump was anchored with 12 pieces of concrete, weighed 25 kg each; six pieces on the both side of a pump (*Figure 3-4a*). Steel wires (6 mm in diameter, EN 1.4404) were used as anchoring ropes.

To estimate the needed pumping capacity, **oxygen consumption rates** (mg l-1 d-1) were calculated using earlier measurements. The total amount of oxygen consumption was obtained multiplying oxygen consumption rates with calculated sub-pycnocline bottom water volumes. The calculated oxygen demand for Sandöfjärden and for Lännerstasundet was 2 600-6 000 and 180-250 kg d-1 respectively.

The calculated oxygen demand (calculated from observed changes in oxygen concentration) for Sandöfjärden and for Lännerstasundet was 2 600-6 000 and 180-250 kg d-1 respectively. These calculations give a rough estimate of oxygen consumption. The estimate represents the net result of consumption and increase due to primary production or inflows.

In order to estimate the **sediment oxygen demand** potential oxygen demand was also calculated based on the area of bottom water (sub-pycnocline). In eutrophic lakes the sediment oxygen demand has been between 0.5-1 g m^{-2} d^{-1} (Liikanen et al. 2002). In lakes about 1 g m^{-2} d^{-1} has been observed to be a good general estimate for dimensioning of oxygnenation devices (Vesi-Eko, unpublished).

For Sandöfjärden the calculated sediment oxygen demand was 4 500-8 100 kg d-1, the high variation of values was based on inadequate information of the depth of pycnocline. However, for Lännerstasundet exact calculations could not be carried out because of the regularly anoxic conditions. Calculations were based purely on the sediment area (bottom water; about 0.265 km^2) gave an estimate of around 265 kg day-1 for the sediment oxygen consumption.

In ***Sandöfjärden*** six pumps were used with measured **pumping capacity** ~ 82 000 m3 d-1 each. The total capacity was 5.64 m^3s^{-1}, i.e. 487 000 m^3d^{-1}.
In 2011 the pumping capacity was increased by replacing pumps #3 and #5 (Figures 3-5, 3-6) with bigger units. The pumping capacity for the bigger pumps were ~ 131 000 m^3/day, and the total capacity increased to ~ 590 000 m^3d^{-1}. During the full capacity of pumping the theoretical residence time for the water volume below pycnocline (below sill depth) was calculated as 89 (in 2011) to 109 days (2009-2010) for Sandöfjärden and 24 days for Lännerstasundet.

The **oxygen transfer capacity** (calculated with 9 mg O_2 l-1 concentration of surface water) was ~ 740 kg day^{-1} for normal pump unit and corresponding value for bigger unit was ~ 1180 kg day^{-1}. In 2009 and in 2010 the total capacity was ~ 4440 kg day^{-1}, and in 2011 corresponding value was ~ 5320 kg day^{-1}. The electric power consumption for normal unit was ~ 2,5 kW and corresponding value for bigger unit was ~ 5,5 kW. Thus, the **total energy demand** in 2009 and 2010 was ~ 15 kW (12.3 kg/kWh O_2) and in 2011 ~ 21 kW (10.6 kg/kWh O_2).
In 2009 the water intake of the pumps were at the depth of ~ 3,5 m and the outlet at the depth of 20 m; the distances of the pumps from the bottom vary from 6 to 8 m. In 2010 and 2011 water tubes were shorter and consequently the outlet was raised at the depth of ~17m and the distances from the bottom vary from 9 to 11 m. In 2011 the water intake depth was lowered down to ~ 7 m in early summer to minimize the warming of bottom water, but the outlet remained at the depth of ~17 meters.

In ***Lännerstasundet*** **only one pump was needed** to compensate the oxygen demand. The water intake depth was ~ 3.5 m. In 2009 the water outlet was at the depth of ~ 15 m, in 2010 and 2011 it was raised at the depth of ~ 11 m.

In Finland the artificial oxygenation is mainly used in lakes to fulfill the requirements of environmental permits (e.g. wastewater treatment plants, pulp mills). The pumps are a part of environmental management and no permits are required by the authorities. However, in PROPPEN, which is an independent research project, the pumps were installed at private-owned water areas. Thus, permits from both land-owners and environmental authorities were needed. For Sandöfjärden the permit was given by the Uusimaa Environmental Center and for Lännerstasundet by Nacka municipality. Additionally, permissions from Defence Forces and maritime traffic authorities (Finnish Transport Agency and Swedish Transport Agency) were needed.

In case that the electricity cables have to be installed below official marine route, environmental permits from Regional State Administrative Agency (in Finland) would be needed. In PROPPEN project no such permits were needed.

3.2.1 The oxygenation experiments 2009-2011

2009

In 2009 the main task was to install the oxygenation equipment in Sandöfjärden and in Lännerstasundet. The work was started in the beginning of June in ***Lännerstasundet***, where one pump was installed and tested for a couple of hours. During summer and autumn very high hydrogen sulphide concentrations were measured in sub-pycnocline waters. Consequently, the start of pumping was postponed, to avoid the risk mixing the poisonous bottom-water with upper oxygen-rich water layers. As the concentrations decreased towards late autumn, the actual experimental pumping could be started on 9/12/2009 during the field cruise (see chapter 4) (*Figure 3-5*). However, the pump had to be stopped on 23/12/2009 because of formation of the ice cover. The main reason for the interruption was to avoid possible harmful effects to the ice cover; in Lännerstasundet skaters and other outdoor people are active. Total amount of water pumped in 2009 was about 1.2 million m^3 (*Figure 3-6*).

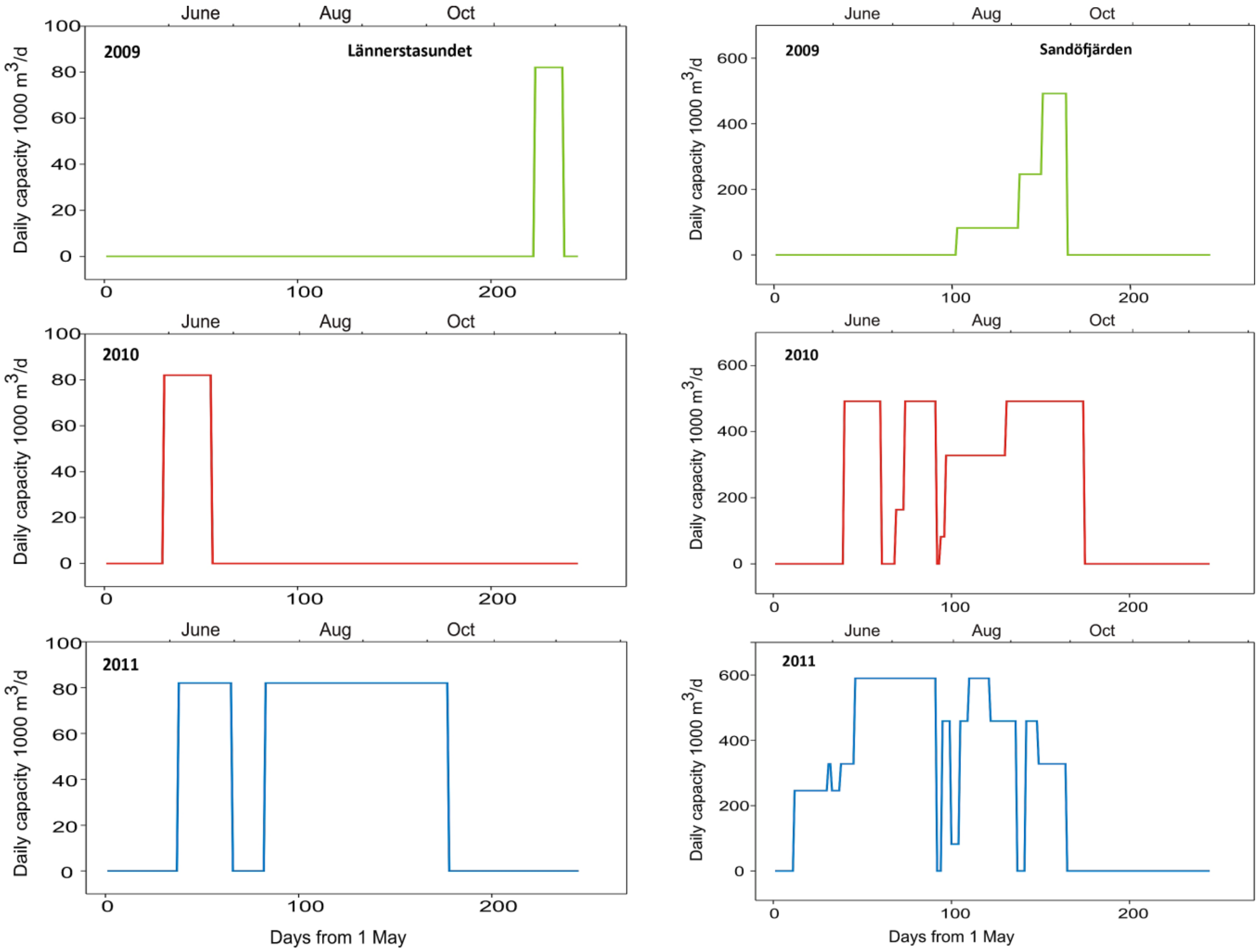

Figure 3-5. Amount of water pumped daily in Lännerstasundet and Sandöfjärden (Day 0 = 1/5/).

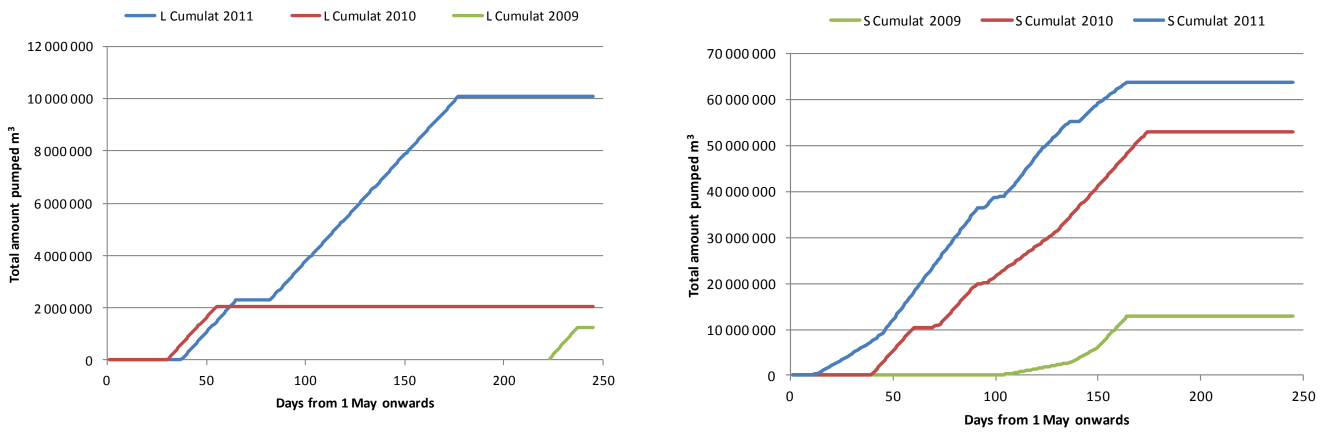

Figure 3-6. Cumulative amount of water pumped in Lännerstasundet and Sandöfjärden. Day 0 = 1.5.

The work started later in June in ***Sandöfjärden***, where six pumps were installed. The first pump (Mix 6) was started on 11/8/2009 (*Figure 3-5*), the next pumps (Mix 3 and Mix 5) on 15/9/2009 and the rest (Mix 1, 2 and 4) on 28/9/2009. All the pumps were stopped on 11/10/2009 after the seasonal overall turnover due to winds and the cooling of surface water layers.
Total amount of water pumped in 2009 was about 13 million m^3 (*Figure 3-6*).

2010

In ***Lännerstasundet*** the pump was started on 31/5/2010 and stopped on 24/6/2010. Regardless of the interruption of artificial oxygenation the oxygen conditions remained good during winter 2010-11 and no pumping was performed. Total amount of water pumped in 2010 was 2 million m^3.
In ***Sandöfjärden*** the pumps were started on 9/6/2010 (*Figure 3-6*) and stopped in the end of the month, in order to avoid the fast warming of near-bottom water during a warm surface-water period that was caused by the very high air temperature. All the pumps were restarted on 13/7/2010 and stopped again on 30/7/2010 before the rhodamine experiment on 2-5/8/2010 (chapter 5.1). During these experiments some major corrosion problems in the pumps were observed and two pumps had to be removed. The four pumps remained operating from 5/8/2010 to 8/9/2010. After fixing of removed pumps all six were operating from 9/9/ to 20/10/2010.
Total amount of water pumped in 2010 was 53 million m^3.

2011

In ***Lännerstasundet*** the pump was started on 7/6/2011 and it was stopped again 5/7/2011. The pump was re-started on 22/7/2011 and stopped again on 25/10/2011. Total amount of water pumped in 2011 was 10 million m^3.
In ***Sandöfjärden*** three pumps were started on 12/5/2011. The anchoring of pumps were re-build with scuba-divers in spring/ early summer 2011 and the fourth pump was started on 7/6/2011. The pumping capacity was increased by placing bigger pumps to #3 and #5. All six pumps were runnig on 15/6/2011, when enlargement on the electricity capacity for bigger pumps was ready. The pumps kept operating until the anchor wires of the pump #5 were broke off in the end of August and the pump had to be re-installed. **There were also some electricity malfunctions during late summer/ early autumn due the heavy winds**. Total amount of water pumped in 2011 was 63 million m^3.

3.3. Technical knowledge gathered from the pilot studies

In 2009 the ***installations*** of pumps were made according to lake experiences. The pumps worked well in marine conditions and no big differences were found during first year of the experiment.

In ***Sandöfjärden*** the pumps were left for the winter 2009-2010 to be ready for early start in 2010. At beginning of the summer in 2010 no technical problems appeared. However, during the rhodamine experiment (1/8/- 3/8/2010) severe **corrosion problems** were observed on the frames of pumps. Two (out of six) pumps had to be taken away for maintenance and were replaced with smaller pumps (Mixox MC 1000, capacity about 70 000 m^3d^{-1}) for the rest of the season.

In autumn 2010 strong winds harmed working and the pumps had to be removed from ice in February. All pumps were maintained thoroughly and re-installed in May-June 2011. In addition, corrosion problems occurred in anchoring wires which had to be replaced (scuba-diver) before re-start of the pumps. Two pumps were replaced with new units made of duplex-steel EN 1.4462 and equipped with more powerful motor (2,5 kW--> 5,5 kW) in order to increase the pumping capacity to the maximum the electricity set-up could allow. Estimated improvement in the pumping efficiency (kWh m^{-3} transferred water) can be significant with redesign of the pump.

The importance to use appropriate materials was already revealed in the Pojoviken Bay in 1995 (Malve et al. 2000). There the steel EN 1.4044 proved to be reliable and it was also used in PROPPEN coastal sites. Nevertheless, the selected steel alloy had been corroded in August 2010 in ***Sandöfjärden***, where two out of six pumps had to be removed and replaced with two Mixox MC 1000 pumps. There was a need to change the anchor wires as well, but due to hard winds in autumn that had to be postponed. During May-June 2011 all six pumps were equipped with new anchor wires

3.4 Biofouling

In order to prevent **bio-fouling** on the equipment two kind of anti-fouling paints were used: copper-based self-polishing Hempel Mille XTRA and copper-free Mille Alu-Safe. Most of the pumps were painted with copper-based paint, only two pumps in ***Sandöfjärden*** during 2011 were painted with copper-free paint. After four-month experiment a massive fouling of bay barnacles were observed in copper-free surface (*Figure 3-7a,b*). In copper-painted surface there were only some barnacles, which were easily removed using pressure washer.

Figure 3-7a. Mixox pump with copper-free paint (Sandöfjärden, 2011).

In ***Lännerstasundet*** the filamentous algae caused problems. At present (03/2012) the pump is still in water and the final condition of the pump will be checked later. Growth of bay barnacles and/ or filamentous algae can block the water intake of pump and jam the anchoring mechanism.

According to experiences from PROPPEN project in 2009-2011 the anti-fouling paint must be renewed every second year. In this project common consumer products for boats were used, but also industrial products could be taken into account in the future. The biofouling problems occur also in water intake channels of power plants in similar conditions and research is done to solve the problem.

Callow & Callow (2011) stated in their review that primary strategy for combating biofouling has been to use biocide-containing paints. However, the environmental concerns and legislation are driving towards non-biocide solutions, i.e. based on physico-chemical and material properties of coatings. In practice it means the use of nanotechnology and polymer science. If pumping experiments are carried on in the future, some of the new polymer-based coatings should be tested in order to avoid biofouling. Copper-based solutions are not suitable for long-time use because of relatively short repaint interval. Copper-based antifouling paints are also forbidden in some parts of Baltic Sea (for instance in Stockholm archipelago) because of the toxicity. In PROPPEN's case the permission for the use of copper-based antifouling was given by the Municipality of Nacka.

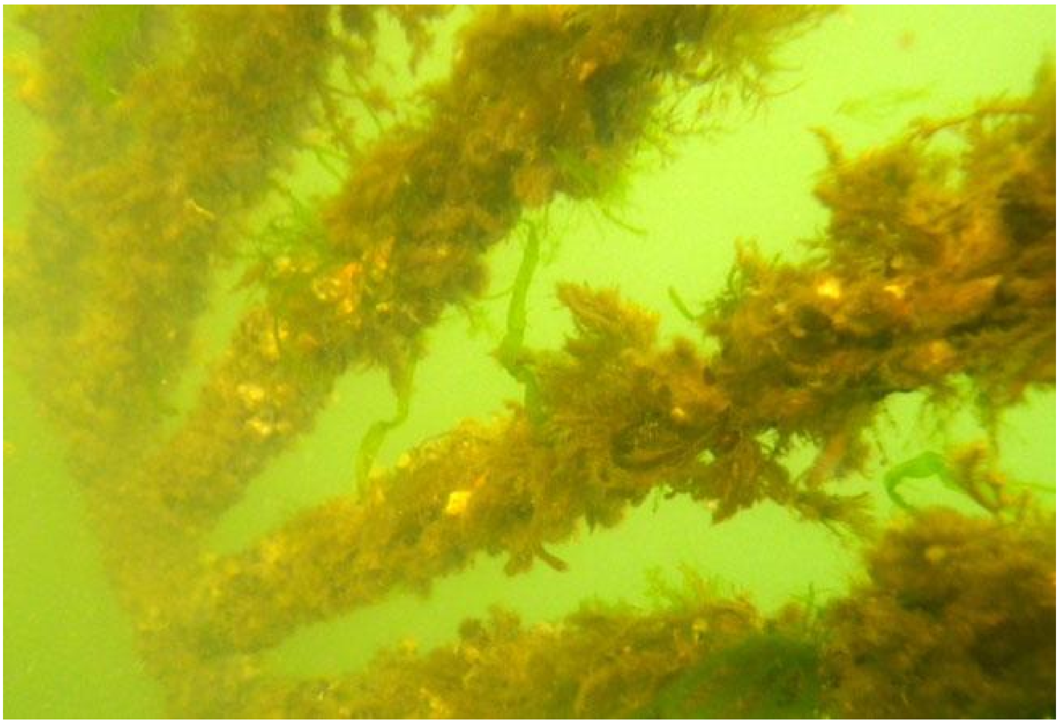

Figure 3-7b. An example of biofouling: filamentous algae attached on ropes in the Turku archipelago (Photo: Milla Suutari). Note: photo is not connected to PROPPEN project.

3.5 A laboratory simulation of the oxygen on the sediment-water interface

A laboratory experiment was carried out to study the effect of artificial pumping on the oxygen concentrations at the sediment-water interface. The sediment used in the experiment was sampled from Sandöfjärden; the height of sediment placed in aquarium ranged from 42 to 48 mm. The height of two artificial sediment sill built into the aquarium was 80 mm each (*Figure 3-8*). Aquarium was filled with deoxygenated salt water and divided to two sections with tight plastic (PVC) stoppers. The height of water was about 150-160 mm before the addition of anoxic salt water. Temperature in aquarium was 6 degrees.

The oxygen concentrations were measured with microelectrodes from water and sediment and the water in the aquarium was aerated. After that hypoxic water (no oxygen in the sediment, 6%

saturation) was pumped into aquarium to create a two layer system. Oxygen concentrations were measured again after aeration (70% saturation in water, no oxygen in sediment).
Saline and hypoxic water was syphoned into the system until the water level rose up to 60 mm (flow rate about 250 ml min-1). There was a clear grayish layer in water above the sediment where the saltier water accumulated (did not show the actual pycnocline, which was about 1 to 2 cm deeper). The salinity difference between the oxygen-rich surface water and bottom hypoxic water was 2.5‰ after the addition of anoxic water. The difference was close to that measured from Lännerstasundet.

Peristaltic pump was used to create a constant flow of surface water to the bottom-water layers. Flow rate was adjusted to 9 ml min^{-1}. All together 300ml of oxygen rich surface water with rhodamine was pumped into bottom-water layer 5 cm above the sediment. Oxygen concentrations were measured from the top of the sill and from a site, where there was a water layer without rhodamine near the sediment-water interface.

The rhodamine layer maintained its position well in aquarium for further analysis. Rhodamine samples were taken 1.5 cm - 2 cm above the sediment colored by rhodamine layer and below the rhodamine layer on the right side of the sill where rhodamine was not visually observed. Oxygen measurements were started from two sites where rhodamine hit the surface of the sediment i.e. sill and deep site and a site where rhodamine color was at the strongest.

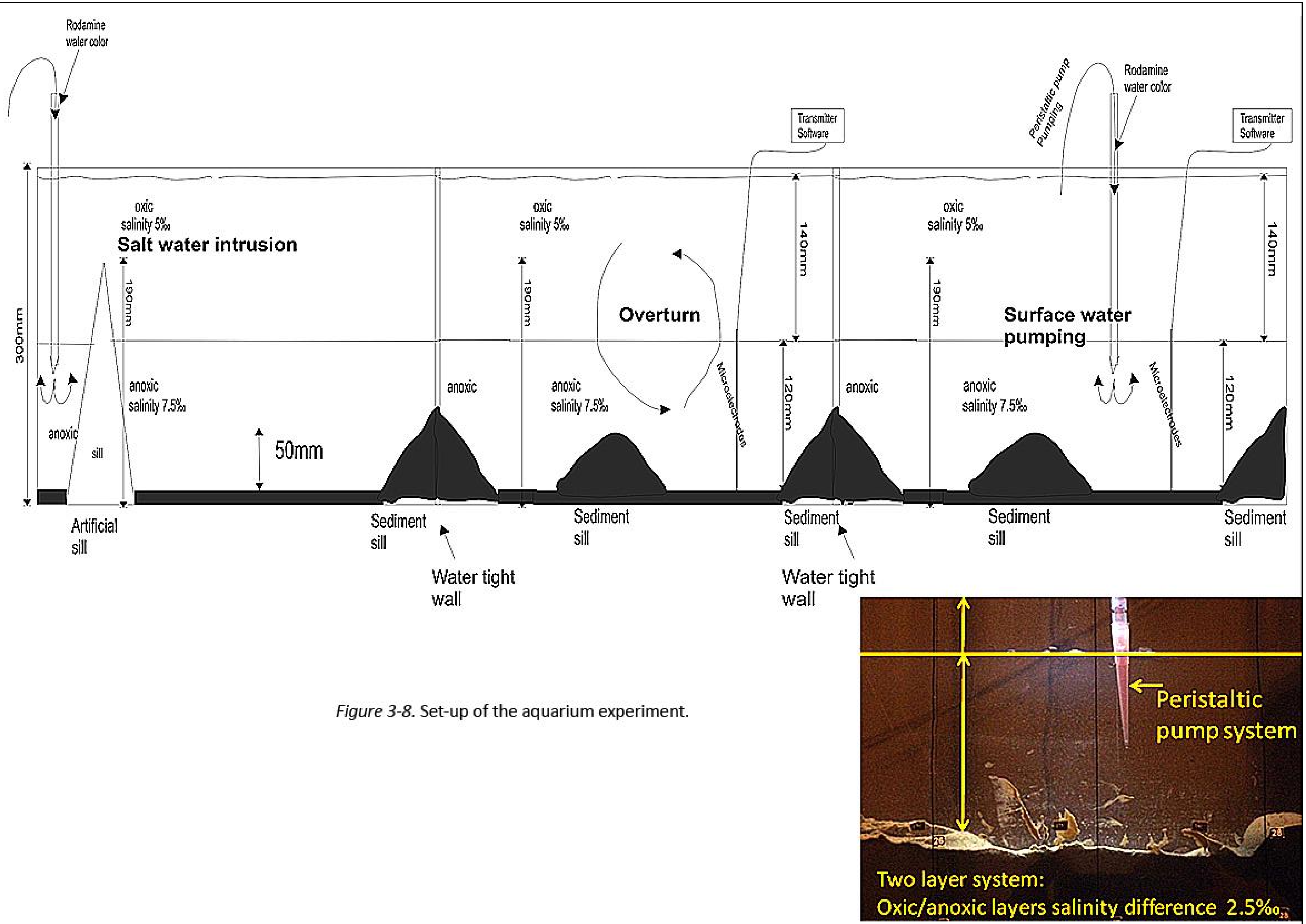

Figure 3-8. Set-up of the aquarium experiment.

3.5.1 Results of the laboratory simulation

Pumping created a rhodamine concentrated layer below the salinity stratification and above the sediment-water interface (~ 2cm) (*Figure 3-9*). However, rhodamine layer reached the created sediment sills.

Artificial pumping of surface water caused mixing of the surface and bottom-water. Mixed water rose upwards, but it did not go through the pycnocline instead it moved rapidly horizontally beneath/below the pycnocline forming a clear separate water layer in the aquarium. The pumped volume was 443 ml whereas the volume of the rhodamine colored area was 3011 ml in aquarium giving a mixing rate of about 6.8.

The distance of formed layer from the bottom sediment was dependent of the distance of the tube outlet from the sediment surface. The closer the outlet was from the sediment surface, the closer at the sediment the mixed water layer was formed. When mixed water layer reached the sediment sill it formed a clear layer which was above the sediment at the height of the sill. Overflow experiment was carried out and water went above the sill and formed a new layer into the next basin.

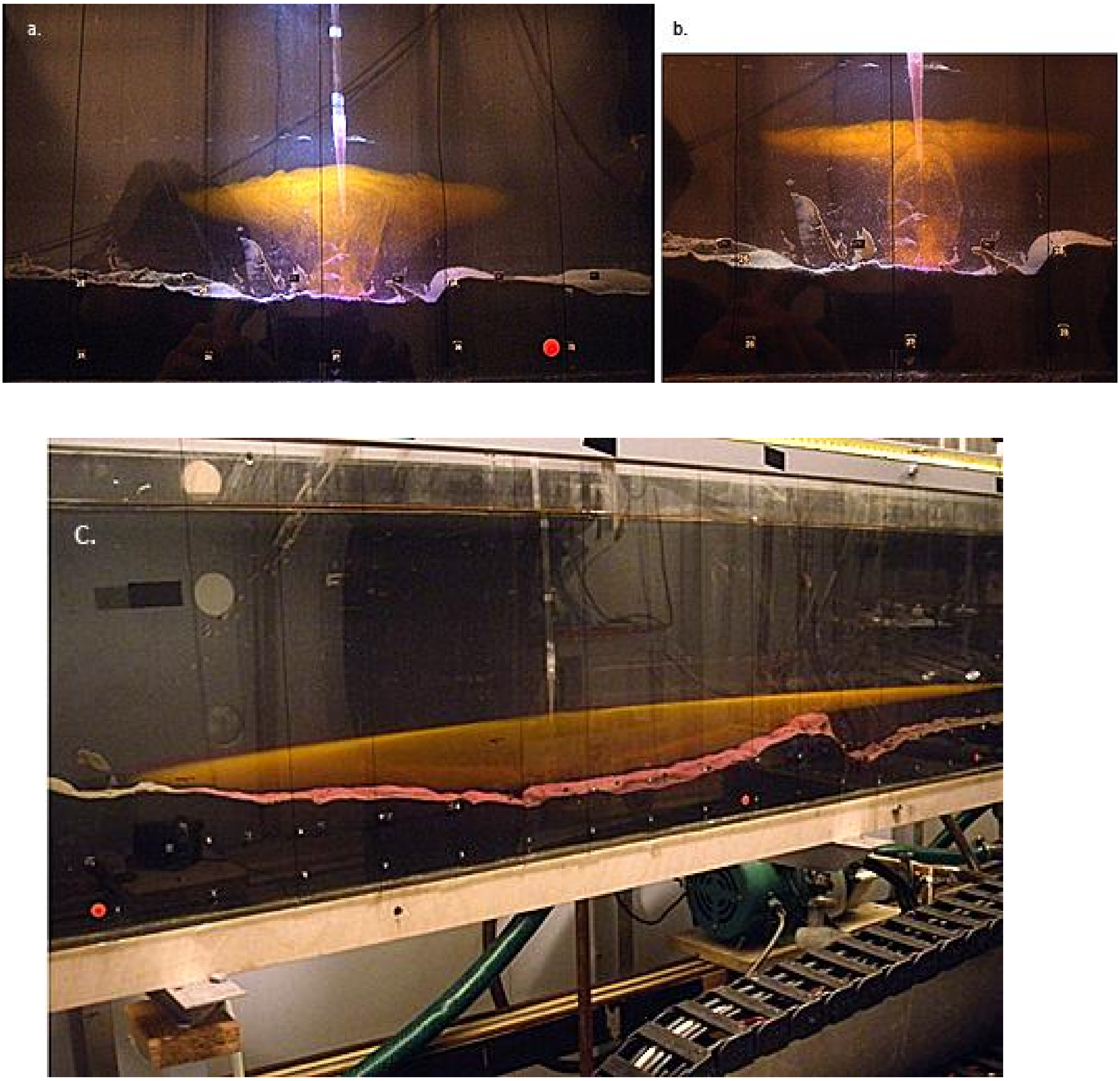

Figure 3-9. Pumping simulations in aquarium. Pictures show the spreading (a.→b.) of rhodamine in the beginning of the experiment. After pumping there was no indication on transport of Rhodamine up into oxic surface water layer (c.).

3.6 Discussion and conclusions

The dimensioning of the pumping was based on estimated **oxygen consumption** during summer stratification period, and was estimated as 2600-8100 kg day^{-1} in Sandöfjärden and about 270 kg day^{-1} in Lännerstasundet. Estimations included a lot of uncertainty due to errors in maps, variability of pycnocline depth and uncertainties on the dynamics of stratification. The accuracy of common maps as a basis for estimation of areas below certain depth are poor; in most cases the depth curves are "in the neighborhood" meaning errors between 10-30 % in the area. Further, the typical curves are for only 10 and 20 meters, and no information in between these. Interpolating the area gives some more error, and as a result the accuracy of area or volume estimates below certain depth is at least of the order of 15 %. In practice, the accuracy of dimensioning can be within a range of 20-50 %. The oxygen **pumping capacity** used in the PROPPEN project in Sandöfjärden was about 4400 kg day^{-1} for 2009 and 2010 and about 5300 kg day^{-1} for 2011. In Lännerstasundet the capacity was about 740 kg day^{-1}, i.e. strongly above the estimated oxygen consumption.

Stainless steel **material** (EN 1.4404) suitable for use in inner archipelago was not good for use in Sandöfjärden and severe corrosion problems existed. Duplex steel (EN 1.4462) did not suffer corrosion at least during four-month test period in summer.

If corresponding experiments would be made again, dimensioning of the pumping capacity would be done with more available pumping capasity in Sandöfjärden. In Lännerstasundet, however, the pump was "oversized" and no extra capacity would be needed. In this PROPPEN project the depths of both experimental areas were echo-sounded (*Figure 2-5*) and in possible future works the uncertainties originating from background data are less important.

Also the reliability of the operation of pumps would need some more detailed planning. During this project many details learned from lakes have been proved to work. However, compared to lakes, in the coastal marine environment the most important issues to be taken into account and affecting installation and operation of pumps are the high salinity (chlorine), heavier wind conditions and intensive biofouling. Effect of salinity can be solved with material selections. Wind conditions by using bigger floats and installations during night. Biofouling can affect the capacity and operation of the pumps if prober antifouling is not used. At the time copper-free antifouling paints seem to work only partially and cannot be used in a long run.

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Appendix 1.

Tables 1 and 2. Pumps used and operating schedules in PROPPEN coastal pilot studies in Sandöfjärden (S) and Lännerstasundet (L). Type of the pump is Mixox MC 1100, if not otherwise marked. I = installation, T = testing, + = operating, / = stopped, * = problem occurred.

Pump (#) type	**Pumping rate l s^{-1}**	**Electric capacity kW**	**Oxygenation capacity (O_2 9 mg l^{-1}) kg d^{-1}**
Mixox MC 1100	940	2,5	740
(1Mixox MC 1000	810	2	630
(2Mixox MD 1100	1520	5,5	1180

Site	**S**						**L**
Date	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#1**
2009							
06/2009	I	I	I	I	I	I	I,T
07/2009	T	T	T	T	T	T	
11/08/2009						+	
15/09/2009			+		+	+	
28/09/2009	+	+	+	+	+	+	
11/10/2009	/	/	/	/	/	/	
09/12/2009							+
23/12/2009							/
2010							
31/05/2010							+
09/06/2010	+	+	+	+	+	+	+
24/06/2010	+	+	+	+	+	+	/
30/06/2010	/	/	/	/	/	/	
08/07/2010			+		+		
13/07/2010	+	+	+	+	+	+	
30/07/2010	/	/	/	/	/	/	
02/08/2010					+		
05/08/2010	+	+	I*	+	+	I*	
08/09/2010	+	+	+(1	+	+	+(1	
22/10/2010	/	/	/	/	/	/	
2011							
12/05/2011	+	I	I	+	I	+	
31/05/2011	+	+	I	+	I	+	
02/06/2011	/I	+	I	+	I	+	
07/06/2011	+	+	I	+	I	+	+
15/06/2011	+	+	+(2	+	+(2	+	+
05/07/2011	+	+	+(2	+	+(2	+	/
22/07/2011	+	+	+(2	+	+(2	+	+
31/07/2011	/*	/*	/*	/*	/*	/*	+
03/08/2011	+	+	+(2	+		+	+
04/08/2011	+	+	+(2	+		+	/*
08/08/2011	/*	+	/*	/*		/*	/*
10/08/2011		+					+
13/08/2011	+	+	+(2	+	I	+	+
18/08/2011	+	+	+(2	+	+(2	+	+
30/08/2011	+	+	/*	+	+(2	+	+
14/09/2011	/*	/*		/*	/*	/*	+
19/09/2011	+	+		+	+(2	+	+
26/09/2011	+	+		+	/*	+	+
12/10/2011	/	/		/		/	+
25/10/2011							/

4 Effects of oxygenation on the status of the pilot sites

Jouni Lehtoranta, Christer Lännergren, Jørgen Bendtsen, Heikki Pitkänen, Kai Myrberg, Harri Kuosa

In this chapter the results and preliminary analysis on the effects of oxygenation on the status of the experimental basins is presented. The results will be disseminated to scientific community in Lehtoranta et al., forthcoming A-C)

4.1 Monitoring of the case areas to examine the effects

An extensive monitoring program was carried out to examine the effects of bottom water oxygenation on physics, chemistry and biology by measuring current patterns, temperature and oxygen and nutrient concentrations in the both pilot sites. To estimate the effects of pumping the existing monitoring programs were improved by establishing new stations on the experimental areas, and by making the monitoring and sampling more frequent.

In ***Sandöfjärden*** two new stations i.e. "Float" and "Sound" (Chapter 2, *Figure 2-3*) were established: Float station was situated in the middle of the basin being in the center of three pumping devices (about 300m from the nearest one), and the Sound station was situated in the deepest inlet between the basin and the outermost archipelago representing currents and water quality of the in- and outflowing water. The vertical and horizontal currents were measured with RDCP and ADCP devices mounted on the bottom by scuba divers. The example of a basic installation is presented in *Figure 4-1*.

In ***Lännerstasundet*** two new stations - in addition to the regularly monitored westernmost basin - were established: *Lännersta 1 (C in Figure 2-2)* was situated about 100 m North-East from the oxygenation device. *Lännersta 2 (B in Figure 2-2)*, the reference station for Lännersta 1 was situated at the deepest point of the western sub-basin of Lännerstasundet.

The both study areas were equipped with on-line data transfer systems for the monitoring of weather conditions via a modem connection. The float station in Sandöfjärden delivered also on-line data on currents, as well as temperature, salinity and oxygen conditions of deep water layers.

Chemical analyses

Water for chemical analyses was sampled with Limnos-samplers. Nutrients and iron concentrations (*Table 4-1*) were analyzed according to the methods of Koroleff (1979) in Tvärminne Zoological Station. In Sandöfjärden the dissolved iron was filtrated through Whatman Nucleopore Track-Etch Membrane (pore size 0.47 µm). The chemical analyses for Lännerstasundet were carried out in Eurofins laboratory Sweden according to their standard methods.

Table 4-1. Sampling stations, sampling intervals and analyses for water quality in Sandöfjärden (Finland) and Lännerstasundet (Sweden). The analyses in parenthesis denote those determined in 2009.

Sandöfjärden	**Depth (m)**	**Analyses**
Sound	10.5	pH, O2, Chl-a, Tot-N, NO2, NO3+NO2, NH4, Tot-P, PO4, DSi, Tot-Fe, DFe, H2S, Turb. Algae
Float	27.0	pH, O2, Chl-a, Tot-N, NO2, NO3+NO2, NH4, Tot-P, PO4, DSi, Tot-Fe, DFe, H2S, Turb. Algae
Lännerstasundet	**Depth (m)**	**Analyses**
Lännersta1	19.0	pH, O2, Chl-a, Tot-N, NO3+NO2, NH4, Tot-P, PO4, (DSi), Tot-Fe, DFe, H2S, Algae
Lännersta2	18.0	pH, O2, Chl-a, Tot-N, NO3+NO2, NH4, Tot-P, PO4, (DSi), Tot-Fe, DFe, H2S, Algae

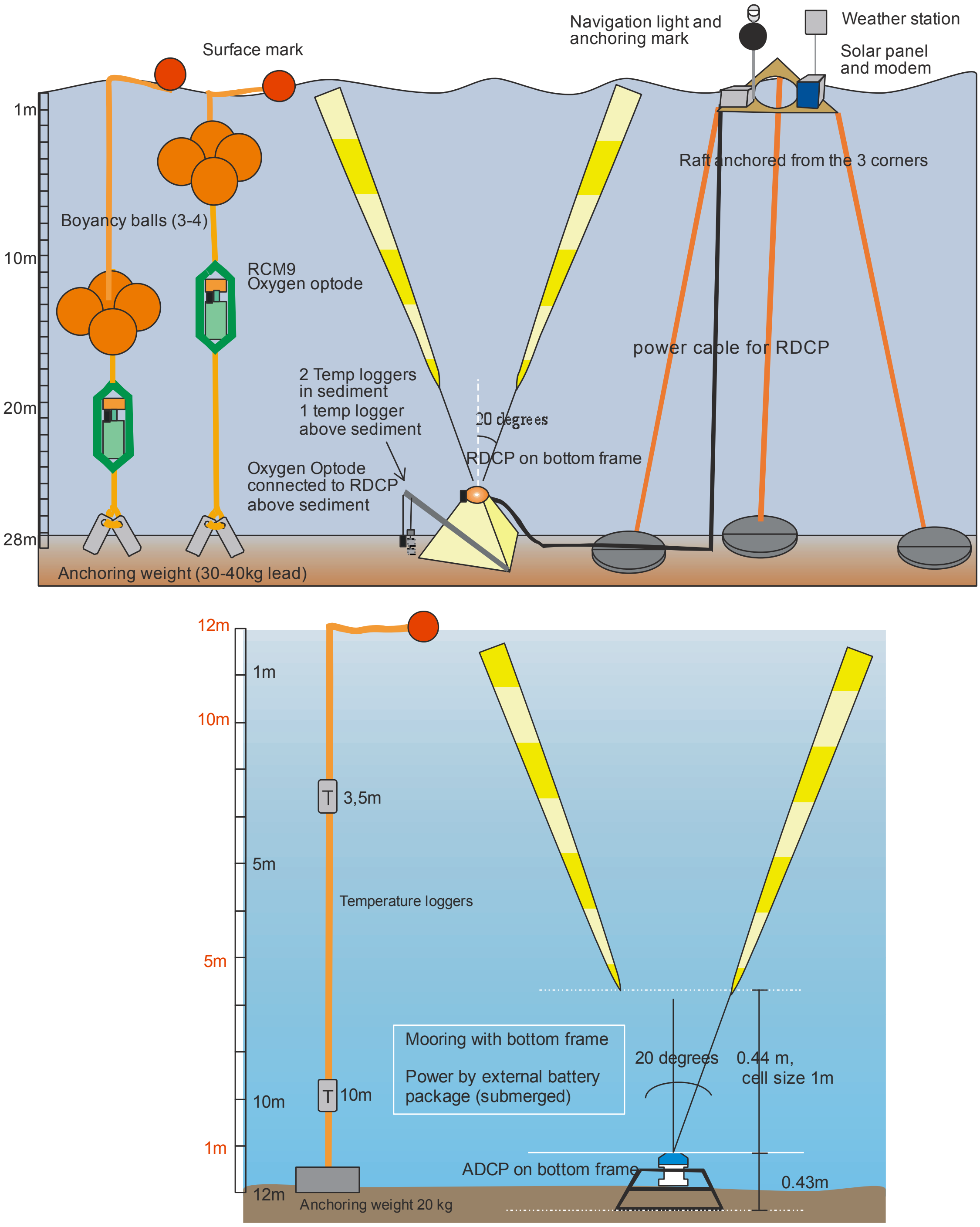

Figure 4-1. Schematic figure of the installations of automatic monitoring devices in the Float (top) and Sound (below) stations at Sandöfjärden.

Sampling of algae and benthic fauna

Samples for dominating algae were collected generally with the same time intervals as for chemical analyses from Sandöfjärden and Lännerstasundet 1 and 2 (*Table 4-1*). In Sandöfjärden the phytoplankton was sampled with Limnos-corer from various water depths in the euphotic layer according to the standard method of HELCOM (HELCOM COMBINE Manual). Samples were pooled into a tub of water. One sub-sample was taken and it was fixed with Lugol-solution and stored in fridge in dark before further analysis.

Bottom fauna was collected with VanVeen-sampler (0.1254 m2) from Sandöfjärden and with Ekman-sampler (area 0.0298 m2) from Lännerstasundet to examine the areas colonized by burrowing animals in late summer-early autumn 2009 – 2011 (see sampling sites from Chapter 2, *Figures 2-3 and 2-6*). In Sandöfjärden the samples were taken from 10 sites from water depths of 15 to 23 m covering well the part of the basin under sediment accumulation. In Lännerstasundet three sampling transects were established to areas covering water depths from 6 to 11 m. The sampling was targeted to areas right below pycnocline because it was not expected that pumping would be able to produce conditions favorable for colonization of animals on the deepest parts of the basins.

4.2 Hydrodynamic changes caused by oxygenation

4.2.1 General observations on the water levels and winds in the pilot sites

The main factors affecting the currents in coastal waters are winds and water level changes (see e.g. Leppäranta and Myrberg 2009). The effect of tides can be considered negligible in the area of investigation. The official monitoring stations nearby the study areas (i.e. Hanko and Saltsjön) showed that the water level has varied significantly in both Sandöfjärden (between -79 and +71 cm) and in Lännerstasundet (between -64 and +53 cm) during the years of the study (2009-2011, *Figure 4.2-1*). The wide natural variation in water level suggests that there has been considerable exchange of water in the both study areas. According to the earlier monitoring data there have been inflows from the adjacent areas into the deep waters of Sandöfjärden basin during stagnation, which have oxidized the bottom water temporarily.

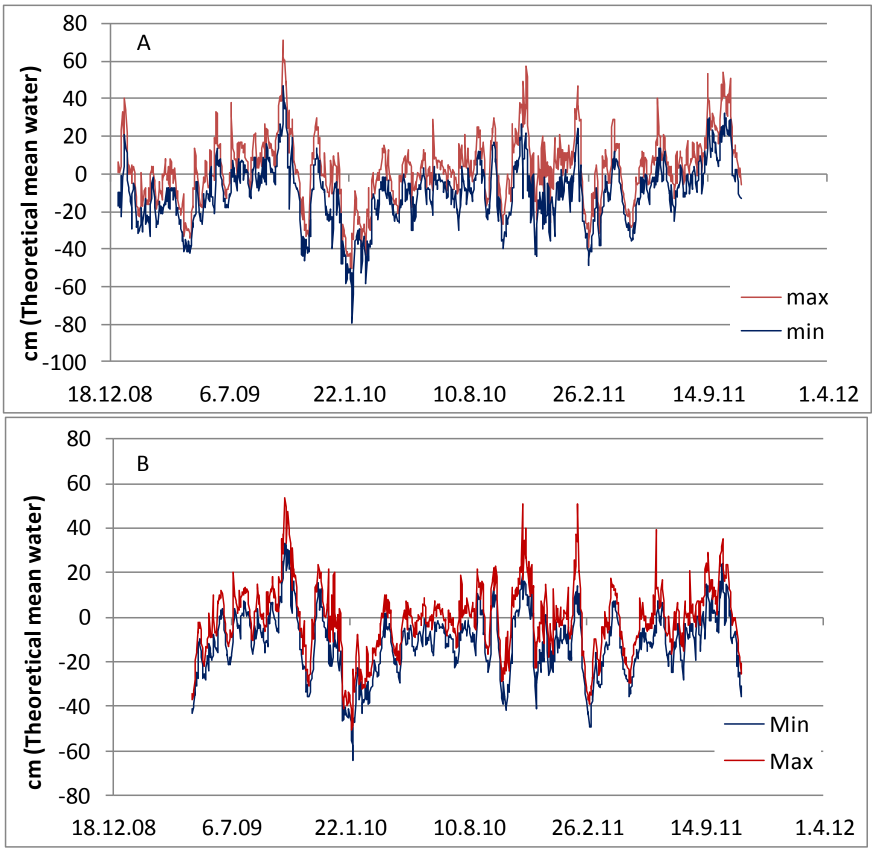

Figure 4.2-1. Water level variation in (A) Hanko and (B) Saltsjön monitoring stations. Data for Hanko are from Finnish Meteorological Institute (FMI) and for Saltsjön from Swedish Meteorological and Hydrological Institute (SMHI).

In Sandöfjärden the high wind speeds increased current velocities in the surface layer (*Figure 4.2-2*), while Lännerstasundet is a well sheltered basin by the surrounding steep and woody hills. Thus the vertical stratification formed by temperature and salinity was not significantly disturbed by the local winds during pumping campaigns. In the both experiment areas the measured low current velocities before the pumping campaigns indicated that the natural physical forcing for the movement of bottom water is limited during stagnation.

During the full capacity of pumping the theoretical residence time for the water volume below pycnocline (below sill depth) was calculated as 89 to 109 days for Sandöfjärden and 24 days for Lännerstasundet.

4.2.2 Background monitoring and the effect of short term oxygenation in 2009

Sandöfjärden

In 2009 only short term pumping campaigns were carried out in August-September due to the need of representative background monitoring data for the entire area. Two inflow events were recorded in the sound by the automatic current monitoring which showed that there were significant exchange of water between the adjacent sea and the Sandöfjärden basin without pumping. For example, a summer storm in June and autumn storm in September increased the temperature and improved the oxygen conditions in the basin during pumping (*Figure 4.2-2*).

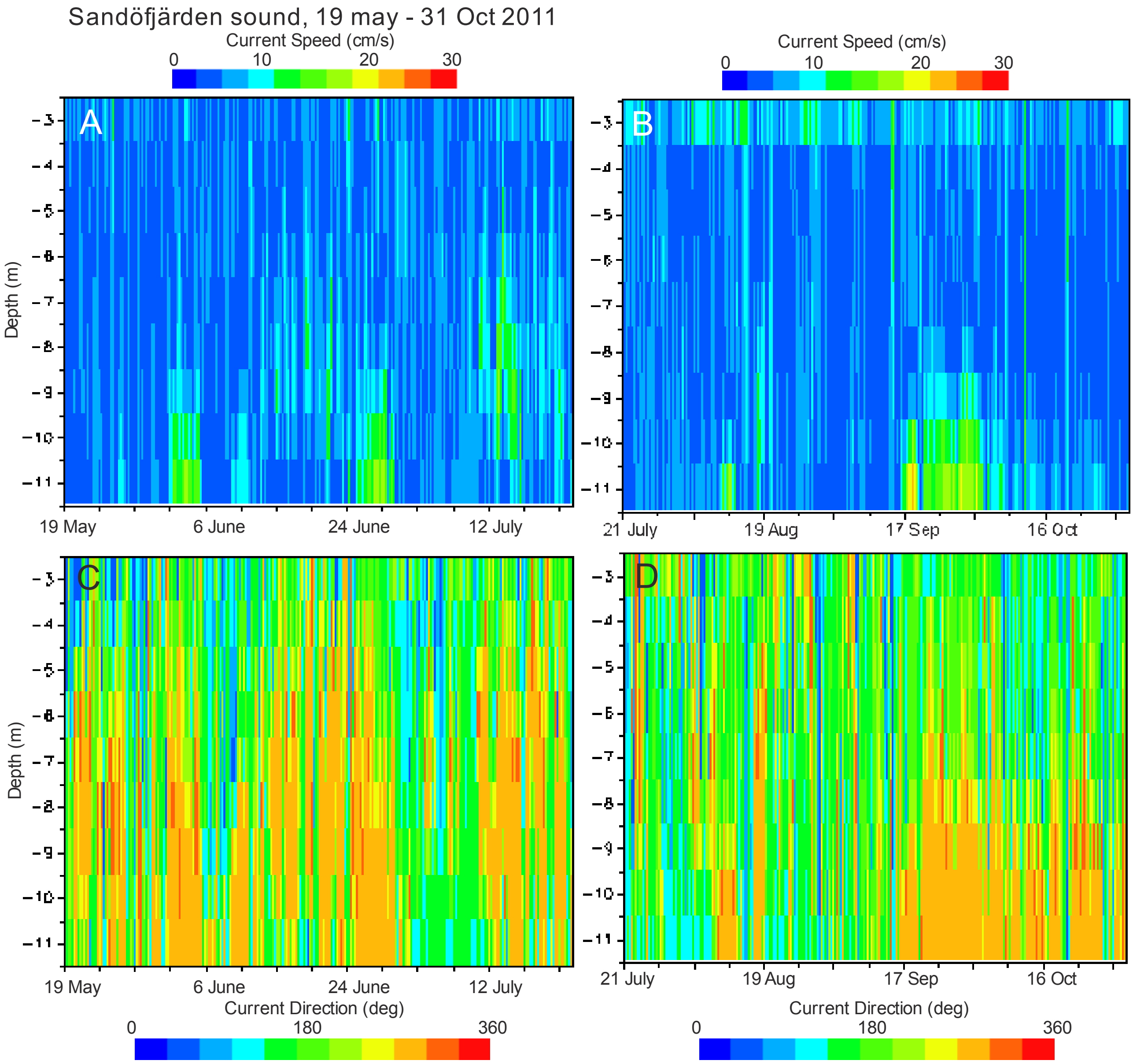

Figure 4.2-2. (A and B) Current speed and (C and D) current direction according to ADCP profiling current meter in the Sound station in **Sandöfjärden** in May-October 2011. The yellow color in A and B denotes inflows caused by storms from the adjacent sea area into the Sandöfärden basin in late June and September 2011.

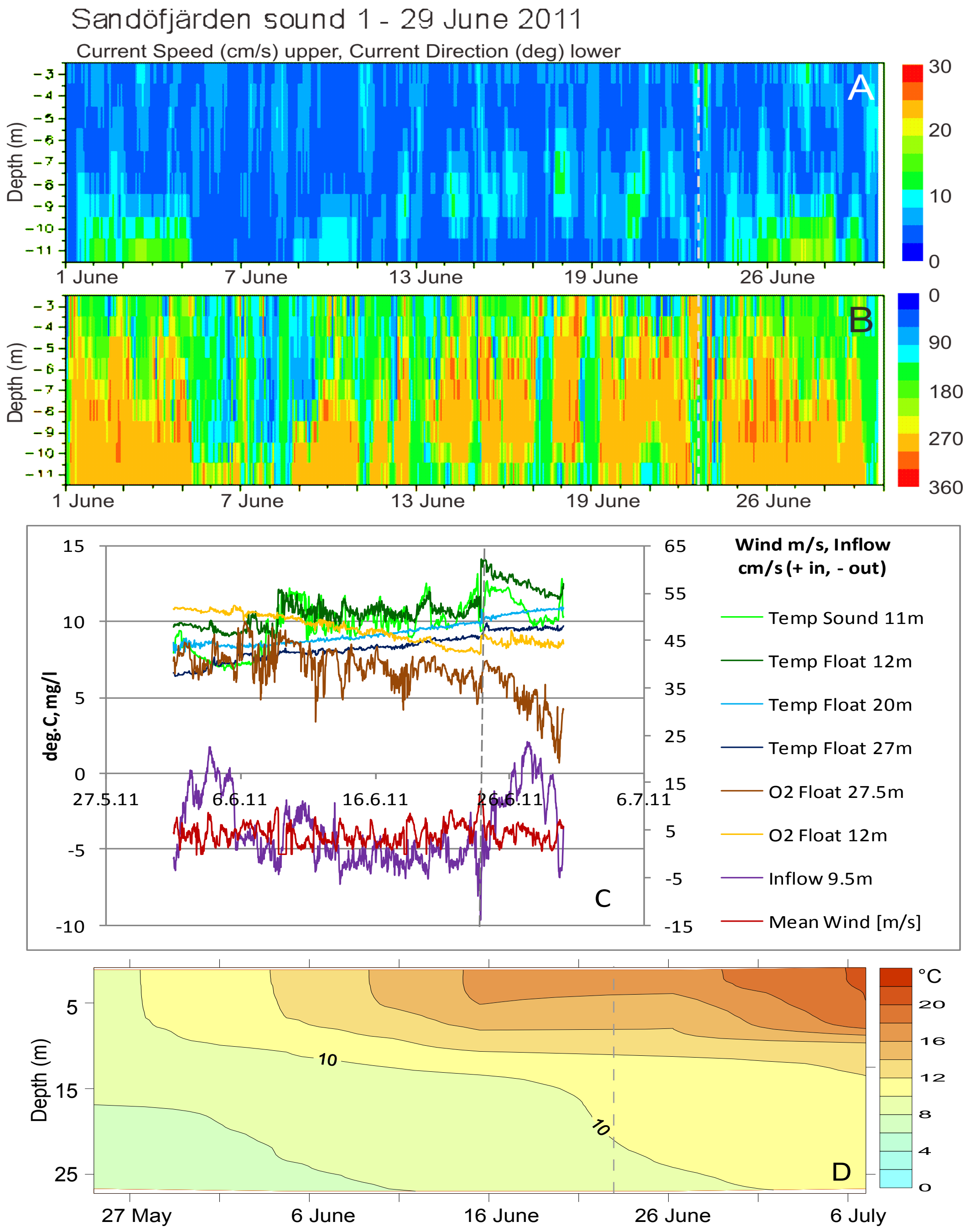

Figure 4.2-3. Effect of mid-summer storm 23rd June 2011 (A and B) on the water exchange in the sound and (C and D) its effect on the water temperature and oxygen conditions in the sound and Sandöfjärden basin in following days. The dash line in the figures denote the storm day.

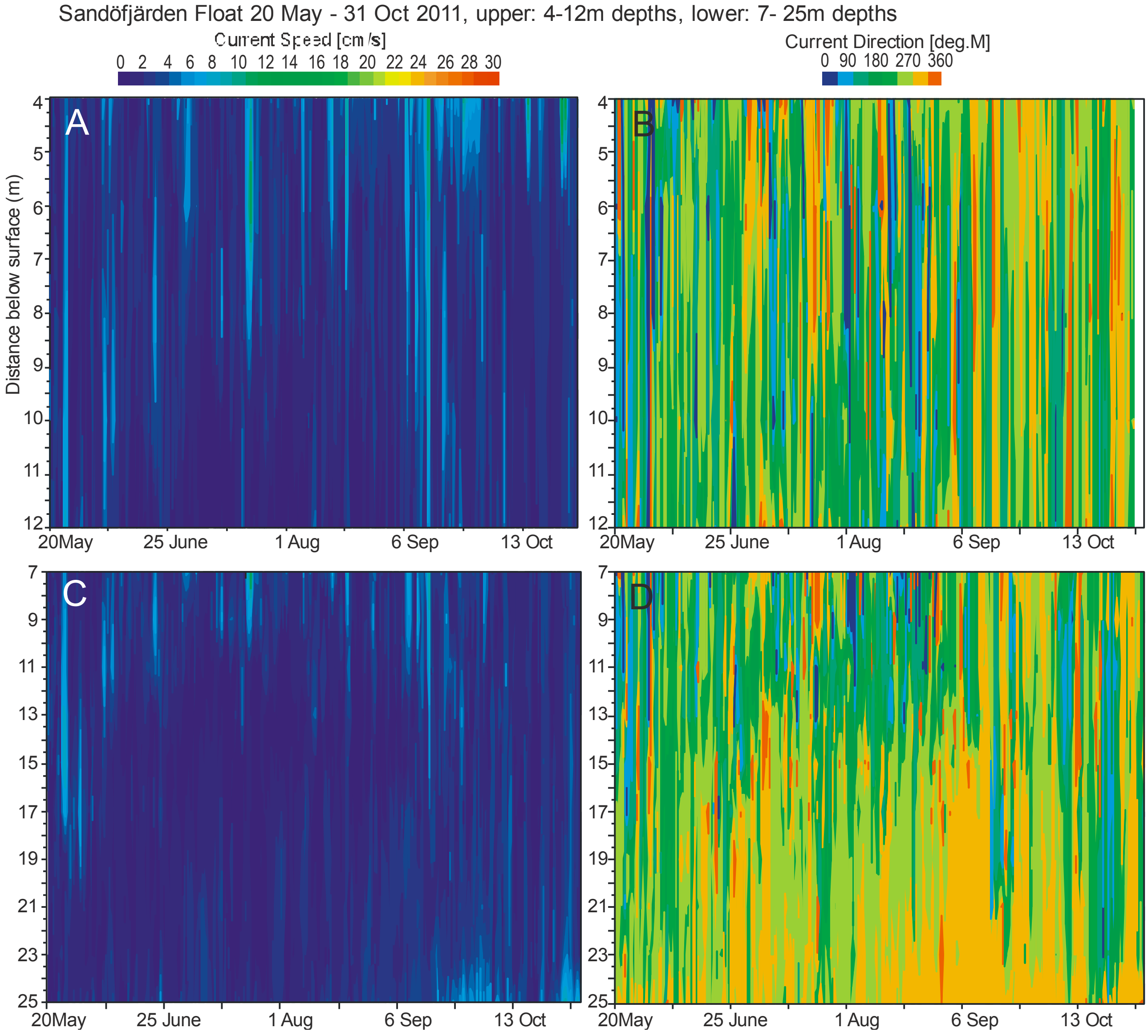

Figure 4.2-4. (A) Current speed in 4 to 12m depth and (C) 7 to 25m depth and (B and D) corresponding current direction according to RDCP profiling current meter in the Float station in ***Sandöfjärden*** in May-October 2011.

The effect of pumping on oxygen conditions were first tested with only one device in an experiment carried out in August 2009. Pumping affected rapidly, i.e. within hours, on temperature and salinity close to the outlet of the pump. As could be expected, the pumping lifted up the thermocline by 4 to 5 meters in the vicinity of the pumps. A notable increase in temperature of the near-bottom water as well as in sediment was observed within few days at about 250 m distance from the pumps (*Figures 4.2-5*).

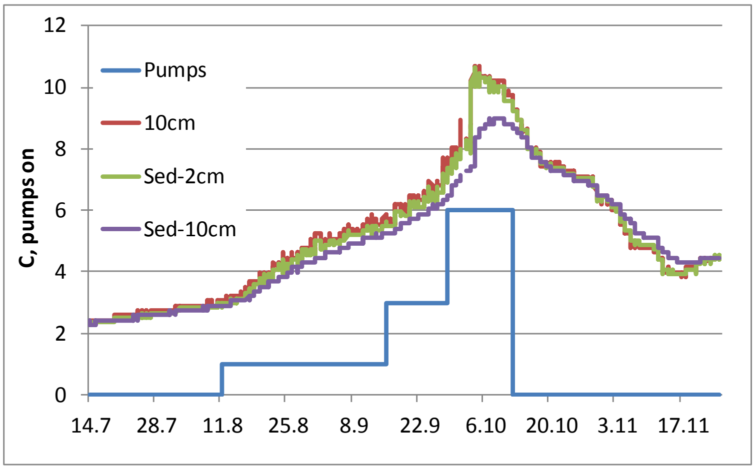

Figure 4.2-5. Variation of temperature in near-bottom water (10 cm above sediment) and sediment (-2 and -10 cm below the sediment surface) in the Float-station, **Sandöfjärden**, in 2009. Number of pumps in operation is denoted with blue line. The sharp increase in temperature in beginning of October is due to autumn mixing (Lehtoranta et al. Forthcoming B).

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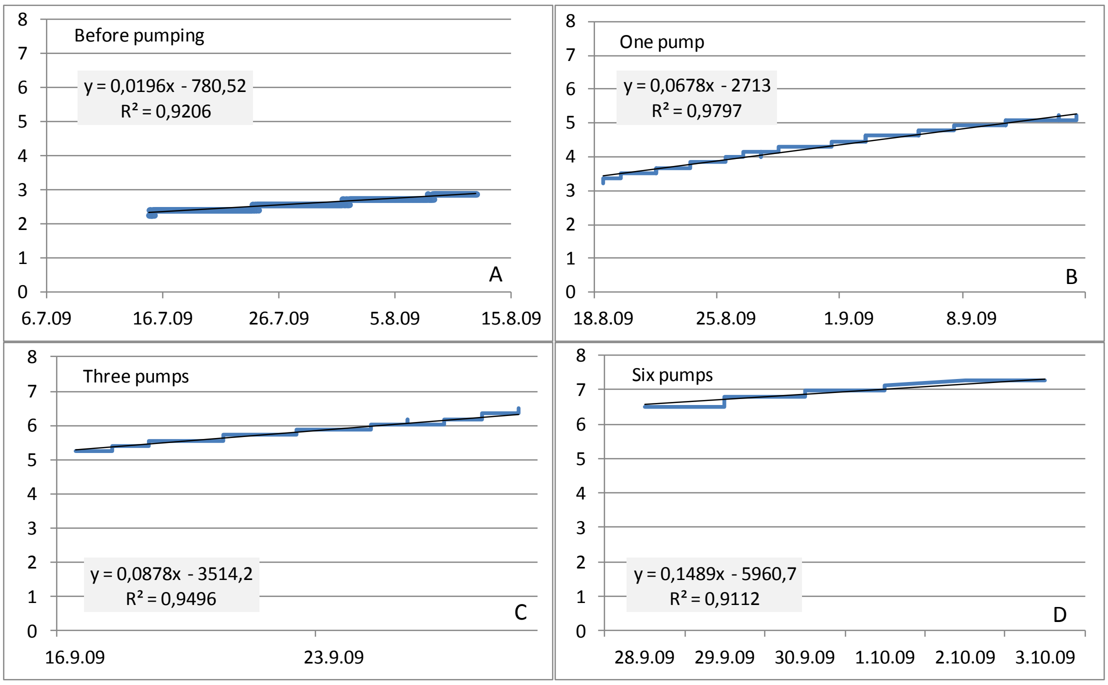


Figure 4.2-6. Regression analysis on the effect of increasing pumping capacity (i.e. number of pumps in operation (A) no pumps, (B) one pump, (C) three pumps, and (D) six pumps) on the warming of the sediment in -10 cm depth (Lehtoranta et al. Forthcoming B).

A significant signal of the warming of sediment was noticed as well, when new pumps were switched on showing a steepening in the slope of warming in the sediment (*Figure 4.2-6*). The pumping itself did not increase the current velocities significantly on larger scales, i.e. the change in velocity was not detectable with the acoustic profiling devices used. The current velocities remained relatively low in the bottom water being commonly only few centimeters per second (*Figure 4.2-4*). These were expected results, because, for example, the volume of pumped water per unit of time is small compared to the overall volume of the basin. The pumped water is entrained efficiently with surrounding waters and water is largely spread as disc-shaped form below the pycnocline (c.f. Chapter 5). Therefore the pumping is not able to increase the current velocities significantly further than some tens of meters from the pump.

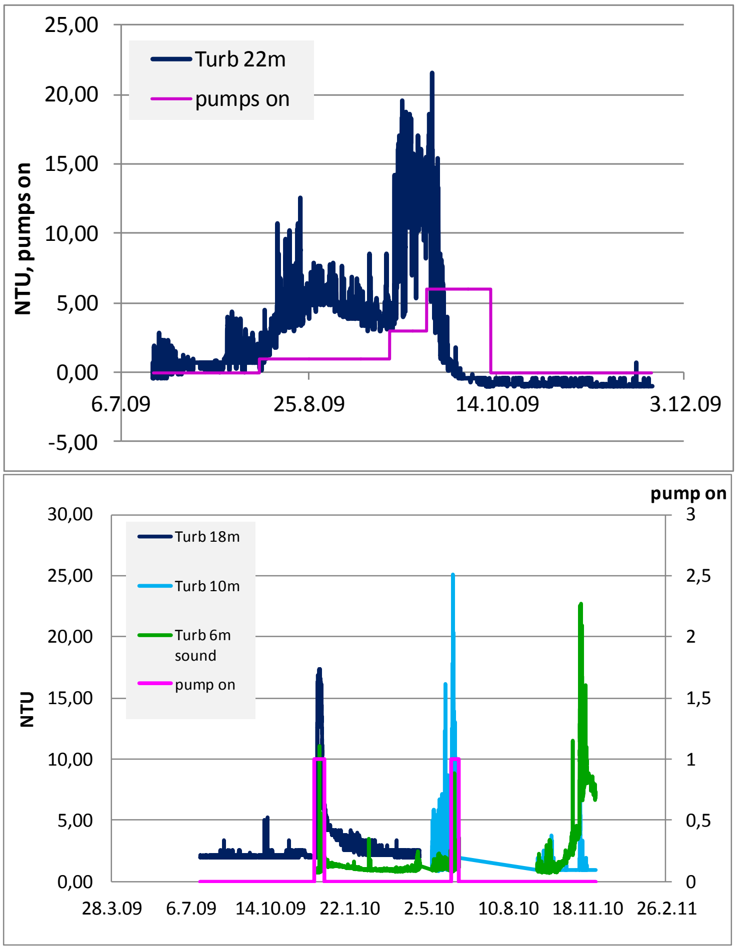


Figure 4.2-7. Variation of turbidity along increasing pumping capacity (top) in 22 m in ***Sandöfjärden*** 2009 (number of pumps in operation is denoted with pink line) and (below) in ***Lännerstasundet*** in 6m (sound), 10m and 18 m during the pumping campaigns 2009-2011 (Lehtoranta et al. Forthcoming C).

Therefore it was somewhat surprising that the pumping increased significantly turbidity in near-bottom water within hundreds of meters from the nearest pump, and that the start-up of the additional pumps was also denoted as an increase in turbidity (*Figure 4.2-7*). The turbidity caused by the pumping lasted several weeks. Also storms increased turbidity considerably, for example, the storm and the inflowing water evidently resuspended particles to near-bottom water in September 2011.

The use of one pump did not decrease hydrogen sulphide (H_2S) concentrations or increase the oxygen concentration in the experiment in August-September 2009. However, the use of three pumps started to decrease hydrogen sulfide concentration, and during the use of all six pumps also oxygen concentrations started to increase. After few days pumping with full capacity autumn convection started due to cold air masses and decrease in sea surface temperature. Thus the effect of the pumps alone can't be assessed.

Lännerstasundet

In Lännerstasundet anoxic conditions prevailed in the both experimental and reference basins throughout the summer and autumn in 2009 (*Figure 4.2-8*). The hydrogen sulfide concentrations were very high (up to 25 mg l-1) in the deep water layers of experimental basin throughout the summer 2009. H_2S is a highly oxygen consuming substance and to minimize the risk that some of the H_2S could be transported to the surface layer before its oxygenation, the first pumping campaign was carried out until December 2009 when H_2S had decreased to ~20 mg l-1. The surface water temperature and deep water concentrations of H_2S decreased after autumn cooling, which made possible to make an 11 day long pumping together with intense monitoring. Due to the late timing there was no risk for increased phytoplankton production even if upwelling of nutrient rich water would have taken place.

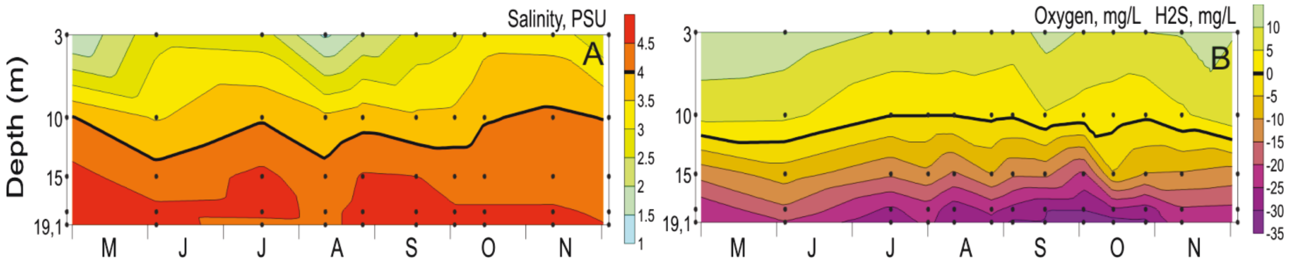


Figure. 4.2-8 a-b. a) Salinity and b) concentrations of oxygen in ***Lännerstasundet*** from May to November in 2009.

The start-up of the pumping did not have strong effect on the current velocities in the deep-water layers, although a slight increase in current speed at 10 m depth was measured. At the start of the pumping the temperature of the surface water was lower than in bottom water and the pumping cooled bottom-near water below the halocline. Furthermore, pumping lifted the halocline – originally present in 12–13 m – upwards by about 0.5 m per day, which indicated that the dimensioning of the pump was adequate enough to achieve basin wide effects in less than 24 hours. The rise of the halocline stopped at about 8 m depth (i.e. sill depth) within a week from the start of the pumping. After 11 days pumping redox conditions improved (*Figure 4.2-9 a-b*) a total disappearance of H_2S was observed at the distance of 100 m from the pump (*Figure 4.2-9 c-d*) suggesting that the pumped oxygen rich water could oxidize H_2S completely without breaking the pycnocline.

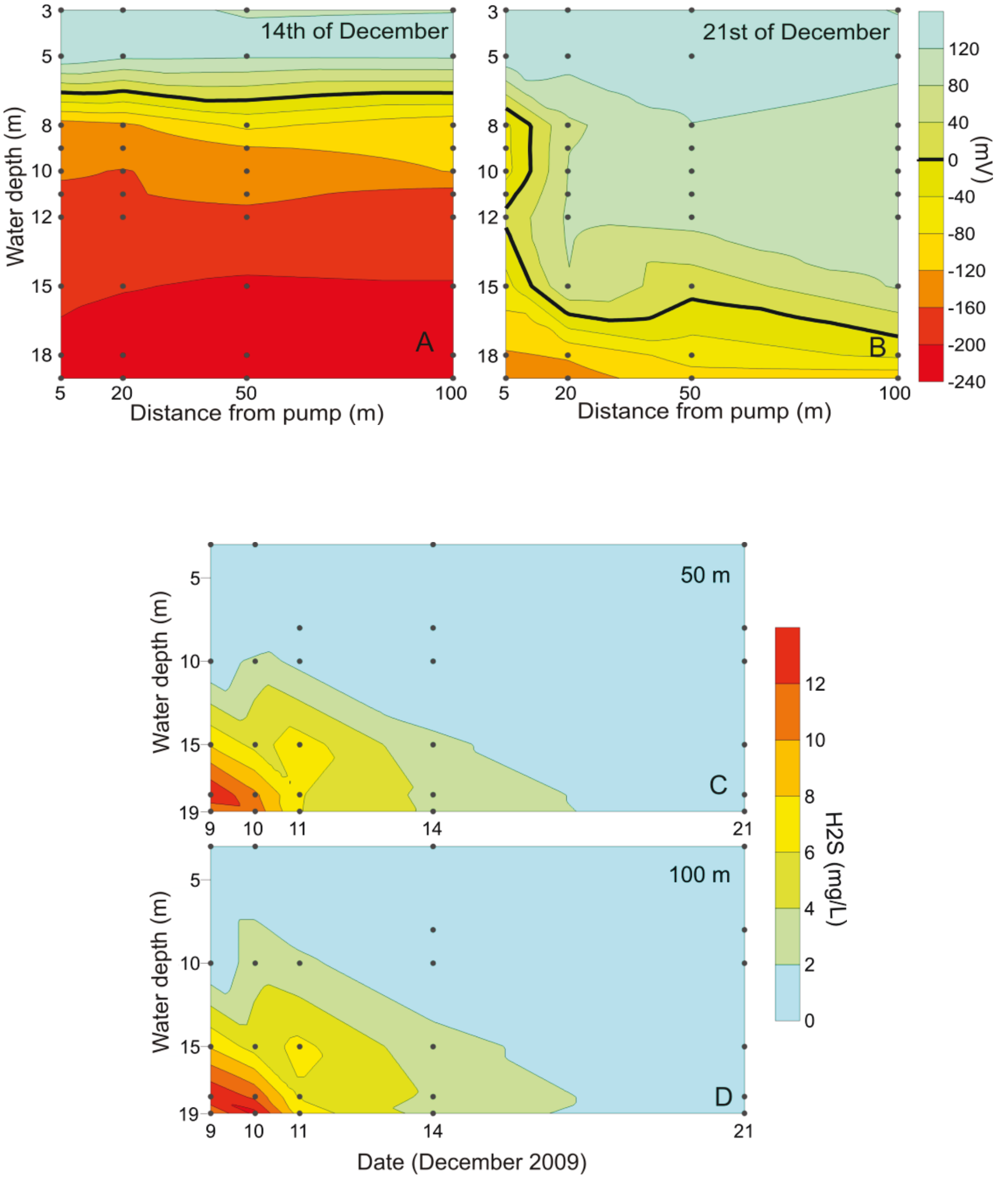


Figure 4.2-9 a-d. Redox-state (A) before and (B) after 11 days of pumping along the distance from the pump, and distribution of hydrogen sulfide concentrations at (C) 50 and (D) 100 meters distance from the pump during the same period of time. The data indicates considerable improvement in the redox-state and the disappearance of hydrogen sulfide from the bottom water in easternmost sub-basin of ***Lännerstasundet*** in December 2009.

As in Sandöfjärden also in Lännerstasundet the turbidity of deep water increased when the pump was switched on (*Figure 4.2-7*). The increase was observed in the both sound and basin sites. The current velocity measurements as well as experiments with rhodamine (c.f. Chapter 5) support the conclusion that the pumping itself cannot create large scale currents with high velocities in bottom-near water. It is therefore likely that the increase in turbidity is explained with the resuspension induced by the downward water-flow by the pumps immediately below them, and that the resuspended particles were not readily settled.

4.2.3 Effect of oxygenation on hydrodynamics in summer experiments in 2010-2011

Sandöfjärden

In early summer the temperature stratification was formed as in previous years (*Figure 4.2-10*). The vertical stratification was formed by the thermocline whereas the vertical density difference caused by the salinity was small (*Figure 4.2-10*). The pumping was started during the formation of thermocline in June and it warmed the water significantly in 2010 and 2011. The pumping will induce an outflow of water from the basin to the adjacent sea area when the bottom water expands and reaches the sill depth as shown in laboratory experiment, where rhodamine colored water extends over the artificial sill (Chapter 3, F*igure 3-9*).

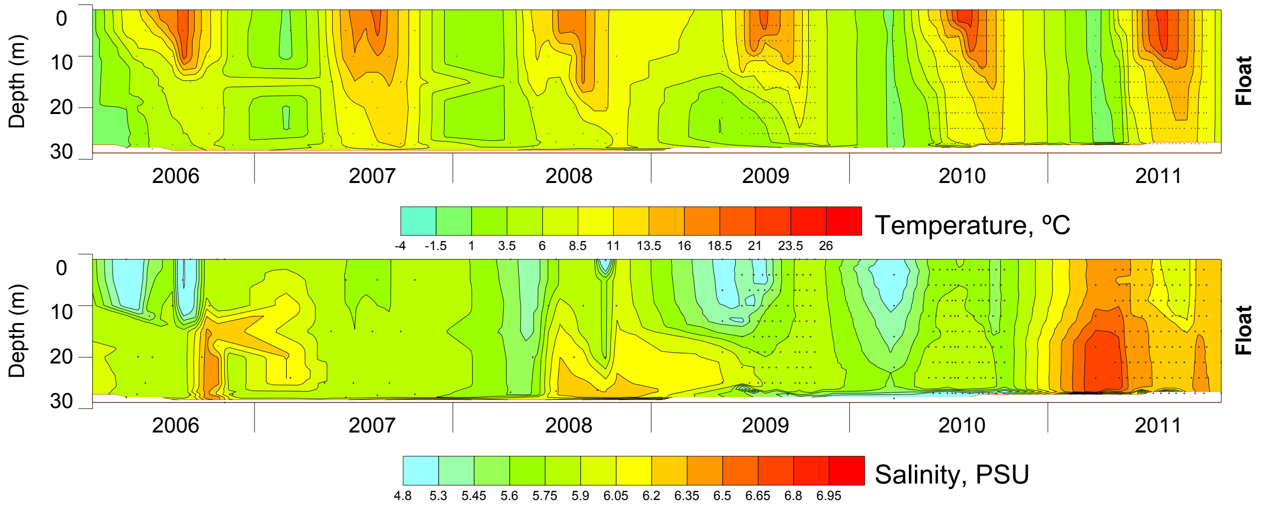


Figure 4.2-10. Progress in temperature and salinity in **Sandöfjärden** in 2006-2011.

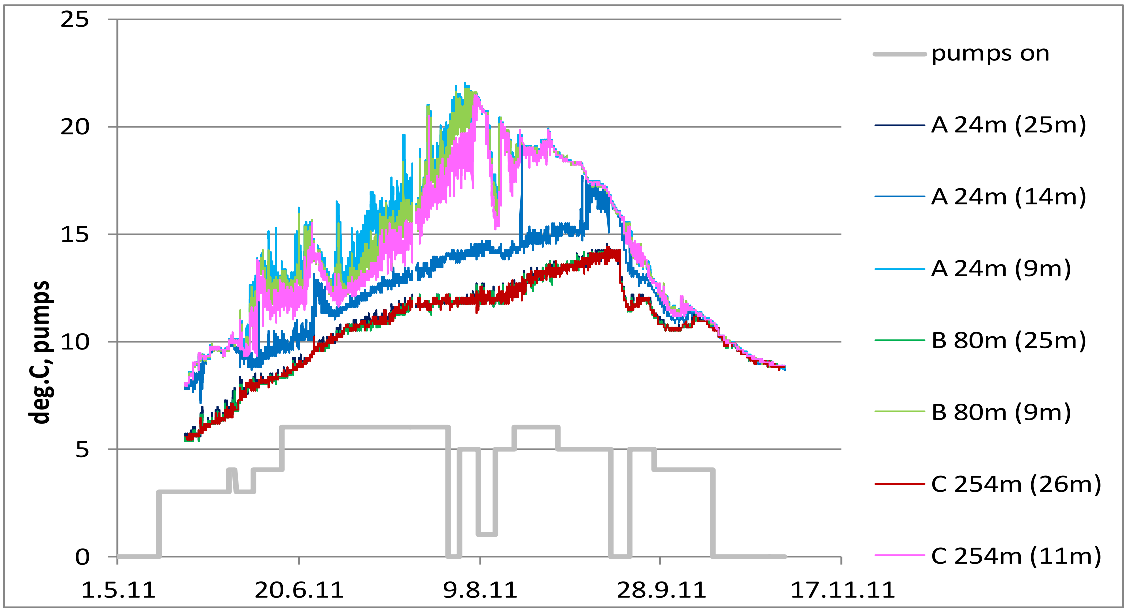


Figure 4.2-11. Changes in temperature in metalimnion and bottom water along distance from the pump nr 6 (legend shows the distance of the temperature logger from the pump and water depth of logger is in brackets.

The pumping warmed significantly deep water and the lower part of thermocline thus steepening the stratification. The pumping of several months showed that the effect of pumping was detectable in thermocline up to the distance of 100 m but not at 250 m distance from the pump (*Figure 4.2-11*). The result for the direct effect in thermocline was consistent with the observations found in the rhodamine experiment (cf. Chapter 5.1). No similar pattern was observed when transect of temperature sensors was mounted in the westward direction. This indicated that the currents affect the movement of the plume and that it does not spread out symmetrically in all directions. This was also observed in the rhodamine-experiment. However, the possible return-flow towards the pump in the deep water layers was not measurable (see deep water temperature along distance from the pump in *Figure 4.2-11*) although the overall pumping warmed significantly bottom water. Vertically the pumping mixed well the water mass below the pycnocline and there was only a slight increase in temperature between 25 to 28 m depth (data not shown).

The increase in deep water temperature can be largely explained by the pumping. However, occasionally the temperature peaked and rose faster than what could be explained by the pumping alone, for example due to the storm event in June 2011 (*Figures 4.2-3,4.2-12*). The increase in temperature below the pycnocline was a combination of a) the pumping of warm surface water, b) the turbulent mixing of water towards bottom and c) intrusion of more dense, warm water from the outer sea. It is clear that the pumping weakened the vertical stratification which, in turn, eased the inflows from the outer sea into the basin. During the pumping period exceptionally large inflows were observed (*Figure 4.2-2*), when temperature changed clearly within hours in the deep water (*Figure 4.2-12*). It is important to note that in the weather conditions 2009-2011 the autumn turnover did not occur much earlier than normally despite the clear weakening of temperature stratification by the pumping.

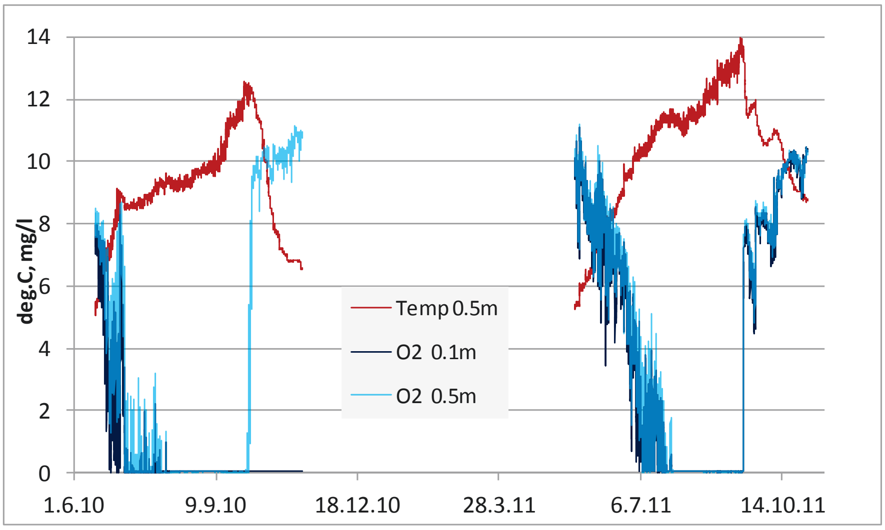


Figure 4.2-12. Variation of temperature (red) and concentration of oxygen half a meter and ten centimeters from the bottom surface (blue) in Float station in **Sandöfjärden** during 2010 and 2011.

The pumping warmed also the sediment. A strong correlation between the near-bottom water and sediment temperature were recorded by three temperature loggers mounted just above and inside the sediment (*Figure 4.2-13*). The sediment responded fast on warming of water and, as expected, the surface layer of the sediment responded faster to the temperature change than the deep layer. The temperature difference between the water and sediment was generally less than 1.5 degrees. The stops in the pumping were detected as lower increase in sediment temperature.

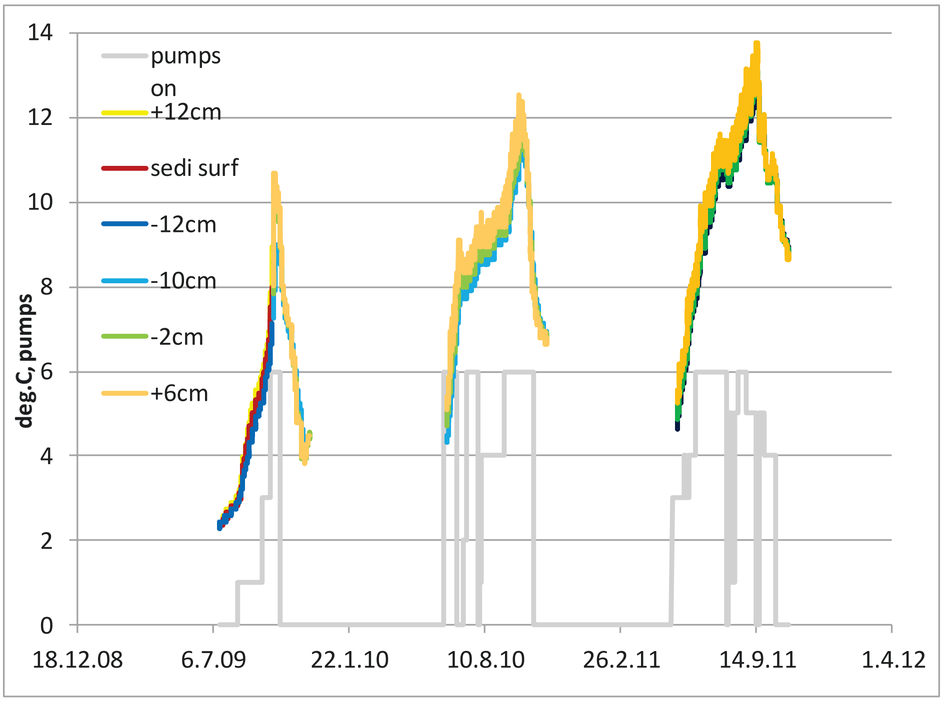


Figure 4.2-13. Relationship between near-bottom water and sediment temperatures during pumping campaigns in **Sandöfjärden** 2009-2011. Number of pumps in operation is marked with grey line (Lehtoranta et al. Forthcoming B).

The measurements suggested that the increase in bottom water temperature warmed the sediment even at 10–12 cm depth. When the pumping of surface water warmed the deep water it was reflected rapidly in sediment temperature. This may enhance the sediment's microbial activity and oxygen consumption. There exists strong evidence that sulfate reduction is favored by the warming of sediment (Jørgensen 1977). After the autumn overturn temperature was higher in the sediments than in bottom water indicating that some of the heat was still retained by the sediment. The cooling period when the density of sediment pore-water is lower than in bottom water may induce convectional fluxes which may enhance oxygenation of sediment.

Lännerstasundet

The summertime pumping warmed the water and decreased the salinity below the halocline (*Figure 4.2-14*). The pumping capacity was high enough to keep the water well mixed below the thermocline. In the reference basin the pycnocline formed by the thermo- and halocline remained unchanged (*Figure 4.2-14*).

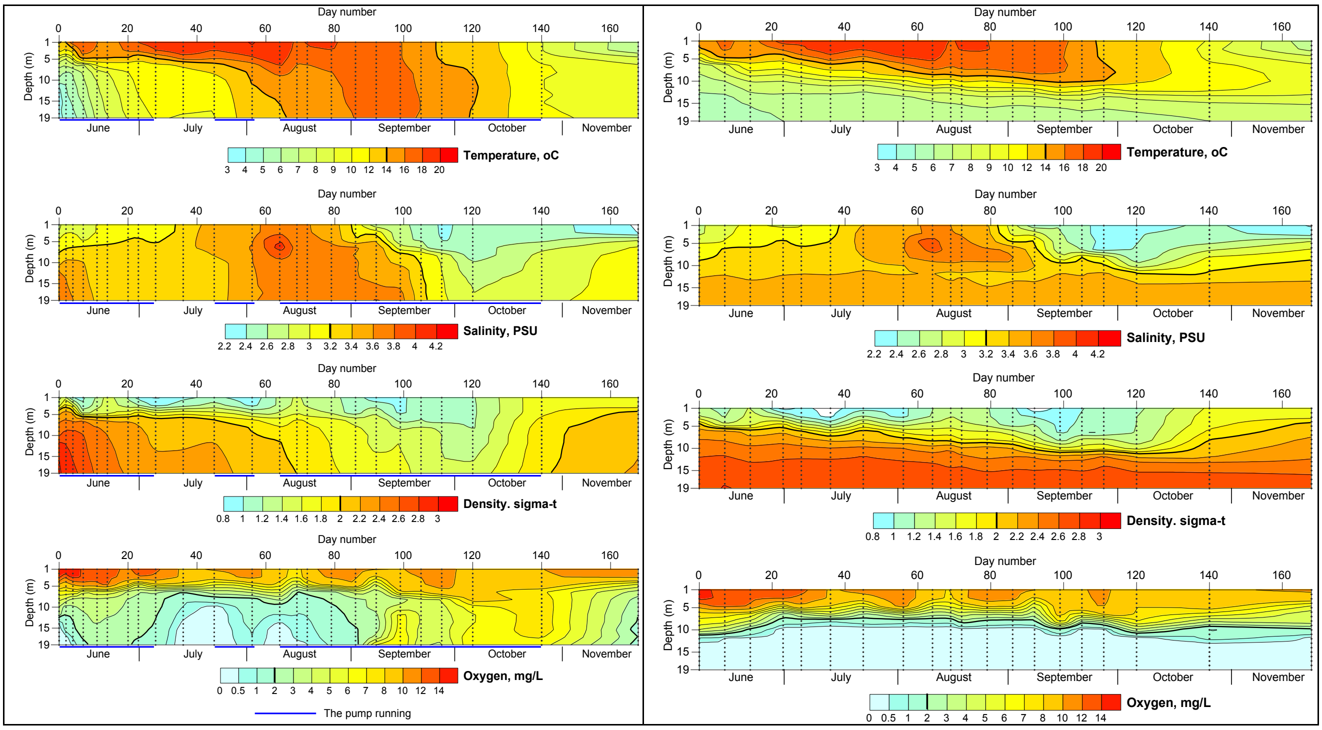


Figure. 4.2-14 Vertical variation in temperature, salinity, density and oxygen in the pumped basin (left) and reference basin (right) in **Lännerstasundet** in 2011. The blue line above month in the panels on the left denote periods when pump was in operation (Lehtoranta et al. Forthcoming A).

One of the most significant consequences of pumping was the reduction of bottom water density. The presence of low-density bottom water enabled inflows of more dense water from the adjacent areas into the experimental areas which would not have occurred without pumping (*Figure 4.2-15*). As a consequence of the reduced bottom water density, a three weeks pumping resulted in a two month oxic period which was maintained by the water exchange between adjacent and the experimental area. The several inflows maintained experimental basin oxic until the end of April 2011, while no corresponding intrusions of water were observed in th**e reference basin.**

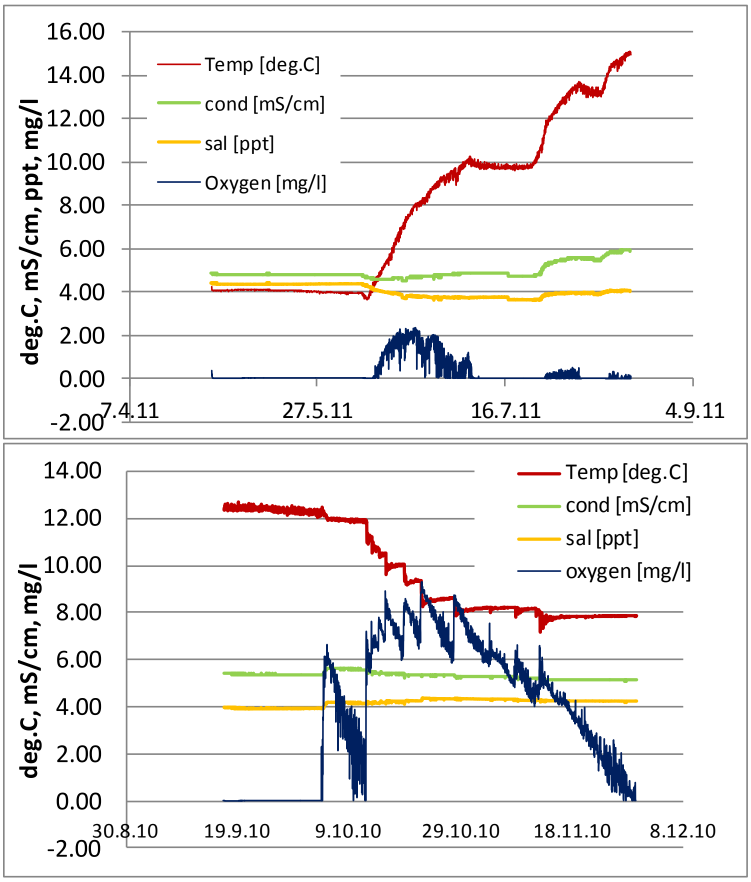


Figure 4.2-15 The effect of pumping periods on the temperature, salinity and oxygen concentration (top) and relationship between concentration of oxygen, salinity and water temperature in bottom water when pump was not in operation on late autumn 2010 (below) in the easternmost basin in Lännerstasundet (Lehtoranta et al. Forthcoming A).

4.3 General trends in water quality

4.3.1 Effects of summertime oxygenation on oxygen and hydrogen sulfide

Sandöfjärden

In Sandöfärden the decrease in concentration of oxygen started when the temperature stratification started to form isolating the deep water layers from those in surface. The turbulent mixing and the occasional inflows of water into the basin induced high variation in the concentration of oxygen in the central basin (*Figure 4.2-12*). However, similar inflows have occurred also before as indicated by the sudden increases in temperature and oxygen concentration in bottom water during 2000-2008 (data not shown). Therefore, the rapid increases in temperature and concentration of oxygen in bottom water from the mid-June to the early July were evidently explained by the inflowing water together with the turbulent mixing of water layers below thermocline. The quick formation of anoxia/hypoxia in the beginning of July 2010 was evidently explained with the anoxic water present in the basin that reached the monitoring station (*Figure 4.2-12*). After this event the coinciding increases in temperature and oxygen can be largely explained with the pumping and the turbulent mixing in the deep water layers.

The capacity was not adequate enough to maintain the basin oxic and anoxia was reached in the bottom water in early August 2010 and in July 2011. Thus pumping did not postpone significantly the appearance of anoxia compared to previous years (*Figure 4.3-1*). In 2011 also leakage of hydrogen sulfide into the water were observed.

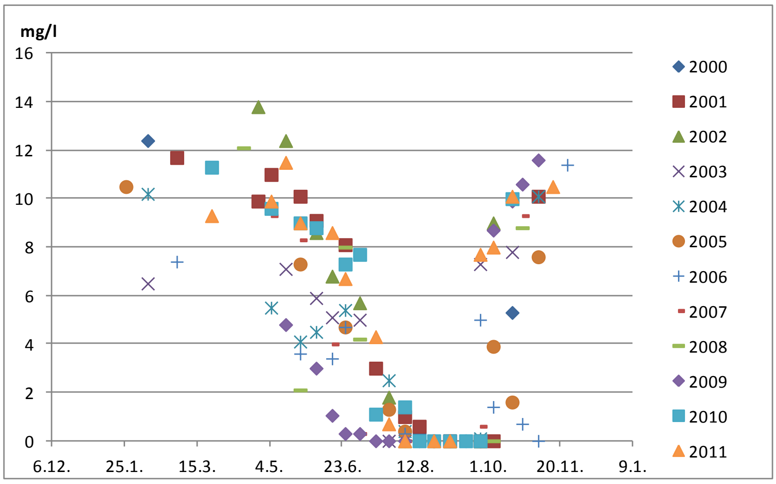


Figure 4.3-1. Formation of summer-time anoxia in bottom water before (2000-2009) and after the pumping campaigns (2010-2011) in Sandöfjärden (Lehtoranta et al. Forthcoming C).

The measured low concentrations of oxygen below the thermocline and the anoxia in deep water indicated that the pool of oxygen was similar to that on previous years in Sandöfjärden (*Figure 4.3-2*). The overall oxygen content of water was not much affected by the pumping although a large amount of oxygen was transported into the deep water system. When the pumping capacity (mean 5300 kg d-1) is compared to the estimated oxygen consumption (4500–8100 kg d-1, cf. Chapter 3), pumping should have been able to oxidize or at least to postpone the formation of anoxia, but still anoxia was faced as in previous years. When the pumped amount and the storage of oxygen are taken into account the total oxygen consumption was estimated to be about 10 000 kg d-1 in 2011. The consumption rate here is abnormally high compared to the volume and the bottom area below 12 m depth in Sandöfjärden. The explanations for the inadequate oxidation and the high consumption rate are following: a) pumping warmed the bottom water and increased both aerobic and anaerobic mineralization and pumping was not able to compensate the oxygen consumption created; b) the lifting of thermocline increased the bottom area below the pycnocline resulting as additional oxygen consumption; and c) a significant part of the oxygen pumped to bottom water was out-flown from the basin to the adjacent area.

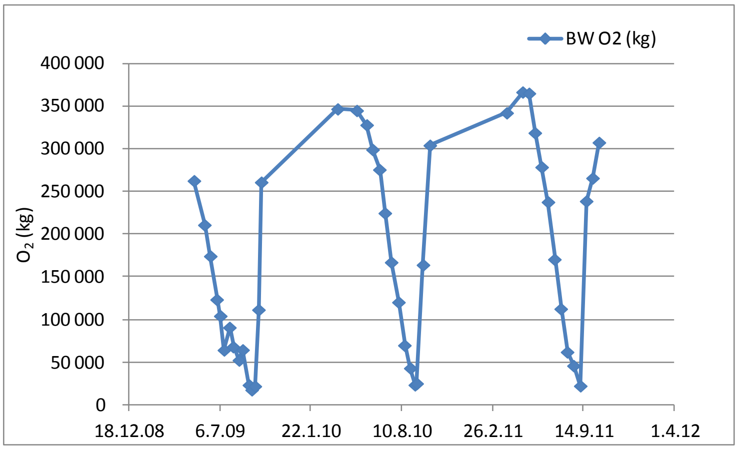


Figure 4.3-2. Variation of oxygen pool (kg) in bottom water in **Sandöfjärden** during 2009-2011.

Lännerstasundet

The first summertime pumping campaign was carried out for a period of three weeks in June 2010 (*Figure 4.3-3*). During the time there was a thermocline and halocline in water column and the bottom water was anoxic. Hydrogen sulphide concentration was depleted within days indicating that it was oxidized as in the first experiment in December 2009. Later on the concentrations of oxygen increased and the pumping itself was able to keep the basin oxic. In summer 2011 the effect of pumping on salinity, temperature and oxygen was very similar to that in previous summer (*Figure 4.2-14*).

The summertime pumping campaigns showed that even though the pump was not running after Midsummer 2010 the bottom water remained oxic for months after the stopping. For example, it was until late August when the oxygen conditions in the basin weakened (*Figure 4.3-3*) but they improved again and the water was oxic until the end of April 2011. The pumping was re-started in June 7th on 2011 and the stopping on October 25th did not lead to anoxia since 23rd of November due to the inflows (*Figure 4.2-14*). No corresponding changes in oxygen conditions were observed in the adjacent reference basin. The results show that there were episodic water inflows from the adjacent areas to the pumping area: pumping decreased the density of bottom water in the easternmost basin enabling the penetration of oxic water into the deep water layers, which maintained the bottom water oxic for longer periods (*Figure 4.2-15*).

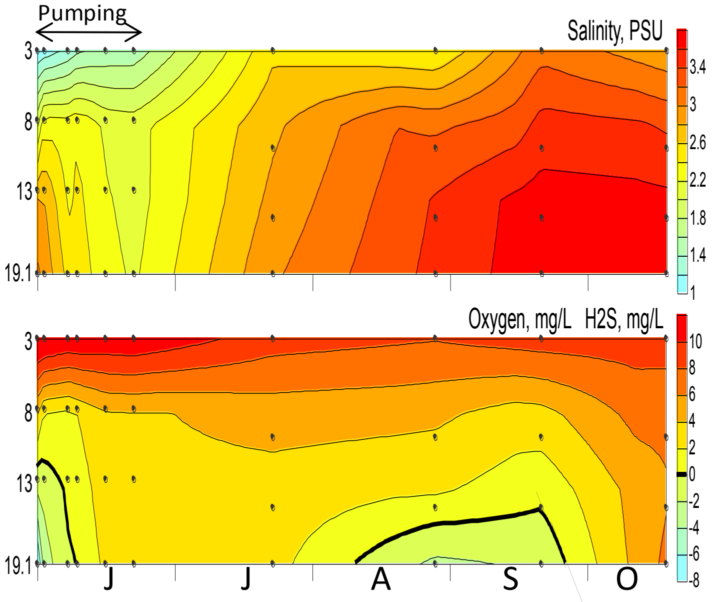


Figure 4.3-3. Effect of pumping on salinity and oxygen concentration in Lännerstasundet's experimental basin in 2010. The letters on the x-axis denote month.

To test does the absence of pumping trigger instant inflow from adjacent basin, pumping was stopped intentionally in July 2011. However, no inflows occurred and the stopping led rapidly to the depletion of oxygen. There was also an unintentional stop from July 5th to 22nd and a similar decrease in oxygen concentration was observed as a week earlier. In both cases the restart of pumping oxidized the water even though the temperature had risen considerably due to the earlier pumping. The pumping in Lännerstasundet was able to oxidize and remove the hydrogen sulfide from water although the temperature rose considerably. Pumping induced also long-term effects by lightening the water which enabled inflows of oxic water from adjacent basins. No parallel changes in the reference basin could be detected.

4.3.2 Effect of anoxia and oxygenation on concentrations of nutrients and iron in water

The artificial oxidation does not affect on the oxidation state of phosphate itself but it may affect oxidative and reductive cycles of iron responsible for phosphorus cycling together with uptake and mineralization of phosphate. One of the differences between lake and marine system related to the ability of the sediment to retain phosphorus is the high concentration of sulfate in the latter (Roden and Edmonds 1997). The microbial sulfate reduction leads to formation sulfides which together with iron forms iron sulfides unable to capture phosphorus. Therefore, when sulfate reduction is efficient, the phosphorus bound to iron oxides is released to water whereas iron remains in solid form and is buried as iron sulfide. As a consequence of anoxia there is often a high release of phosphorus from the sediment to water without concomitant efflux of iron in marine systems whereas in sulphate-poor lakes both phosphorus and iron tend to accumulate in water (Blomqvist et al 2004).

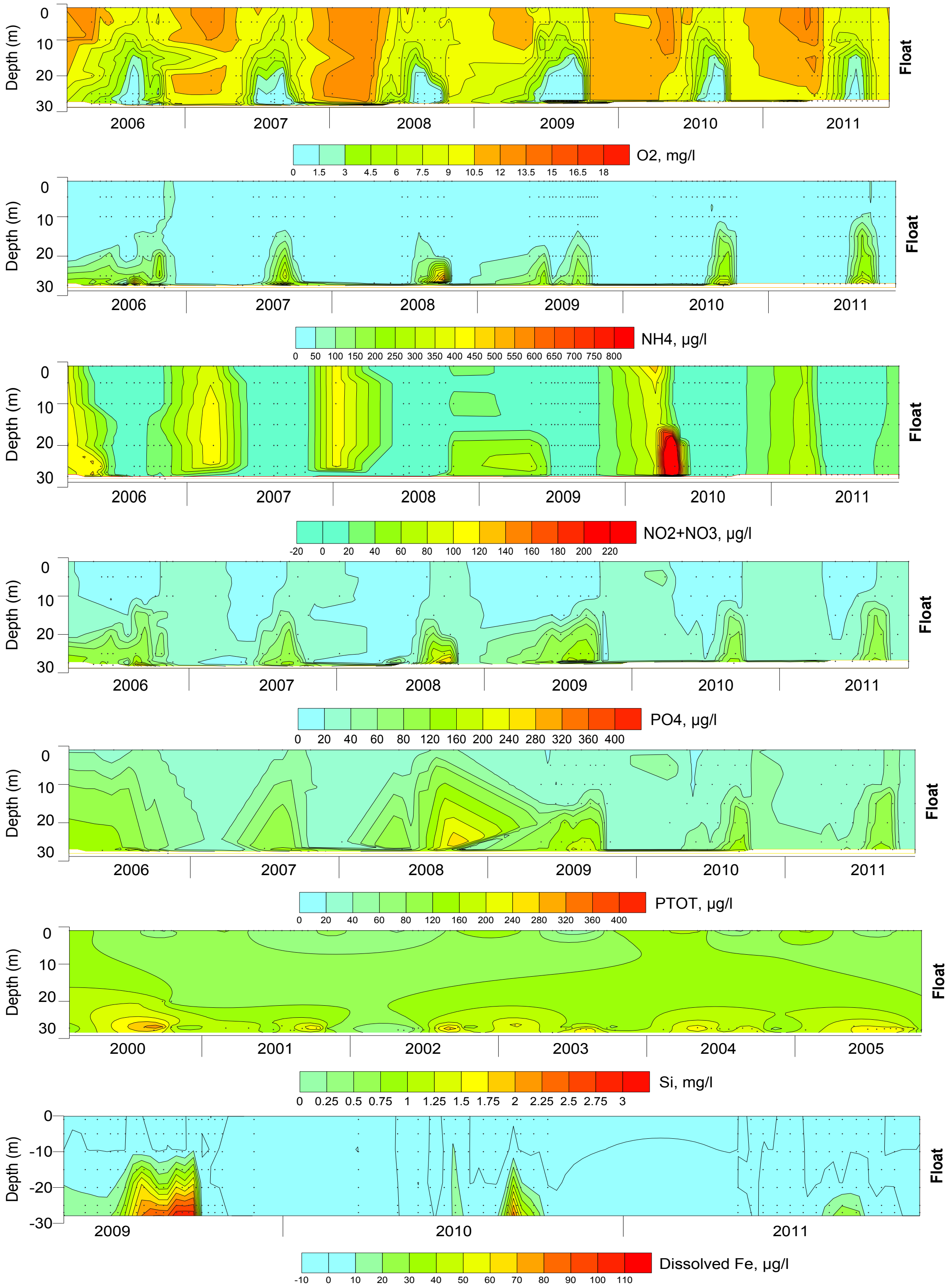


Figure 4.3-4. Variation in concentrations of a) oxygen, b) ammonium, c) sum nitrite-nitrate, d) phosphate, e) phosphate, f) total phosphorus, g) silicate and h) dissolved iron (only 2009-2011) in Sandöfjärden basin 2006-2011 (Lehtoranta et al. Forthcoming C).

Sandöfjärden

It is notable that when the pumping and the turbulent mixing could maintain the water oxic in 2010 and 2011, the concentrations of ammonium and phosphate remained low in bottom water (*Figure 4.3-4*). However, despite the full capacity pumping the basin faced anoxia which triggered the accumulation of ammonium and phosphate as in previous years. The prevailing anoxia led only to release of phosphate – not iron – in the bottom water and the iron to phosphate ratio remained low despite the anoxic conditions (*Figure 4.3-5*). The results here underline the importance of oxygen for the retention of both nitrogen and phosphorus in brackish systems.

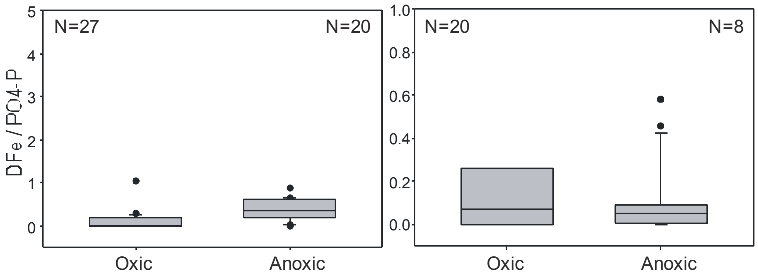


Figure 4.3-5. Dissolved iron and phosphate ratio in oxic and anoxic bottom water (A) in ***Sandöfjärden*** and (B) ***Lännerstasundet*** during 2009-2011. Denote different scales (Lehtoranta et al. Forthcoming C).

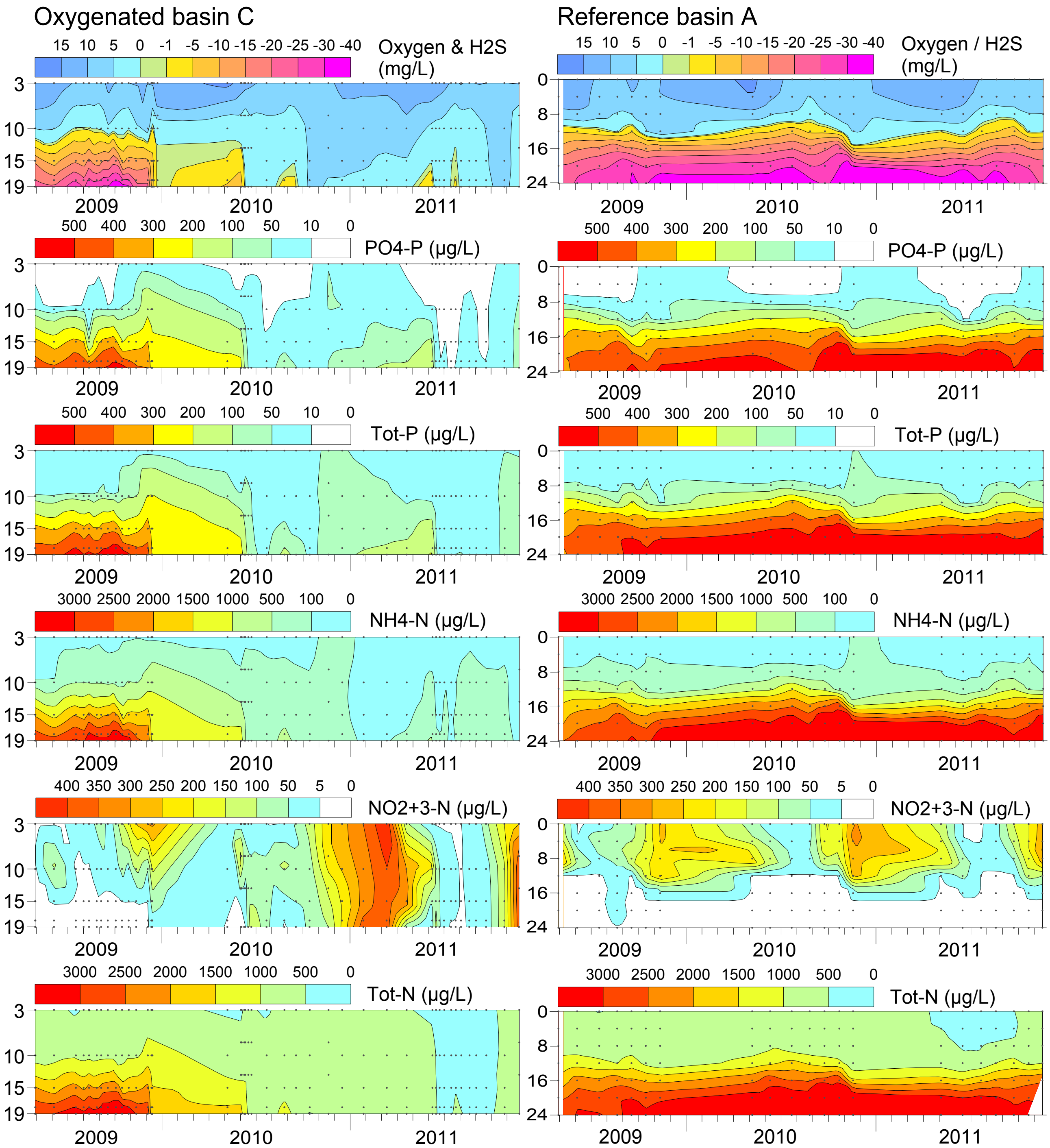


Figure 4.3-6. Variation in concentration of oxygen and H_2S, phosphate, total phosphorus, ammonium, nitrite-nitrate sum and total nitrogen in the pumped area (oxygenated basin C, left panels) and regularly monitored area (reference basin A, right panels) in **Lännerstasundet** (Lehtoranta et al. Forthcoming C).

Lännerstasundet

In Lännerstasundet the concentration and the pool of phosphate decreased clearly after oxygenation despite the low iron concentrations measured (*Figure 4.3-6*). On the basis of the decrease it is not possible to judge whether the phosphate was bound by iron or some other element or taken up by the micro-organisms in sediments. It is possible that the up-take occurred in the sediment surface by the microbes capable to bind large quantities of phosphorus in oxic conditions (Deinema et al. 1985, Hupfer and Gächter 1995). This phosphorus binding process has been documented well from the sewage treatment plants (Fuhs and Chen 1975). It is, therefore, possible that when the oxidation of deep water occurs the phosphate is scavenged largely by the bottom sediment and insignificantly by the iron and micro-organisms present in the water column in the environments comparable to Lännerstasundet. However, also the resuspension of particles containing reduced iron could be oxidized in water column and then sequester phosphate from water.

In Lännerstasundet, when there were no inflows, the stop of pumping led to anoxia and subsequently to the increase in the concentrations of ammonium and phosphate but not iron. This indicated that to maintain the ability to retain phosphate the oxygenation has to be continuous and the system may return to poor state rapidly when the pumping is stopped.

As a summary the results suggested that the release of phosphorus into bottom water is low when oxygen is present. However, it is unlikely that the oxidation of water would result in efficient phosphate removal by iron present in water column as the coupled iron, sulfur and phosphorus cycling processes were active in the both study areas. This was confirmed by the significant increase in the concentration of phosphate but that the concentrations of dissolved iron increased only slightly being at a low level throughout the anoxic period (*Figure 4.3-5*). It was common that the concentration of phosphate surpassed that of total iron. Therefore the iron to phosphorus ratio in the near-bottom water was low and inadequate to scavenge all the phosphate from the water column even though it would be oxic. The pattern in the behavior of iron and phosphate found here is comparable to those observed in laboratory and bottom water studies from the eutrophic sub-basins of the Baltic Sea (Lehtoranta and Heiskanen 2003, Blomqvist et al. 2004).

4.3.3 Variation in nitrogen fractions due to the oxygenation

Sandöfjärden

During pumping campaign in 2010 there was a significant increase in the concentration of nitrate (sum NO_3+NO_2) which may have been induced by the pumping before formation of anoxia (*Figure 4.3-4*). However, this was an exception, and in general, the pumping was not efficient enough to form detectable concentrations of nitrate in anoxic water. It is possible that the nitrate formed by the pumped oxygen was rapidly consumed or that oxygen was used to oxidize other reduced substances (i.e. sulphides, reduced iron and manganese). When the pumping was not able to induce oxic conditions the concentrations of ammonium increased in the bottom water and exceeded those measured in previous years (*Figure 4.3-4*). The increase was positively correlated with the warming of sediment (*Figure 4.3-8*) indicating that pumping enhanced the mineralization of organic nitrogen to ammonium.

Lännerstasundet

A part of the oxygen was evidently consumed in nitrification during pumping i.e. the concentration of ammonium decreased and that of nitrate increased (*Figure 4.3-6*). The presence of nitrification was supported also by the vertical profile of nitrate, i.e. the concentration increased from the surface towards the near-bottom layers below thermocline. This observation is exceptional compared to the data from the coastal monitoring stations where nitrate concentration commonly decreases from the surface towards bottom water having low concentrations of oxygen. Especially high concentration of nitrate was measured without pumping in early winter when the concentration exceeded that of ammonium. The results indicate that the pumping of oxic water may lead to nitrification and induce nitrogen removal by denitrification. The finding is somewhat controversial to the assumption that denitrification should be more effective in anoxic condition.

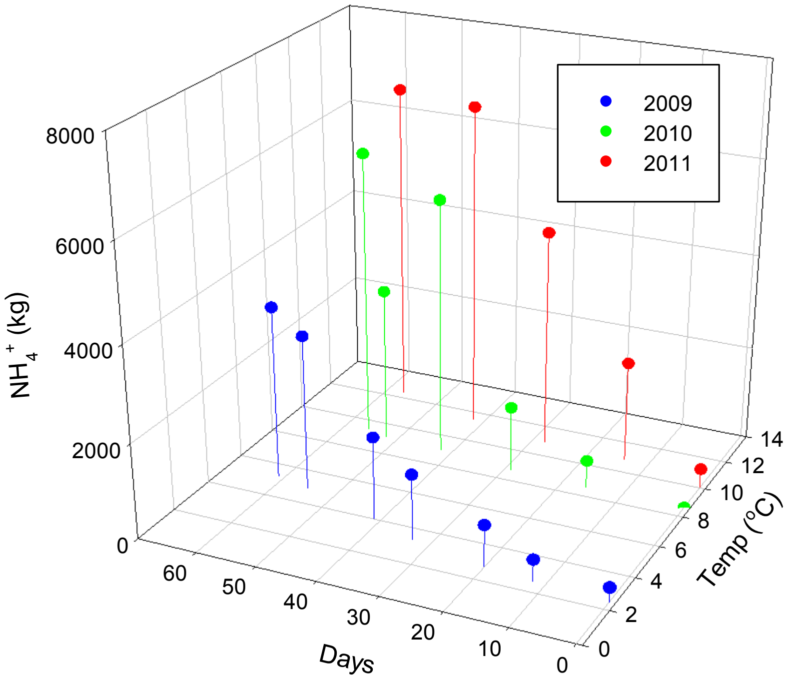
4.3.4 Changes in nutrient pools

Sandöfjärden

The calculations based on the changes in the nutrient pools showed a clear difference in the behavior of nutrient pools between Sandöfjärden and Lännerstasundet during campaign years. In Sandöfjärden no significant change in the entire pool of total phosphorus or phosphate was observed between the years of pumping compared with the previous years (*Figure 4.3-7*). There was no change – excluding the mid-summer period in 2010 – in nitrate pool which was depleted from the bottom water as in previous years. However, there was a significant increase in the pool of ammonium explained by the increase in concentration below 10 m depth covering a large volume of the basin. Although high concentrations have been observed previously, the pumping increased the water volume in which ammonium accumulated and, thus, the whole storage of ammonium became large (*Figure 4.3-8*). The increase in the pool of ammonium seemed to be in relation to the warming of the sediment and the occurrence of anoxia (*Figure 4.3-7*). It is notable that despite the significant temperature increase the accumulation of ammonium didn't start until total anoxia was reached. The pumping seemed to be adequate enough to warm the sediment but not sufficient enough to keep the bottom water oxic which resulted as an accumulation of ammonium in bottom water. When the monitoring period 2000–2008 is reviewed for comparison to campaign period, it seems that pumping didn't affect DIN:DIP ratio significantly (*Figure 4.3-8*).

Lännerstasundet

In Lännerstasundet the pools of total phosphorus, phosphate (~DIP), total nitrogen, and ammonium decreased clearly from the start of each pumping campaign (*Figure 4.3-9*), whereas no parallel decrease was found in the adjacent reference basin. The decrease in the pools is explained by the removal of nutrients due to the pumping, by the dilution, and the inflows of oxic water from the adjacent areas. Although the pools of both DIN and DIP decreased, the increase in the DIN:DIP ratio suggested that phosphate was affected more than DIN by the oxic conditions induced (*Figure 4.3-9h*). On the contrary, when oxygen was depleted the DIN:DIP ratio decreased in bottom water. The variation in DIN:DIP ratio suggests that during the pumping and inflows, phosphate was more efficiently removed than nitrogen whereas formation of anoxia triggered accumulation of phosphate in higher amounts than nitrogen into bottom water. The results here follow that observed from the Gulf of Finland and other areas suffering from periodic anoxia.



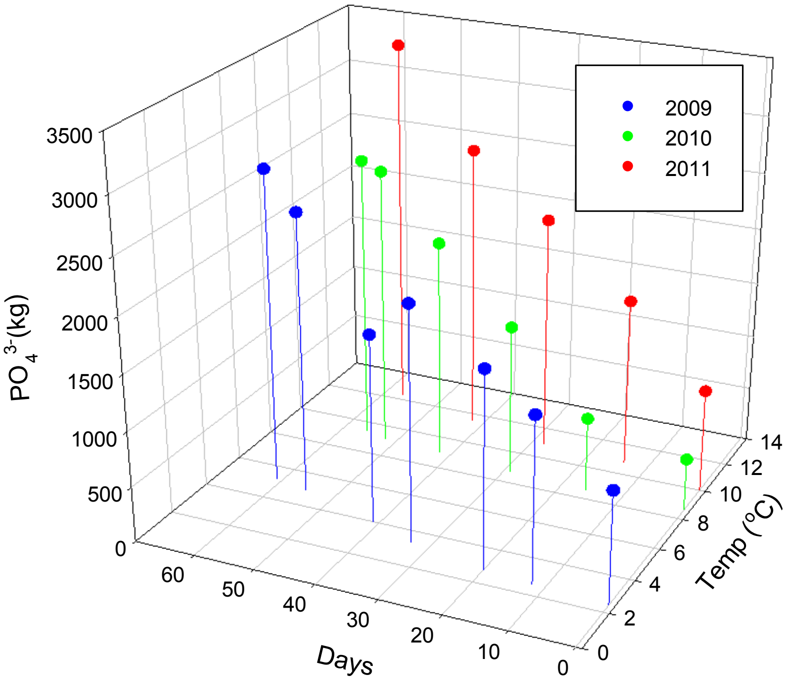


Figure 4.3-7. Accumulation of ammonium (top) and phosphate (below) in bottom water (below sill depth 12 m) explained by the duration of anoxia (days) and by the sediment temperature. It is notable that the pools of nutrients are comparable immediately before the formation of anoxia but that the sediment temperature varies significantly from 2 to 10 °C at the same time between the years (Lehtoranta et al. Forthcoming C).

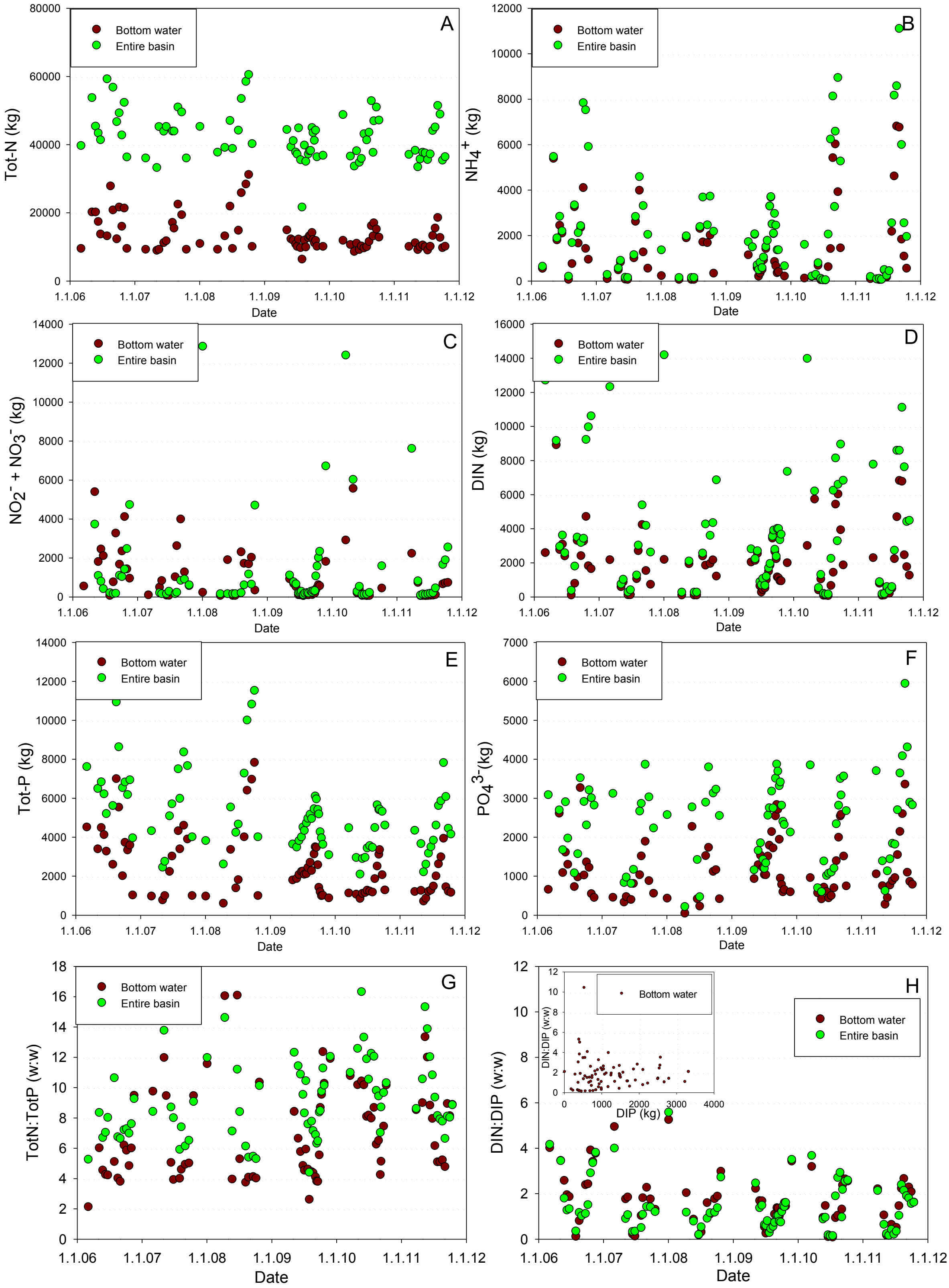


Figure 4.3-8. Changes in the pools a) total nitrogen, b) ammonium, c) nitrite+nitrate, d) DIN, e) total-P, f) phosphate, g) Total-N:Total-P ratio and h) DIN:DIP ratio in the bottom water (below sill depth 12 m) and entire experimental basin of

Sandöfjärden in 2009-2011. The figure inside h) highlights the trend in the DIN:DIP ratio (y-axis) when the pool of phosphate (x-axis) decreases in bottom water (Lehtoranta et al. Forthcoming C).

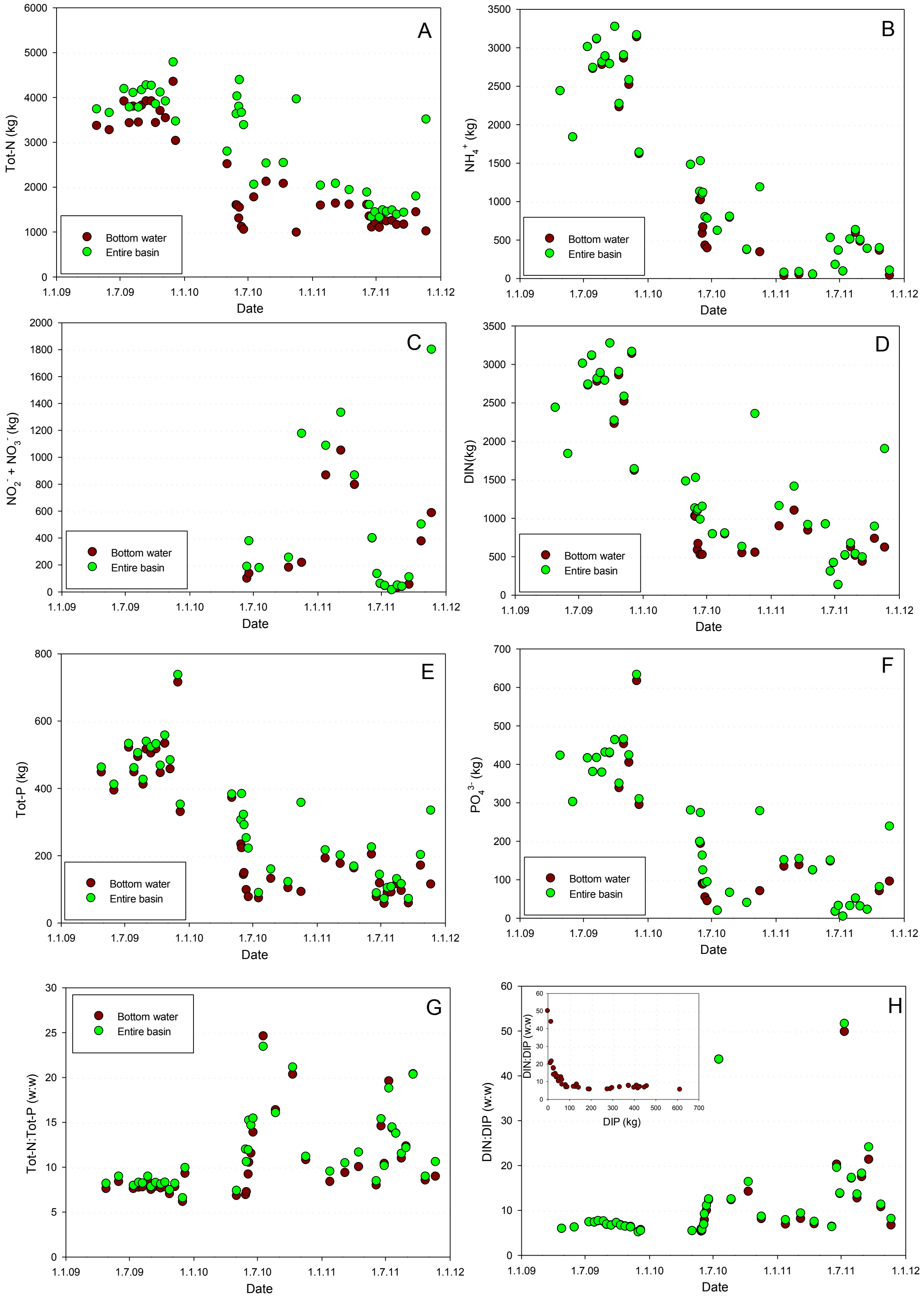


Figure 4.3-9. Changes in the pools for a) total nitrogen, b) ammonium, c) nitrite+nitrate, d) DIN, e) total-P, f) phosphate, g) Total-N:Total-P ratio and h) DIN:DIP ratio in the bottom water (below sill depth 8 m) and entire

experimental basin of **Lännerstasundet**. The figure inside h) highlights the increase in the DIN:DIP ratio when the pool of phosphate decreases in bottom water (Lehtoranta et al. Forthcoming C).

4.3.5 Estimates of nutrient removal

Sandöfjärden

In Sandöfjärden no decrease in the late summer pools of ammonium and phosphate could be observed due to the pumping. It is, however, possible to estimate an idealized case for successful pumping by assuming an insignificant release of phosphate from sediment to water in oxic conditions (Per Hall, pers. comm.). The idealized case, therefore, presents an estimate for the upper limit of phosphate retention which could have been achieved with pumping. The estimate here is based on the increase in the phosphate pool below the sill depth (12 m) after the formation of anoxia. The time period for the examination extends for the years 2009–2011 from the mid-July to the early mid-September when the concentration of phosphate was at low level and then peaked to its maximum in early autumn, respectively. The potential retention of phosphate (*i.e.* upper limit for phosphate) would be in range 0.38 – 0.51 g m-2 if near-bottom water would have been able to keep oxic by the pumping (*Table 4.3-1*). These figures correspond well to those real values calculated for Lännerstasundet (*Table 4.3-2*).

Table 4.3.-1. Idealized nutrient retention that could have been achieved by oxygenation in **Sandöfjärden**. Calculations are based on increase in DIN and DIP storages before and after formation of anoxia (Lehtoranta et al. Forthcoming C).

Year	Retention lost DIN (kg)	Retention lost DIP (kg)	Retention lost DIN (g N m-2)	Retention lost DIP (g P m-2)	DIN:DIP (w:w)
2009	3499	1798	0.74	0.38	2.0
2010	5962	2081	1.26	0.44	2.9
2011	6281	2402	1.32	0.51	2.6
Average	5247	2094	1.11	0.44	2.5

Table 4.3.-2. Nutrient removal calculations for the entire experimental basin in Lännerstasundet based on changes in nutrient pools during two pumping periods in 2010-2011.

Date	Tot-P (kg)	PO_4 (kg)	Tot-N (kg)	NH4+ (kg)	NO2+NO3(kg)	DIN(kg)	DIN:DIP(w:w)
2.6.10	382	272	4011	1517	259	1776	6.5
9.6.10	289	123	4375	1106	234	1340	10.9
Outflow for 7d	36	15	520	163	37	200	13.8
Inflow for 7d	13	0	375	8	23	31	-
Removal	70	134	-509	256	11	267	2.0

Date	Tot-P (kg)	PO_4 (kg)	Tot-N (kg)	NH4+ (kg)	NO2+NO3(kg)	DIN(kg)	DIN:DIP(w:w)
7.6.11	223	148	1867	518	394	913	6.2
21.6.11	86	15	1320	170	130	299	19.4
Outflow for 14d	36	6.0	496	74	57	131	21.6
Inflow for 14d	22	1.2	448	0	3.6	3.6	3.0
Removal	122	128	499	275	211	486	3.8

The definite upper limit for the instant and local phosphate retention was estimated by taking into account the highest pool of phosphate i.e. 5920 kg for the entire basin calculated for date 8.9.2011. Then, it was assumed that the bottom area below 4 meters (7.52 km2) would have been able to maintain its' ability to retain this amount of phosphate due to pumping. This would have resulted to a retention capacity of ~0.8 g m-2 for phosphate in Sandöfjärden.

In Sandöfjärden, the potential ability to retain nitrogen by pumping was estimated on the basis of the accumulation of inorganic nitrogen - almost all in form of ammonium - after the formation of anoxia. Assuming that the oxygenation would be able to maintain the nitrification and subsequent denitrification (i.e. coupled nitrification-denitrification processes) and that the release of nitrate would be negligible, we end up to a upper-limit for the removal of inorganic nitrogen about 1 g N m-2 (*Table 4.3-1*). However, there seems to be large variation about how efficiently nitrate produced in ammonium oxidation is denitrified between the summers (30 to 100%, Jäntti et al. 2011) and thus the removal of nitrogen is likely an overestimation. Based on the estimated retention of inorganic nitrogen and phosphate, the DIN:DIP ratio would be 2.5 on average in Sandöfjärden. The retention estimates for of DIN and DIP as well as for the ratio in Sandöfjärden are close to those calculated for Lännerstasundet.

Lännerstasundet

The instant nutrient retention (i.e. within few weeks) induced by the pumping alone was estimated on the basis of the change in nutrient pool in the experimental basin. Nutrient pools calculations are based on the measured nutrient concentrations and the volume of various water layers according to echo-sounding data (*Figure 2-5* in Chapter 2) In the basin there were two cases when no noticeable inflows occurred from the adjacent area *i.e.* in June (2.6.-9.6.2010 and 7.6. – 21.6.2011). These periods were used in the calculations separately (*Table 4.3.-3*). The calculations were made by assuming that there was an outflow from the basin in sill depth which equaled to the pumping rate (1 m3 s-1) and that there was a corresponding and compensating inflow of surface water from the adjacent basin. The nutrient concentration used in the in- and outflow calculation was taken from the surface depth of 3 m and from the sill depth (8 to 10 m) for the sampling dates 9.6.2010 and 21.6.2011. There was a significant difference between the removal of phosphate and DIN during pumping. For example, the proportion of removal was 49% for phosphate and for DIN 15% from the initial pools which increased the DIN:DIP ratio in the basin during pumping campaign in 2010 (*Table 4.3-2*).

The calculations suggested that the total phosphorus retention was between 70–122 kg and that of phosphate 128–134 kg when in- and outflow was taken into account (*Table 4.3-2*). The removal calculated for the area below sill depth for phosphate is 0.49–0.52 g P m-2 (*Table 4.3.-3*).
Calculated similarly as for Sandöfjärden, the definite upper limit for instant retention of phosphate in Lännerstasundet would be 583 kg which is a total amount of phosphate on Dec. 2nd 2009. If all that phosphate in water column would be removed, it gives a removal of ~1.1 g m-2 for phosphate in Lännerstasundet.

The calculation shows that there was significant removal of phosphate and that the sediments may play a significant role here. However, the calculation is not able to give the explanation for the removal process which may include sorption to sedimenting particles, to formed Fe (III) oxides or other substances at sediment-water interface. Also microbial uptake at the sediment/water interface may partly explain the removal. In other words, during oxygenation the phosphate is removed from the water column and the role of sediments in the removal can not be ruled out.

Table 4.3.-3. Estimated nutrient removal in **Lännerstasundet** for an area below the sill depth 8.6 m (area 0.26 km2) (Lehtoranta et al. Forthcoming C).

Year	DIN retention (kg)	DIP (PO_4) retention (kg)	DIN retention (g N m^{-2})	DIP (PO_4) retention (g P m^{-2})	DIN:DIP (w:w)
2010	267	134	1.03	0.52	2.0
2011	486	128	1.87	0.49	3.8

In the coastal accumulation bottoms of the Baltic Sea the nitrification and denitrification rates have been at the highest in summer and the bulk of denitrification has been based on the coupled nitrification-denitrification (Hietanen and Kuparinen 2008, Jäntti et al. 2011). If pumping increases nitrification and subsequent denitrification, it should be detected as a decrease of DIN pool. According to the calculations the removal for inorganic nitrogen would be between 267–486 kg, which correspond a removal rate of 1.0–1.9 g N m-2. The values are likely to be overestimates, because the values here are close to the annual removal rates calculated for the Gulf of Finland (1.3–1.5 g N m-2 y-1, Hietanen and Kuparinen 2008, Tuominen et al. 1998). However, the modeling and nutrient balance calculations give higher retention value of ~2.3 g N m-2 y-1 for the Gulf of Finland (Savchuk 2005, Kiirikki et al. 2006), but still the values here seem to be too high.

According to the measurements total nitrogen pool increased significantly during the pumping in 2010 (*Table 4.3-2*). The increase in total nitrogen was exceptional and it and it can be explained by either or both the resuspension of organic particulate matter caused by the down-ward flow of water induced by the pump (*c.f. Figure 4.2-5*) and by the uptake of inorganic nitrogen by biota. The resuspension may be more plausible explanation. The resuspension may also explain the lower removal of total phosphorus compared with phosphate calculated for the same time period (*Table 4.3-2*).

4.4 Effect of oxygenation on algal communities and on benthic animals

Algal communities

The pumping did not increase chlorophyll-a concentration in Sandöfjärden or in Lännerstasundet (*Figure 4.4-1*). There was a significant rise in the chlorophyll-a concentration in late summer 2010, but a similar increase was observed also in the coastal areas of the Gulf of Finland. In the coastal areas of the Gulf of Finland chlorophyll-a varies specifically during the late summer according to meteorology and water stratification. The intensity of e.g. cyanobacterial blooms is sensitive to water temperature, and long stratified season may result in dinoflagellate growth. Thus the higher values are more indicative of annual variability than pumping effect.

Similar to chlorophyll-a the interannual variability of phytoplankton communities is marked. In Sandöfjärden, after the typical diatom dominated spring bloom, the intensity of cyanobacterial bloom varied as did the share of small flagellated cells (e.g. Dinophytes and Cryptophytes). The same variability was observed also in Lännerstasundet. However, the comparison to the reference stations showed similar variability proving that the pumping campaigns did not affect significantly on the algae community (*Figure 4.4-2 a and b*).

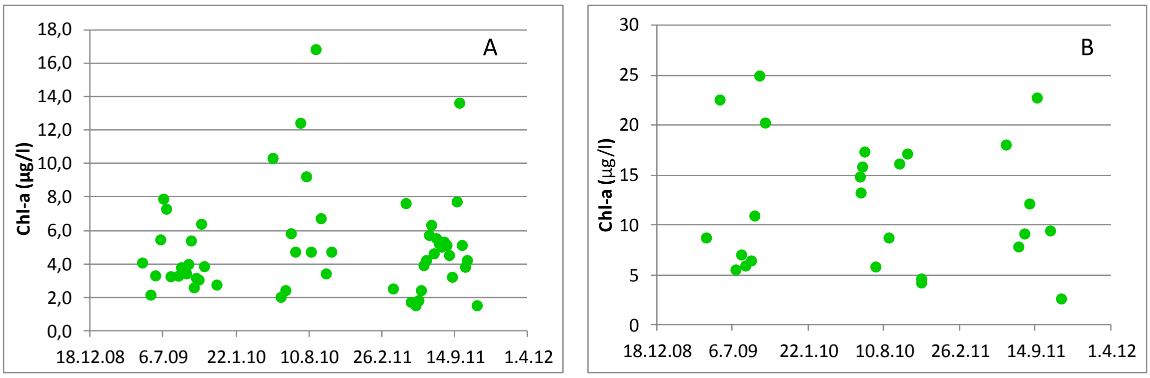


Figure 4.4-1. Chlorophyll-a concentrations in the surface water in (A) **Sandöfjärden** and (B) **Lännerstasundet** in 2009-2011 (Lehtoranta et al. Forthcoming C).

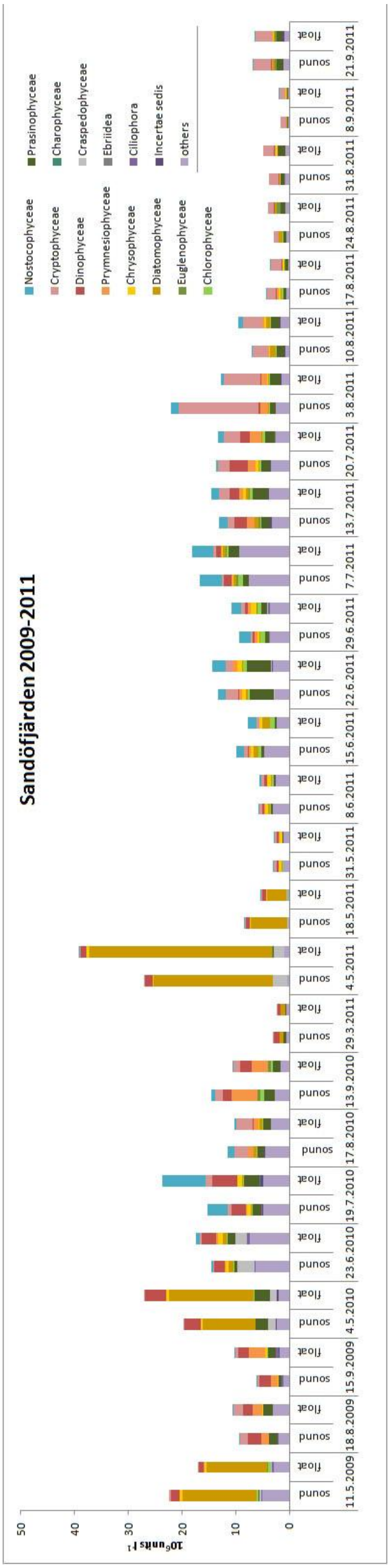


Figure 4.4-2a. Phytoplankton groups in the Sound and Float stations in **Sandöfjärden** 2009-2011 (Kalso, M. unpublished, Lehtoranta et al. Forthcoming C).

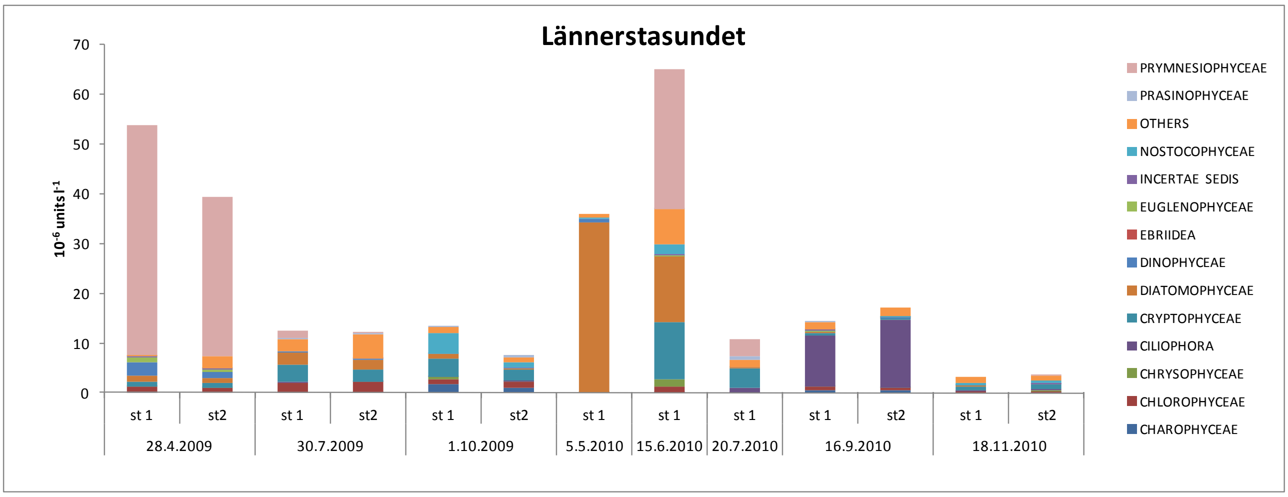


Figure 4.4-2b. Phytoplankton groups in the pumping (st1) and reference basin (st2) of **Lännerstasundet** in 2009-2010 (Kalso, M. unpublished, Lehtoranta et al. Forthcoming C).

Benthic animals

In Sandöfjärden the benthic community was sparse and only few animals were found from the surroundings of the deep basin before the pumping (*Figure 2-3* for sampling sites). The most abundant species were chironomids, *Macoma baltica* and ostracods. No marked change in the abundance of benthic animals could be linked to the pumping campaigns (*Figure 4.4-3*).

In Lännerstasundet the presence of H2S below halocline restricts the abundance of benthic animals and they were found only from the shallow areas before pumping campaigns (*Figure 4.4-4*). In the three transects sampled (*Figure 2-6* for sampling sites) the most abundant animals were species tolerant for low oxygen levels - oligochaetas and chironomids - which abundance was not markedly affected by the oxygenation in 2010 and 2011 (*Figure 4.4-4*). Despite the oxygenation no indication of abundance of animals were found in the deep parts of the basin. It was likely that the concentration of oxygen was too low and the duration of the oxic period too short for the spreading of benthic animals to the oxygenated area.

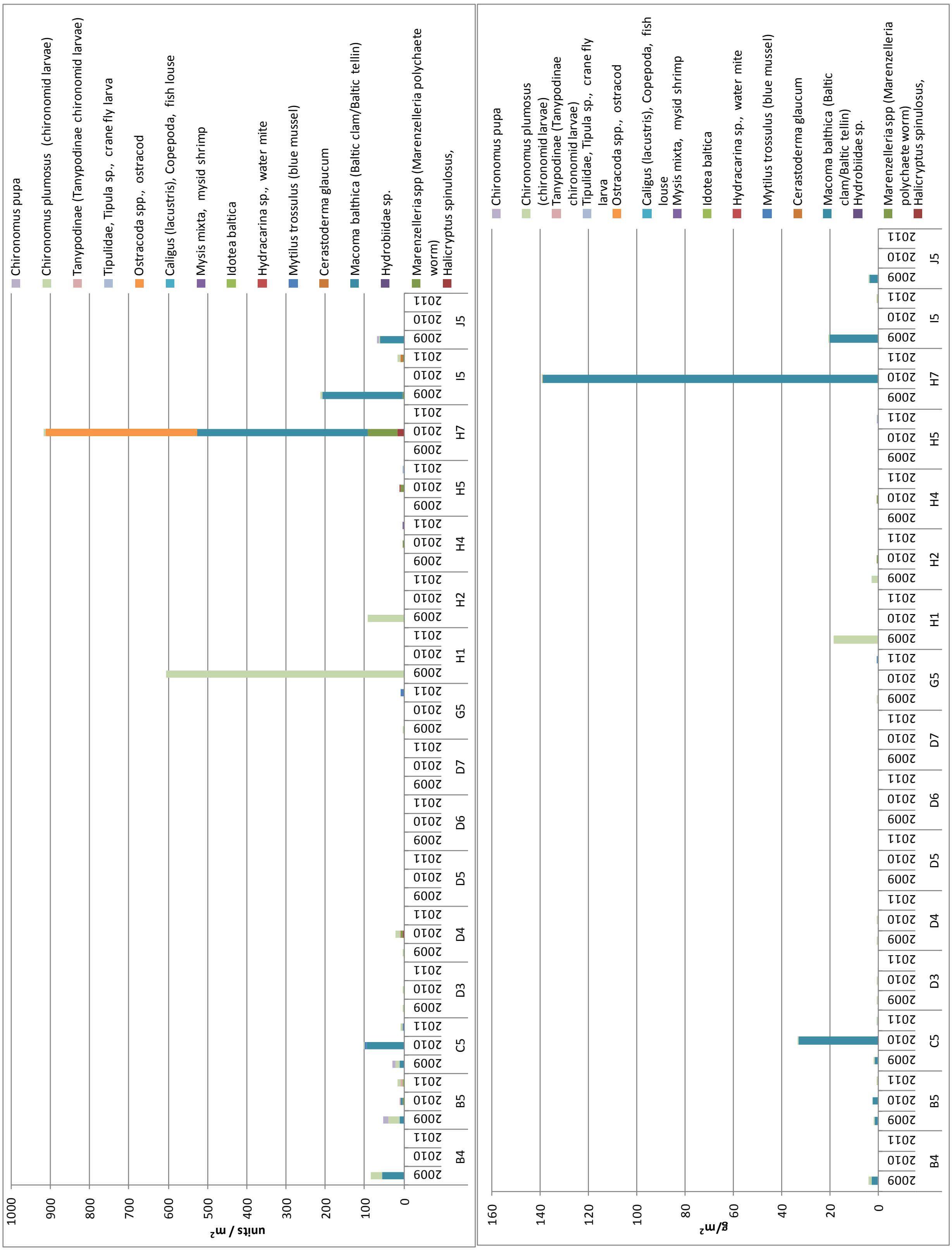


Figure 4.4-3. (top) Abundance and (below) wet weight of benthic animals in the **Sandöfjärden** basin (Lehtoranta et al. Forthcoming C).

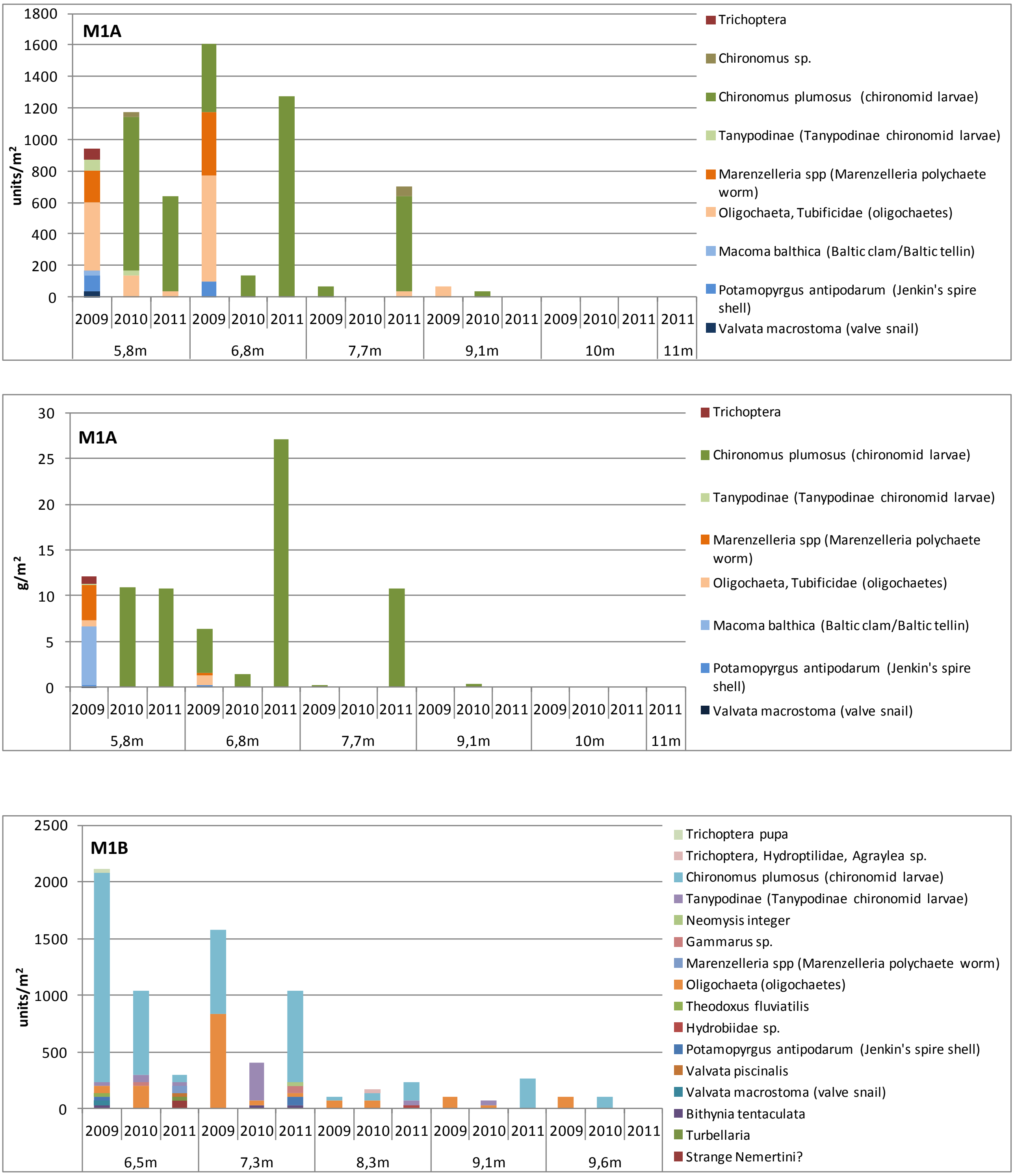


Figure 4.4-4 Abundance and wet weight of benthic animals along transects M1A-M1C in the easternmost basin of **Lännerstasundet** (Lehtoranta et al. Forthcoming C) (see sampling transects from *Figure 2-6*). Note that the figure continues at next page.

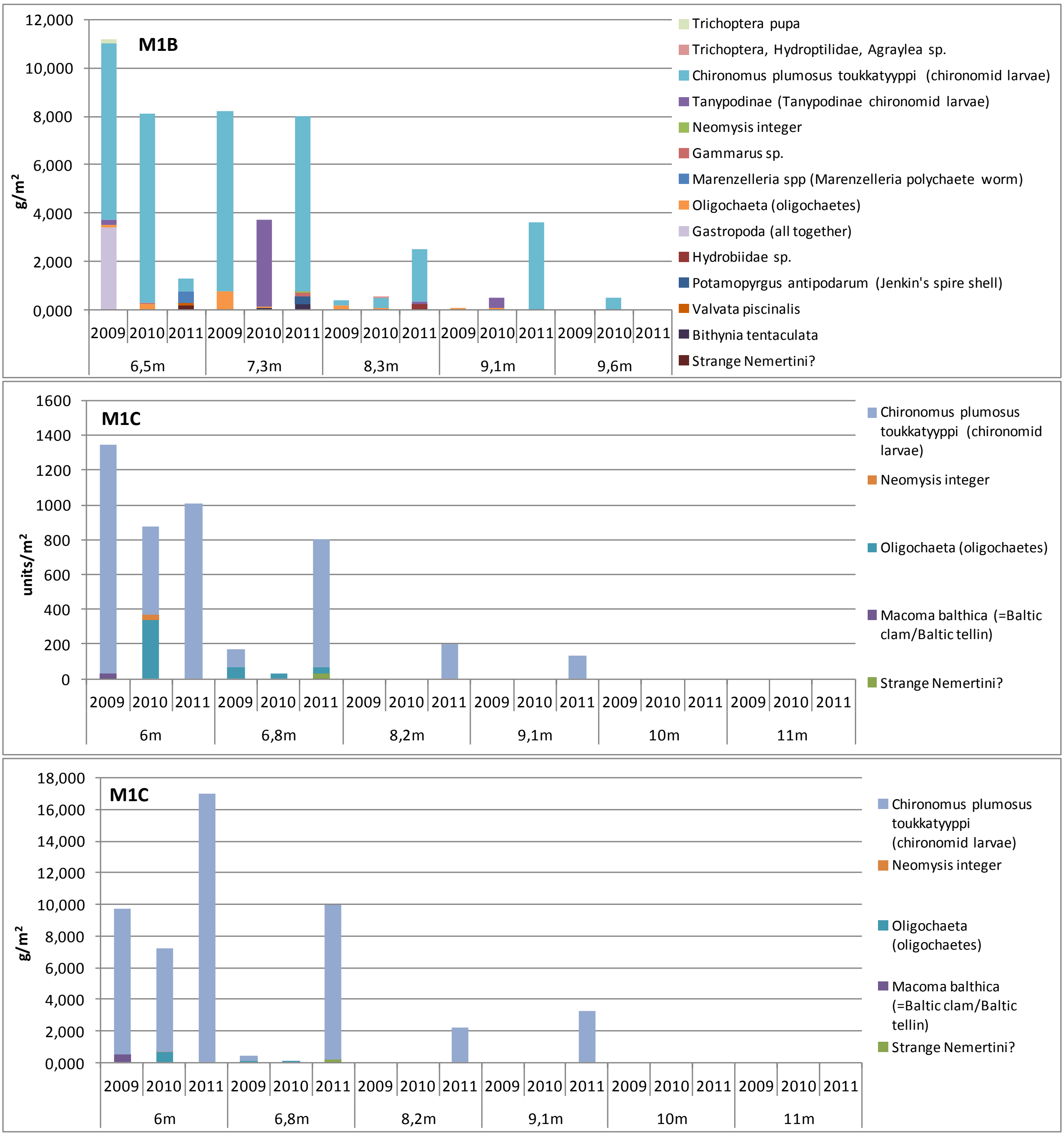


Figure 4.4-4 Abundance and wet weight of benthic animals along transects M1A-M1C in the easternmost basin of **Lännerstasundet** (Lehtoranta et al. Forthcoming C) (see sampling transects from *Figure 2-6*).

Final remarks

The capacity of pumping was adequate enough to form measurable and basin wide effects in the physical and chemical parameters in the both study areas. The effects of pumping on temperature and salinity were close to what could be expected according to the modeling for the areas (cf. Chapter 5). Although the pumping weakened the stratification, no complete breakdown of thermocline was observed in either of the study areas.

The pumping was not efficient enough to maintain the Sandöfjärden basin oxic. It is evident that the pumping capacity was not able to compensate the increased oxygen consumption produced by the pumping, or that the oxygen consuming area below thermocline increased, or that significant part of the pumped oxygen was transported out from the basin. It is possible that all these three reasons together affected the result obtained. According to the calculations there was a need of additional oxygen of 2 300 kg d-1 to compensate the consumption in Sandöfjärden. Therefore, the dimensioning of the pumping is fundamental for the success of the bottom water ventilation. If the capacity is inadequate to form oxic conditions, the anaerobic microbial processes may be favored by the warming and increase e.g. the accumulation of ammonium into bottom water.

The pumping in Lännerstasundet showed that using high enough pumping rate, the basin can be oxidized within a week. However, the pumping rose thermocline and the oxygen conditions weakened in water depths in which oxygen was found in considerable concentrations during stagnation. One of the clear positive effects of pumping was the decrease in the density stratification which induced long-term conditions favoring inflows from the adjacent basin. The inflows were capable to oxidize the bottom water and depending on the volume of the water, they may even exceed the oxygenation capacity produced with the pumps. For example, assuming an inflow of 2 m3 s-1 containing half of the amount of oxygen to that delivered by the pump equals the oxygen transport created by the pumping. Therefore, even moderate inflows may decrease the pumping capacity needed in the areas where pumping will induce inflows of oxic water as a secondary effect.

The experiments carried out showed that the biogeochemical cycles of nutrients were strongly affected by the pumping of oxic water. The delivery of oxygen to the stagnant and anoxic water resulted as an oxidation of hydrogen sulfides and ammonium. It was evident that induced nitrification produced nitrate for denitrification process, which may partly explain the decrease in the pool of inorganic nitrogen. However, the processes related to the cycling of nitrogen are complex due to its several oxidation states and multitude of biological processes participating its cycling and the conclusion made may be an oversimplification. The pumping led also to significant decrease in phosphate pool in Lännerstasundet, but that the sequestering process is unclear. The results indicated that phosphorus can be removed more efficiently than nitrogen. Therefore, oxygenation, when successful, may turn the sulphate rich system towards phosphorus limitation in conditions comparable to those in Lännerstasundet.

It is evident that in the oxygenated areas nutrient cycling processes will respond to the formation of anoxia similarly as before pumping. In other words, pumping does not affect significantly on the mineralization processes and oxygen consumption rate on a time scale of few years pumping. Therefore, it is evident that the stop of pumping will lead to anoxia, which triggers the effluxes of ammonium and phosphate from the bottom back to water.

Need of future studies

Biogeochemical cycles

One of the options which could decrease the warming effect of pumping but was not implemented is that the pumping would be started not until the oxygen level decreases to low 2–3 mg l-1 level. With this approach the pumping would not warm the water and sediment as much as it does when it is started in good oxygen conditions in early summer.

The objective of the project was to remove phosphorus with artificial oxygenation, but it seems that the cycling of nitrogen was affected, too. A specific study regarding the removal processes of nitrogen is necessary, especially when there are theoretical explanations, why oxygenation would remove nitrogen (c.f. Info Box 1-1). It is unclear, how the pumping affected the oxidation pathways of reduced substances in specific and it is not possible to conclude was the oxidation chemical or biological. In marine systems the oxidation of ammonium and sulfides cover the bulk of the consumption of oxygen in sediments. It may well be that the majority of the pumped oxygen was consumed to oxidize sulfides (H2S, HS-) having an insignificant effect on nutrient removal in Sandöfjärden. The research on bottom water ventilation should be widened to cover the microbial oxidative and reductive processes responsible for the biogeochemical processing of nitrogen and phosphorus by studying how the rates of oxidation and reduction for N, Mn, Fe and S are affected by the oxygen supplied and temperature variation induced with the pumping. The future studies call for analysis of the potential effects of the artificial oxygenation to ecosystem services having a need for a major input of information on the effects towards fisheries, nutrient cycling and algal dynamics.

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5 Modeling the effects of oxygenation in variable spatio-temporal scales

Jørgen Bendtsen, Karin Gustafsson, Kai Rasmus

Modeling the effects of oxygenation of hypoxic water bodies involve physical and biogeochemical processes working on a large range of spatial and temporal scales. Pumping of surface water deeper into the water column causes the formation of a "buoyant plume" at the pump outlet where buoyancy forces on the lighter surface water will cause an upward motion. The ascending water will entrain surrounding water and thereby the total volume transport will increase and the whole dynamics can therefore be characterized as a "plume" of rising buoyant water (*Figure 5-1*).

The plume of ascending water can be compared to similar phenomena observed in the atmosphere, for example plume formation of warm air or smoke rising from industrial chimneys or from the more extreme cases related to plume formation of warm gases from volcanic eruptions. Analysis of plume dynamics in the atmosphere has primarily focused on the dynamics within the plume itself, for example for quantifying the direct effects from pollutants in the plume on the surroundings. However, oxygenation of water bodies is expected to influence the surrounding environmental conditions through the relatively slow dispersion of oxygenated water within the plume together with additional indirectly forced transports caused by changes in the density field. Therefore, both the direct effect from the plume as well as the longer term effects from the interaction of the plume with the surrounding water is important for understanding the impact from oxygenation. The model studies of oxygenation in the PROPPEN project considered these aspects of plume dynamics and the subsequent dispersion of oxygen-rich water in the surrounding environment.

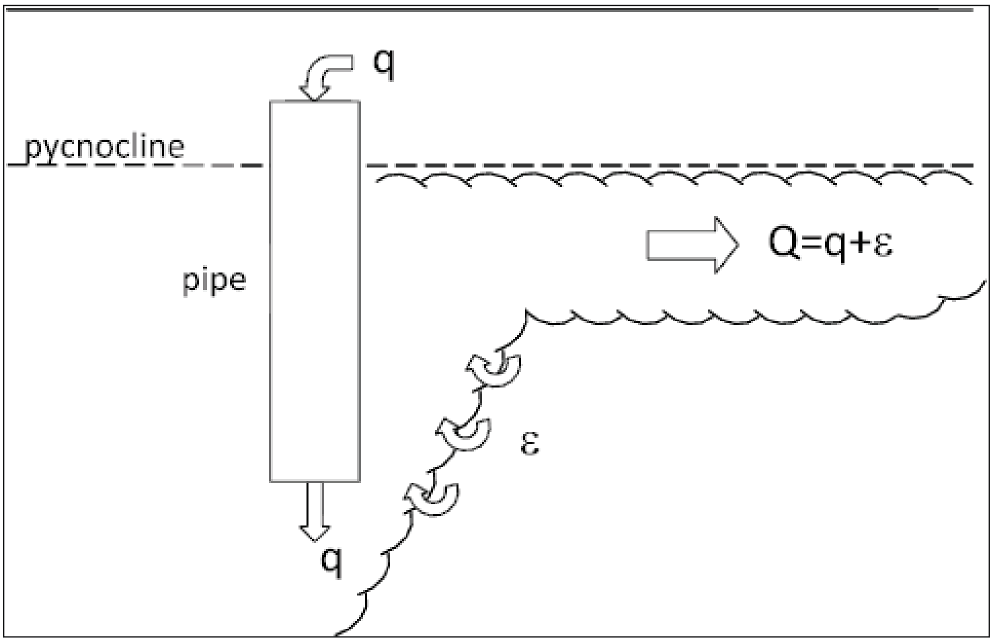

Figure 5-1. Conceptual figure of a buoyant plume around the oxygenator. The oxygenator transports surface water into the bottom layer with a constant flow rate (*q*). Relatively light surface water rises as a buoyant plume and entrains surrounding water (*ε*), and when the plume reaches the top level it spreads out laterally (Q) below the pycnocline .

Overview of modeling results

On the ***local scale*** we analyzed the near-field dynamics close to the oxygenator with a high-resolution hydrodynamical model where flow dynamics down to a centimeter scale were simulated and transport and entrainment (water mixed into the plume) rates have been analyzed. On a larger spatial scale, within about ten to hundred meters around the oxygenator, we analyzed the plume dynamics through a combined tracer release experiment and model study. We developed and implemented a new plume model in a regional circulation model and simulated the detailed distribution and dispersion of the plume from the oxygenator as it was observed from the tracer release experiment. These near-field studies are described in ***section 5.1***.

On the ***coastal basin scale*** the conditions from the two local study areas in Lännerstasundet and Sandöfjärden were simulated and analyzed in a regional circulation model. A detailed study of the oxygenation experiment in Lännerstasundet in June 2010 simulated the observed changes in temperature, salinity, H_2S and oxygen in good accordance with the observed fields. A sensitivity study analyzed the impact on the temperature and oxygen concentration if the pump rate from the oxygenator were modified. An analysis of the observed near-bottom oxygen concentration in Sandöfjärden indicate a significant variability close to the bottom and model simulations suggest that oxygenation may indirectly increase such near-bottom vertical mixing, and this intensification of vertical mixing was analyzed. The coastal basin scale model studies are described in ***section 5.2***

On the ***regional scale*** the impact from oxygenation was analyzed in a high-resolution circulation model of the whole Baltic Sea area where the impact from large scale oxygenation was simulated and analyzed. Three different cases of oxygenation were analyzed ; (1) ***deep hypoxic areas in the western Baltic Sea***, (2) ***coastal areas in the Gulf of Finland*** and (3) ***deep areas in the Gulf of Finland***. These simulations were carried out with a 3D-circulation model with a relatively high horizontal resolution (~3.6x3.6 km) and for a 5 month period. The three cases represent different strategies for deep water ventilation by oxygenation pumping in the Baltic Sea. The regional scale model studies are described in ***section 5.3*** and conclusions from the model studies are summarized in ***section 5.4***.

5.1 Model analysis of the local scale near-field dynamics

The near-field dynamics close to the oxygenator was analyzed with a high-resolution hydrodynamical model (***section 5.1.1***). A new plume model was developed suitable for implementation in regional scale modeling (***section 5.1.4***) and this model was subsequently validated against observations from a tracer release experiment (***section 5.1.5***).

5.1.1 High resolution non-hydrostatic modeling

A frequent applied assumption in regional scale ocean circulation models is the so-called "hydrostatic balance" where the hydrostatic pressure at a given depth is assumed to arise solely due to the weight of the water above. However, forces due to the vertical acceleration associated with the plume motion may become important when the circulation is resolved on very small spatial scales, i.e. on length scales of about centimeters to meters. Therefore "non-hydrostatic" effects are included in the high-resolution Elmer-model results described below, where the flow field near the oxygenator were simulated.

5.1.2 Elmer model setup

The purpose of this study was to analyze the near-field circulation of a vertically orientated mechanical mixer and to establish a parameterization of the radial out-flowing velocity and the entrainment associated with the ascent and lateral dispersion of the buoyant plume as a function of the pumping flux Q_p and the associated pumping velocity W_p (*Figure 5-2*). The model analysis focused on the general dynamics associated with the pumping from a mixer, and therefore the dimensioning of the model setup was not directly comparable to the applied oxygenators in the field experiments. For example, the radius in the model setup was about twice as large as in the Mixox mixer. The model application used in this study was based on the finite element Elmer multi-physical modeling package (http://www.csc.fi/english/pages/elmer 11.11.2011) developed by the Computer Science Center (CSC) in Finland. It has been used in many studies to solve a variety of fluid dynamical problems.

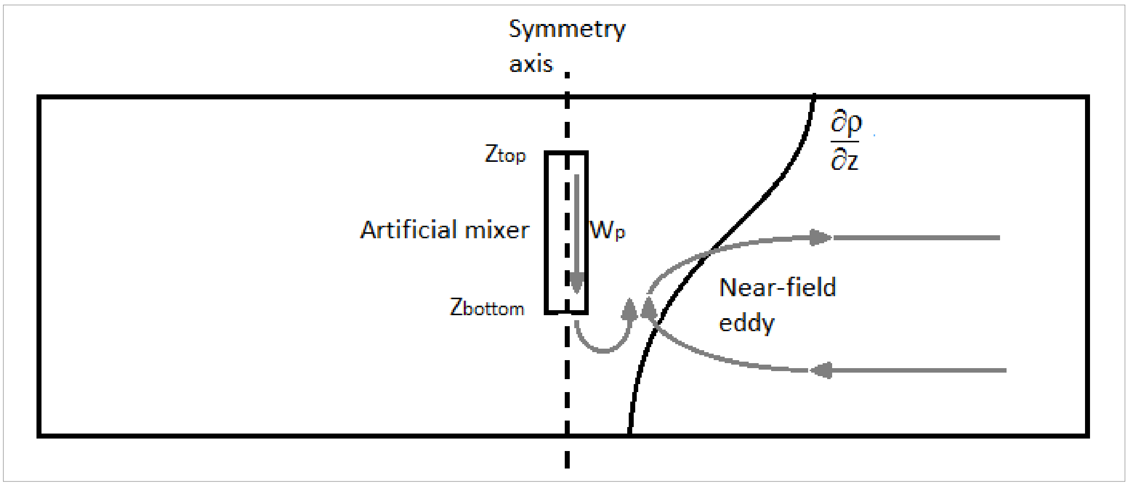

Figure 5-2. Schematic illustration of the Elmer model setup. The oxygenator is located in the center and initial stratification and model variables are indicated.

Info Box 5-1: High-resolution non-hydrostatic model: Elmer

*The Elmer model solve*s the coupled system of equations composed of the non-hydrostatic Navier-Stokes equations for motion, the heat equation for temperature and the k-epsilon model for turbulence. The water density was determined by a temperature dependent equation of state.

The model domain was axis-symmetrical with the symmetry axis aligned with the centerline of the pump (*Figure 5-2*). The transverse velocities were thereby assumed to be zero so only the vertical and radial velocities were considered. The influence from external flow and the coriolis force were neglected. The oxygenator had a diameter of 2 m, the inlet was 5 m from the surface and the outlet was located 10 m above the bottom and it was included in the model by specifying the boundary conditions around the oxygenator. The model domain was 30 m deep and had a radius of 50 m with a rectangular cross-section. The finite element calculation mesh was produced so that it consisted of triangles (18653 in total) which varied in size between 0.1 and 1.0 m (*Figure 5-3*).

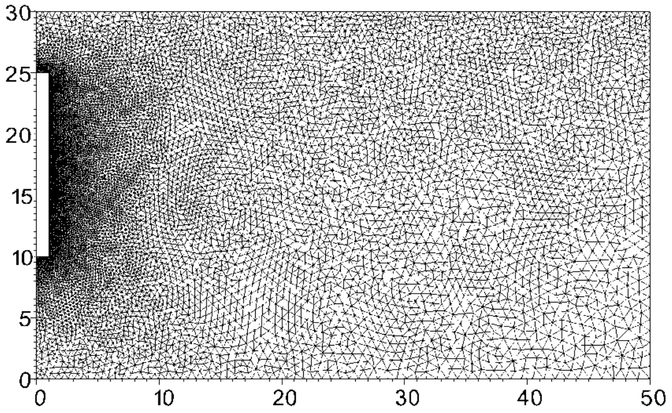

Figure 5-3. Model grid in a vertical section. The depth of the model domain was 30 m and the radial symmetric horizontal distance was 50 m. The oxygenator is indicated with a white column located between 10 and 25 m above the bottom.

The initial velocities were set to zero and the initial temperature profile had a density difference between the top and bottom layer of 0.84 kg m^{-3}. The boundary condition at the surface was 14.9 °C and a zero velocity boundary condition was imposed at the outer edge boundary where the temperature was prescribed from the initial temperature profile. Heat was not transferred through the bottom and the symmetric boundaries. The bottom boundary and the pump walls had a no slip condition and the symmetry axis had a zero radial velocity component. The top of the pump simulated the pumping action of the pump by having a prescribed downward velocity and a zero radial velocity. The bottom of the pump used a periodic boundary condition for all variables mirroring the values at the top of the pump. The model domain did not extend into the pump itself. To analyse the effect from the pump, five different pumping speeds evenly spaced between -0.20 m s^{-1} and -0.70 m s^{-1} were used. These corresponded to flow rates of 0.6, 0.9, 1.3, 1.6 and 2.2 m^{3} s^{-1}, respectively.

5.1.3 Elmer model results

In all five simulation cases (Info Box 5-1) the pumped water flowed initially straight down with a small amount of entrainment after the water exits the outlet pipe of the pump. The upward flowing thermal plume entrained water from the surroundings.(*Figure 5-4*). After 11 minutes the upward flow was situated within 6 m from the pump in all cases. A small eddy, with a diameter between 1 and 3 m located close to the bottom below the pump were established in the two cases with the highest pumping rates. It was noticeable that the upward flow were located right next to the pump. All cases produced a radial outflow below the thermocline after 11 minutes. The return flow was seen in the surface layer and in the deeper layer below the thermocline. The thickness of the outflowing layer was larger for the low pumping rates whereas the higher pumping rates produced larger water velocities but in a thinner layer.

To quantify the entrainment, the positive radial flux at 30 m from the pump was calculated as the radial velocity times the area through which it flowed. At a distance of 30 m and after 10 minutes of pumping the entrainment had increased the outflow by a factor of about 5 compared to the flux pumped through the oxygenator.

The flow field showed a recirculation close to the pump and large velocities were centered at the pump outlet and also at the top of the pump where it converged at the pump inlet (*Figure 5-5*). The outflowing radial velocity magnitude was below 0.01 m s^{-1}. Above the thermocline there was some detrainment (*water transported out of the plume*) occurring which could be water originating from the surface layer or pumped water mixed into the thermocline from below. However, the velocities related to this were relatively small.

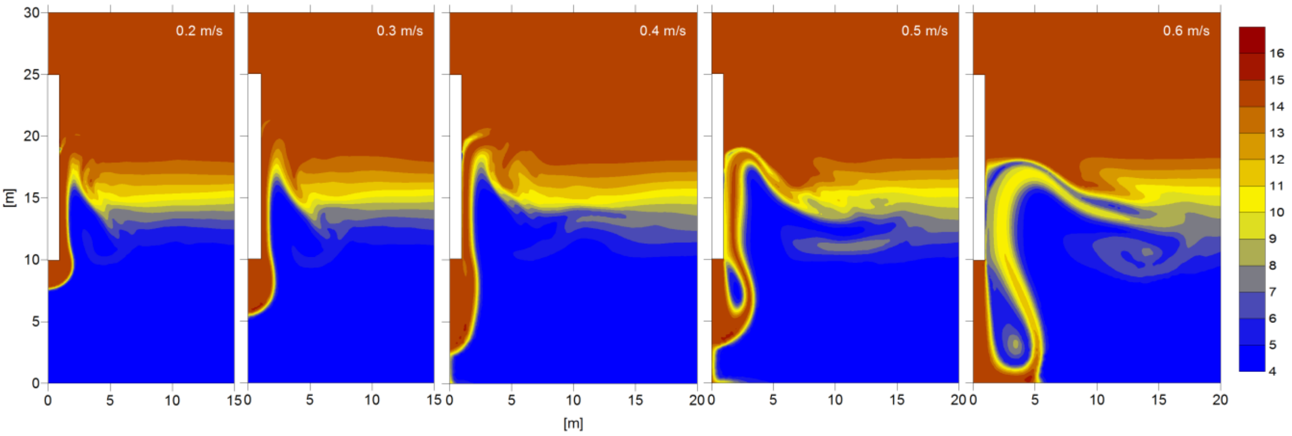

Figure 5-4. Temperature for five different pumping speeds after 11minutes. All cases have produced a plume that has reached the thermocline and the plume has started to propagate radially outwards.

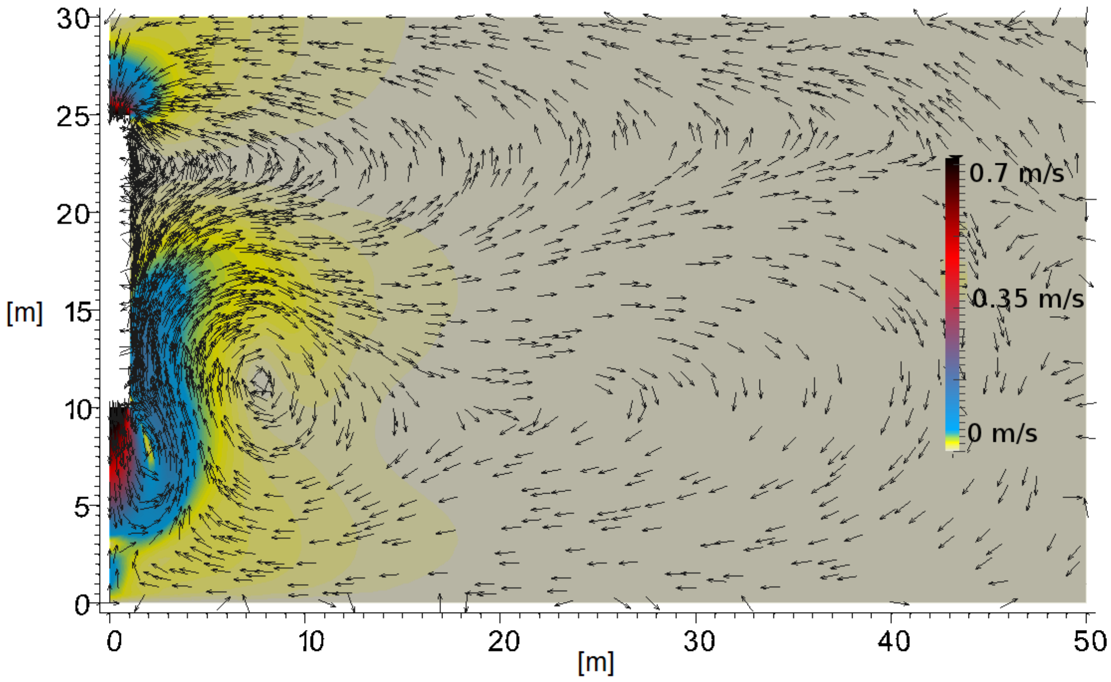

Figure 5-5. Flow field after 20 minutes for a pumping speed of 0.7 m s^{-1}. The arrows indicate the direction of the flow and the color indicates the flow magnitude. The motion is mainly located close to the pump with an outflowing plume with small velocity values just underneath the thermocline. Note that arrows have the same size and only show directions and that the current speed is indicated by colors. Gray areas correspond to velocities less than 0.01 m s^{-1}.

5.1.4 Development of a new oxygenator model

On larger spatial scales the explicit modeling of oxygenation can be based on relatively simple entrainment parameterizations which in principle describe the complex dynamics on small scales (*cf. the Elmer model results above*) integrated over larger spatial scales. We assumed that the entrainment rates were determined by buoyancy differences between water within the rising plume and the surrounding water. Such a parameterization of entrainment processes is supported by laboratory studies of plume dynamics in stratified environments (Turner 1979; see also section 3.4) and have for example been applied in atmospheric modeling of dispersion of pollutants from point sources (forming similar buoyant plumes in the atmosphere) or in modeling of pollutants from waste water outlets in the sea. Of primary interest in the atmosphere is the direct effect from substances transported within buoyant plumes on the surroundings and such problems have successfully been described in plume models (i.e. so-called “integral models”) where the detailed information about the dynamics inside the plume is determined. However, such models only give limited information on the response of the far-field dynamics on the rising plume (i.e. outside the plume itself). The indirectly forced circulation or mixing, for example secondary circulation generated by changes in the density field, is also of interest when the influence from artificial oxygenation is considered in the open ocean.

The far-field response from plume dynamics has been studied around hydrothermal vents in the deep ocean (Lavelle 1995) and also high resolution dynamical plume models have been coupled to a far-field circulation model (Choi and Lee 2007). However, the understanding of the impact from a rising buoyant plume in the sea on the far-field circulation is still limited. Entrainment and the influence from detrainment and the lateral spreading at the top level of the plume depends on turbulent viscous and diffusive fluxes. These processes are critical and difficult to describe in ocean circulation models.

To assess the potential of bottom water ventilation by oxygenation pumping in the open sea, and to understand the primary physical transports we investigated the dynamics around a buoyant plume in a short term tracer release field experiment in ***Sandöfjärden***. Subsequently we used the high-spatial resolution field data to constrain the parameters in a new simple buoyant plume model (Info Box 5-2). The plume model is suitable for implementation in large scale regional circulation models and was used in the model analysis of the conditions in Sandöfjärden and Lännerstasundet (*5.2*) and in the large scale Baltic Sea oxygenation simulations (*5.3*).

Info Box 5-2: Plume model description

A new buoyant plume model was developed and is described in detail in Bendtsen et al. (submitted). The model was implemented in the COHERENS regional circulation model (Luyten et al., 1999). The buoyant plume model is assumed to be located within a single horizontal grid cell in the regional model. The plume model permanently covers a water column from the bottom ($z = -H$) to the surface ($z = \eta$) and mass in the plume is conserved through the continuity equation (Eq. 1); $\nabla\cdot\mathbf{u_p} = 0$, and the transport equation (Eq. 2); $\partial_t\phi_p + \mathbf{u_p}\nabla\cdot\phi_p + A_h(\mathbf{U_h}, \Phi, \phi_p) = \mathbf{0}$ for the various dissolved substances transported through the plume, where $\mathbf{u_p}=(u_p, v_p, w_p)$ and ϕ_p are the velocity components and the tracer concentration in the plume, respectively. The transport between the surrounding grid and the plume is described by the advection operator $A_h(\mathbf{U_h}, \Phi, \phi_p)$ where U_h is the horizontal (i.e. far-field) velocity vector in the surrounding grid and Φ and ϕ_p are the tracer concentrations in the surrounding grid and in the plume, respectively. The plume is assumed to cover a small area (δa) which is significantly smaller than the area of the surrounding grid cell (δA) and the timescale for substances in the plume area is assumed to be sufficiently short such that additional sink or source terms can be neglected in Eq. 2.

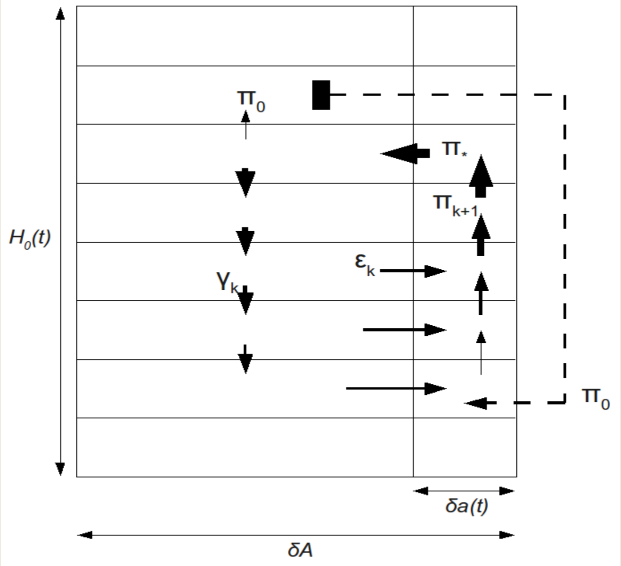

Figure 5-6. The buoyant plume model constitute a constant volume ($V_0 = H_0(t)\ \delta a(t)$) and the vertical layers are defined by the surrounding grid in the circulation model. The constant flow rate (π_0) transports water from the intake level (k_i, solid rectangle) in the regional model to the bottom plume level (k_b, dashed arrow). Transport in the plume increases due to entrainment of surrounding water (ε_k) and at the final top level water is transported from the plume to the surroundings. The return flow (γ_k) compensate the transport due to entrainment and inflow at the pump intake.

The assumption that the plume covers a relatively small area is a good approximation when the plume model is implemented in regional models with relatively large horizontal grid sizes. The plume model is assumed to have a constant volume $V_0 = \delta a(t)\ H_0(t)$, where changes in water level (H_0) are compensated by changes in the surface area of the plume. Horizontal transports between the surrounding grid and the plume grid are determined by an upwind scheme.

The buoyant plume model considers the inflow to the oxygenator and the outflow is represented as a point source of buoyancy and dissolved substances. The buoyancy flux (F) at the bottom of the pipe is determined from the flow rate through the pipe (π_0) and the buoyancy as: $F = \pi_0 B$ where the buoyancy is given by $B = g\ (\rho_0 - \rho_p)/\ \rho_0$. The densities ρ_p and ρ_0 represents the density in the plume and in the surrounding water, respectively, and g is the acceleration of gravity. The water is assumed to ascend when $B > 0$ and the entrainment of surrounding water then depends on the horizontal buoyancy difference and the height (z_p) above the buoyancy source. From dimensional analysis (Turner 1979) the entrainment transport can be related to F and z_p as Eq. (3): $\varepsilon = \varepsilon_0 F^{⅓} z_p^{-⅓}$, where ε_0 is an entrainment parameter to be determined. Detrainment is assumed to take place at the plume top level where $B \leq 0$. A compensating return flow (γ_k) for balancing the entrainment from the "regional" grid cell where the plume is located, is assumed below the detrainment depth level and, correspondingly, a return flow of π_0 is assumed to take place towards the intake of the pipe (*Figure 5-6*). The compensating return flow due to the entrainment and pump intake results in a local mass balance within a single vertical column in the regional model.

5.1.5 Model validation against a tracer release experiment in Sandöjärden

A tracer release experiment was carried out with rhodamine (a non-toxic, fluorescent red substance) in Sandöfjärden in August 2010 (Info Box 5-3). The aim of the experiment was to observe the spreading of the buoyant plume directly by monitoring the rhodamine distribution. The rhodamine was added to the water at the intake of the pump and subsequently the fluorescence from rhodamine was measured in the surrounding water.

Info Box 5-3: Rhodamine experiment in Sandöfjärden in August 2010

Measurements of temperature, salinity, oxygen and rhodamine were made on a closely spaced sampling grid within a distance of 300 m from the pump. Two 100 m long ropes were placed in a cross with the pump in the center and they were directed North-South and East-West, respectively. Two boats were operating during the experiment and close to the oxygenator they were maneuvered manually without engines along the ropes to reduce mixing in the surface layer. A single pump was started on the 3rd August at 12:03 and rhodamine was added to the intake of the pump. The experiment was carried out during calm weather conditions. Initially the rhodamine was measured close to the pump and immediately after the introduction of rhodamine a first section was made in the northward direction within a distance of 50 m from the pump (*Figure 5-7a*). Thereafter, a southward section was measured within a distance of 45 m (*Figure 5-7b*) followed by a westward section (*Figure 5-7c*). In the westward section rhodamine was only observed within a distance of 40 m from the pump, and this could be explained by the observed weak eastward current. After the end of the rhodamine release an eastward section was measured and the rhodamine was more dispersed and may have had advected away from the pump location (*Figure 5-7d*). Measurements and instruments are further described in the data report on the PROPPEN Rhodamine experiment and in Bendtsen et al. (submitted).

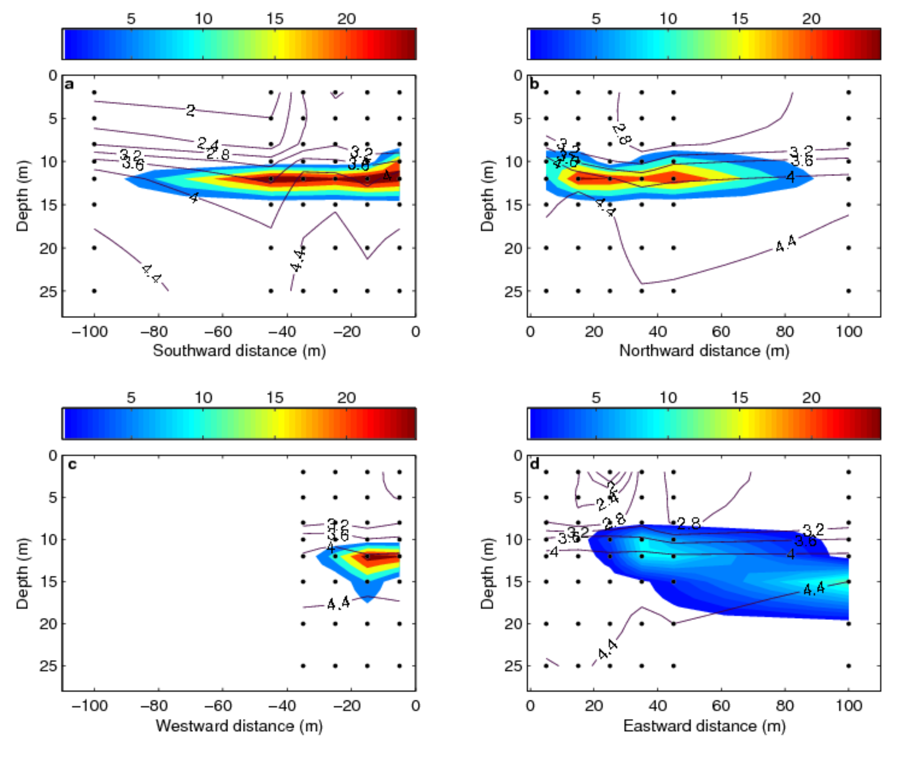

Figure 5-7. Rhodamine concentration (color scale in µg l^{-1}) along transects towards the South (a), North (b), West (c) and East (d). Black lines are contours of constant σ_t (kg m^{-3}). The rhodamine release ended at 17:39 and measurements at the transects started at 16:15 (b), 16:52 (a), 17:27 (c) and 17:54 (d), respectively.

Rhodamine was observed in a well-confined layer of water spreading laterally from the pump area and only minor concentrations of rhodamine were observed above the pycnocline. This observation suggests that the associated plume convection from the pump only transported a very limited amount of bottom water into the surface layer locally and that the lateral spreading mainly occurs below the pycnocline. Therefore the potential risk of directly transporting nutrient rich bottom water into the surface layer was considered minimal with the applied flow rate and the observed stratification. No significant amount of rhodamine was observed below a depth of 15 m and at a distance of 5 m from the pump. A direct influence from the pumping on the water close to the bottom was therefore not observed during the experiment. It is, however, probable that the relatively narrow plume just below the pump were not detected by the applied sampling grid. The entrainment of surrounding water into the rising plume would establish a compensating current close to the pump and thereby affect the circulation in the bottom layer. Therefore, a recirculation in the bottom water towards the pump may be significant but the duration of the rhodamine release was probably too short to re-circulate the rhodamine back to the plume area through the bottom layer.

By constraining the entrainment parameterization with the observed distribution of rhodamine the plume model simulations resulted in a mass distribution of rhodamine around the oxygenator and the lateral dispersion in accordance with observations. The total detrainment from the plume was found to be about 7 times larger than the pump rate from the oxygenator.

The sensitivity of the plume model to changes in the far-field current field and the total pump rate through the oxygenator was analyzed for different values of a constant east-west cross flow velocity (U) and pump rate (Q). Increasing the horizontal velocity from zero to 0.1 m s^{-1} led to a significant decrease in the height of the top level of the plume .The horizontal velocity caused an exchange with the plume at all depth levels and this reduced the height of the rhodamine plume compared to the case with no horizontal velocity (Bendtsen et al., submitted).

The distribution of the buoyant plume from oxygenation in the open sea may be affected by the far-field current field. The model simulations suggest that high current velocities would tend to bend the plume before it reaches its maximum top level. This behavior can be compared to the influence from the atmospheric flow on plume dynamics, i.e. the bending of smoke from a chimney in strong winds. Numerical ocean studies also suggest a strong relationship between the horizontal velocity and the top level of a buoyant plume (Lavelle 1997) in accordance with experience obtained from laboratory studies (Turner 1979).

5.2 Model analysis of coastal basin scale oxygenation

Coastal basin scale oxygenation was analyzed through high resolution 3D modeling of the two experimental sites: ***Lännerstasundet*** and ***Sandöfjärden***. The models are based on the COHERENS model system which is a primitive equation ocean circulation model (Luyten et al., 1999). The buoyant plume convection model, described in section 5.1, was implemented in the circulation model in the simulations described below.

A detailed model analysis was made of the oxygenation experiments in ***Lännerstasundet***. In particular, the experiment in June 2010 was analyzed because this three week experiment showed significant responses to the oxygenation. The model simulations were validated against observations of temperature, salinity, hydrogen sulfide and oxygen, and simulations with a passive tracer were performed to determine the dynamics and dispersion of water from the oxygenator. A sensitivity study with different pumping rates was carried out to determine the influence from different pumping rates on the temperature and oxygen in the water column.

In ***Sandöfjärden***, we analyzed the variations in temperature and oxygen close to the bottom which were observed from the near-bottom temperature and oxygen sensors. Model simulations with passive tracers were carried out to study the potential influence from pumping on the background mixing level.

5.2.1 Model simulation in Lännerstasundet

Lännerstasundet is a relatively small fjord-like basin in the Stockholm archipelago (see also Chapter 3 and 4). The bottom water of the basin is mostly anoxic and contains hydrogen sulphide (H_2S) during long periods between occasional inflows of new deep water. It is influenced by freshwater from Lake Mälaren, and is connected to nearby basins by shallow sill passages.

The model setup corresponded to the conditions in the experimental setup of the oxygenation field experiment described above (cf. Chapter 3 and 4). In the field experiment, the pump was placed above the deepest part of the basin where it pumped water from 3 m depth to near bottom depths with a pumping rate of 1 $m^3 s^{-1}$. The pumping started on the 1st of June and temperature, salinity, oxygen and hydrogen sulphide were monitored regularly during pumping. H_2S was oxidized and the oxygen content of the bottom water increased from anoxic to 2-4 mg l^{-1}. The observations also showed that the temperature of the bottom water increased due to downward pumping of warmer surface water. The pumping continued until 21st of June and after then the basin water was completely oxygenated.

Info Box 5- 4: Model set-up of Lännerstasundet

The model set up for Lännerstasundet was based on the COHERENS model (Luyten et al., 1999) and was formulated on a 40x40 m Cartesian grid (*Figure 5-9*) with 30 vertical sigma layers. The vertical turbulent diffusion was described by a k-ε closure scheme. Oxidation of H_2S occurred at a constant oxidation rate of $5 \cdot 10^{-5}$ µM s^{-1} when oxygen was present and the pelagic respiration of oxygen (or production of H_2S if there were no O_2) was described by a constant sink of $2.2 \cdot 10^{-5}$ µM O_2 s^{-1}, corresponding to an export to the bottom water of 10 g C m^{-2} $month^{-1}$ (this was estimated from observed changes in nutrient concentrations in June 2008 below the mixed layer). The model domain was 1.4 km long and 0.6 km wide, the maximum depth was 19.7 m and the maximum sill depth towards the west was 6.0 m and towards the north (in the eastern part of the basin) it was 3.8 m.

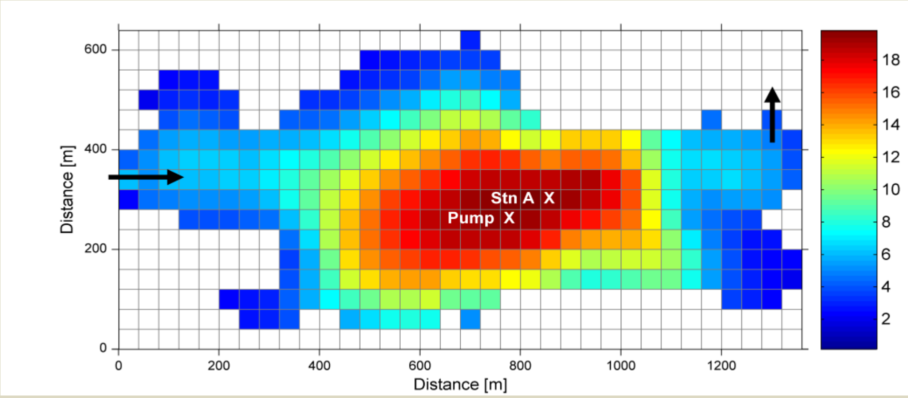

Figure 5-9. Model bathymetry of Lännerstasundet. The color scale shows depth in [m] and the pump and observational station A, situated about 100 m from the pump, are indicated. The two arrows indicate the in- and outflows to the area.

The model was forced with hourly meteorological fields of air temperature, insolation, wind stress, cloud cover and relative humidity obtained from a weather station located at Lännerstasundet. Initial fields of temperature, salinity, oxygen and hydrogen sulphide are obtained from profiles observed the 31st of May at a station located in the deep part of Lännerstasundet (St. A).

A general through flow of surface water from west to east was observed during the experimental period. This through flow was considered in the model because it was found to be important for maintaining the shallow mixed layer with a depth of only a few meters. Therefore a flow of 1.3 m^3 s^{-1} across the western and eastern sills was prescribed in the model.

At the open boundaries a no-flux condition was applied for temperature where as the salinity was prescribed from observations made the 31st of May at Stn A. A no-flux condition was applied for H_2S, O_2 and the passive tracer (rhodamine). The oxygen at the sea surface was set to be supersaturated by 15%, in accordance with observations during the experimental period.

The buoyant plume model (cf. section 5.1) simulated the dynamics related to the pumping of near surface water deeper into the water column. The plume model was located at the central deepest part of the basin (*Figure 5-9*), and water was pumped from 3 m to 16 m depth with a pumping rate of 1 m^3 s^{-1} in accordance with the conditions in the field experiment.

5.2.2 Results model simulations in Lännerstasundet

In accordance with observations the model simulation was effectively ventilating the bottom water. Simulations with a passive tracer (referred to as "rhodamine" below) showed that the buoyant plume rose from the outlet close to the bottom to its top level below the pycnocline, where it subsequently spread laterally (*Figure 5-10*, t = 1-10 days). The entrainment of deeper water into the plume mixed the bottom waters via a basin wide recirculation and the rhodamine gradually filled the bottom water of the basin (*Figure 5-10*, t = 10-20 days). Temperature increased correspondingly in the bottom water due to the downward transport of warm surface water.

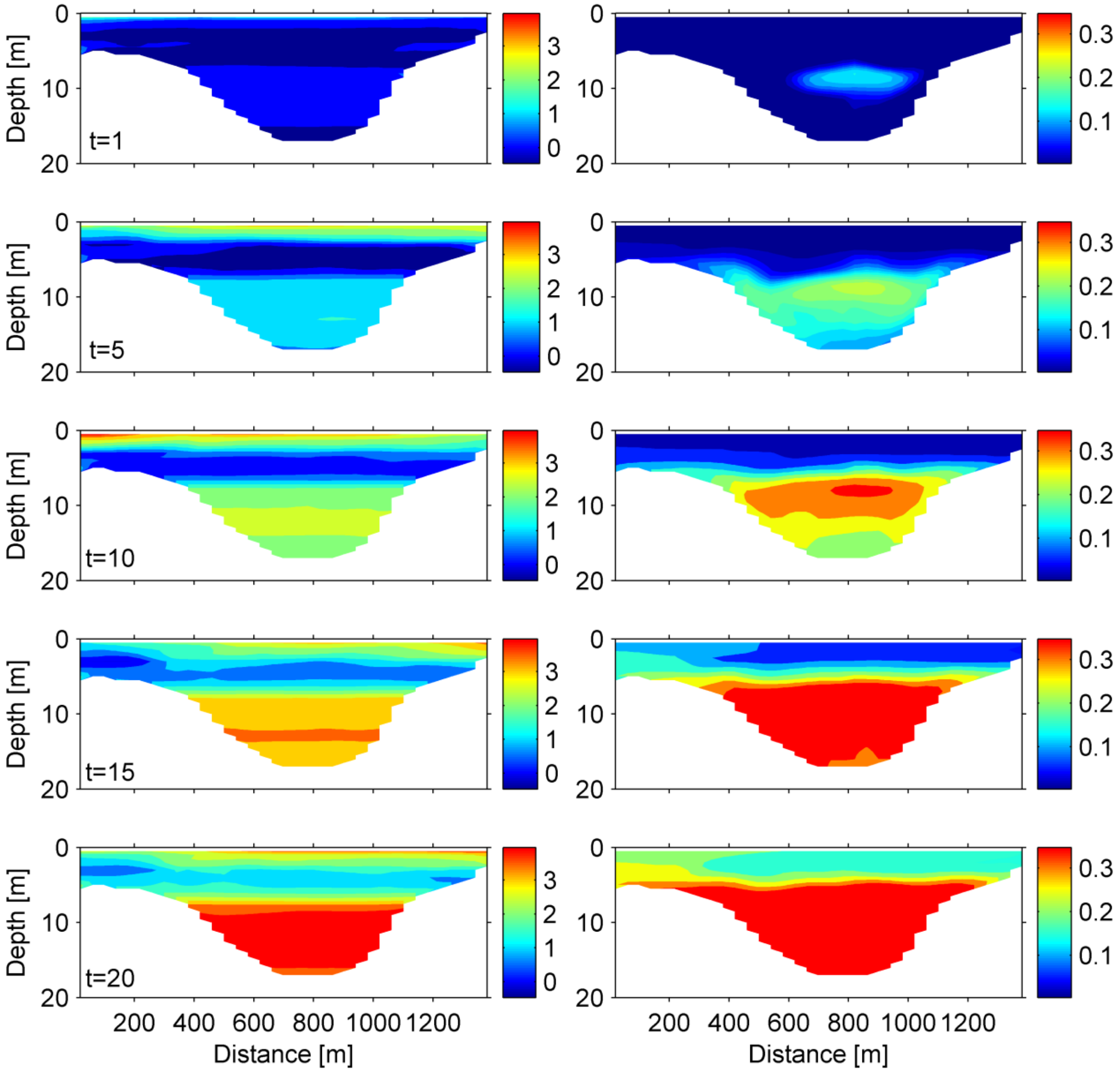

Figure 5-10 . Model simulations in a West-East transect across Lännerstasundet after t = 1, 5, 10, 15 and 20 days of pumping. Left panels show the difference in temperature [°C] compared with the initial values. Right panels show the simultaneous distribution of rhodamine.

Model solutions with a pumping rate of 1 m^3 s^{-1} were in good accordance with the observed distribution of temperature during the 21 days of pumping (*Figure 5-11*). Direct comparison between model simulations and the observed vertical profiles of temperature and salinity in the end of the experiment by the 21st of June showed a good accordance (*Suppl. Figure S5-2-1*). A case without a pump was also analyzed and this case showed a minor change in the bottom water, and could therefore not explain the observed temperature changes (*Figure 5-11*, lower panel). Corresponding changes in oxygen concentration was measured during the period and model simulations showed a good accordance between observations and model results in the case where a pump rate of 1 m^3 s^{-1} was applied in the simulations (*Figure 5-12*). The case without pumping could not explain the observed oxygen distribution during the period (*Figure 5-12*, lower panel).

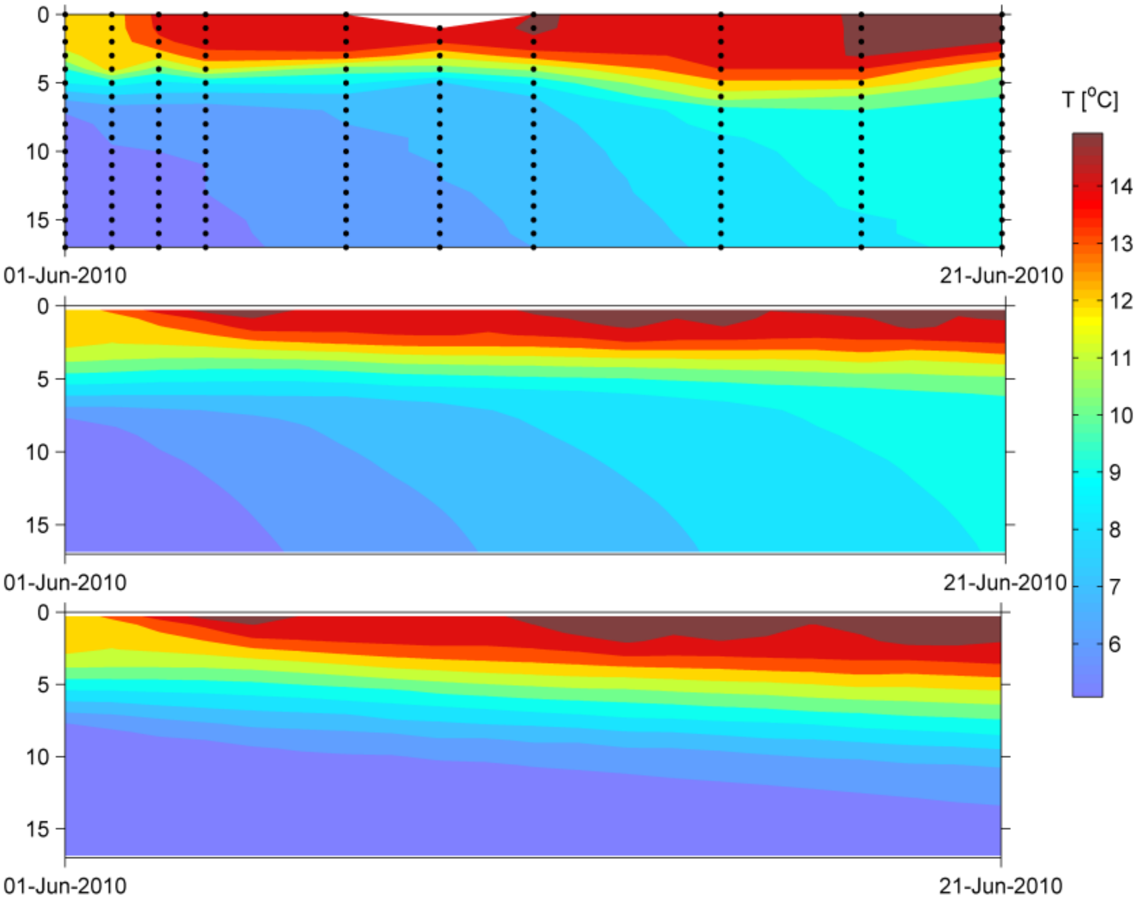

Figure 5-11. The temperature observed in Lännerstasundet from 1st - 21st of June (top panel). Model solutions with a pumping rate of 1 m^3 s^{-1}, corresponding to the Mixox pump rate (middle panel). Model solution without pumping is shown in the lower panel. Observations are marked by dots.

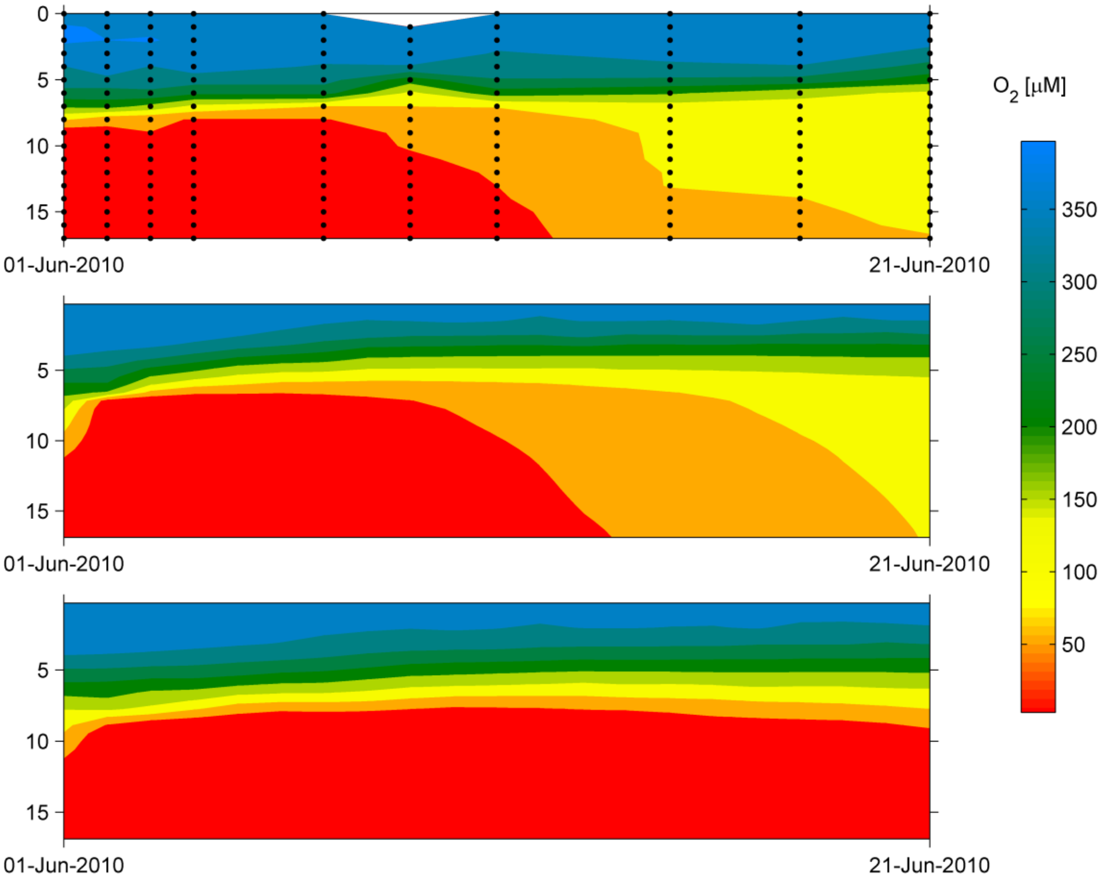

Figure 5-12. The oxygen observed in Lännerstasundet from 1st - 21st of June (top panel). Model solutions with a pumping rate of 1 $m^3 s^{-1}$, corresponding to the Mixox pump rate (middle panel). Model solution without pumping is shown in the lower panel. Observations are marked by dots.

In line with the monitoring observations, the model simulations also showed that the temperature of the bottom water increased significantly due to the downward pumping of warmer surface water. A model sensitivity study quantified the influence from different pumping rates on bottom water temperature in three cases where the pump rate was 0, 1, and 2 $m^3 s^{-1}$, respectively. The temperature in the bottom water increased by about 3.5 °C by the 21st of June with a pump rate of 1 $m^3 s^{-1}$ compared to a case without pumping (*Figure 5-13*). In the case with a pump rate of 2 $m^3 s^{-1}$ the bottom temperature increased by about 4 °C.

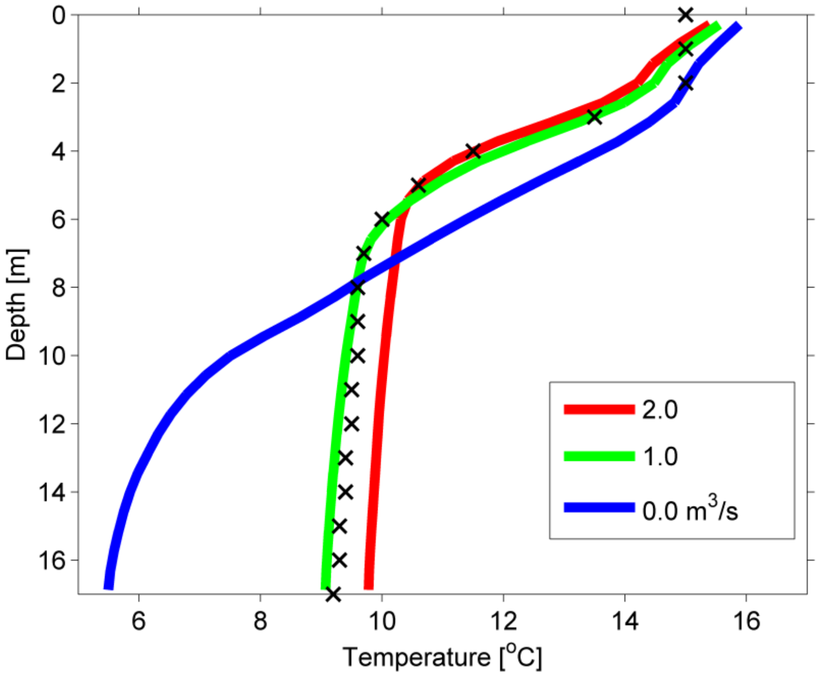

Figure 5-13. Model simulation of temperature at station A (100 m from the pump) at the 21st of June with a pump rate 0 $m^3 s^{-1}$ (blue), 1 $m^3 s^{-1}$ (green), and 2 $m^3 s^{-1}$ (red). Crosses are observations at the 21st of June.

It was found that the model simulation of oxygen was sensitive to the initial conditions of H_2S and if only the initial profile of H_2S was extrapolated horizontally from the profile at St. A, the model simulations resulted in too high oxygen concentration after three weeks of pumping. We suggest that this difference were due to an underestimation of the actual initial amount of H_2S present in the basin, as explained below.

The observed and simulated amounts (moles) of H_2S and O_2 below 10 m depth are shown in *Figure 5-14*. In order to achieve the same oxygen levels as observed at the end of the experiment, the initial H_2S field had to be increased by a factor of about 3 (*Figure 5-14*, lower panel). We suggest that such a difference could be explained if high concentrations of H_2S were present along the bottom also at shallower depths and therefore the amount of H_2S would have been underestimated by using a H_2S profile from the center of the basin as representative for the depth distribution. Other possibilities could be an underestimation of the respired organic material and also inflow of oxygen poor water from nearby basins could reduce the oxygen in the bottom water.

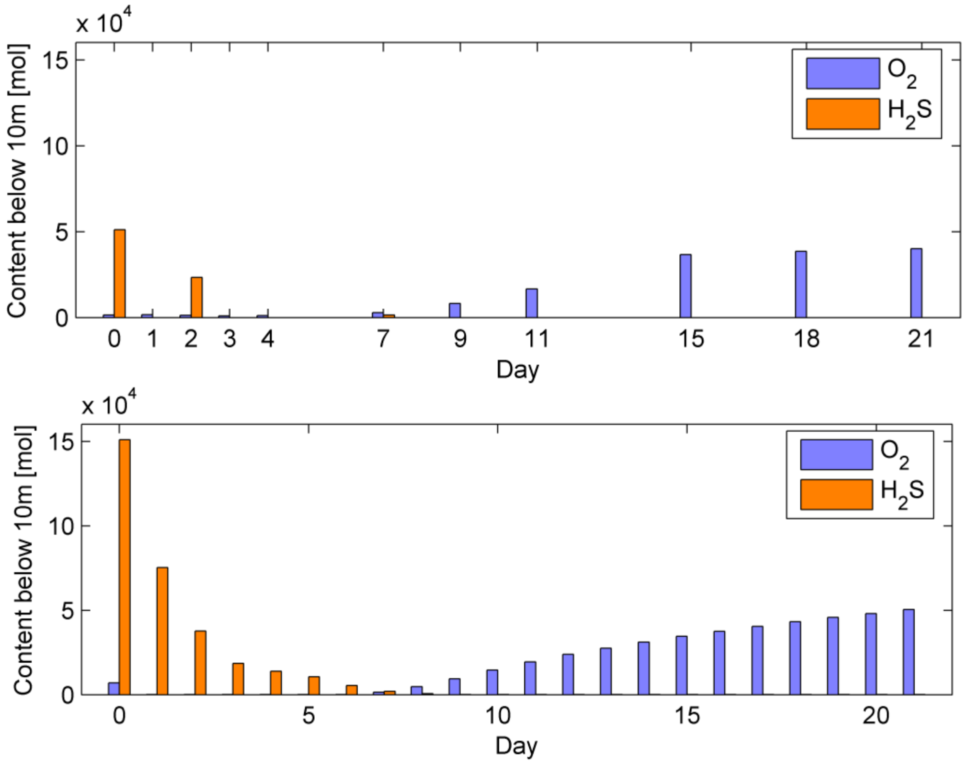

Figure 5-14. Observed (top panel) and simulated (lower panel) O2 and H2S content (mole) below 10 m depth. The x-axis indicates day in June 2010, where 0 is the initial value at 31st of May.

5.2.3 Simulation of near-bottom mixing in Sandöfjärden

Sandofjärden is a semi-enclosed archipelago basin in the northern Gulf of Finland by the Finnish southern coast. It is connected to nearby basins by several passages. The maximum depth of the basin is 31 m, and the basin water is regularly anoxic during the summer season (cf. chapter 2).

During the oxygenation in Sandöfjärden, time series of temperature and oxygen close to the bottom were recorded with a high temporal resolution (~5 min). The observations showed relatively large variations of both temperature and oxygen on short time scales (*Suppl. Figure S5-2-2*). The time series were analyzed for the impact of any periodic forcing but no particular frequency (with periods above about 10 minutes) could explain the observed variability. A possible explanation of the observed variability could be due to an increase in the mixing intensity due to the pumping. This was investigated through high resolution 3D modeling of Sandöfjärden together with the buoyant plume model described above (cf. section 5.1). Passive tracers were used in a sensitivity study with different pumping rates to determine the influence from pumping on the background vertical mixing levels.

Info Box 5-5: Model setup for Sandöfjärden

The model set up for Sandöfjärden was based on the COHERENS model (Luyten et al., 1999) and formulated on a 100 m x 100 m Cartesian horizontal grid and 60 vertical sigma layers. The buoyant plume convection model (cf. section 5.1) simulated the dynamics related to the pumping of near surface water deeper into the water column. In the model setup, 6 pumps were placed above the deepest part of the basin in accordance with the field experimental setup and water was pumped from 3 m depth below the surface to 5 m above the bottom. The model was integrated for a two month period from the 1st of June to the 1st of August, and weather forcing from 2007 is applied. The model bathymetry is shown in *Figure 5-15*. The model domain is about 8 km x 5 km. The maximum depth is 31 m. The maximum depth of the model bathymetry is 26.9 m. Initial fields of temperature and salinity were obtained from observations at the monitoring station in Sandöfjärden from the 22nd of May 2007. A no-flux condition was applied along the boundaries of the model domain.

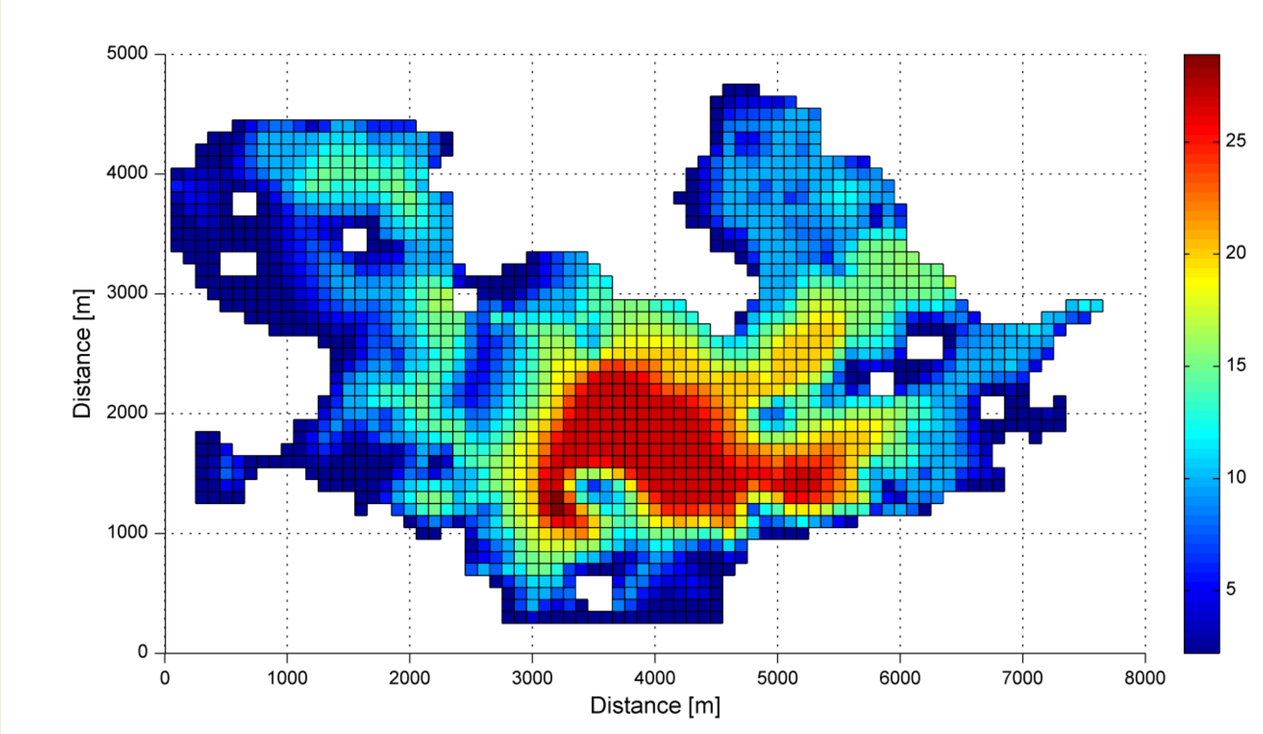

Figure 5-15. Bathymetry of ***Sandöfjärden*** in the model domain on a 100 m x 100 m grid. The color scale show the depth in meters.

The general model response to the pumping was analyzed by simulating a two month period from June to August, and as a reference the meteorological forcing from 2007 was chosen. The purpose was to analyze whether the pumping activity in general could induce significant additional mixing close to the bottom in the model.

The model was analyzed in three cases with different pumping rates (q): Case I with q = 0 m^3 s^{-1}, Case II with q = 1 m^3 s^{-1}, and Case III with q = 2 m^3 s^{-1}. In order to reveal the influence of different pumping rates on the background vertical mixing levels, a passive tracer were initially added to the near bottom water. The tracer was added in the grid cell in the model just above the bottom and the initial concentration was assigned the value of one.

During the simulation the tracer gradually became mixed upward in the water column and thereby the concentration above the bottom decreased with time. The average concentration just above the bottom in the center of the basin showed an almost exponential decrease in the case without any pumping activity, as would be expected due to the vertical background mixing in the model (*Suppl. Figure S5-2-3*). Including the pumping from six pumps in case II and III increased the near-bottom vertical mixing and the concentration of the passive tracer decreased significantly faster than in Case I. The mixing intensity increased by about 5 and 10 % in case II and III, respectively. This indicates that part of the short-time variability in oxygen observed by automatic monitoring could have been due to the pumping.

5.3 Model analysis of regional scale oxygenation

The potential of regional scale oxygenation for increasing oxygen content of near-bottom water and phosphorous retention in the sediment was assessed through an analysis of several Baltic Sea model simulations. From our current understanding of the pumping oxygenation, as described in the two previous sections, depending on the oxygenation efficiency, there will be direct effects from oxygenation on the sediment below the pumps but these may have a very limited impact on regional scales. Therefore, the focus in this section is on the effects caused by the relatively oxygen rich water which spreads out from the top level of the buoyant plume region around the oxygenator. The top level is generally located just below the pycnocline (comparable to the observed spreading of water below the thermocline in the rhodamine experiment in Sandöfjärden, cf. section 5.1). In case oxygen enriched water reaches the sediment in areas where the pycnocline meets the bottom, i.e. at a sloping bottom, the oxygen concentration above the bottom may increase and potentially this would increase the oxygen concentration in the upper part of the sediment. At the sediment-water interface the transport of oxygen is regulated by molecular diffusion and, therefore, depends on the concentration of oxygen in water just above the sediment surface and in sediment pore water and these near-bottom processes are not resolved in the analysis below. However, the resulting near-bottom oxygen concentration depends on the pumping capacity and the duration of the pumping.

A number of different cases have been analyzed where both the role of pumping capacity, location and the depth of intake and outlet of the pumps were considered. The different cases were supposed to provide a qualified estimate of what dynamical changes there might follow oxygenation on larger scales and also of how much pumping capacity there would be needed to obtain a given change in near-bottom oxygen concentrations. Reducing the pumping capacities in the different cases would reduce the oxygenated areas but this could be compensated if the duration of the pumping was increased accordingly. This would in particular be the case for the deep oxygenation where the pumped water is taken from below the seasonal thermocline, i.e. the “Baltic Sea” case below. Therefore the listed total pumping capacities (Box 5.7) are intended for making an estimate of the relative impact of a given scenario, and not to be adopted as specific optimal values.
It is emphasized that the relatively high pumping capacities applied in the simulations are used for determining the model sensitivity to pumping oxygenation. Thus, using high total pumping efficiencies will give us indications of the possible effects of long-term pumping of longer periods with relative smaller total pumping capacities.

Info Box 5-6: Baltic Sea Model Set-up

The Baltic sea model was based on the COHERENS model system (Luyten et al., 1999). The model domain was formulated on a 2 x 2 nautical mile horizontal grid (about 3700 m x 3700 m) and the model has 30 equidistant vertical sigma-layers (*Figure 5-16*). The model was forced with 6-hourly meteorological forcing fields. Runoff from rivers were derived from a data set based on 81 rivers and 48 point sources located around the Baltic Sea for the period 1995 - 2000.

In addition to runoff, loadings of N, P and Si were also included in monthly resolution for the period 1995 - 2000. Fields of Atmospheric deposition of N were included as annually averaged climatologies. The physical model has been validated for the Gulf of Finland area in an international inter-comparison project (EMAPS) and the results and model description are further described in Myrberg et al. (2010).

The biogeochemical model includes three functional phytoplankton groups, one zoo-plankton group and two organic carbon pools. Particulate organic matter (POM) was sedimented in a fluff layer and benthic and pelagic remineralisation included aerobic and anaerobic remineralisation (considering O_2, NO_3^- and SO_4^{2-}). Model integrations of temperature and salinity was started in January 1996 and integrated until 1st of May. A field of nutrients and oxygen derived from observations from stations representing the whole Baltic sea in April 1996 was used as initial fields for integrating the coupled physical-biogeochemical model from May to September.

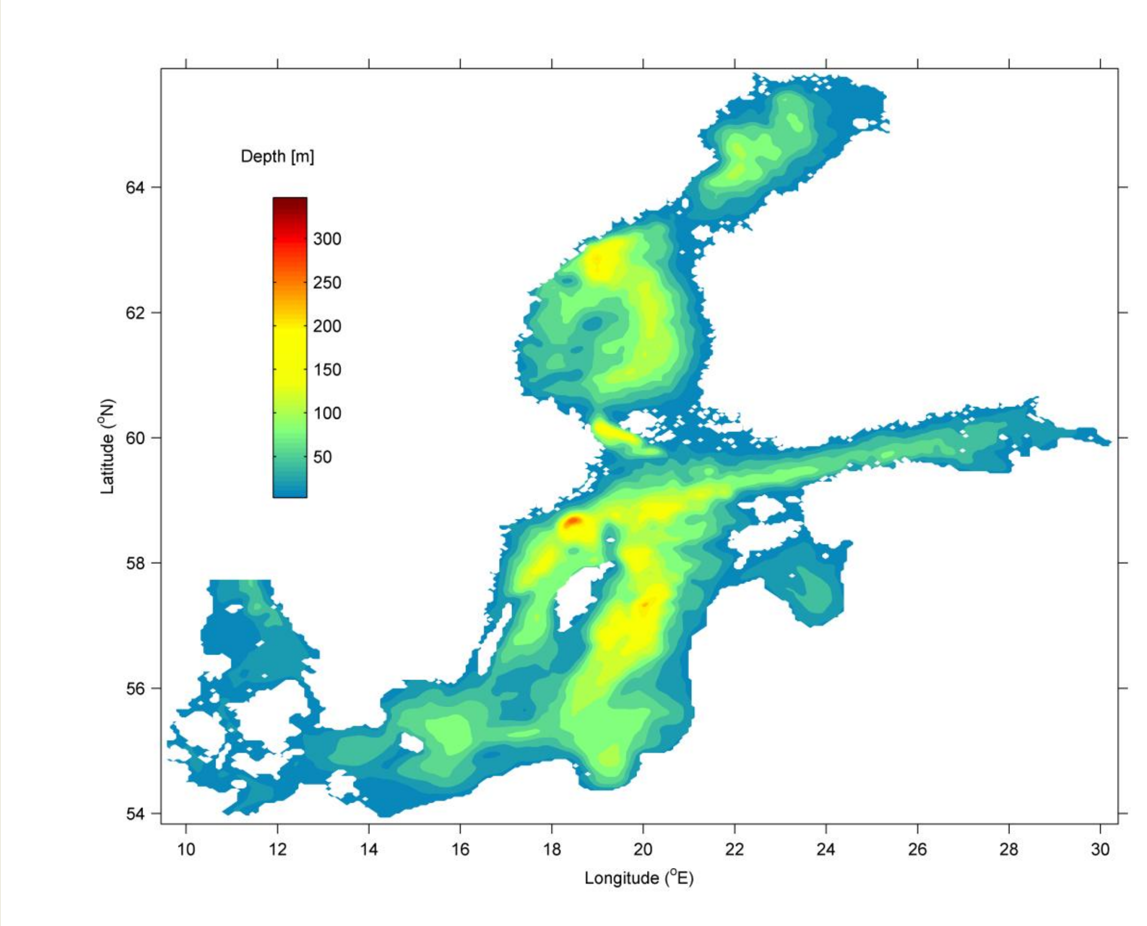

Figure 5-16. Baltic sea model bathymetry.

5.3.1 Baltic sea model validation of temperature, salinity and oxygen

Validation of the applied physical model setup for the Gulf of Finland (GoF) has been described in detail in Myrberg et al. (2010). Further validation of water level, temperature, salinity and oxygen for different stations in the whole Baltic Sea region is given below.

Water level at Helsinki shows a relatively large variability due to the general in- and outflow to the Gulf of Finland. This dynamics is primarily regulated by winds over the surrounding areas, air pressure and the density distribution (Alenius et al., 1998). The model simulation was in general accordance with the longer term variability of the sea level variations observed in Helsinki (*Figure 5-17*) and this supported the capability of simulating the general water transports to the Gulf of Finland. Deviations between observations and model simulations were seen during some periods and this may have been due to the initial conditions, a too coarse meteorological forcing or other limitations in the model setup.

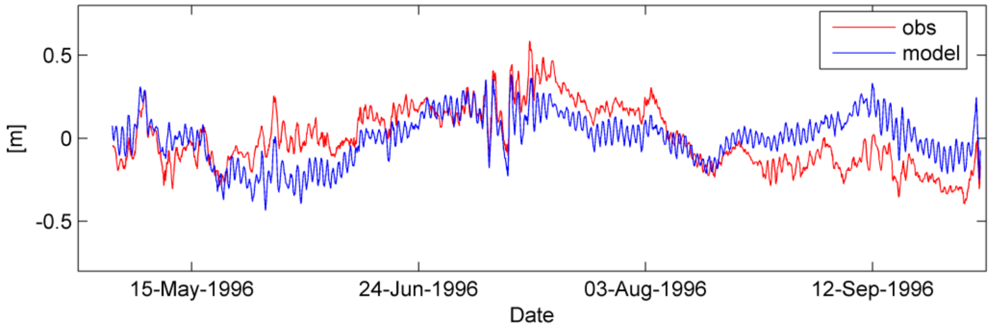

Figure 5-17. Example of observed (red) and modeled (blue) water level at Helsinki.

Model simulations of temperature, salinity and oxygen are shown for a station located at the entrance to the Gulf of Finland (Längden) and in the Baltic Proper (B29) and a general agreement is seen between observed fields and the model solutions for the two stations (*Figure 5-18*). The model did not describe the observations in all details, but overall the seasonal thermocline was well described as well as the formation of low-oxygen bottom concentrations during late summer. Also the formation of a cold intermediate layer centered around 50 m depth in the Baltic Proper was simulated well (the so-called winter water) and intake of this relatively cold water mass was used in the design of one of the pumping cases described below.

The Baltic Sea model was applied in a study of the regional impact from oxygenation. The impact from oxygenation was assessed through a sensitivity study where the relative change between a reference simulation (with no pumping) and the various model cases are determined, as outlined below.

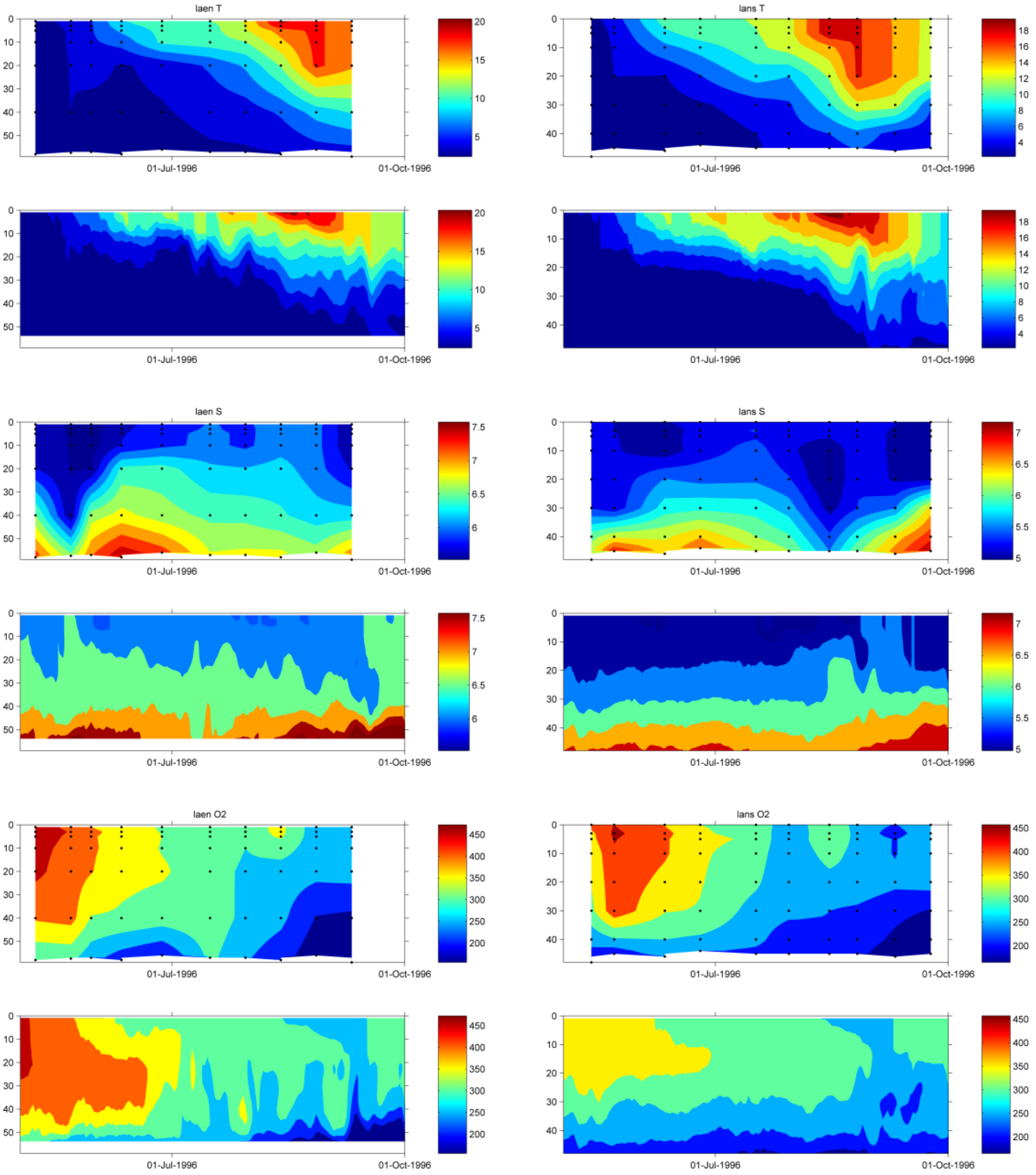

Figure 5-18. Validation of T, S and O_2 at Längden (left) and BY29 (right). Observations (dots) are shown in the upper panel and the model solution from May - September 1996 is shown in the lower panel.

5.3.2 Description of three scenario cases of oxygenation

Three cases of model simulations were performed to analyze the effects of pumping. One with pumps located in both the Baltic Proper and in the Gulf of Finland (Case I), and two cases where pumps were located in the coastal (Case II) and deep or open Gulf of Finland (Case III), respectively (Info Box 5-7).

In case I, pumps were placed so that the pumping intake was located at 50 m, corresponding to the depth level of the relatively cold winter water below the permanent halocline and down to 5 m above the bottom in the Baltic Proper. Potential effects on the sediment were expected along the coasts where the pumps are placed. In case II, the purpose was to ventilate the coastal areas of the Gulf of Finland, so the pumps were distributed as close to the coast as possible, but with a minimum depth of 30 m. In case III, the pumps were distributed above the deepest parts of the Gulf of Finland in order to ventilate the deeper waters of the basin. A detailed description of the three cases was given in table 5-1 and the locations of the pumps in the various cases were shown in *Figure 5-20*.

Table 5-1. Model simulations of oxygenation. The experiments f1-f4 analyzed the dynamical changes from oxygenation in the Gulf of Finland and the experiments f7-f9 considered the regional scale impact from oxygenation on the bottom oxygen concentration in the Baltic Sea and in the Gulf of Finland.

	Experiment ID	**Description**	**No. of pumps**	**Intake depth**	**Flow rate pr. pump ($m^3 s^{-1}$)**	**Total capacity ($m^3 s^{-1}$)**
Analysis of oxygenation on T, S, nutrients and transports	f1,f6	Reference	0	-	-	-
	f2	Case ll: Shallow GoF	90	3 m	100	9000
	f3	Case ll: Shallow GoF	90	3 m	500	45000
	f4	50% nutrient load reduction	0	-	-	-
Analysis of oxygenation on hypoxic area	f7	Case l: Baltic Sea	396	50 m or 25 m	300	118800
	f8	Case ll: Shallow GoF	90	3 m	300	27000
	f9	Case lll: Deep GOF	90	25 m	300	27000

Info Box 5-7: Three cases of Baltic Sea oxygenation

Three cases of model simulations were performed to analyze the regional effects of pumping.

Case I – Baltic Sea: 11 pump farms with 36 pumps in each, adding to 396 pumps in total. The minimum water depth at a pump location was 40 m in the Gulf of Finland and 66 m otherwise. Water was pumped from 50 m depth to 5 m above bottom with a rate of 300 $m^3 s^{-1}$, adding to 118800 $m^3 s^{-1}$ in total.
Case II – shallow Gulf of Finland: 5 pump farms with 18 pumps in each, adding to 90 pumps in total. The minimum water depth at a pump location was 30 m. Water was pumped from 3 m depth to 5 m above bottom, and different pumping rates were used.
Case III – deep Gulf of Finland: 5 pump farms with 18 pumps in each, adding to 90 pumps in total. The minimum water depth at a pump location was 68 m. Water was pumped from 25 m depth to 5 m above bottom with a rate of 300 $m^3 s^{-1}$, adding to 27000 $m^3 s^{-1}$ in total.
The model simulated the period from 1st of May to the 1st of October 1996. A number of model simulations, all listed in Table 5-1, were carried out to evaluate the effects of pumping in the three cases. This included a reference simulation (f1) describing the normal development during the simulation period, and in case II two different pumping rates were evaluated (f2, f3) as well as a simulation without pumps but with a 50% nutrient load reduction for comparison (f4). The first three simulations (f2-f4) were evaluated with focus on the effects of pumping on T, S, transports and nutrients, whereas the second group of simulations (f7-f9) were analyzed with the focus on reducing hypoxic bottom areas.

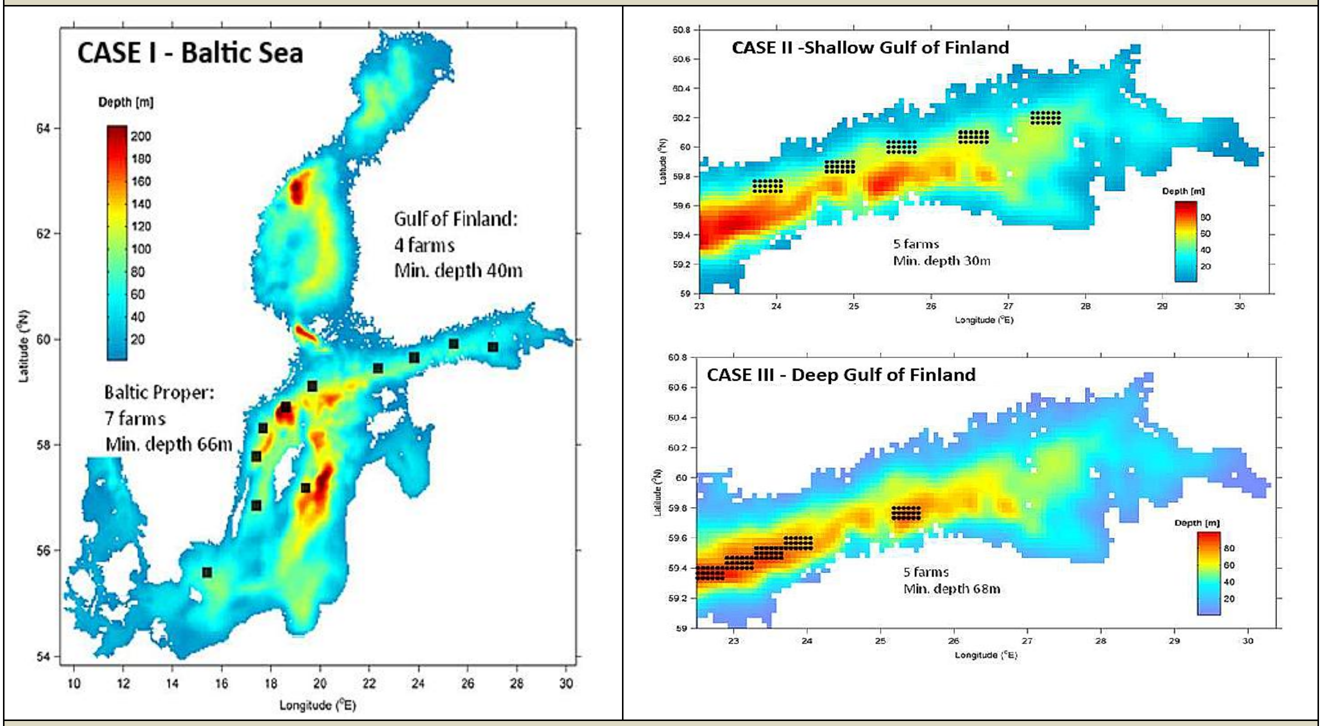

Figure 5-19. Locations of farms of oxygenators in Case I-III.

5.3.3 Simulated hydrodynamical changes from oxygenation in the Gulf of Finland

The impact of oxygenation on salinity and temperature in the Gulf of Finland was analyzed in case II in the experiments f1, f2 and f3 (*Table 5-1*). The model fields were compared after four months of simulation on 30th of August (*Figure 5-20*) were the seasonal thermocline reached the depth of about 20 m. The effect of 4 months of pumping was seen as a decrease in both salinity and temperature in the near-bottom water due to the downward pumping of warm surface water. The entrainment of cold bottom water, associated with the ascending buoyant plumes, caused a corresponding cooling higher up in the water column. The effects from the pumping were seen to increase with increased pumping rates.

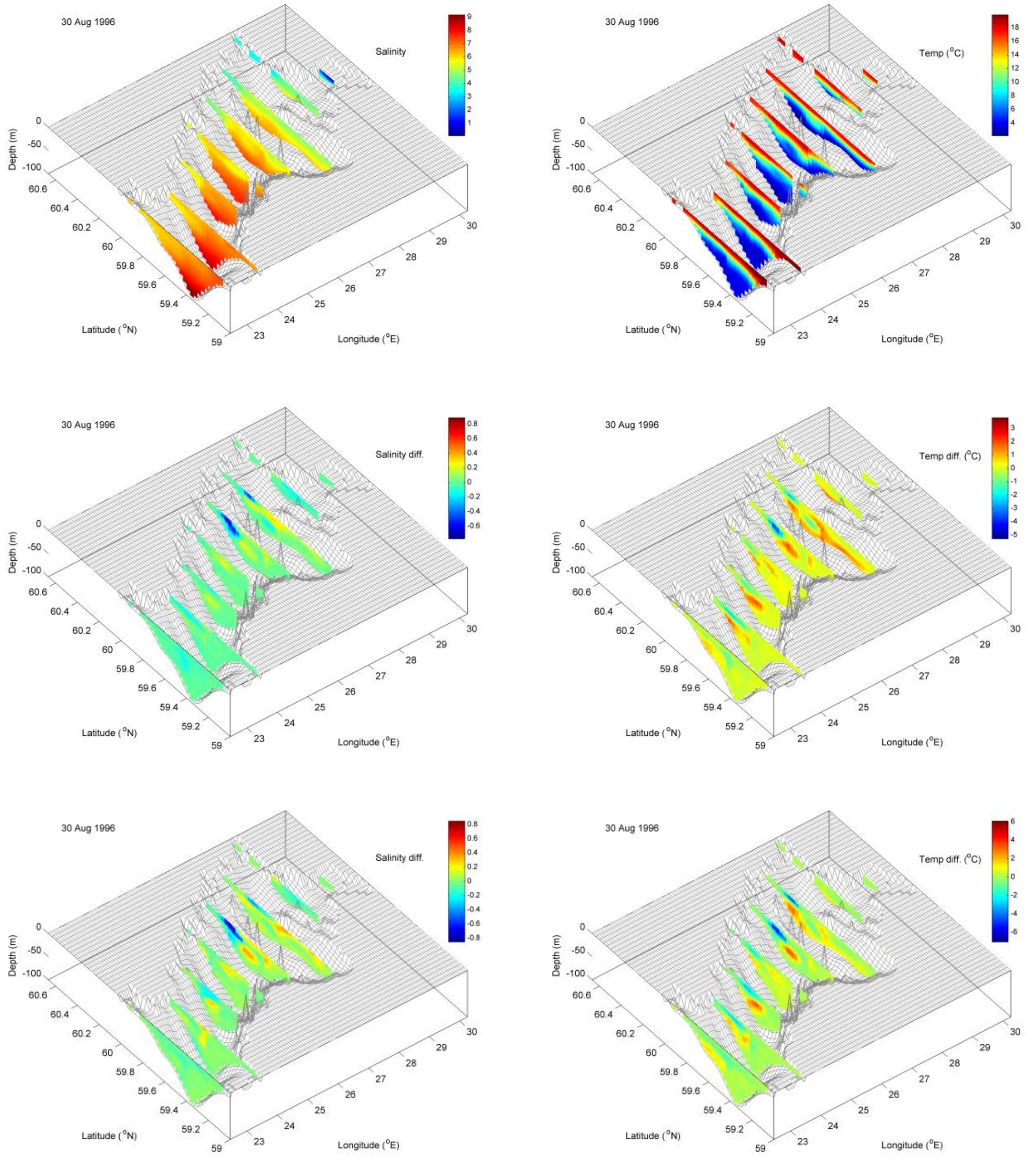

Figure 5-20. Fields of salinity (left) and temperature (right) for the experiment f1 (top panels), the difference between experiment f2-f1 (middle panels) and the difference between experiment f3-f1 (lower panels). Note the different color scales. (Details can be seen by zooming in on the figure in the electronic version of the report).

Figure 5-21 shows the passive tracer distributions (i.e. rhodamine, representing water originating from the pumps) after 3 to5 months of pumping in Case II and for two different pumping rates. The passive tracer distribution reflects the spreading of oxygenated water at intermediate depths (at the top level of neutral buoyancy) along the coast. The rhodamine is relatively well confined and is exported out of the model domain along the coast, although low tracer concentrations can be seen in the whole Gulf of Finland, especially for the case with large pumping rates (simulation f3, right panels of *Figure 5-21*). Significant amounts of the passive tracer reach the bottom (down to about 30 m depth) along the shallow coastal area (*Figure 5-22*).

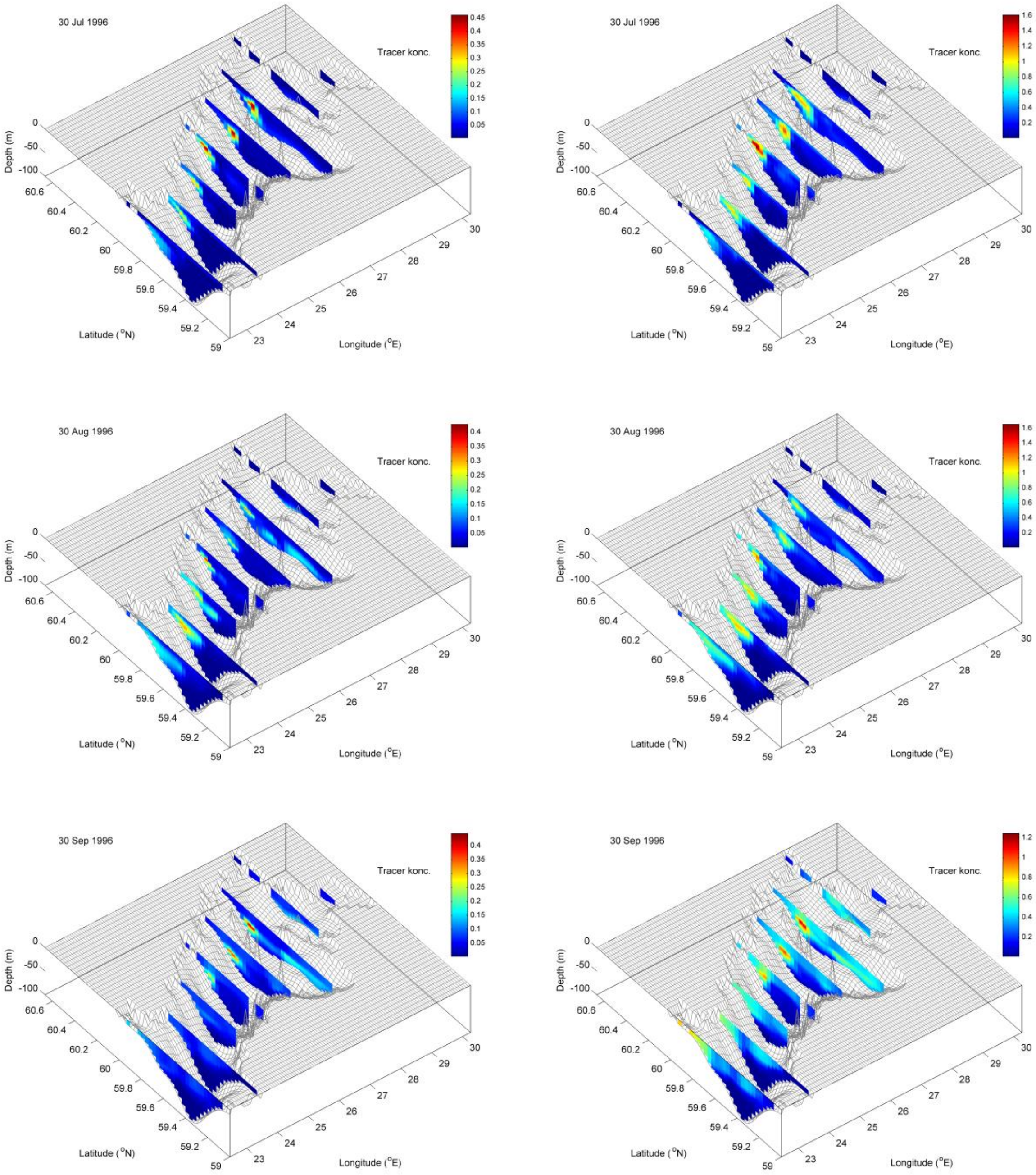

Figure 5-21. Passive tracer distributions for experiment f2 (left) and f3 (right) at 30th of July (top panels), 30th of August (middle panels) and 30th of September (lower panels). Note the different color scales. (Details can be seen by zooming in on the figure in the electronic version of the report).

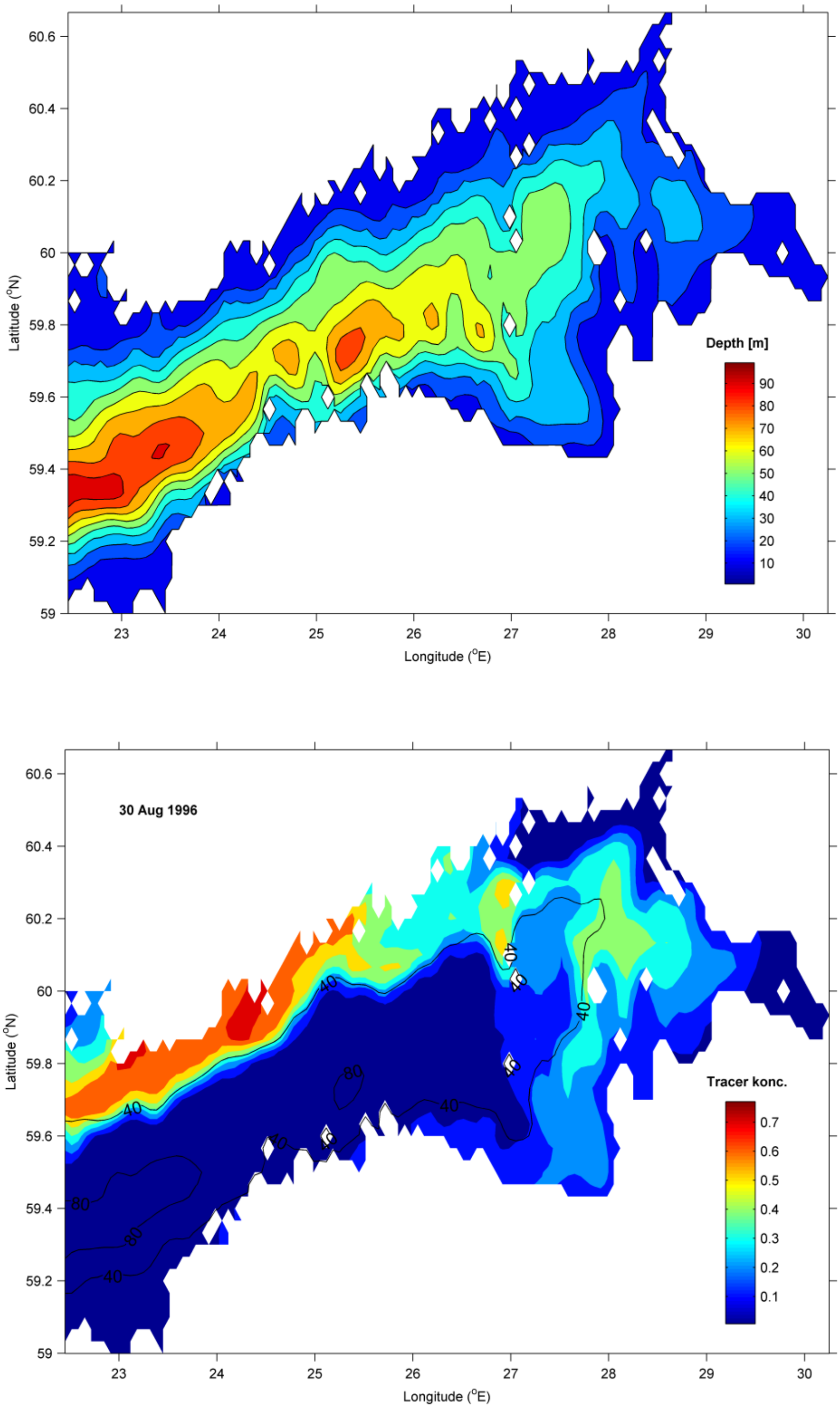

Figure 5-22. Depth in meters (top) and near-bottom distribution of the passive pump tracer for experiment f3 on the 30th of August (bottom panel).

Heat and salt transports were analyzed along transect across the Gulf of Finland at the entrance to the Baltic Proper (23.7 °E), and a case with a high total pumping capacity (case II, f3) was compared with the reference case (f1). The oxygenation increased the total salinity transport into to Gulf during the five month period with about 1 %. This change is relatively small compared to the total transports into the Gulf of Finland. The heat transport out of the Gulf increased in total by 13 % after five months. The change in heat transport is also relatively small compared to the general energy balance of the area.

After four month of simulations in the coastal Gulf of Finland case (case II, f2) the oxygenation caused the bottom water concentration of nitrate and phosphorous to decrease by up to 1 and 0.1 µM, respectively. Correspondingly, the coastal nitrate and phosphorous concentration in the outer coastal waters increases by up to 2 and 0.2 µM, respectively. The reference initial nutrient concentrations in the outer waters was about 5 and 0.5 for nitrate and phosphorous, respectively. The reference simulation of the nutrient concentrations in the Gulf of Finland were somehow higher than observations in the late summer period and this was probably due to a too high initial nutrient field in the inner part of the Gulf of Finland (this issue was improved in the f6, case I and case III experiments). However, the relative change between the case with coastal oxygenation (case II) and the reference simulation showed a significant increase of the nutrient concentration in the coastal waters in the Gulf of Finland.

5.3.4 Results of large-scale oxygenation simulations

Figure 5-23 shows the tracer distribution after 3 months of pumping in the Baltic Sea (Case I). As expected, the passive tracer spread laterally below the halocline of the Baltic Proper and reached nearby shallower bottom areas. The effects after 4 months of pumping can be seen in *Figure 5-24*, where both the reference simulation and the difference between the simulation with pumping and the reference are shown (i.e. exp. f7-f6). The effects on temperature and salinity were in general small, whereas the effect on oxygen was seen as an increase of oxygen levels in the deep water, and a decrease of oxygen in the more oxygen rich waters of the lower halocline. This change was consistent with the downward pumping of oxygen-rich water and subsequent entrainment of oxygen-poor water in the ascending plume. The pumping had mainly affected the near-bottom waters close to the oxygenators where the plumes meets the bottom (*Figure 5-25*), although small bottom temperature effects could be seen basin wide and at relative large distances from the locations of the oxygenators (*Figure 5-25*). Bottom oxygen levels rose in deep anoxic waters, and decreased in sub-halocline waters although the tracer concentrations were relatively low there (see, for example, the area of O_2-difference east of Gotland in *Figure 5-25*), suggesting a relatively high efficiency when pumping takes place over a large oxygen gradient into anoxic waters, and also that relative large bottom effects of the oxygenation can be obtained on the rim of hypoxic areas.

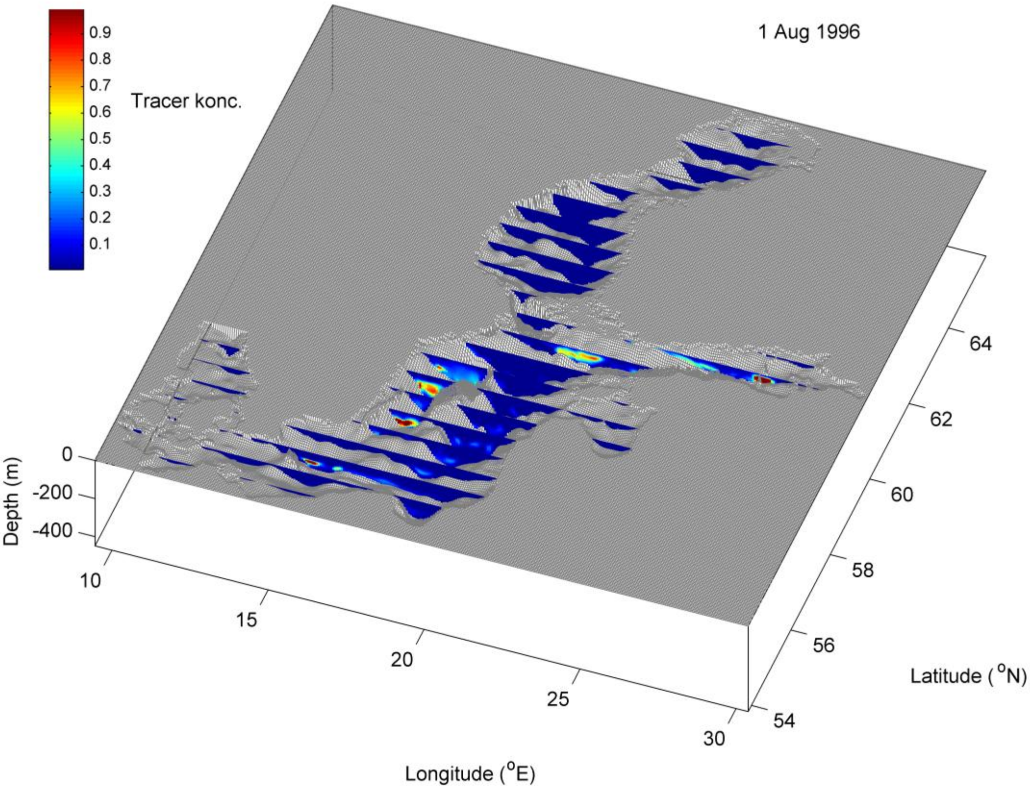

Figure 5-23.Tracer concentration in the Baltic Sea case I (f7) the 1st of August. (Details can be seen by zooming in on the figure in the electronic version of the report).

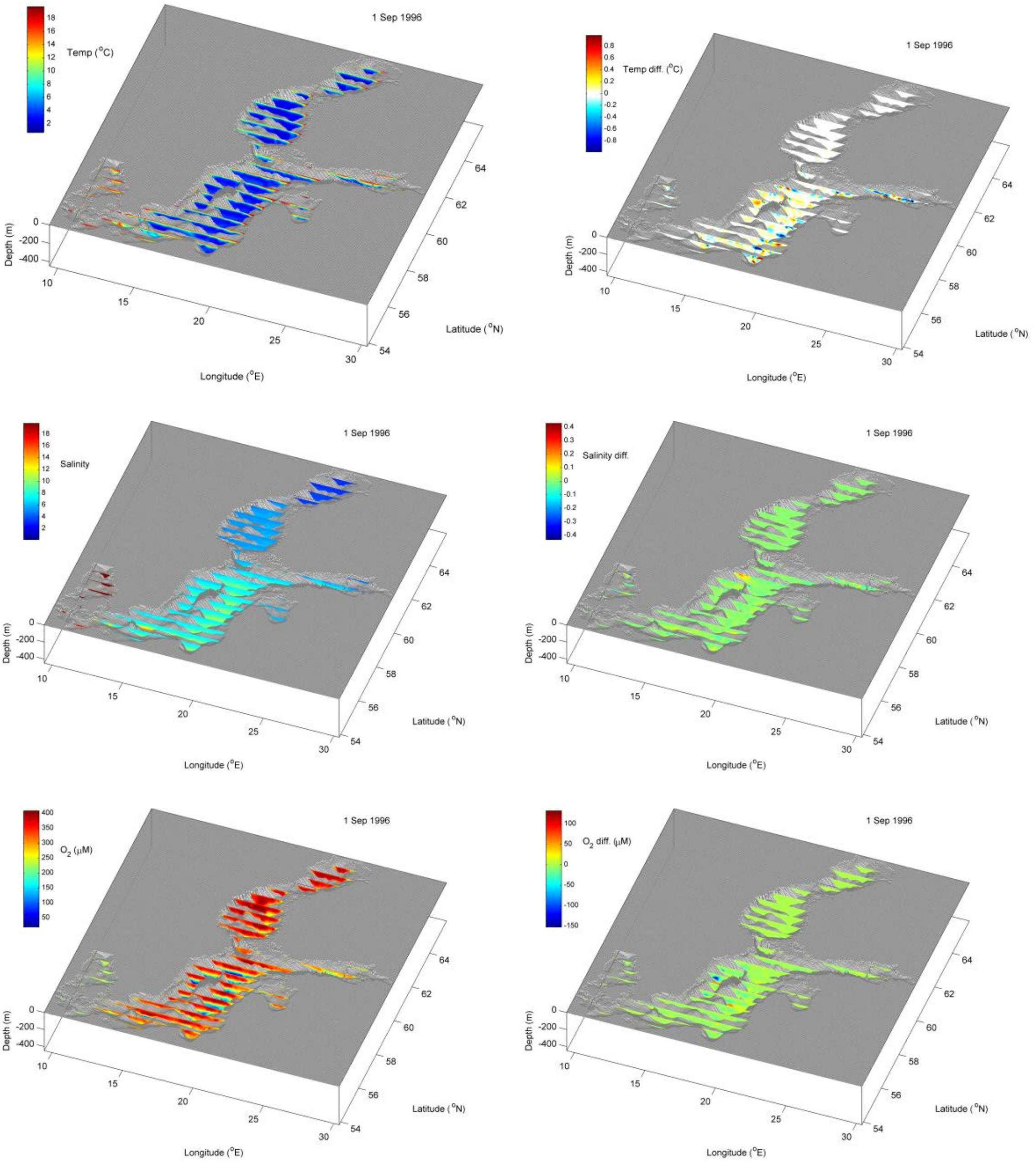

Figure 5-24. Temperature (top), Salinity (middle) and Oxygen (bottom panels) for the reference experiment (f6, left) and the changes in the Baltic Sea case I (f7-f6) at the 1st of September (right). (Details can be seen by zooming in on the figure in the electronic version of the report).

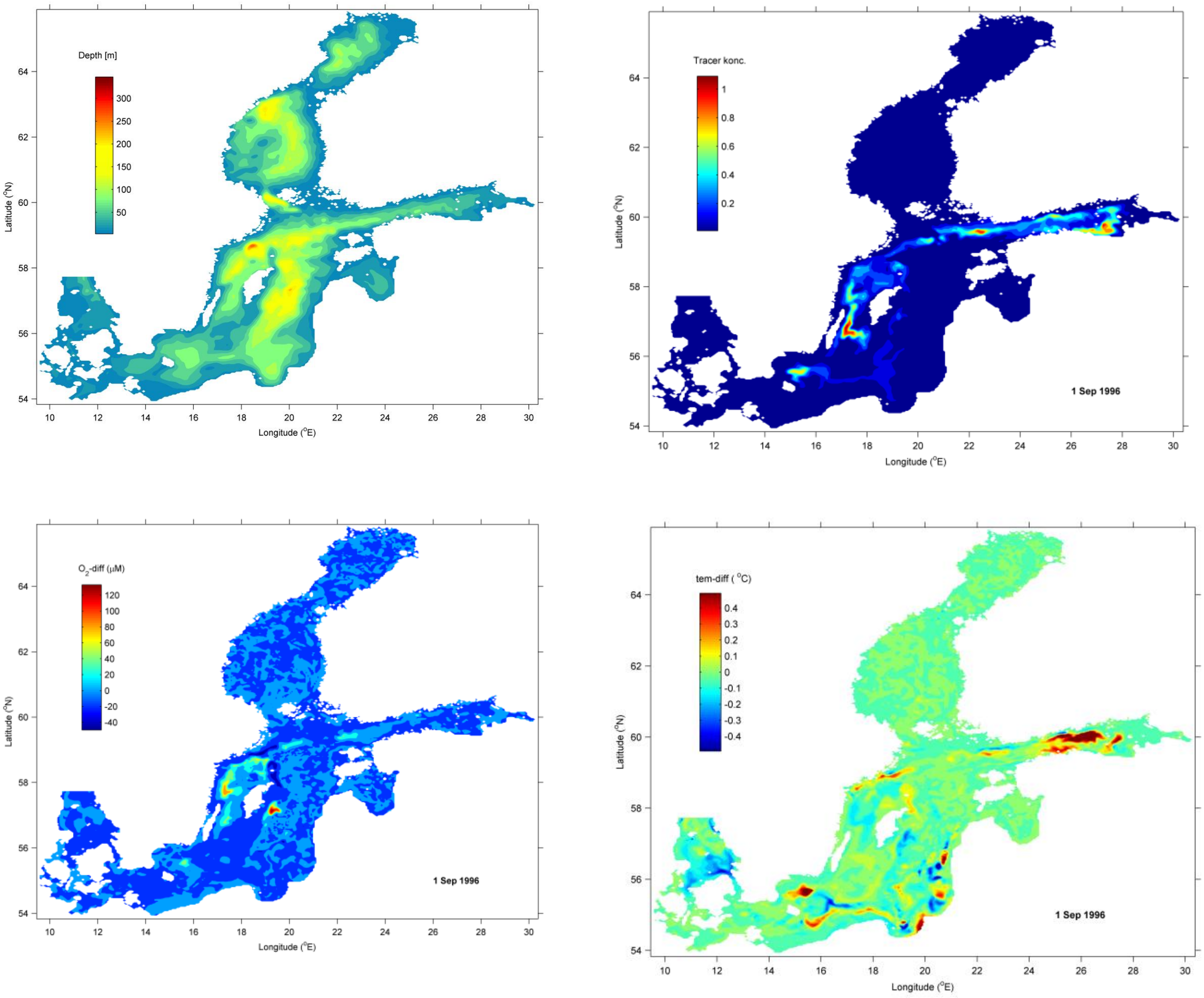

Figure 5-25. Depth (upper left), passive tracer concentration in the bottom-near water (upper right), O_2 difference in the bottom-near water (lower left) and T difference in the bottom-near water (lower right) in the Baltic Sea case I (f7-f6) on the 1st of September. (Details can be seen by zooming in on the figure in the electronic version of the report).

Figure 5-26 shows the extent of hypoxic near-bottom water areas with and without pumping where the difference is marked by a blue color. During the simulation the area of oxygenated near-bottom water increased gradually in the Baltic Sea case I, and by the end of September the hypoxic area had decreased by 7300 km^2 along the rim of the hypoxic area compared to the reference case (*Figure 5-26*). In the simulation for the deep Gulf of Finland case III the deep hypoxic water area had decreased by 120 km^2 and here the changes were mainly located at the entrance to the Gulf (*Figure 5-26*, lower right panel)

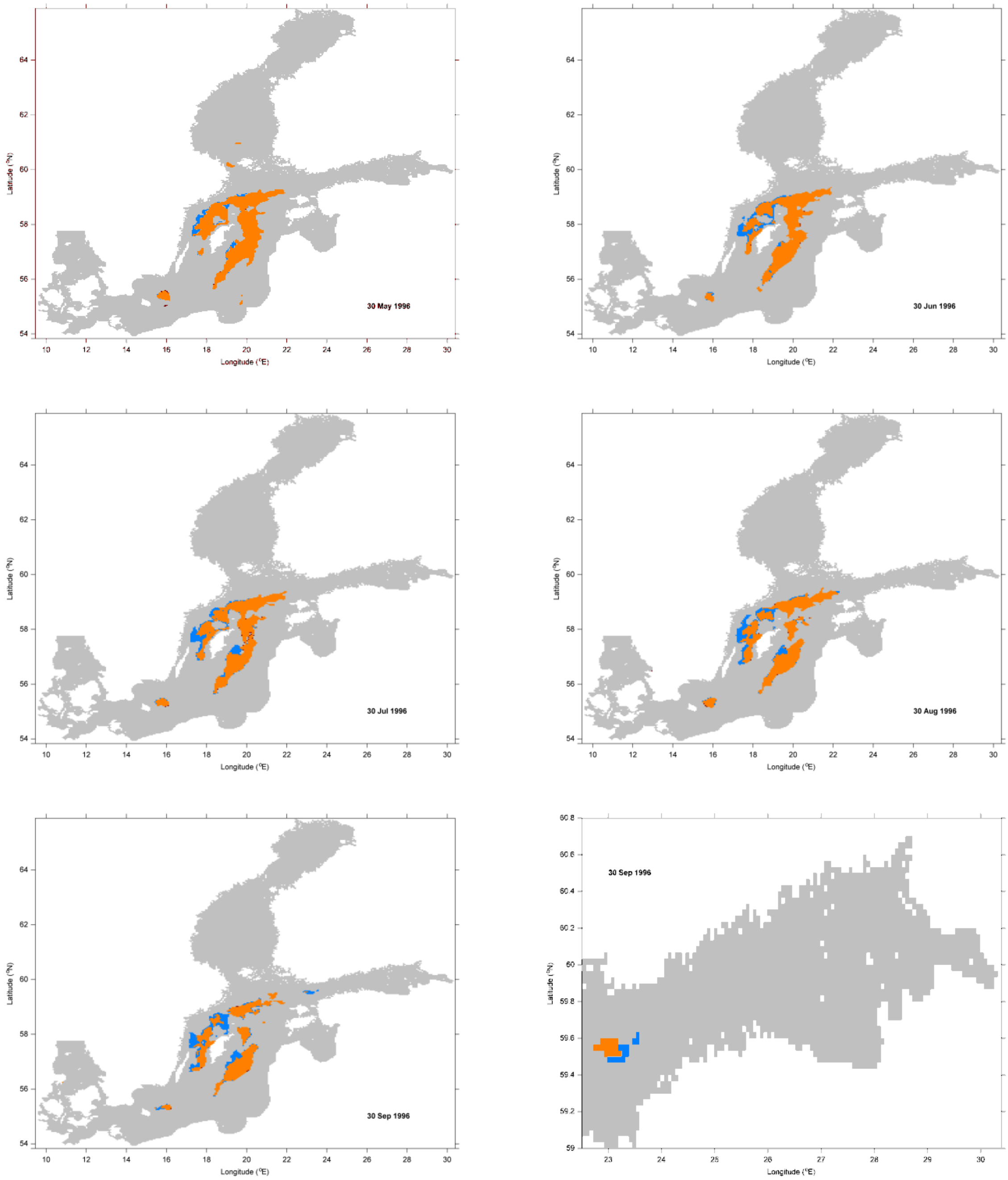

Figure 5-26. Hypoxic near-bottom water area (defined by O_2<62.5 µM, equivalent to 2 mg l^{-1}) with (orange) and without (blue and orange) pumping in Case I (f7) at the end of May, June, July, August and September, and in Case III (f9) at the end of September (lower right panel).

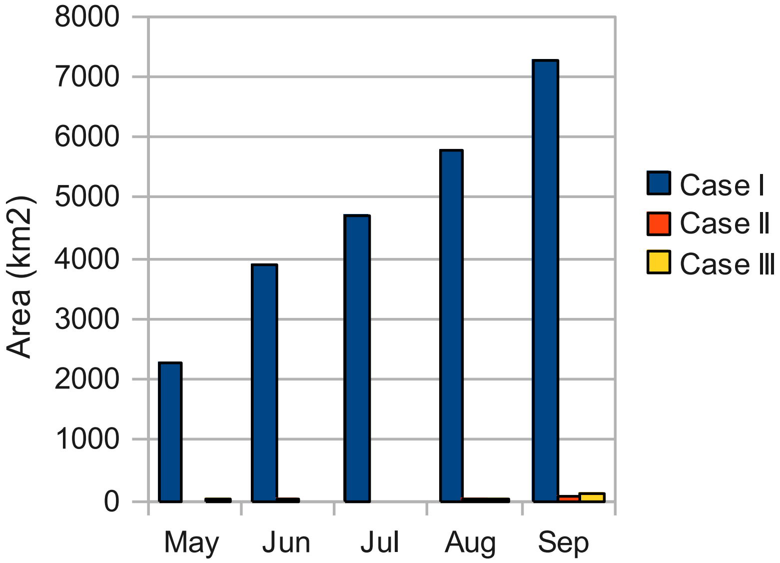

Figure 5-27. Changes of total hypoxic bottom-near water areas in the Baltic Sea region (defined by O_2<62.5 µM, equivalent to 2 mg l^{-1}) for the three cases and in the end of the 5 months of simulation, i.e. changes from May to the end of September.

5.4 Conclusions: Simulated effects of oxygenation

The impact from oxygenation has been analyzed on spatial scales ranging from a few meters from the pumps to the regional Baltic Sea scale. The main results from the model studies are summarized below.

5.4.1 Near-field modeling

Near field modeling and the rhodamine field experiment resulted in a qualitative and quantitative description of the dynamical processes associated with oxygenation:

- The dynamics at the outlet can be characterized as a buoyant plume and the plume ascend through the water column until it reaches its top-level, typically below the pycnocline.
- The ascending buoyant plume entrains water from the surroundings and for depth levels considered in the coastal experiments (~ 30 m) the entrainment rate corresponds to a factor of about 7 times the pumping rate.
- Near-field modeling and the observed rhodamine distribution close to the pump demonstrated the potential for ventilating deep water through artificial oxygenation and elucidated the convective motion and near-field dynamics.
- Near-field modeling and the rhodamine distribution showed that the lateral dispersion of the plume takes place in a thin few meter thick layer below the pycnocline.

5.4.2 Coastal scale modeling

Coastal basin scale oxygenation was modeled with high-resolution 3D-models in Lännerstasundet and Sändofjärden.

- Model simulations of oxygenation in Lännerstasundet during June 2010 were in good accordance with the observed changes in the bottom layer temperature and oxygen. A model sensitivity study showed that the case with oxygenation could account for the observed changes in temperature and oxygen, whereas a case without pumping could not describe the observed changes. This finding supported that the observed changes were due to the oxygenation.
- Changes in the pump rates of +/- 50% resulted in significantly different temperature, salinity and oxygen fields in Lännerstasundet, so therefore changes of the pumping rate was critical to the oxygenation efficiency in this case.
- Near bottom dynamics of oxygen was analyzed in Sandöfjärden and model results suggested that the pumping activity increased the near-bottom mixing significantly.

5.4.3 Baltic Sea modeling

Significant regional scale impact in the Baltic Sea was simulated on temperature, salinity, nutrients and oxygen after 5 month of oxygenation in cases with total pumping capacities between 9.000 – 118 800 $m^3 s^{-1}$. The high pumping capacities were used in order to assess the potential effects of long-term pumping with relatively smaller pumping capacities. The regional changes are summarized below:

- **Temperature in the Baltic Sea**: Temperature changes due to oxygenation of deep areas in the Baltic sea was minimized by locating the pump intakes at 50 m depth and thereby relatively cold "winter-water" from the upper part of the water column was pumped into warmer bottom water. Pumping from this depth level reduced the temperature increase in the bottom water and in general the temperature only changed by ±0.5 °C in the deep water after 5 months of simulation. In some parts of the central Baltic Proper the pumping even *reduced* the deep temperatures, whereas the temperature increased higher in the water column but below the halocline due to entrainment of relatively warm water into the ascending buoyant plume around the oxygenators (F*igure 5-24*).

- **Temperature in the Gulf of Finland:** Oxygenation along the coast of the Gulf of Finland (case II) where the pump intake was placed at 3 m depth resulted in a significant temperature increase of up to +3 °C of the deep water after four month of simulation and an associated reduction of temperature in the water column above (cf. Case II, f2; *Figure 5-20*). Deep oxygenation of the Gulf of Finland (case III) resulted in smaller temperature changes below +1.4 °C in the deep water because the intake was placed in the colder water at a depth of 25 m.

- **Salinity**: Salinity changes in the **Gulf of Finland** were relatively small in all three cases of pumping oxygenation. The coastal Gulf of Finland simulation (case II) showed salinity changes less than 0.3 after four month of simulation (cf. case II, f2; *Figure 5-20*). In the Baltic Sea oxygenation case (case I) the changes in salinity after five months of simulation were also found to be relatively small with maximum changes below ±0.4 (cf. *Figure 5-24*).

- **Heat and salt transports to the Gulf of Finland**: Changes in heat and salt transport was analyzed in a transect across the Gulf of Finland at the entrance to the Baltic Proper (23.7 °E) and a case with a rather high total pumping capacity (case II, f3) was compared with the reference case. The oxygenation caused only a minor change of about 1% in the total salinity transport into the Gulf during the five month period. The corresponding heat transport out of the Gulf increased in total by 13 % after five month. Both changes in salinity and heat transport were found to be relatively small compared to the reference salinity/freshwater transports and the energy balance in the area.

- **Nutrients**: After four month of simulation in the coastal **Gulf of Finland** (case II, f2) the oxygenation caused the bottom water concentration of nitrate and phosphorous to decrease by up to 1 and 0.1 µM, respectively (*Figure S5-3-1*), due to the relatively effective pumping of surface water low in nutrients into the sub-thermocline layers. Correspondingly, the coastal nitrate and phosphorous concentrations in the upper coastal water increased by up to 2 and 0.2 µM, respectively, due to weakened stratification caused by the efficient pumping. The case with coastal oxygenation (case II) did not suggest any improvement in oxygen conditions but increased the nutrient concentrations significantly in the surface layers of the Gulf of Finland.

- **Oxygen**: **Baltic Sea** model simulations suggest that in areas with low oxygen near-bottom water, the oxygenation could increase oxygen concentration significantly (*Figure 5-25*). Decreased oxygen concentrations were simulated at intermediate depth levels below the halocline due to entrainment of low-oxygen bottom water in the buoyant plumes (*Figure 5-24*).

- **Hypoxic bottom water area**: During the five month simulation period the oxygenated near-bottom water area with concentrations above 2 mg O_2 l^{-1} increased gradually in the **Baltic Sea case** I. By the end of September the hypoxic area had decreased by 7300 km^2 compared to the reference case (*Figure 5-27*). In the case with oxygenation of the **deep Gulf of Finland (case III)** the hypoxic area decreased by 120 km^2 and here the changes were mainly located near the entrance to the Gulf of Finland.

According to the model simulations of the PROPPEN project, the applied relatively high pumping rate would rapidly increase deep water oxygen concentrations and result in a decrease of hypoxic bottom water areas in the Baltic Sea. It should be considered that the relatively short term model simulation period did not consider the potential limiting effects of phosphorous retention which may occur due to large-scale intrusions of oxygen-rich water. Such intrusions are, for example, observed inter-annually in the Gulf of Finland area, and such variability is also observed in the ventilation of the Baltic Sea bottom water. Also, the pumping would decrease oxygen concentrations at the intermediate depths of the lower halocline and just below it. How these changes would impact on redox state and nutrient retention capacity of sediments in various parts of the Baltic Proper and the Gulf of Finland depends on complicated physical and biogeochemical interactions, and cannot be assessed here.

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Supplementary figures: S5-2-1, S5-2-2, S5-2-3

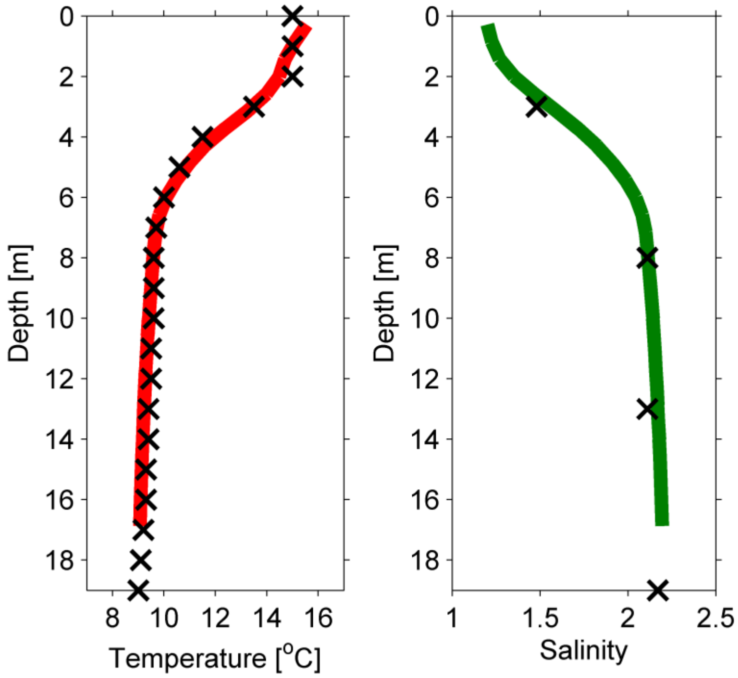
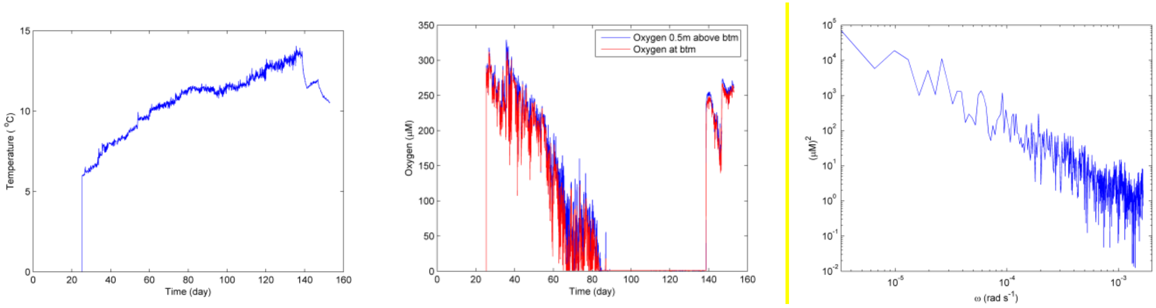


Figure S5-2-1. Model solutions (red and green lines) and observations (crosses) of temperature and salinity at stn A in the end of the experiment after 20 days of pumping (21st of June 2010).

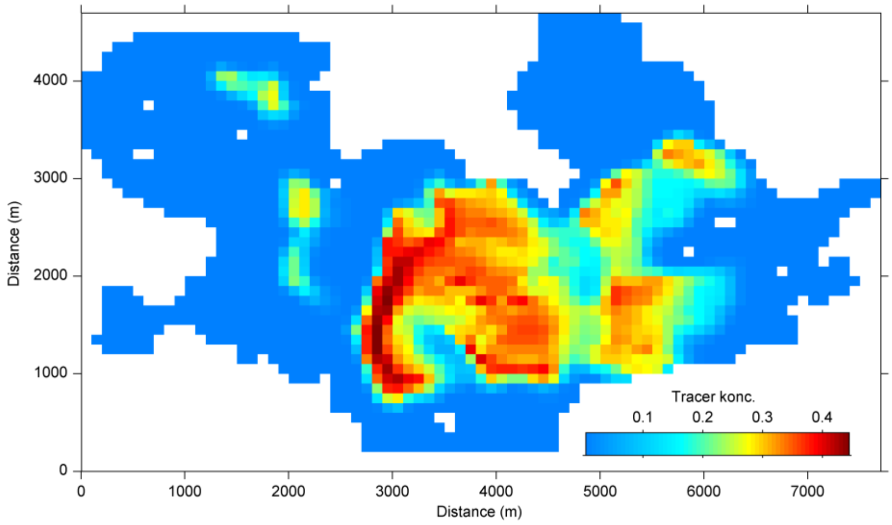


a

b

c

Figure S5-2-2. a) Near-bottom time series of Temperature at 0.5m above the bottom and b) Oxygen at 0.5 m above bottom (blue) and oyxgen measured at the bottom (red). The x-axis shows days since 26th of May, 2011. c) Power spectra of the time series of O_2 at bottom.



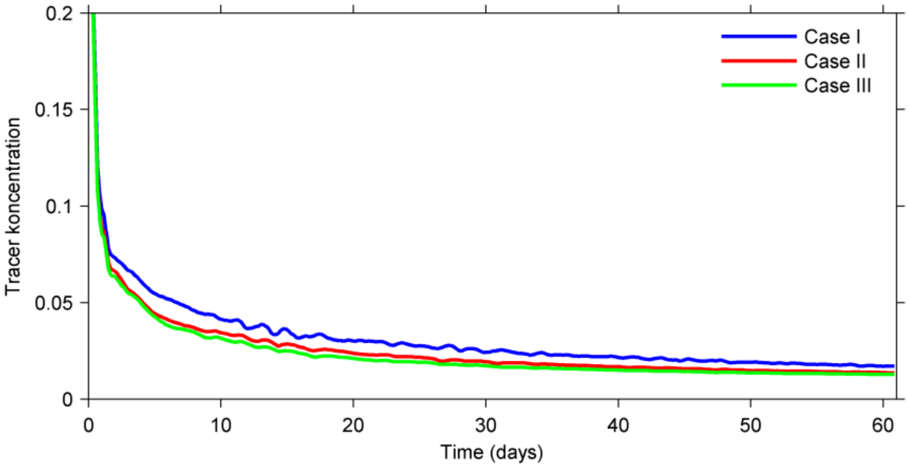


Figure S5-2-3. **Top**: Concentration of bottom tracer concentration after four hours of simulation (initially the concentration was set to a value of one just above the bottom when the depth is larger than 12 m).
Below: The evolution of the tracer concentration with time averaged over the center of the basin in the case without pumping (Case I; blue), and the case with six pumps pumping with a flow rate of 1 $m^3\ s^{-1}$ (Case II; red) and the case with a flow rate of 2 $m^3\ s^{-1}$ (Case III; green).

Supplementary figure: S5-3-1

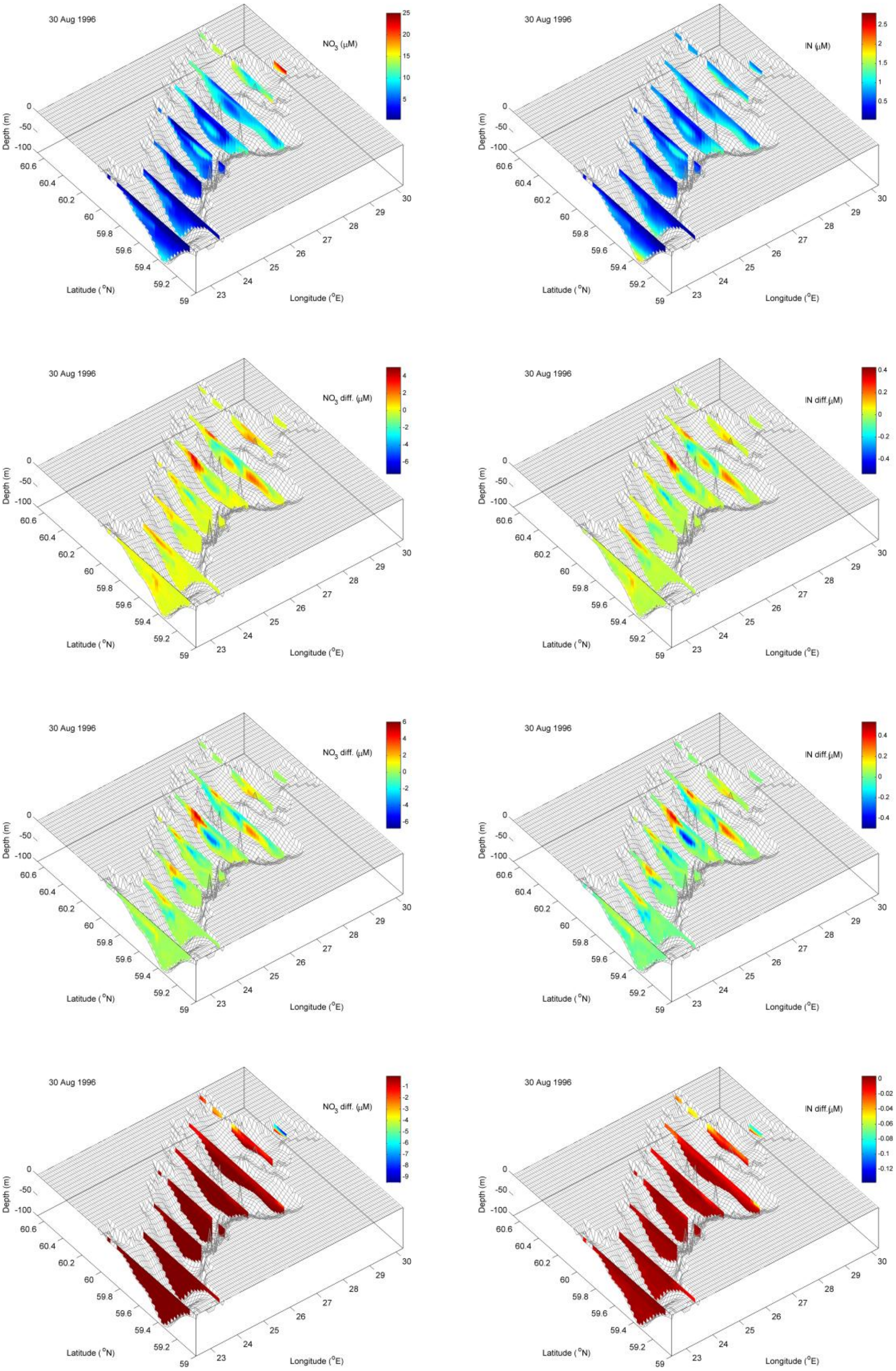


Figure S5-3-1. Fields of NO$_3$ (left panels) and PO$_4$ (right panels) on the 30th of August for (from top to bottom) f1, f2-f1, f3-f1 and f4-f1. Note the different color scales.

6 Economic analyses and risk assessment

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This chapter links the previous discussion and results to the social sphere. We examine how the Finnish and Swedish citizens value the benefits that pumping of oxygen-rich water to bottom layers generates, and how citizens perceive possible risks associated with small and large scale pumping. Risk assessment is a social activity, which can be systematized by formal procedures. A systematic analysis of risks based on expert evaluation is provided after citizens attitudes. The chapter ends with a comprehensive cost-benefit and cost-efficiency analysis of pumping to discuss the social desirability of pumping.

6.1 Monetary valuation of water quality improvement in the Baltic Sea

6.1.1 Introduction to the Contingent Valuation Method (CVM)

A contingent valuation method (CVM) is a stated preference technique used to measure the value of environmental goods and services for which the market fails to assign a price. CVM is the first and most extensively used approach in disentangling values of non-market goods directly in the absence of markets in terms of measuring the benefit they provide to the society. The major objective of CVM is to elicit the social value, which would result from environmental change manifested by an improvement in the quantity and/or quality of the good of interest.

6.1.2. The Survey

The survey combines a monetary valuation of water quality improvement in the Baltic Sea caused by oxygenation pumping and a public risk perception study of the potential ecological risks involved. The Survey was conducted in Finland, Lithuania and Sweden during 2011, preceded by a focus group testing in August 2010 in Sweden. Whereas the surveys in Finland and Lithuania were conducted in cooperation with the BONUS funded project, PreHab, in order to save survey costs, the survey in Sweden was conducted as a stand-alone survey. Annex A contains the full version of the survey applied in Sweden. See also Zandersen and Ollikainen (forthcoming).

The survey consisted of following parts:

1) Introductory section asking about ***respondents' connection to the Baltic Sea*** (F1 to F9) including distance to the Sea, professional and leisure time connection and frequency of use;
2) Familiarity questions relating to ***algal blooms*** (F10). In the Swedish sample we also included a familiarity question relating to ***oxygenation pumping*** (F11) and an own-experience question relating to perceived water quality (F12);
3) Information on ***eutrophication*** as an environmental problem in the Baltic Sea, HELCOM targets and internal loading. Information on oxygenation pumping and its expected effects;

4) Description of ***valuation scenario and payment vehicle***. In the Swedish survey we provide the information on improvements in water clarity and in the Finnish and Lithuanian sample we provide information on the expected improvements in Chlorofyll A. The storyline remains identical: Without oxygenation pumping, the planned policy measures under the HELCOM would be delayed by some 30 to 50 years. With oxygenation pumping at large-scale, the HELCOM target of a Baltic Sea unaffected by eutrophication would be achieved by 2021-2030. The payment vehicle was an earmarked tax put on households (Sweden) or on individuals (Finland & Lithuania) for 10 x 10 years, where the project would be evaluation after 10 years and if found efficient continued for another 10 years. We also stated that all households around the Baltic Sea would be subject to the tax, including Russia, and that the tax would be adjusted for household income.

5) ***Valuation question*** (F13) using a payment card;

6) ***Valuation follow-up questions*** (F14 to F15 & F20) to distinguish between protest answers and legitimate zero values; and to identify whether information and questions about ecological risks has changed the value held by the respondents;

7) Information on the ***potential ecological risks*** describing the types and levels of potential ecological risks. We split the sample in each country into two samples that receive the same types of risks but for different levels of risk;

8) ***Risk perception questions in relation to oxygenation*** pumping (F16 to F18) using four point Likert scale and choice between statements;

9) ***Risk perception questions in relation to other human activities*** in and around the Baltic Sea (F19) using four point Likert scale;

10) Environmental attitude questions using the New Environmental Paradigm (F21) using a five-point Likert scale; and

11) ***Socio-demographic questions*** (F23 to F30) enquiring about age, gender, income, household composition and living area.

Data was collected using national web-panels in each of the three countries. Annex E contains details on the data collection mode and sampling.

6.1.3 Valuation study results

Description of the CV samples

As the cost- benefit analysis only refers to projects relevant to Finland and Sweden, we only report the results of the surveys from Finland and Sweden. Appendix B shows results from all three countries.

The CV survey was sent to between 2000 and 3100 persons from national web-panels in Finland and Sweden. The response rates were 22% in Sweden and 26% in Finland. Details of the sampling can be found in Appendix E. Responses to the scenario to improve water quality through oxygenation pumping are presented in *Table 6-1* below. Between 75% and 80.5% of the respondents stated they would be willing to pay a yearly tax for the oxygenation pumping of the Baltic Sea.

Table 6-1. Responses to the valuation scenario, weighted sample.

	WTP>0	WTP=0	Protests or cannot state	Observations
Finland	80.5	3.5	16.01	709
Sweden	74.9	1.1	24.0	700

Follow-up questions were posed in the survey to identify protest answers from legitimate zero bids. *Table 6-1* shows that there are far more protest answers or people who cannot state than legitimate zero answers. A protest answer is defined as the cases where the respondent clearly attributes a value to the scenario, but who chooses not to bid a real price for reasons such as:

- I pay enough taxes
- I have no trust in governments
- Polluters should pay
- I do not trust this plan
-

Legitimate zero bids were characterised as zero-bids if the respondents chose one of these statements:

- I don’t care about the condition of the Baltic Sea
- I can’t afford to pay for this plan
- The plan is not worth this much

Table 6-2 reports the legitimate and protest answers below. Interestingly, less than half respondents in Sweden stated 0 or don't know than in Lithuania and Finland. The Finnish sample revealed a far higher disbelief in the scenario (12.5% of people who stated a 0 value) compared to only 0.8% in Sweden. The dominant reasons for not wanting to pay an 'oxygenation pumping tax' across the three countries are lack of financial resources (23-26%); that those who caused the environmental problem should pay (25%-26%); and the opinion that they pay enough taxes already (30-40%). Especially the Swedish sample shows a high reluctance to pay a tax due to the current perceived tax pressures.

Table 6-2.What is the main reason why you do not wish to pay for the oxygenation tax? Per cent respondents in each country, weighted sample

	Finland	**Sweden**
I don't care about the condition of the Baltic Sea	4.7	0
I can't afford to pay for this plan	26.2	24.9
The plan is not worth this much	0.3	0
Total legitimate answers	31,2	24,9
I have no trust in governments	0.8	1.5
I pay enough taxes already	30.3	39.8
Polluters should pay	25.2	21.5
Others should pay	0	0
I do not believe in the scenario	12.5	0.8
This is not the right way to amend the situation	n.a.	2.6
Other reason	n.a.	6.7
Don't know	n.a.	2.2
Total protest answers	**68.07**	**75.1**
Nobs	**108**	**54**

Willingness to Pay (WTP) estimates based on bids

Table 6-3 and *Table 6-4* show the bids made on the payment cards for Finland and Sweden. The chosen bid represents the lowest amount that a respondent is willing to pay whereas the next level is too high. The true willingness to pay lies somewhere in between these two levels. We therefore treat the data as interval data. The stated bid is treated as the lower bound and the next level as the upper bound. The interval average is the average between these two bounds. We use the interval data in the following econometric analyses rather than the stated bids.

The tables below show the mean, median and standard deviations for the willingness to pay, with and without protest answer. A conservative estimate of the stated willingness to pay is the lower bound of the positive and legitimate zero bids. For Finland, this amounts to an average value of 42 euro and a median of 21 euro per year and in Sweden the average and median lower bound WTP per household amounts to 40 euro and 18 euro (both PPP adjusted) per year respectively. The willingness to pay in the Finnish sample was elicited on an individual basis and in the Swedish sample on a household basis. Based on findings in other studies (e.g. Munro, 2004; Lindhjem & Navrud, 2008) and as the stated results between the samples are relatively similar, we assume that households in Finland and Sweden pool their income, which ensures that individual and household WTP are equal. In order to ensure conservative estimates, we proceed with values on a household basis. Whether CVM surveys should rather elicit individual or household WTP is subject to discussions in the literature (e.g. Quiggin, 1998) as well as discussions on whether respondents have understood the response format correctly (e.g. Hasler et al., 2008) and findings that household and individual stated values do not differ significantly (Lindhjem and Navrud, 2008).

Asking the respondents about whether their WTP had changed after information and questions on potential ecological risks involved with oxygenation pumping, close to half the respondents in Finland and Sweden stated they would pay the same. Surprisingly, more respondents from Finland and Sweden state they would be willing to pay more (15-22% in Finland and 14-17% in Sweden) after the information on risks than those stating they would be willing to pay less (8-9% in Finland and 6-9% in Sweden). Please refer to Appendix C, Table C.5. for frequencies.

The values shown in the below tables are based on weighted sample statistics. The weighting ensures that the sample is statistically identical with the national population with regard to gender, age, region and education (See Appendix E for more details on the weighting procedure).

Table 6-3. Stated WTP for scenario (euro) – Finland, weighted sample.

Bid type		**Average**	**Median**	**Std. dev.**	**N**
Positive & zero bids	Lower bound	36	16	57	709
Positive and legitimate zero bids	Lower bound	42	21	59	678
Positive and legitimate zero bids	Upper bound	53	26	60	676
Positive and legitimate zero bids	Interval average	47	23,5	56	678

Table 6-4. Stated WTP for scenario (euro PPP) – Sweden, weighted sample

Bid type	**e**	**Average**	**Median**	**Std. dev.**	**N**
Positive & zero bids	Lower bound	38	18	62	700
Positive and legitimate zero-bids	**Lower bound**	**40**	**18**	**63**	**654**
Positive and legitimate zero bids	Upper bound	45	22	54	645
Positive and legitimate zero bids	Interval average	42	20	53	654

Econometric estimation of willingness to pay functions

For each country sample, we carry out interval regressions using the upper and lower bound of the stated WTP amounts as the dependent variable. We correct for heteroscedasticity by using a robust variance estimator.

Parameter estimations of the WTP functions show the willingness to pay in euro per year that the respective socio-economic group has as an addition to or deduction from the willingness to pay of the average respondent.

Finnish Sample

We carry out the interval regression on the weighted sample in order to ensure a representativity of the national population. We show the unweighted estimates for comparison (*Table 6-3).* The following descriptions refer to the weighted results. Respondents in the income group 1.000-1.499 euro per month (INC_1499) have a WTP that is close to 13 euro less than the average respondent in the sample. This relationship between the level of income and level of WTP is as it could be expected. Respondents with a prior knowledge or experience with algal blooms (ALGAL); higher score on one of the NEP sub-scale measuring a pro-ecological worldview (NEPcrisis) have a higher WTP than the average respondent.

We did not find a significant distance decay in the willingness to pay for the project to help the Baltic Sea recover faster in the weighted sample. For the unweighted sample, we find a declining marginal effect of distance on the average WTP (LNDIST). Respondents living in a town (TOWN) appear have a ca. 10 euro lower WTP than on average. Concerns about large-scale pumping (Q17C_CONCERN) appear surprisingly in the Finnish sample to have a positive influence on the level of the WTP. We would expect to find a negative relationship, as we do in the Swedish and Lithuanian sample. Willingness to accept the risks and uncertainties of large-scale pumping given the prospects to a faster recovery of the Baltic Sea (Q18LARGE) has a positive influence on the level of WTP. This is what we would expect intuitively to find: people who accept the risks may also be the ones with a higher WTP than the average respondent. *Table 6-5* below shows the regression results.

Table 6-5. Estimation of the WTP Function, Finland
ML interval Willingness to Pay

	Weighted sample		**Unweighted sample**	
Variable	**Parameter**	**Sign.**	**Parameter**	**Sign.**
Concern large-scale pumping [Q17C_CONCERN]	16.5	***	12.4	**
WTA risk – largescale [Q18LARGE]	24.0	***	20.9	***
Living in a town [TOWN]	-10.6	**	-9.3	*
Income 1000-1499 euro [INC_1499]	-16.6	***	-12.6	***
Knowledge of algal blooms [ALGAL]	22.3	***	15.5	***
NEP scale sub-score [NEPcrisis]	6.9	***	5.9	***
Education level (EDUC)	n.s.		5.4	**
Income > 2500euro [INC_HIGH]	n.s.		14.1	***
log of distance to nearest coast [LNDIST]	n.s.		-2.4	**
Constant	-44.9	**	-39.7	**
N	**670**		**670**	
Log pseudolikelihood	-2284.6		-2193.6	

*Notes: Significance is reported for the 1%, 5% and 10% level, marked by ***, ** and * respectively.*

Swedish Sample

Weighted and unweighted estimates are provided in Table 6-4 below. Respondents in the income group 896-1970 euro per month have a weighted WTP that is about to 17 euro less than the average respondent in the sample; for each year older than the average respondents, WTP increases by 0.3 euro; respondents stating they know about algal blooms prior to the survey (ALGAL) have a WTP that is ca. 28 euro higher than average.

Also, the higher the willingness to pay for the pumping project (f17_1_AGREE) and a higher the score on the NEP facet possibility of an ecological crisis (NEPcrisis) (i.e. a higher pro-ecological world-view) has a positive influence on the willingness to pay. Unlike the Finnish sample, education level and age proved non-significant and were excluded: education level, showed a higher WTP for a higher level of education, and distance to nearest coast showed a reduced WTP the further away from the coast. The unweighted sample regression had a significant and positive relationship between level of education and level of WTP. The unweighted sample also showed a positive but non-significant relationship.

Table 6-6. Estimation of the WTP Function, Sweden
ML interval Willingness to Pay

	Weighted sample		**Unweighted sample**	
Variable	**Parameter**	**Sign.**	**Parameter**	Sign.
Concern medium scale pumping [f16_22]	-15.2	**	-11.3	**
WTA risk - small scale [f17_1_agree]	16.2	**	21.8	***
Age	0.3	**	0.4	**
Income 896-1970 euro [INC10_21]	-17.1	***	-18.5	***
Knowledge of algal blooms [ALGAL]	27.8	***	24.9	***
NEP scale score [NEPcrisis]	9.0	*	6.4	***
Education level [EDUC_CLASS]	n.s.		11.7	***
Constant	-80.7	**	-83.9	***
N	**654**		**654**	
Log pseudo likelihood	-2398.4		-2371.8	

*Notes: Significance is reported for the 1%, 5% and 10% level, marked by ***, ** and * respectively.*

Predicted Willingness to Pay Values

The parameter values of *Table 6-5* and *Table 6-6* are further used to estimate the willingness to pay of the average person in each country by multiplying the significant parameter values based on a weighted sample with the weighted sample average of each parameter and adding these up. The results are shown in Table 6-7 below. For comparison the above listed unweighted regression estimates reveal a higher WTP, 54euro for Finland and 51euro for Sweden. Both unweighted and weighted predicted values lie within the lower and upper bound of the stated willingness to pay, shown in Table 6-3 and Table 6-4. In the subsequent calculations, we apply the weighted results.

Table 6-7. Parameterized willingness to pay of the average citizen, weighted

	Finland	**Sweden**
WTP/yr/person (euro)	48.0	44.8

6.1.4 Application of valuation study results

Determination of WTP per tons of phosphorous removed (marginal WTP)

The basis for the WTP statements was a hypothetical scenario whereby the entire Baltic Sea would recover 30-50 years faster with pumping than without pumping, i.e. meeting the targets for eutrophication set by HELCOM (2007). In order to establish the marginal WTP (i.e. WTP per unit P removed), we first need to calculate total benefits for the population living in the Baltic Sea drainage basin and then divide the total benefits by the estimated amount of P that large-scale pumping should remove in order to meet the HELCOM targets 30-50 years faster.

Total benefit estimates were calculated by transferring value results from Sweden and Finland to Lithuania, Estonia, Latvia, Russia, Poland, Denmark and Germany. The transfer approach applied was GDP per capita and the total annual willingness to pay amounts to 954 million euro per year.

Uncertainty exists regarding the rate of pumping and the amount of P that can potentially be removed while being able to ensure a faster recovery of the Baltic Sea. Basis for the applied range is the observed natural interannual variability between 1991-1997 (Stigebrandt and Gustafsson, 2007a&b). We apply a range of 15 000 to 20 000 tons of phosphorus removed per year:

- 15 000tP removed per year – this assumption of P retention efficiency is based on the derived relationship between dissolved inorganic phosphate and oxygen conditions in the Baltic Sea (Conley et al., 2002) applied to an approximate anoxic area of 40 000km^2.

- 20 000tP removed per year – This assumption of P retention is based on the potential for bottoms to bind about 0.5 g P m^{-2} found during pilot experiments at Lännerstasundet applied to an approximate anoxic area of 40 000km^2.

In order to link the amount of P removed from bottom layers of the Baltic Sea with the subsequent effects on eutrophication in the surface layers (the indicator used in the valuation survey was absence of eutrophication and not phosphorous removal), we compare the findings of Stigebrandt and Gustafsson (2007a) with the Baltic Nest model results (HELCOM, 2007, Tables 1-3). Stigebrandt and Gustafsson showed that "the halving of winter time P concentrations in the surface layers of Baltic Proper in the period 1991-1997 occurred at the same time that the oxygen concentration in the 60-125m depth interval increased" from a major inflow of oxygen-rich deep water. The Baltic Nest model results (HELCOM, 2007) indicate that winter surface dissolved inorganic phosphorus (DIP) would need to reduce by at least 27% from 0.52 µmol l-1 to less than 0.38 µmol l-1, taking Baltic Proper as an example. Reducing P concentration to less than 0.38 µmol l-1 would lead as a minimum improve Secchi depth from presently 6.3 to 7 meters in the Baltic Proper and chlorophyll-a values would decrease from 2.3 to 1.5mg l-1. Assuming these relationships hold, we apply the annual P retention of 15 000 to 20 000tP in order to calculate the marginal benefits (WTP/kg P).

Table 6-8. Summary of estimating marginal benefits.

P removed (t yr^{-1}) [A]	Total benefit (euro yr^{-1}) [B]	Marginal benefit (WTP/kg P removed) [A/B]
15 000	953 853 952	63,6
20 000		47,6

In the following we use the range of marginal willingness to pay of 48-64 euro per year per kg P removed.

6.1.5 Discussion and conclusions

Our valuation survey found that 75-81% of the samples in Finland and Sweden would be willing to pay a yearly tax over 10 years, possibly renewable another 10 years, should the project turn out efficient. 16-24% protested against the undertaking and few stated a legitimate 0 value (1-4%). Parameterised, average WTP values were 48euro per year per household in Finland and 45euro per household per year in Sweden. These values are valid for meeting the HELCOM targets with respect to eutrophication 30-50 years faster than without oxygenation pumping. We thereby make the assumption that large-scale pumping will be able to achieve this. In order to scale this value from meeting the HELCOM target to a per T Phosphorous value per household, we transfer value results to the remaining households in the catchment areas in each country surrounding the Baltic Sea and divide this by the expected needed removal of P-eq. in order to meet the HELCOM targets.

We make two different assumptions on how much pumping would be able to remove of phosphorous, all expected to meet the BSAP targets faster than with reductions in external loading alone. The resulting average yearly WTP per kg phosphorous per household ranges between 48 euro and 64 euro. In the estimations of benefits, we apply this range of marginal values. Changing these assumptions significantly changes the benefits applied in the Cost-Benefit Analysis.

6.2 Public perception of risks of oxygenation

The analysis and survey carried out in relation to the public risk perceptions were funded under the BOX project. As the valuation and the risk perception surveys were developed and carried out in parallel and with close involvement of the PROPPEN project, we have cordially been granted permission from the BOX project to bring the results of the public perception of risks also in the PROPPEN report. Please, refer to Zandersen (forthcoming) for a full account of the survey on public perception of risks of oxygenation pumping.

6.2.1 Identification of Ecological Risks

The survey of risk perception towards pumping oxygen rich water to deeper layers in the Baltic Sea covers oxygenation pumping at different scales:

- Small-scale pumping only at selected coastal stretches with temporary lack of oxygen;
- Medium-scale pumping covering the whole coastal area in the Baltic Sea in places with periodic lack of oxygen; and
- Large-scale pumping covering the whole coastal area and the open sea in the Baltic Sea experiencing lack of oxygen.

Our intent with the survey was that it should be based on an easy-to-understand overview of the different types of risks and the level of risks involved, and that respondents were not required to have any previous knowledge of the subject. We deliberately excluded the aspect of the likelihood of a risk occurring in order to avoid too complex information. The types and levels of risks should be based on the assessment of independent experts.

In order to establish an overview of the various potential ecological risks of oxygenation pumping for use in the public risk perception survey, we undertook in-person interviews with experts[1], not involved in the oxygenation project, during November/December 2011 and a short literature review[2]. These interviews were conducted prior to the identification of ecological risks, which are presented in Section 6.3. The risks identified during the interviews are presented in Appendix C, Table C.1.

It soon became clear that science is not in full agreement regarding the types of ecological risks and the likelihood or seriousness of risk occurrence. Rather than seeking to obtain a scientific consensus in this area, which was beyond the scope of the risk perception survey, we chose to investigate how people respond towards different levels of potential risks. A focus-group session was carried out in Stockholm[3] to test the understanding by lay-people of the survey and corrections were made to the survey text and format.

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[1] Interviews were carried out with Jacob Carstensen (Aarhus University) and Alf Norkko (SYKE). Contacts were also made to Erik Bonsdorff (Åbo Akademi University), Claire Bradshaw (Stockholm University), and Daniel Conley (Lund University), but it was not possible to obtain an interview during the period mid-November to mid-December 2011.

[2] Conley et al. 2009a & 2009b; Conley et al. 2002

[3] The focus-group session is an in-depth discussion and test of the survey by 8-9 lay-persons during 3 hours. The Focus group session was recruited and facilitated by a professionals from SIFO TNS and was videotaped.

6.2.2. The Risk Perception Survey

The risk perception survey followed the monetary valuation survey and the steps in the survey are described under Section 6. Appendix A contains the full survey. We split the sample in each country into two where we provide the split samples with identical types of risks, but with different levels of risks.

Our reason for the split samples was to investigate how people respond to different information of risks rather than investigating the response to one ‘true’ set of risks, which does not exist. One splitsample (hereafter called ‘low risk’) received a description of a rather low risk level, where effects would not be irremediable and rather local. The other split sample (hereafter called ‘high risk’) received information of severe and irremediable effects of oxygenation pumping. Risks levels were specified for the three scales of pumping: small, medium and large-scale (*Section 6*).

6.2.3 The Risk Perception Survey Results

The survey allows us to answer four aspects in relation to risk perceptions and oxygenation pumping:

- Respondents’ stated level of concern relating to oxygenation pumping at three different scales (small, medium and large-scale);
- Respondents’ willingness to accept the potential risks and uncertainties of pumping in order to have the Baltic Sea recover faster (30-50 years) than without oxygenation pumping at three different scales (small, medium and large-scale);
- Respondents’ choice of condition under which oxygenation pumping could be allowed to take place given a set of predefined criteria; and
- Respondents’ stated level of concern towards other human activities in and around the Baltic Sea, permitting us to put the stated level of concern of oxygenation pumping into a wider picture.

Concern about oxygenation

Figure 6-1 shows the results of respondents’ stated level of concern towards oxygenation pumping for each of the three countries and for each of the two split samples. ‘Not concerned’ groups the answers ‘not especially concerned’ and ‘not concerned at all’. ‘Concerned’ pools answers in the categories ‘very concerned’ and ‘somewhat concerned’.

We chose to split the samples in each country and provide them with different risk profiles in order to test how people respond to different levels of risks and to find out whether the scale of pumping efforts determines the level of concern. We test whether the means across the two weighted split samples are identical or not for the category ‘concerned’ and ‘not concerned’. As we base our study on the weighted statistics of the samples, we perform linear regressions of the indicator variables to examine mean differences across the split samples for each country[4.] Appendix G reports the frequencies and F-statistics of the two-sample t-test for each country sample and provides an interpretation.

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[4] This is equivalent to a two-sample t-test, but uses the F-statistic

Generally across the countries, we find that respondents are increasingly concerned when the scale of pumping increases from small-scale to large-scale. The Lithuanian sample appear more risk averse than the Swedish and Finnish sample with 56-57% concerned about large-scale pumping compared to 42-47% in Finland and 44-53% in Sweden. The same pattern is found also for medium-scale and small-scale pumping. Vice-versa, we find that the number of respondents not concerned decreases as the scale of pumping increases. The number of respondents stating they don't know is at the same level across the three countries and across the two split samples (ca. 20%).

Looking at statistically significant differences between the splitsamples in each country, we find that for all three scales, the Finnish respondents have a significant higher level of concern in the high risk sample than in the low risk sample. In the Lithuanian sample, we find no significant difference between the low and high risk splitsamples and in the Swedish case, only at the small-scale pumping do we find a significant higher level of concern in the high risk splitsample than in the low risk sample. Our interpretation of this is:

- The Swedish sample with regard to medium and large-scale oxygenation pumping and the Lithuanian sample with regard to all three scales of pumping react according to the scale of pumping. People find pumping so worrying that there is no significant difference in concern between the low and high risk sample, hence the scale of pumping rather than the explicit risk level appears to determine how respondents state their level of concern;

- The Finnish sample for all scales of oxygenation pumping and the Swedish sample with regard to small-scale pumping react according to the severity of risk presented in the low and high risk split samples. This means that the level of risk determines how people state their level of concern rather than the scale of pumping.

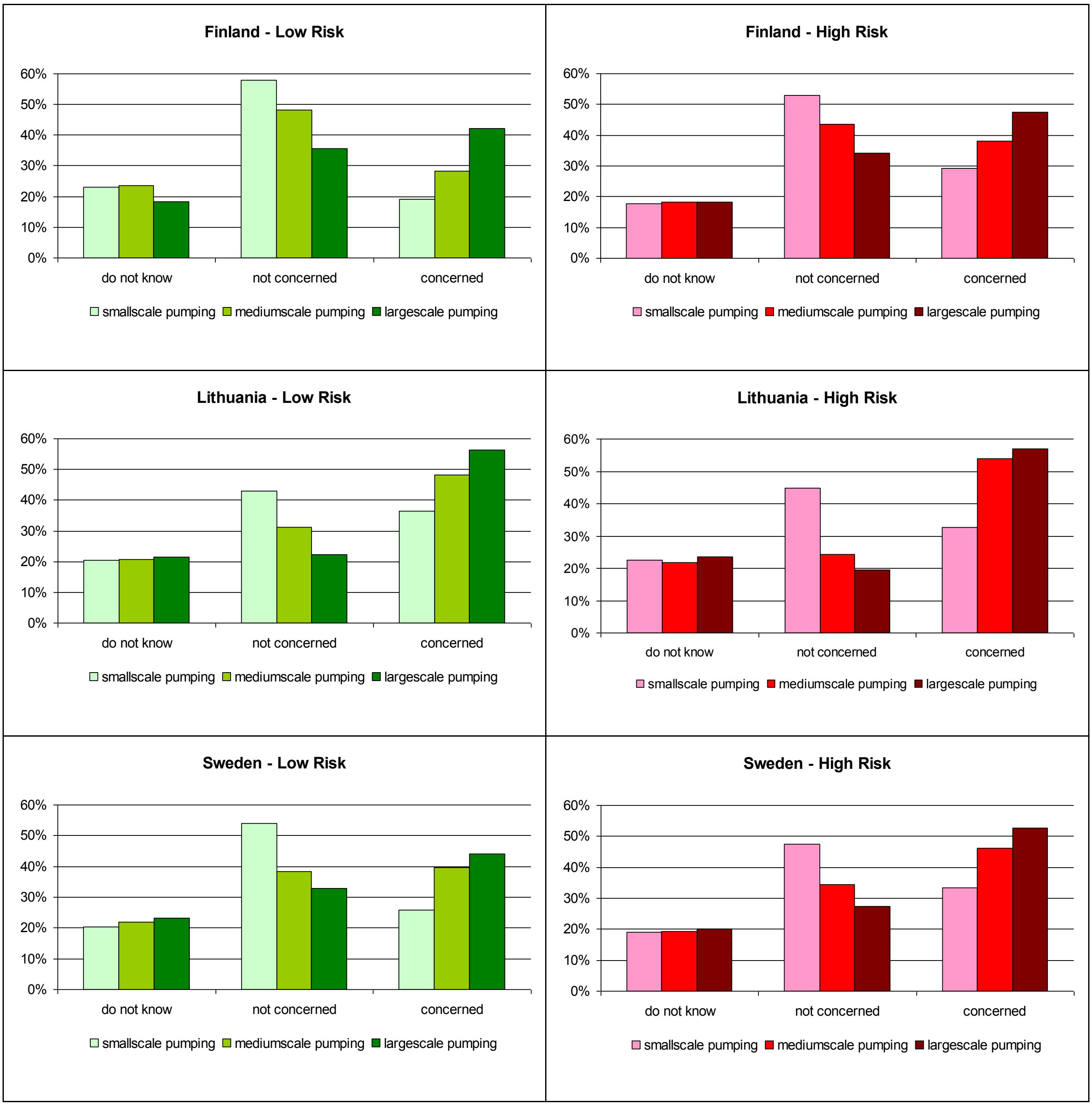


Figure 6-1. Level of concern towards oxygenation pumping at low and high risk levels, per cent respondents, weighted sample.

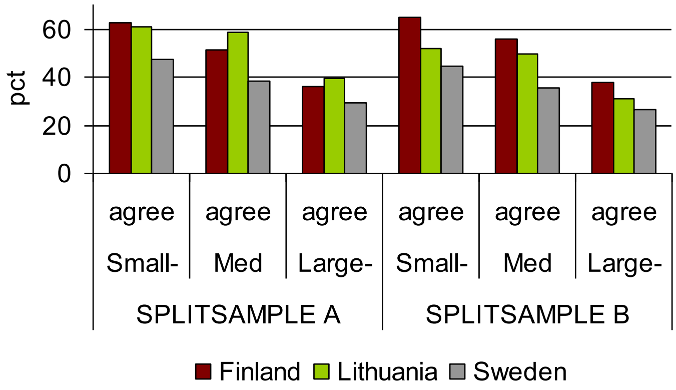
Willingness to Accept Potential Risks

We asked respondents their agreement with the statement "I am willing to accept the potential risks and uncertainties for a faster (30-50 years) recovery of the Baltic Sea than without oxygenation pumping." Our intention was to gain insights as to how severe people perceive the current state of the Baltic Sea that they would be willing to accept specified types and levels of risks.

Generally, across the countries, we find that as pumping scale increases, people are less willing to accept risks and uncertainties involved. Still, between 27-38% of people across the three countries state their willingness accept the high level risk profile for a faster recovery of the Baltic Sea. This may indicate how important people perceive the need for a faster recovery of the Baltic Sea and how seriously they perceive the related ecological problems. In general, the Swedish respondents appear to the most risk averse (i.e. not willing to accept risks) and the Finnish sample as the least risk averse (i.e. willing to accept risks).

Across the splitsamples in Finland and Sweden, we find no evidence of sensitivity to risk levels. Scale of pumping is the main factor behind the results. In the low risk sample, willingness to accept risks across samples, countries and scales of pumping vary from 29% to 63%. In the high risk sample, we find a range between 27% and 65%. Only in the Lithuanian sample did we find a significant difference between the splitsample results.

Figure 6-2. Willingness to Accept potential risks and uncertainties of pumping at different scales of pumping, per cent respondents stating strongly agree or somewhat agree.



Conditions for Undertaking Oxygenation

Respondents were asked under which conditions they would accept an implementation of oxygenation pumping. They could choose one of six conditions. Please refer to Appendix C, Table C.3. for a listing of frequencies for each country and splitsample.

We included two statements reflecting a trade-off approach to deciding upon carrying out oxygenation pumping, often used in cost benefit analysis. The first statement requires that *significantly higher benefits than costs and risks* and the second statement simply requires that *benefits should outweigh costs and risks*. Results show that most respondents in the Finnish and Lithuanian samples agree with the trade-off conditions (44-46% in the Finnish samples and 56-59% in the Lithuanian samples).

Both country samples agree the most with the condition based on significant higher benefits. In comparison, relatively few in the Swedish sample chose this requirement (12-13%). A larger share (25-27%) of the Swedish sample chose the more lenient requirement that benefits should simply outweigh costs and risks, whereas only 12-13% of the Finnish and Lithuanian samples agreed with this more lenient condition.

We included two statements based solely on the requirement to minimize risks. The largest share (27-30%) of the Swedish sample focused on the requirement *only to pump if risks can be shown to be minimal*. A similar absolute level of agreement to this requirement was found in the Finnish and Lithuanian samples (25-29% and 30-32% respectively). Between 6% and 9% of the samples in all three countries find it a requirement that *pumping should only take place in coastal waters in order to minimize risks*.

Posing the requirement that no large-scale *pumping should be allowed under any circumstance*, we find that only few respondents select this statement in Finland and Lithuania. The Swedish sample differs clearly by having as many as 13-16% of respondents being against large-scale pumping.

The relatively high emphasis in the Swedish sample on letting risks determine whether or not to start oxygenation pumping and on avoiding large-scale pumping indicates a higher level of risk aversion than in Finland and Lithuania.

There were no statistically significant differences between the split samples in all 3 countries on the above mentioned statements. This indicates that the level of risk has little influence on how people select the condition for going ahead with oxygenation pumping or not.

Risk perceptions related to human activities in and around the Baltic Sea

We ask respondents about how concerned they are for the ecosystem in the Baltic Sea with regard to human activities and human induced impacts in and around the Baltic Sea. Our intention is to compare the level of concern that people state toward oxygenation pumping and toward other human activities. Results are illustrated in Table 6-9 below. The two set of questions (F16 and F19) used the same 4-point Likert scale.

We take the median value of the Likert scale for each type of activity/impact and rank these from very concerned (red), somewhat concerned (yellow) to not especially concerned (green). There is no individual ranking within each level of concern, and activities are shown in alphabetical order.

Comparing the level of concern about oxygenation pumping and other human activities, we find that none of the median respondents in the three countries consider pumping to be ‘very concerning’ for the ecosystem in the Baltic Sea. The median respondent in Lithuania finds large-scale pumping (both high and low risk sample) to be of ‘somewhat concern’, whereas the Swedish high risk sample finds large-scale also to be of ‘somewhat concern’. The Swedish low risk sample finds large-scale pumping to be on ‘no particular concern’. The median Finnish sample finds large-scale pumping of ‘no particular concern’ (both high and low risk sample). All respondents state that medium and small-scale pumping is of ‘no especial concern’ regardless of the risk profile of the split samples. It is noteworthy that the median respondents across all countries consider the impacts from recreational boating to be at the same level as at medium and small-scale pumping.

Table 6-9. Concerns about impacts of human activities on the ecosystem of the Baltic Sea.

Human activities in and around the Baltic Sea	**Lithuania**	**Sweden**	**Finland**
	Median		
Chemical Accidents	4	4	4
Hazardous substances	4	4	4
Oil transportation	4	4	4
Municipal wastewater	4	3	3
Radioactive Pollution	4	3	3
Agriculture emissions	3	3	3
Alien species	3	3	3
Climate Change	3	3	3
Fish farming	3	3	3
Maritime Traffic	3	3	3
Fishing	3	3	2
Large-scale pumping high risk	3	3	2
Large-scale pumping low risk	3	2	2
Medium-scale pumping high risk	2	2	2
Medium-scale pumping low risk	2	2	2
Recreational boating	2	2	2
Small-scale pumping high risk	2	2	2
Small-scale pumping low risk	2	2	2

2	Not especially concerned
3	Somewhat concerned
4	Very concerned

Environmental Attitudes Results

We chose to include the updated full set of NEP questions at the end of the survey in order to measure the environmental attitudes of the respondents and thereby hoping to gain some insights into the motivations behind the risk perceptions stated. The NEP questions count 15 questions and have been constructed to measure specific hypothesized facets of an ecological world-view[5]. Please refer to Appendix D for a full list of frequencies. The NEP scale ranges from a minimum count of 15 to a maximum count of 75.

Survey results show a similar picture across the countries with average and median scores between 44 and 47. Using the NEP-score as explanatory variable in the WTP regression shows a highly significant and positive influence, indicating that people with a higher NEP-score are willing to pay more for oxygenation pumping than people with a lower score.

Table 6-10. Sum of NEP scale across all dimensions.

	Finland	**Lithuania**	**Sweden**
Median	45.2	44.2	46.9
Mean	45.7	44.5	47.1
Min	27.1	31.7	25.0
Max	59.0	59.0	60.0
Std.dev	5.0	3.9	4.4
Nobs	709	763	700

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[5] Dunlap et al (2000); Dunlap & Van Liere (1978)

6.2.4 Discussion and conclusions

The risk perception survey finds that as the scale of pumping increases from small- to large scale, people are i) more concerned about the potential ecological risks and ii) less willing to accept the risks and uncertainties of pumping for the prospects of a faster recovery of the Baltic Sea through pumping. Across several dimensions, the Swedish sample appears as the most risk averse and the Finnish sample as the least risk averse towards potential risks and uncertainties associated with oxygenation pumping.

We only find partial evidence that the level of risk (high vs. low risk) is a determinant for the stated opinions. In relation to concerns towards pumping, we find evidence of this in the Finnish sample at all three scales of pumping and at small-scale pumping in the Swedish sample. We also find evidence of risk sensitivity in the Lithuanian sample at all three scales of pumping with regard to willingness to accept risks of pumping for a faster recovery of the Baltic Sea.

Where the opposite is the case (i.e. no risk level sensitivity), people react to the scale of pumping and they do not let the differences in information (high vs. low risk) have a statistically significant impact on their answers. We interpret this as an indication that for these people, pumping appears so worrying that the amplitude of pumping and not the level of risk associated determine their concerns and willingness to accept pumping.

Still, between 27-38% of people across Finland, Sweden and Lithuania state they would be willing to accept high risks associated with pumping for the prospects of a faster recovery of the marine environment. This gives an indication that around one third of the populations in the three countries find the state of the Baltic Sea so severe that they would be willing to accept even high risks induced by oxygenation pumping for a faster recovery.

A noteworthy finding is that for 50% of the samples in the three countries, pumping ranks at the lower end of a ranking of concerns about impacts of human activities in and around the Baltic Sea. This is far behind chemical accidents, hazardous substances, and oil transportation, which in all three countries rank as ‘very concerning’. In Finland, all three scales of pumping rank as ‘not especially concerning’. In Sweden, large-scale pumping at high risk and in Lithuania, low and high risks of large-scale pumping rank as ‘somewhat concerning’. All lower scales of pumping rank as ‘not especially concerning’.

In relation to the conditions under which pumping should be allowed or not to proceed, we find a strong preference for requiring that benefits outweigh costs and risks in the Finnish and Lithuanian sample (44%-59%) and less so in the Swedish sample (37-39%). Across all countries, similar shares of people agree that pumping should be undertaken only if risks can be shown to be minimal (25-32%). More people in the Swedish sample compared to the other two countries require that pumping should only be undertaken on a coastal scale to minimize risks (ca. 9%) or that large scale pumping should not be undertaken under any circumstance (13-16%).

The survey reveals the complexity of understanding the determinants of people’s risk perceptions and the differences between and within populations.

6.3 Technical, ecological and economic risk assessment of oxygenation in various scales

Background

At the start-up phase of the PROPPEN project, potential risks and need for risk assessment (RA) were foreseen in two different areas of implementation. The types and targets of risks were anticipated rather different firstly during the PROPPEN research project aiming at studying the background conditions, impacts and oxygenation methodology based on laboratory and coastal oxygenation experiments, and secondly in a situation where the oxygenation method would be up-scaled to open sea applications.

Hence the risk assessment was decided to be conducted in two separate phases. In Phase 1 the risk analysis was primarily pointed to the technical and financial performance of the project, but the accomplishment of the scientific goals was included where applicable.

In case of encouraging results from the project experiments, an up-scaling of the method to the whole Baltic Sea level could be considered. However, such an effort would most probably involve various types of risks, which might restrict the successful up-scaling of the applied technology. To obtain a more comprehensive picture of the future possibilities of the oxygenation method, a Phase 2 risk assessment beyond the research project itself was included in the project plan.

For both risk assessment phases Pöyry's project risk management concept (Co-Pilot™) was applied. The concept is based on Temper System for project risk management, which has originally been developed in VTT Building Technology, and further developed at Pöyry.

The initial risk assessment of the coastal experiments (Phase 1) was carried out prior to starting the field work in selected areas in Finnish and Swedish coasts.

6.3.1 Phase 1 risk assessment of pilot-scale coastal oxygenation

As a first step a proactive risk list was created to fit the specific features of a research project. New risks were identified in the risk assessment session with the project core team and with the assistance of a project risk knowledge browser. Concurrently the actions to mitigate risks were also evaluated. The information gathered in the risk analysis session was completed with personal interviews of the team members.

The financial impact of each individual risk on the project was evaluated (in euros) where appropriate, and the probability of the risk materializing was determined (in %). However, when it comes to a research project, not all risks cause direct financial implications but rather compromise the validity of the study results. In addition the outcome of the project's results cannot be unambiguously valued, and a scientifically proven failure in the study hypothesis can also be considered a valid result.

For further analysis of the impacts of the identified risks, they were divided into four main categories, depending on the impact type:

0) Risks that cause short delays which are not probable to postpone the original project schedule are not valued in euros (delays < 6 months and minor financial impacts).
1) Risks for such failures / delays in the project implementation that lead to need for additional financing to complete the project or alternatively restrict the planned program.
2) Risks that cause other additional costs due to rises of expenses, underestimates in the original budget, unexpected expenses etc.
3) Risks that lead to waste of human resources / loss of the possibility of using the resources for other useful tasks in case of project or subproject failure.

It is to be understood that the individual numbers used may be somewhat subjective and do not represent the correct absolute value. They should rather be considered as relative to each other for judging the importance of the identified risk item. The sum impact of the risks was not evaluated, because many of the risks are overlapping and would not materialize in parallel. In this review focus was set on identifying individual risks and determining their impact in order to be able to prioritize the risks and plan actions to mitigate the risks of the most significant impacts on the project's budget or schedule.

6.3.1.1 Main results

Altogether 36 risks were identified in the assessment process. In general the probabilities for the risks to materialize were estimated low (5 to 25 %) except for a couple of cases where the risks are well known and the probability was estimated to be ≥ 50%.
The most probable risks concerned overall budget exceeding and currency exchange rate between euros and SEKs (funding currency) as well as exceeding costs of subcontracting services and installation costs. In addition the schedule of start-up of the laboratory experiments and automatic monitoring and the availability of Finnish and Swedish climatological data for modeling was estimated to entail rather high risk. Changes in the key personnel merited also attention.

Many of the identified risks could be categorized into two important groups of risks: those that cause delays in the planned experiments and those that prevent carrying them out. In principle the project delays can be dealt by either prolonging the project possibly with extra funding or by adjusting the work program accordingly. The latter was considered the more probable solution for the delay risks, and hence the outcome of the materializing of the above mentioned groups of risks is more or less directed at the success in achieving the project's objectives, and requirements for extra funding for prolonging the project is assumed unlikely. In these cases a reverse assessment of a financial impact was applied (category 3): what would be the value of the wasted human resource in case of a failure in project or subproject implementation?
It was estimated that short delays (< 6 months) can be caught up during the project, and significant financial impacts are not probable although organizing work load within the project may become more challenging. However, in case many risks that cause delays in the project implementation occur simultaneously the probability of substantial impacts increase. The risk for

these shorter delays concern mostly difficulties in technical assembly, procurement or damages to the experimental apparatus, which can be fixed with moderate effort.
The risks for major delays in the implementation of the project were estimated to concern permitting process with the authorities and the land owners, changes in the original project plan as well as the risk of NGOs starting a complaining process, but the whole experimental setup would not be compromised by these issues.

In addition, the risks concerning the availability of human resources were considered substantial. The availability of key experts of a very specific competence area in the project group - and ultimately them leaving the project - would cause significant delays. Likewise, concentration of expertise to one/few specialists can lead to bottleneck situations and delays.
The most substantial experimental risk concerned automatic field monitoring including delayed delivery of the equipment, although field monitoring may be partly compensated by manual sampling. A delay in the start-up of laboratory experiments was also considered highly probable due to work load of specialist resources.

To conclude, none of the identified risks was estimated to be serious enough to compromise the achievement of all project objectives. However, in case of simultaneous realization of several risks, some parts of the project would remain lacking or inadequate.
As a final step of the risk assessment process, actions to mitigate the risks were also defined including naming of the main responsible persons from the project team.

6.3.1.2 Summary and conclusions

The initial project risk assessment of the coastal experiments (Phase 1) was carried out prior to starting the field work in selected areas in Finnish and Swedish coasts. The results of this RA were very useful when ensuring that all prerequisites for the experiments had been taken into account, and some additional improvements and control measures were carried out after the RA.

Actions should be taken early enough to mitigate and eliminate the identified risks and reduce the financial impact. Typically, during the project, the key team members of the project shall participate in risk review meetings and this will guarantee that the most accurate information for risk analysis is available and also ensure commitment of project key resources on the actions determined for risk mitigation and elimination.

When it comes to a research project, not all risks cause straight financial implications but rather compromise the validity of the study results and conclusions drawn from them. In addition the outcome of the project's results cannot be unambiguously valued, and a scientifically proven failure in the study hypothesis can also be considered a valid result.

Many identified risks in PROPPEN project were considered to be lacking of sufficient research data at this stage due to failures in completing parts of the experiments for various reasons. In addition keeping the budget and schedule of the experiments and managing the specialist resources were estimated to be the most challenging tasks.

In addition, the experiments have been followed up during the 3-year experimental period and the following main risks have been identified with regards to coastal zone oxygen pumping:
The required oxygenation capacity turned out to be initially calculated on the low side in Sandöfjärden which was observed on the 2nd year of experiments when the oxygen pumping was planned to be on the whole summer. On 3rd experimental year the capacity was increased to the extent practically possible.

The experiments on especially 2 nd and 3 rd years showed that the warming of the midwater zone was somewhat higher than anticipated originally.

6.3.2 Phase 2 Risk assessment of up-scaling oxygenation to open sea conditions

The objective of the Phase 2 Risk assessment (RA) within the PROPPEN project was to proactively identify, evaluate and analyze the potential risks involved in case of up-scaling the oxygenation of deep waters with Mixox pumping method into several anoxic areas of the Baltic sea. The risk scheme encompassed aspects concerning 1. Ecological risks, 2. Hydrographical risks, 3. Socio-economic risks and 4. Technical risks. The level of up-scaling was divided to the open sea areas of the Gulf of Finland (GoF) and to Gotland deeps of the Baltic Proper (BP), which were examined separately where applicable.

In the PROPPEN Phase 2 Risk assessment the Co-Pilot™ method and tool developed for project risk assessment was applied. It is based on Temper System for project risk management, which has been developed in VTT Building Technology. The method was considered well applicable for a risk assessment, which targets at a preparative ranking of the significance of different risk sources in a situation where:

- the up-scaling concept is at a very preliminary phase,
- no actual experimental data exists for the up-scaling,
- the available oxygenation experience is based on the 3 years' coastal experiments.

The aim set for the risk assessment was to identify as widely as possible the potential risks related to up-scaling oxygenation with Mixox pumping based on the presently available information, and to assess the probability and impact of the identified risks in order to pinpoint the most significant ones to be taken into further analysis.

The qualitative approach results in a risk matrix, where the risks are located by their probability and magnitude of impact. The risk matrix method makes it possible to effectively compare the risks from different events, even when the level of detailed knowledge varies. The Co-Pilot™ project risk management tool) was modified for the qualitative risk assessment required for an organized ranking of the probabilities and impacts of the risks related to the up-scaling of oxygenation.

The probability and impact of each risk was evaluated on a predefined ordinal scale including indicative descriptions of each rank. The probability was divided into four ranks from unlikely to very likely, and the magnitude of impact into five ranks from minor to catastrophe, described individually for the four separate risk categories.

A stepwise process was selected for the risk assessment of up-scaling of oxygenation:

1. Definition of the generic risk hypotheses and risk categories,
2. Preparation of a conceptual model of risks related to the up-scaling process and a preliminary list of potential risks classes,
3. Interviews of experts from various expertise areas to identify all potential risks,
4. Compilation of a joint risk sheet, the so-called 'long-list' of identified risks, divided into risk classes within categories,
5. Risk assessment session with the project core team, resulting in risk matrix (Co-Pilot^{TM} tool),
6. Compilation of a 'short-list' of the most significant up-scaling risks (an initial risk sheet),
7. Analysis of the 'short-listed' risks.

As a preliminary step for the risk assessment a generic framework of the up-scaling risks was defined (*Figure 6-3*), where H0 is the option that no attempts to improve the eutrophication situation of the Baltic Sea by oxygenation will be started. H1 assumes that oxygenation will be started, resulting in successful changes in water quality with no adverse impacts. The risk assessment questions this assumption by searching and identifying potential risks related to oxygenation.

At this stage four categories of risks could be foreseen:

1. Ecological risks,
2. Hydrographical risks,
3. Socio-economical risks,
4. Technical risks.

To make a tentative allocation of different types of risks and resulting impacts that may arise from up-scaling of oxygenation, a conceptual model was created for a basis for structured interviews of the experts and a background framework for the detailed identification and assessment of risks (*Figure 6-4*).

It was also seen that the risks related to the oxygenation of the open sea areas of the Gulf of Finland (GoF) and of the Gotland deeps of the Baltic Proper (BP) might be partly diverse, and thus they should be separated in the detailed assessment where applicable.

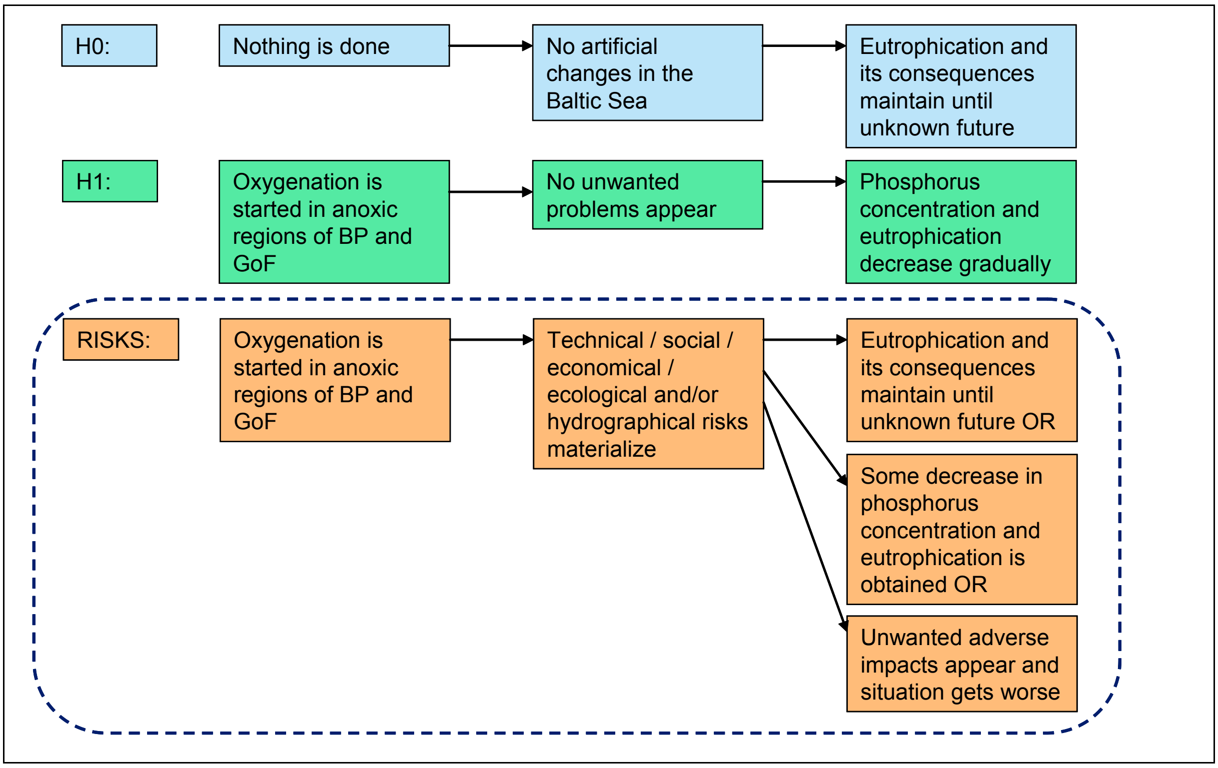


Figure 6-3. Framework of the Phase II risk assessment.

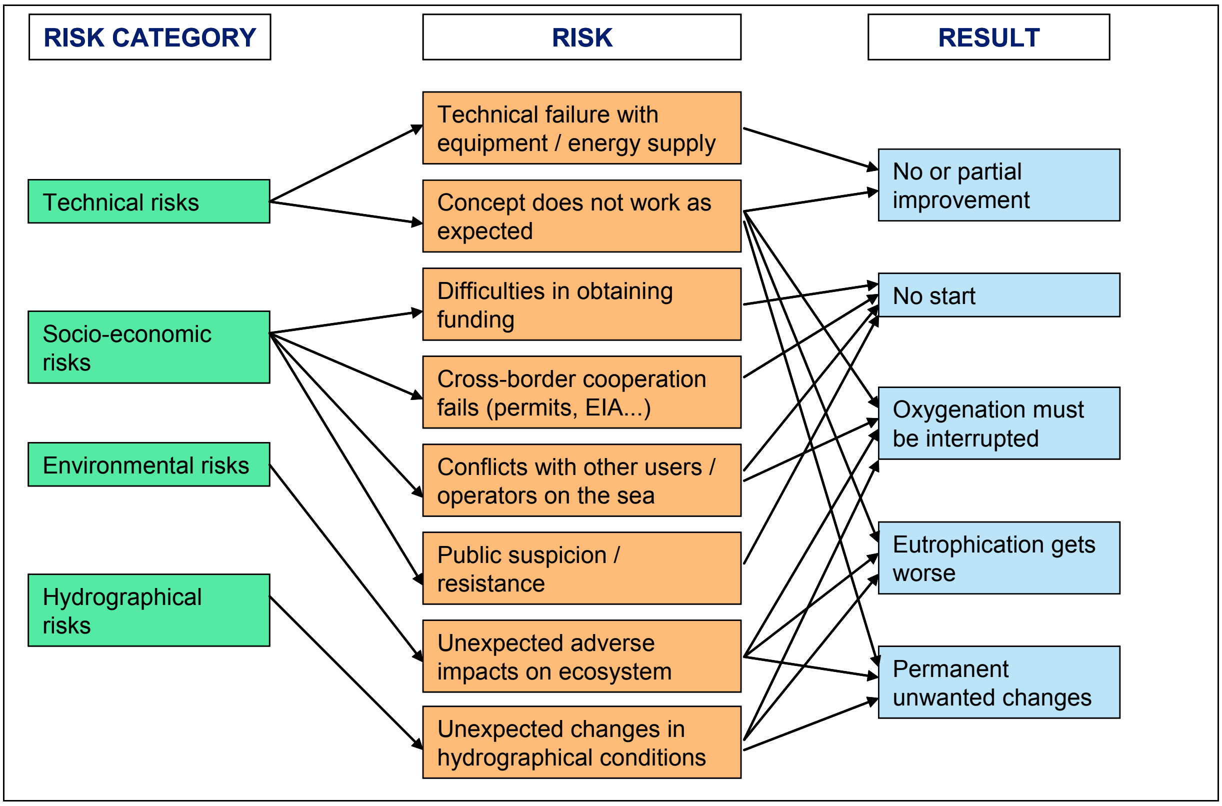


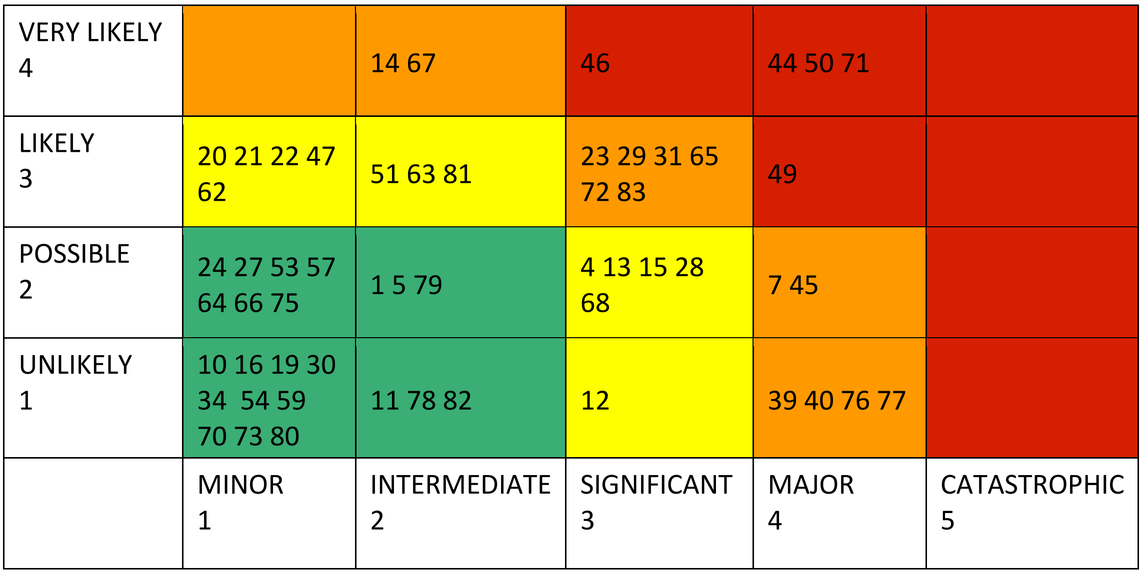
Figure 6-4. Conceptual model of the risk assessment.

6.3.2.1 Main results and discussion

In the risk assessment session the probabilities and impacts of the identified 'long-list' risks were estimated in order to be able to prioritize the most significant oxygenation risks for further analysis. The 'long-list' was compiled based on interviews of a selected advisory group, the experimental experience from the first two years of this project, and on the mapping of potential problems from literature.

The ranking of all previously identified risks concluded in the RA session is shown in the risk matrix (*Table 6-11*). The risk ID numbers in the matrix refer to the ID numbers in the risk list. The colours of different ranks are meant to visualize the significance of the risk so that 'green' and 'yellow' risks are less significant and 'orange' and 'red' risks are more serious.

Table 6-11. Risk ranking matrix (ID numbers of the identified risks).



VERY LIKELY 4		14 67	46	44 50 71	
LIKELY 3	20 21 22 47 62	51 63 81	23 29 31 65 72 83	49	
POSSIBLE 2	24 27 53 57 64 66 75	1 5 79	4 13 15 28 68	7 45	
UNLIKELY 1	10 16 19 30 34 54 59 70 73 80	11 78 82	12	39 40 76 77	
	MINOR 1	INTERMEDIATE 2	SIGNIFICANT 3	MAJOR 4	CATASTROPHIC 5

The matrix shows that no 'catastrophic' risks were identified. However, a number of 'significant/major' and/or 'likely/very likely' risks (19) were foreseen for the upscaling of oxygenation. Instead, 37 of the identified risks were considered of lesser significance and probability.

Most of the 'very likely' risks were seen in socio-economic consequences related to EIA, transport safety and conflicting data or views in political decision making as well as to concept failures in oxygen pumping, whereas 'major impacts' were considered in regard to cod reproduction and changes is water temperature and stratification as well as to legislative, economic and political difficulties. Additionally realization of certain technical risks was estimated to have major impacts on upscaling.

The 'short-list' of the most significant risks was compiled by selecting all risk combinations having a rank of 4 either in probability or in impact as well as combinations having a rank of 3 both in probability and in impact (red or orange in the matrix).

Table 6-12. Short-listed significant risks after ranking (RED and ORANGE in the risk matrix).

ID	Risk	Area	Prob	Impact	Description
7	Disturbance or failure in cod reproduction	BP +	2	4	Floating cod spawn requires salt concentration of >10 ‰ and ca. 2 mg/l oxygen concentration; changes in these have impacts, positive or negative. Floating spawn must not fall to sediment; floating depth must be oxic; if salinity/density decreases so that the spawn sinks to anoxic depth, it dies rapidly. Hatching in depth with no food causes starvation of fry. Important reproduction areas in southern BP (Bornholm), restriction in fishing could sustain the stock well enough.
14	Negative changes in nutrient ratios	GoF + BP +	4	2	Induction of advanced turnover may have significant impacts on nutrient cycles. Focus on changes in relative ratios of nutrients.
23	Macroscale currents dominate water circulation in GoF	GoF western part +	3	3	The most important driving forces: coriolis + Neva river + salt concentration. Macroscale background issues influence the need of oxygenation, its implementation, or its impacts. Deep water currents are usually very slow and not impacted by the wind induced currents. A shallow coast pushes major streams out from the coastline.
29	Harmful interaction with sea water pulses – GoF	GoF +	3	3	North Sea pulse pushes anoxic water from BP to GoF, which increases oxygen depletion and strengthens the stratification and halocline in GoF. Major salt water penetration to GoF requires a strong E wind that pushes surface water out of the bay, which is replaced by deep water from the BP. This is probably the most dominating effect controlling anoxia in GoF, especially in western GoF, and at least in the open sea area. Continuous smaller deep water flow from BP to western GoF is also probable, because there is no sill separating GoF from BP. An anoxic water pulse from BP to eastern GoF may also impede all the oxygenation efforts. This would be relevant only in the event that oxygenation is not successful in BP.
31	Risk of changing water circulation by changing salinity	BP +	3	3	Mid-water inflows represent 95% of the inflows in BP. If halocline is pushed, for example, from 80 m depth to 120 m, the winter circulation of mid-water to 120 m may bring up increased amounts of nutrients.
39	Warming of deep waters	GoF + BP	1	4	Warming of deep waters during summer stimulates decomposition and further oxygen consumption.
40	Oxygenation breaks stratification too early	GoF +	1	4	Changes of summertime thermal and/or salinity stratification, and possibly of the vertical oxygen profile. Stratification may break down at an unwanted point of time with negative impacts.
44	Resistance may arise in international EIAs	GoF + BP +	4	4	International EIAs will most probably will be required. International EIA requirements may be hard to fulfill. Public resistance may occur.
45	EU restrictions on changing habitats	GoF + BP +	2	4	May prevent oxygenation.
46	Transport safety restrictions	GoF ++ BP (+)	4	3	Marine transport safety may require permits that impact on the way oxygenation is implemented.

49	Cost efficiency of oxygenation is not sufficient	GoF + BP +	3	4	Oxygenation may not improve fish stocks, and salt water pulses and southern reproduction areas may be sufficient to maintain the stocks. Fishing restrictions in BP may be a more efficient way to protect fish stocks. Cost efficiency of P removal from water column is difficult to compare with external P load.
50	Conflicting data and/or views to support the decision making	GoF + BP +	4	4	Amount, quality and eventual disputes of research and experimental data will have an influence on political decisions. Consensus may not be reached.
65	Oxygenation does not extend into sediments	GoF + BP +	3	3	Even if oxygenation of water does succeed, would oxygenation extend to sediments - as diffusion is very slow? On the other hand even if at the first stage of oxygenation, oxidation of H2S is beneficial as such, it might change the Fe-S-P -balance to enhance P precipitation.
67	Deepest bottoms in GoF remain anoxic	GoF +	4	2	Mixing with pumps does not necessarily reach the deepest bottoms because of the high density differences, which would leave part of the sediments anoxic; however the slopes of the deep areas cover a much wider surface area and would be oxygenated, which would stimulate the process even if not complete it.
71	Oxygenation has no permanent impact	GoF + BP +	4	4	GoF: The natural bottom structure in the coast of Finland is such that anoxic/hypoxic conditions may always evolve. BP: Macroscale events may dominate the oxygen conditions. Continuous pumping may be required for making the obtained results sustainable. Attaching a "vertical barrier" with Mixox to the mouth of GoF, in order to prevent the continuous anoxic salt water leaching via close bottom streams to GoF was discussed. Realism should be kept in mind: no rapid changes can be expected with any technology; in any case the improvement in oxygen levels of bottom water and sediments will take many years.
72	Oxygenation has no impact on P storage	GoF + BP +	3	3	Shortage of iron may counteract the impact of oxygenation and P remains soluble. Again, P decrease has been observed without presence of Fe; may be due to biofilm growth (e.g. Beggiatoa).
76	Scaling up of Mixox is technically not feasible - GoF	GoF +	1	4	Scaling up to outer GoF: risk of not finding a suitable energy solution is estimated to be <20%. Larger propellers, up to 5 m in diameter, must be planned; developing and testing may take years, depending on available financing and driving forces. Cooperation with ship builders etc. would be beneficial.
77	Scaling up of Mixox is technically not feasible - BP	BP +	1	4	Scaling up to BP: risks may arise with, for example, extensive cabling (even 200 km might be required if taken from the mainland).
83	Temporary increase in eutrophication	GoF + BP +	3	3	Increase of eutrophication due to mixing may take place for a few years in the early phases.

Risk is defined as a combination of probability and impact where

- low probability with high impact risk or
- high probability with low impact risks

can be regarded as serious risks, although they may be different from risk management point of view.

Here, the risk assessment results (*Table 6-13*) of the most significant risks can be divided roughly into four groups:

Table 6-13. Results of risk assessment

Gr.	Risk combination	Probability rank	Impact rank	Number of risks
1	High probability - high impact	3 - 4 (likely - very likely)	4 (major) (*	4
2	High probability - medium impact	3 - 4 (likely - very likely)	3 (significant)	7
3	High probability - low impact	4 (very likely)	1 - 2 (minor - intermediate)	2
4	Low probability - high impact	1 - 2 (unlikely - possible)	4 (major)	6

*) No rank 5 (catastrophe) risks were identified

The most serious risks for upscaling oxygenation can be classified into four categories as follows.

Category 1:
Political and regulatory risks concerning the initial start-up of oxygenation were considered to be the highest. The risk of failure in the concept of oxygenation was also given a high rank.

- Resistance in international EIA,
- Conflicting data and/or views to support decisions,
- Oxygenation has no permanent impact.

Insufficient cost efficiency in oxygenation was also seen to pose a rather high risk. It is noteworthy that no risks of the highest category were seen in the ecological or hydrographical consequences in the Baltic Sea due to oxygenation.

Category 2:
Likely or very likely risks with significant impacts included risks causing adverse changes in the water circulation as well as risks of concept failure due to e.g. hydrographical reasons and insufficient oxygenation:

- Macroscale currents dominate water circulation in GoF,
- Harmful interaction with sea water pulses - GoF,
- Risk of changing water circulation by changing salinity,
- Oxygenation does not extend into sediments,
- Oxygenation has no impact on P storage,
- Temporary increase in eutrophication.

Category 3:

Likely risks but with rather low impact was seen in changing nutrient ratios and again in insufficient oxygenation:

- Negative changes in nutrient ratios,
- Deepest bottoms in GoF remain anoxic.

Category 4:

Unlikely risks but with high impact were seen in disturbing the cod reproduction and accelerating decomposition due to warming or changing stratification, but also with the technical feasibility of the method. Regulatory risk concerning habitat changes was also recognized.

- Disturbance or failure in cod reproduction - BP,
- Warming of deep waters,
- Oxygenation breaks stratification too early,
- EU restrictions on changing habitats,
- Upscaling of Mixox is technically not feasible - GoF,
- Upscaling of Mixox is technically not feasible - BP.

6.3.2.2 Conclusions

A preliminary risk assessment was conducted concerning the possibility of upscaling Mixox oxygenation to the open sea areas of the Gulf of Finland and/or the Baltic Proper (Gotland Deep) which was the Phase 2 of the Risk Assessment.

It became evident that the mechanisms of nutrient reactions and cycles versus the potential remediation method by oxygenation pumping among other things must be carefully surveyed before any decisions on the remediation techniques and actions.
One of the key findings was that no impacts of the highest risk category (catastrophe) could be foreseen. However, several very likely or likely and major or significant risks were identified.

Parts of the identified risks were seen independent of the oxygenation area, but certain risks were specific to either the Gulf of Finland or to the Baltic Proper as concluded below.

1. Oxygenation pumping in the Gulf of Finland and the Baltic Proper

The most prominent risks related to the upscaling independent of the location concerned issues like public resistance, regulatory obstacles, conflicting data as well as lack of permanent impact of oxygenation. Additionally risks of changing water circulation, stratification and salinity, warming of deep waters and causing temporary increase in eutrophication were foreseen. Additionally upscaling of the Mixox method was considered to pose some risks in technical feasibility, e.g. related with energy supply. Regulatory risk concerning habitat changes was also recognized.

2. Oxygenation pumping in the Gulf of Finland

It was seen that the dominance of macroscale currents in water circulation and harmful interaction with sea water pulses from the Baltic Proper may defeat all the efforts of oxygenation. As well the deepest bottoms in GoF may remain anoxic. Oxygenation may break summer stratification too early, causing negative impacts in nutrient storage.

2. Oxygenation pumping in the Baltic Proper (Gotland Deep)

Unlikely risks but with high impact were seen in disturbing the cod reproduction. Changing water circulation by changing salinity was considered a likely and significant risk in the Baltic Proper.

6.4 Social cost-benefit and cost-efficiency analysis of oxygenation

We apply next the social cost-benefit analysis to examine the net benefits of oxygenating anoxic bottoms by pumping, which define the social desirability of pumping. To this end we have to define what constitutes the social benefits of pumping. Based on the literature, our analysis distinguishes between two alternative approaches to pumping, which define the social benefits in a slightly different way.

The first approach one regards pumping *as an additional means of reducing eutrophication* giving pumping a similar status as actions to reduce loads from external sources (Conley et al. 2009b). From this angle, the social benefits of pumping are the same as those the society assigns to nutrient reductions in external sources. Therefore, the study of the social desirability of oxygenation by pumping ultimately boils down to a comparison of the net benefits associated to these alternative ways of reducing nutrients. Thus, research question is: if society allocates a given sum of money to pumping in order to reduce eutrophication, would this money produce higher or lower net benefits if it were allocated to promote further reductions in nutrient loads from external sources? Under this approach, pumping is desirable only if it produces higher net benefits than reductions in external sources.

The second and more commonly stated approach is to regard pumping as a complementary instrument to reductions of external loads, a means of speeding up the recovery of the Baltic Sea (Stigebrandt and Gustafsson 2007, Conley et al. 2009). The idea behind this approach is that even though the Baltic Sea states would be willing to implement the reductions in nutrient loads as assigned to them by the Baltic Sea Action Plan, these reductions have a very long time horizon before they translate into targeted reductions in eutrophication. Pumping at a larger scale would lead to the recovery of the Baltic Sea faster than would otherwise occur with external load reductions alone. Under this angle, our research question is: assuming that countries implement BSAP does oxygenation by pumping produce positive net benefits, or not? Under this approach, pumping is desirable provided it produces positive net benefits.

These two approaches provide the research questions of this section. We examine pumping as a means of reducing eutrophication merely at the local scale: experiment sites and anoxic coast of the Gulf of Finland. When examining pumping as a means of recovery we focus on both anoxic coastal and anoxic open sea areas of the Gulf of Finland.

In addition to the actual experiments in Lännerstasundet and Sandofjärden, we also examine a hypothetical case for Sandofjärden, called Sandofjärden idealized. Recall, pumping in Sandofjärden failed to produce reduction in nutrients probably thanks to undersized pumping capacity. Thus, the idealized case for Sandofjärden provides a hypothetical assessment of how much the reduction in phosphorus and nitrogen release would have been had the pumping capacity been adequate. It is also needed for the regional generalization of the results.

We start by presenting first the impact and cost data used our analysis in section 6.4.1. We then use this data to examine pumping as an additional means of reducing eutrophication in section 6.4.2. We apply the same data and additional data from the Baltic Sea simulation model to examine the desirability of pumping as a means of recovery in section 6.4.3 and condense our conclusions in section 6.4.4. We omit the theory and calculation principles of cost benefits analysis (for details, see Ollikainen et al. 2012).

6.4.1 Basic data: pumping capacity, impacts on nutrients and costs of pumping

Using the standard Mixox pumping units we recapitulate in Table 6-14 the capacity information given in section 3.3.1. In the theoretical case site "Sandofjärden idealized" we increase the number of pumps to a level, which is expected to reduce nutrient release.

Table 6-14. Experiment sites and pumping capacities

Experiment site	site area km^2	number of pumps	efficiency kWh/pump	flow of water m^3/d	days of pumping
Lännerstasundet actual	0.25	1	2.5	82 000	123
Sandofjärden actual	4.75	6	15.0	492 000	81
Sandofjärden idealized	4.75	19	47.5	1 558 000	100

Table 6-15 reports the estimated reduction in nutrient release obtained by pumping (Table is based on previous Tables 4.3.1 - 4.3.3). We report both phosphate phosphorus PO_4 and dissolved inorganic nitrogen (DIN). The estimates are based on three year measurements and reported as a range minimum-mean-maximum.

Table 6-15. Reductive impact of pumping on phosphorus and nitrogen release

Experiment site	Phosphate phosphorus (kg)			Dissolved nitrogen (kg)		
	min	mean	max	min	mean	max
Lännerstasundet actual	130	145	160	310	321	331
Sandofjärden actual	0	0	0	-2 000	-1 500	- 1 000
Sandofjärden idealized	1 798	2 100	2 402	3 499	4 890	6 281

Reduction in phosphorus and nitrogen release in Lännerstasundet is quite big. The site is fairly closed, so that pumping improves efficiently oxygen conditions in the bottom. Results from Sandofjärden represent the opposite: no reduction in phosphorus release was obtained and even worse, nitrogen release was boosted due to reasons explained in section 4. Thus, instead of reduction, we witness an increase in nutrients in the actual experience from pumping in Sandofjärden. Higher capacity in the idealized case of Sandofjärden suggests that a fairly high reduction of nutrient release, roughly 2 tons of phosphorus, can be obtained. Recall, Sandofjärden area is 4.75 km^2, while Lännerstasundet is roughly 0.25 km^2, that is, roughly 19 times smaller. Dividing the mean reduction of phosphorus (2100 kg) by 19 yields roughly 110 kg. Thus, reduction per unit of area is smaller in Sandofjärden idealized.

Table 6-16 provides data on investment, maintenance and operative costs of pumping based on the bookkeeping data of the project. Costs are defined for one operating pump and one reserve pump. Reserve pumps are required in each site to ensure that technical problems do not stop or endanger the pumping operation. We use one reserve pump for Lännerstasundet and Sandofjärden actual, and three reserve pumps for Sandofjärden idealized. The economic life time of pumps is 20 years and we employ the range of interest rate of 3-5%. Variable costs consist mostly of electricity consumption and maintenance of equipment. Furthermore, we assume that pump(s) operate 4 months and 24 h per day. We use as the cost of electricity 0.12 €/kWh. As Table 6-16 shows, investment costs are the highest cost item.

Table 6-16. Costs of pumping: investment, operational and annualized annual costs

Cost items	**One pump and a reserve pump**		
	r = 3%	**r = 4%**	**r = 5%**
Investment total	**41 500**	**41 500**	**41 500**
Design	5 500	5 500	5 500
Manufacturing	16 000	16 000	16 000
Assembly	20 000	20 000	20 000
Operating costs total	**2 986**	**2 986**	**2 986**
Energy	*886*	*886*	*886*
Maintenance	*2 100*	*2 100*	*2 100*
Sum: investment and operating costs	**85 918**	**82 075**	**78 707**
Annualized costs	**5 775**	**6 039**	**6 316**

We, finally, need monetary estimates to determine benefits of nutrient reductions. When analyzing pumping as a means of reducing nutrient we use 9.92.€/kg N-equivalent as an estimate of the citizens' willingness to pay (WTP) for reduced eutrophication in Sweden and Finland. This estimate is by Gren (2001). The original value of this WTP estimate is 6.7 Euros/kg nitrogen and prolonging it to current values by 4% discount rate gives as the current value 9.92 Euros/kg of nitrogen. When we examine pumping as a means of speeding up the recovery of the Baltic Sea, we use WTP estimate range reported in Table 6-8.

6.4.2 Desirability of pumping as a means of reducing eutrophication

6.4.2.1 Net benefits in the experiment sites

We examine in this section the net benefits of pumping in the experiment sites. Results are then generalized to pumping anoxic coastal areas of the Gulf of Finland. Because the results do not change crucially as a function of real interest rate (Ollikainen et al. 2012), we report all cases for 4% interest rate in Table 6-17. The two first columns report the annual reduction of phosphorus and nitrogen in each case, and the third column adds them up as nitrogen-equivalents using Redfield ratio. Annual economic benefits are obtained by multiplying nitrogen-equivalents by the WTP estimate, 9.92 Euros. The annualized pumping costs are taken from Table 6-16 and are adjusted to the number of pumps in each site. Difference between the annual benefits and costs defines the annual net benefits, and total net benefit is heir net present value over the 20 year period.

Table 6-17. Net benefits from pumping in experiment sites (interest rate 4%)

	PO4/ year	DIN/ year	N-eq./ year	Benefits B/year	Costs, C/year	Net benefits NB/year	Total NB 20 years
Lännerstasundet							
Min	130	310	1 246	12 357	6 039	6 318	**93 998**
Mean	145	321	1 365	13 533	6 039	7 493	**111 482**
Max	160	331	1 483	14 708	6 039	8 669	**128 967**
Sandöfjärden actual							
Min	0	-1000	-1000	-9 918	20 256	-30 174	**-410 081**
Mean	0	-1500	-1500	-14 876	20 256	-35 132	**-477 462**
Max	0	-2000	-2000	-19 835	20 256	-40 091	**-544 856**
Sandöfjärden idealized							
Min	1798	3 499	16 445	163 092	83 932	79 159	**1 075 798**
Mean	2100	4 890	20 010	198 452	83 932	114 519	**1 556 357**
Max	2402	6 281	23 575	233 812	83 932	149 880	**2 036 915**

The pumping experiment in Lännerstasundet was successful: the annual net benefits and their present values are clearly positive. This outcome is robust to changes in the real interest rate and pumping costs thanks to the fairly high reduction in nutrients. The actual experiment in Sandöfjärden did not reduce phosphorus release and, to make the outcome even worse the amount of nitrogen was increased in sea water. Annual net benefits are negative and the present value of net benefits indicates losses of a half a million Euros over the 20 years period. Message from Sandöfjärden is important. Pumping may fail due to uncertainties associated with the design of the pumping area and capacity. At a large scale, this kind of failure can be costly, and for a smaller scale it is harmful.

An idealized case Sandöfjärden was produced by increasing the number of pumps from the original 6 to 19. The estimated mean reduction is 2 tons of phosphorus and 5 tons of nitrogen. Per hectare terms reduction is slightly less than in Lännerstasundet. Due to the higher capacity, total pumping costs increase quite much and exceed 50 000 Euros but costs per pump do not actually differ much from Lännerstasundet. The annual benefits are high and exceed the annual pumping costs by a factor 2-3. Thus, the net benefits are positive.

Results for Lännerstasundet and Sandöfjärden idealized show that pumping produces positive net benefits. As such, this result would lead to a policy recommendation that is favorable for pumping. However, we must first examine whether increasing the efforts in external sources to reduce nutrient loads would lead to higher social net benefits than pumping. We collect unit costs of abatement in Lännerstasundet and Sandöfjärden idealized using 4% real interest rate in Table 6-18. We express the unit costs in two alternative ways: N-equivalents and P-equivalents.

Table 6-18. Unit costs of nutrient reduction in the experiment sites

	P0$_4$ kg	**DIN kg**	**N-eq. kg**	**P-eq. kg**	**costs €**	**c/N-eq. €/kg**	**c/P-eq. €/kg**
Lännerstasundet							
Min	130	310	1 246	173	6 039	4,85	34,90
Mean	145	321	1 365	190	6 039	4,43	31,87
Max	160	331	1 483	206	6 039	4,07	29,32
Sandöfjärden idealized							
	P04	**DIN**	**N-eq.**		**cost**	**c/N-eq.**	**c/P**
Min	1798	3 499	16 445	2 284	83 932	5,10	36,75
Mean	2100	4 890	20 010	2 779	83 932	4,19	30,20
Max	2402	6 281	23 575	3 274	83 932	3,56	25,63

In Lännerstasundet the unit reduction cost of nitrogen equivalents is slightly below 5 €/kg, which is roughly the marginal cost of abating 70% of nitrogen in waste water treatment plants (10 000 PE). The cost of phosphorus equivalents is relatively high and exceeds costs of phosphorus abatement (13-17 €/kg) in WWTPs. Thus, both estimates are higher than abatement costs in most WWTP:s in the Gulf of Finland sub-basin. However, Lännerstasundet is a fairly closed sea area and receives loads mostly from nonpoint sources close by. Pumping reduces nutrients, especially phosphorus, more than the nearby areas load the bay. The costs of reducing external loads would eventually be very high if abatement rate in the external sources is raised close to 100%. Also reducing nutrient from nonpoint sources far away would be quite expensive. *This suggests that in closed inner archipelago sites such, as Lännerstasundet, pumping is a real local policy option to improve the condition of water, provided the local inhabitants have willingness to pay for pumping to promote recovery of the site.*

Average costs of nutrient reduction in Sandöfjärden idealized are slightly lower than in Lännerstasundet. Sandöfjärden is a more open site and its water quality is dependent on nutrients in the surrounding sea areas. Therefore, we ask: How much nutrient reduction in external sources is required to produce the same reduction of nutrients in Sandöfjärden as is obtained by pumping. Using Table 6-23, the theoretical maximum when pumping is very successful, was 2.8 tons reduction in phosphorus-equivalents or 20 tons of nitrogen-equivalents transferred to Sandöfjärden. Suppose that this reduction is made in St. Petersburg. Drawing on EIA-SYKE 3D model calculations, we expect that 0.0194 - 0.0425% of the reduced dissolved phosphorus transfers to the site. Then, the required reduction in phosphorus abatement would be very large 1666,7 – 6194,7 tons. The current average abatement rate in the St. Petersburg WWTP.s is 84% and loads 700 tons Thus, achieving this reduction would be technically simply impossible.

This discussion reinforces our conclusion above: *pumping is a real local policy option also in more open coastal archipelago sites albeit it is a more risky project. Each planned pumping site requires careful background studies and dimensioning, as well as intensive monitoring during the project*.

Thus, we find that pumping can be a *local solution provided local willingness to pay exists*. Local solutions may not, however, be relevant at larger regional scales. Moreover, reductions made in the external sources produce benefits much wider areas and thereby provide net benefits over larger sea areas. Therefore, an adequate comparison of pumping and external sources can only be made at the scales of sub-regions of the Baltic Sea and the whole sea.

6.4.2.2 Generalization to anoxic coastal areas of the Gulf of Finland

We next examine the possibility of extending pumping from a single site to multiple anoxic sites to reduce nutrient release in the Gulf of Finland. We focus on pumping the anoxic bottoms in the deeper parts of the costal Gulf of Finland, an area estimated approximately as 185 km^2. The size and location of anoxic bottom areas are illustrated in Figures 6-5a and 6-5b for the western and eastern parts of the coastal Gulf of Finland.

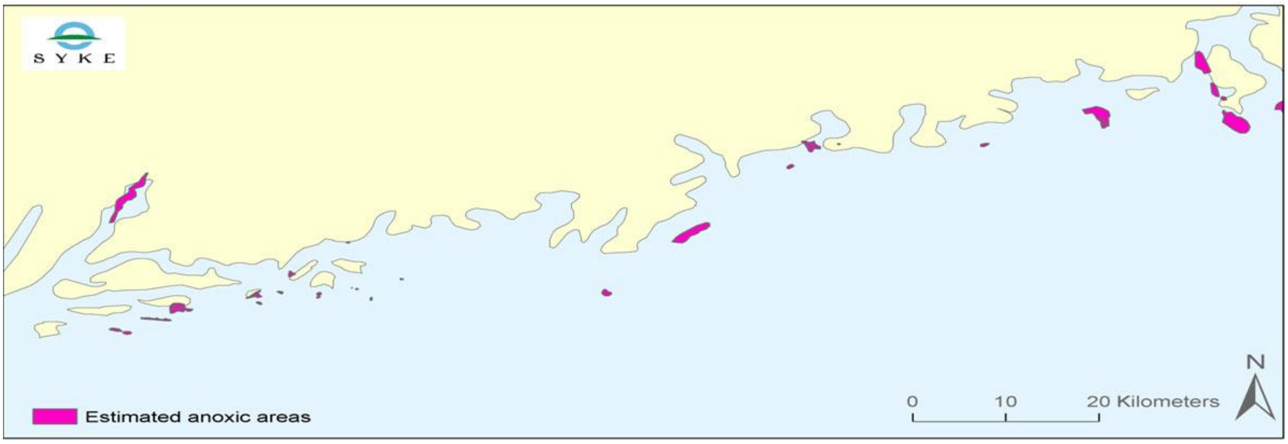


Figure 6-5a. Anoxic bottom areas in the coastal western Gulf of Finland.

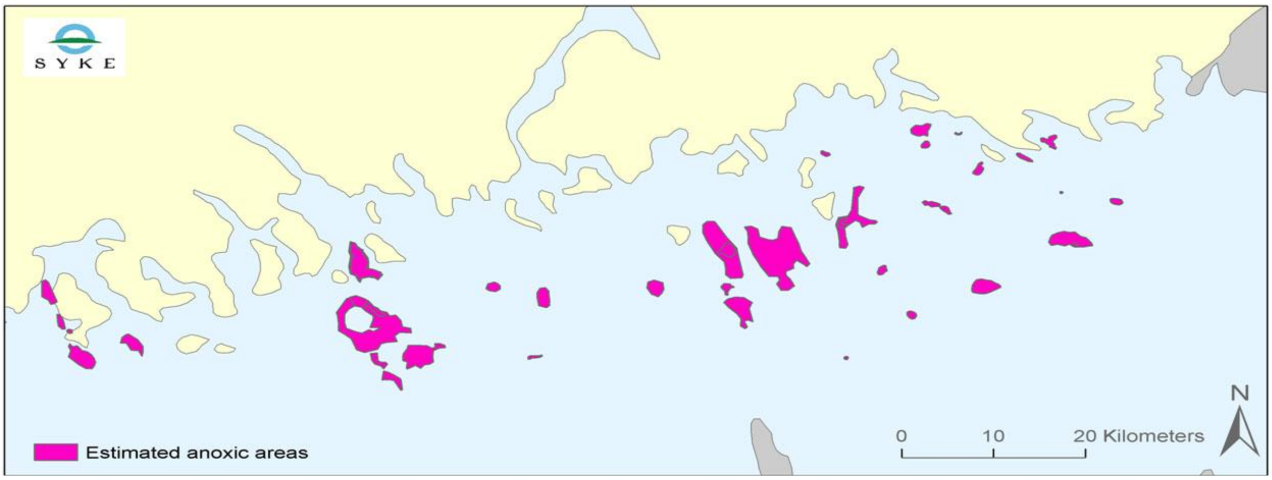


Figure 6-5b. Anoxic bottom areas in the coastal eastern Gulf of Finland

Figure represent the average of anoxic areas (which may vary considerably in each year) and the analysis mostly do not cover the inner archipelago areas. As figures show, anoxic areas constitute a relatively small share of coastal waters and their share increase from west to east.

We generalize the results from pumping sites to the anoxic areas of Figures 6-5 and 6-6. We postulate three scenarios based on linear extrapolation of our results in Tables 6-20, 6-21 and 6-22:

Scenario 1. *Optimistic*: is based on the measured nutrient reduction obtained in Lännerstasundet.

Scenario 2. *Idealized*: is based on the estimated reduction in Sandöfjärden ideal

Scenario 3. *Pessimistic*: is based on the measured negative reduction Sandöfjärden actual

Furthermore, we examine the more realistic case where these scenarios do realize in their pure form but may partly fail, reflecting the fact that risk analysis in section 6.3 highly emphasized the possibility of ecological and technological failure risks of pumping. Thus, we allow pumping be successful in some sites, while failures take place in some other sites, for instance, thanks to problems in operational technology, design of the system or sudden changes in water mass movements.

We group pumps in roughly 2x2 km areas, with 19 pumps in each, in the optimistic and idealized scenarios making together 712 operative pumps. In the pessimistic scenario 3 we have 6 pumps in each area making together 225 operative pumps. Table 6-19 presents the net benefits for the three scenarios. As the choice of real interest rate impacts results only little, we report results just for the case of 4% interest rate.

Table 6-19. Pumping anoxic bottoms in coastal areas of the Gulf of Finland: net benefits of scenarios 1- 3, respectively (interest rate 4%).

	PO_4 185 km^2 (ton)	**DIN 185 km^2 (ton)**	**N-eq. (ton) 185 km^2 (ton)**	**Benefits/ year (M€)**	**Costs/ year (M€)**	**Net benefits B/year (M€)**	**total NB 20 years (M€)**
Scenario 1. Optimistic							
Min	96	229	922	9,1	4,5	4,7	63,6
Mean	107	237	1 010	10,0	4,5	5,6	75,4
Max	118	245	1 097	10,9	4,5	6,4	87,2
Scenario 2. Idealized							
Min	70	136	640	6,3	3,3	3,1	41,9
Mean	82	190	778	7,7	3,3	4,5	60,6
Max	93	244	917	9,1	3,3	5,8	79,4
Scenario 3. Pessimistic							
Min	0	-78	-78	-0,8	0,9	-1,6	-22,3
Mean	0	-58	-58	-0,6	0,9	-1,5	-19,7
Max	0	-39	-39	-0,4	0,9	-1,3	-17,1

From Table 6-19, both optimistic and idealized scenarios reduce phosphorus by 70-118 tons and nitrogen by 130-240 tons. Phosphorus reduction is about the same as can be obtained in all Finnish waste water treatment plants if the abatement rate is increased in all plants to 97-98% (current average abatement is 96%). Nitrogen reduction is small relative to the abatement potential in the Finnish and Swedish waste water treatment plants (average abatement rates are 60 and 67%, respectively). The annual net benefits in scenarios 1 and 3 range from three to six million Euros per year. The last scenario 3 “Pessimistic” provides large negative benefits.

Consider now how the net benefits under the more realistic case with alternative success-failure combinations of scenarios 1-3. Table 6-20 presents the reductions in phosphorus, nitrogen and nitrogen-equivalents for three different success-failure combinations.

Table 6-20. Pumping anoxic bottoms in coastal areas of the Gulf of Finland: nutrient reductions under alternative joint realizations of scenarios 1, 2 and 3.

	Scenario 1. *Optimistic* reduction (tons)		**Scenario 2. *Idealized* reduction (tons)**		**Scenario 3. *Pessimistic* reduction (tons)**		**Total reduction (tons)**
1st combination	**share 0.25**		**share 0,5**		**share 0,25**		**share 1**
	PO$_4$	**DIN**	**PO$_4$**	**DIN**	**PO$_4$**	**DIN**	**N-equivalents**
Min	24,1	57,4	35,0	68,1	0,0	-19,5	531
Mean	26,8	59,3	40,8	95,1	0,0	-14,6	627
Max	29,6	61,2	46,7	122,2	0,0	-9,7	723
2nd combination	**share 0.1**		**share 0,5**		**share 0,4**		**share 1**
	PO$_4$	**DIN**	**PO$_4$**	**DIN**	**PO$_4$**	**DIN**	**N-equivalents**
Min	9,6	22,9	35,0	68,1	0,0	-31,1	381
Mean	10,7	23,7	40,8	95,1	0,0	-23,3	467
Max	11,8	24,5	46,7	122,2	0,0	-15,6	553
3rd combination	**share 0.05**		**share 0,4**		**share 0,55**		**share 1**
	PO$_4$	**DIN**	**PO$_4$**	**DIN**	**PO$_4$**	**DIN**	**N-equivalents**
Min	4,8	11,5	28,0	54,4	0,0	-42,8	259
Mean	5,4	11,9	32,7	76,1	0,0	-32,1	330
Max	5,9	12,2	37,4	97,7	0,0	-21,4	400

Relative to pure scenarios 1 and 2 the reduction of nutrients is now lower and nitrogen-equivalents decrease almost to a half of what scenarios 1 and 2 produced. Overall, the reduction in nutrients is not especially great, yet achieving it in the Finnish waste water treatment plants requires increasing the abatement rate up to 97-98% in all plants.

Table 6-21 determines the respective annual net benefits and their present values over the 20 years period. Figures are calculated by defining the percentage of annual net benefits in the pure scenarios 1-3. Concerning the costs of pumping, this is somewhat arbitrary, because under this procedure we use scenario-specific pumping costs instead of a average cost for all sites; using average pumping would not crucially impact cost of scenarios 1 and 2 but costs in combination 3 would increase and make net present value even more negative.

Table 6-21. Pumping anoxic bottoms in coastal areas of the Gulf of Finland: net benefits of alternative joint realizations of scenarios 1, 2 and 3 (4% interest rate).

	Scenario 1. ***Optimistic*** **Euros**	**Scenario 2.** ***Idealized*** **Euros**	**Scenario 3.** ***Pessimistic*** **Euros**	**Total net benefits Million Euros share 1**	
1st combination	**share 0.25 Annual NB**	**share 0,5 Annual NB**	**share 0,25 Annual NB**	**Annual NB**	**Present value NB**
Min	1 169 444	1 542 363	-411 080	2,3	31,3
Mean	1 387 833	2 231 045	-362 785	3,3	44,3
Max	1 604 387	2 919 728	-314 490	4,2	57,2
2nd combination	**share 0.1 Annual NB**	**share 0,5 Annual NB**	**share 0,4 Annual NB**	**Annual NB**	**Present value NB**
Min	467 778	1 542 363	-657 728	1,4	18,4
Mean	555 133	2 231 045	-580 456	2,2	30,0
Max	641 755	2 919 728	-503 184	3,1	41,6
3rd combination	**share 0.05 Annual NB**	**share 0,4 Annual NB**	**share 0,55 Annual NB**	**Annual NB**	**Present value NB**
Min	233 889	1 233 890	-904 375	0,6	7,7
Mean	277 567	1 784 836	-798 127	1,3	17,2
Max	320 877	2 335 783	-691 879	2,0	26,7

The key message of Table 6-21 is that annual benefits are positive but small relative to pure scenarios 1 and 2; they are reduced almost to a half. As such, positive net benefits would suggest that pumping is a project to be executed. Like above, we, again, must compare net benefits from pumping with benefits from reducing loads from external sources.

We consider two cases for external sources: either Finland or Russia reduces its nutrient loads in their WWTP.s. We choose WWTP.s instead of agriculture as the point of comparison due to two reasons: costs of reducing phosphorus are actually high in the short-run in agriculture and achievable reduction uncertain, because agriculture generates nonpoint loads subject to stochastic variation due to weather conditions. Costs of reducing nitrogen are, admittedly, slightly lower in agriculture than in WWTP.s and in this respect we overestimate the abatement costs of nitrogen.

The current phosphorus abatement rate in St. Petersburg WWTP.s is 84% and the remaining phosphorus load roughly 700 tons per year. We assume here somewhat arbitrarily that WWTP.s in St. Petersburg abate phosphorus exactly the amount that pumping reduces (roughly 820 t N-equivalents). This amounts to 135.5 tons of abated phosphorus, out of which 83% is assumed to be in dissolved form.

Table 6-22 presents the phosphorus and nitrogen abatement potential in the selected Finnish coastal WWTPs (see Ollikainen et al. 2012 for details). Given that the average abatement rate of phosphorus is high (96%), possibility to reduce phosphorus loads is small: increasing abatement rate to 98% would reduce phosphorus only by 37 tons. There is rather high reduction potential of nitrogen, however, as the average abatement rate is roughly 60%.

Table 6-22. Abatement potential in the selected Finnish waste water treatment plants

Phosphorus abatement		**Nitrogen abatement**		**N-equivalents**
abatement %	**reduction (tons)**	**abatement %**	**reduction (tons)**	**reduction (tons)**
96	9,1	70	311,9	377,5
97	**23,1**	**80**	**671,4**	**838,0**
98	37,1	90	1337,0	1604,3

A combination of 97% abatement of phosphorus and 80% abatement of nitrogen yields a nitrogen-equivalent reduction that is roughly the same as obtained by pumping under the pure scenarios and higher than can be obtained when the outcome of pumping was regarded as uncertain with differing combinations of failures and successes. Table 6-23 presents the costs and benefits from load reductions in the selected Finnish WWTP.s and in the WWTP.s in St. Petersburg. The abatement cost calculations are based on Hautakangas et al. (2012).

Table 6-23. Reducing loads in selected waste water treatment plants: net benefits

WWTP.s	**N-eq. (tons)**	**Annual costs (M€)**	**Annual benefits (M€)**	**Annual net benefits (M€)**	**Net present value (M€)**
Finnish Coast					
	378	1,68	3,74	2,06	35,6
	838	**5,05**	**8,31**	**3,27**	**56,5**
	1604	15,38	15, 92	0,54	9,3
St Petersburg					
	819	**1, 8**	**8,83**	**7,01**	**121,2**

From Table 6-23, when abatement in the Finnish WWTP.s is increased benefits increase first more than costs but towards abatement level of 1604 tons, costs start to increase more rapidly. The net benefits are between two and four million Euros annually. The present value of net benefits are defined over 30 years (which is the assumed economic life time of WWTP.s) is large, naturally much larger than present values obtained for the 20-years long pumping period. Phosphorus reduction in St. Petersburg is superior in terms of costs. We employ 13.2 €/kg as the average abatement cost (it reflects 96% abatement rate, thus, much higher rate than in St. Petersburg) and it yields 6.45 million Euros as annual net benefits. This figure is more than double to what can be achieved either in Finland or by pumping the bottom layers with oxygen-rich water.

In Table 6-24 we provide a comprehensive comparison and ranking of all studied alternatives. We rank alternatives with respect to two terms: annual net benefits and rolled over net benefits for 60 years. Rolling over is a method of making comparable the net present values of projects with different life times (pumping 20 years and abatement in the WWTP.s 30 years).

Table 6-24. Ranking the alternatives of reducing nutrients in coastal waters of the Gulf of Finland.

	Net benefits Annual	**Ranking**	**Net benefits Roll over 60 yr.**	**Ranking**
	M€	**#**	**M€**	**#**
Scenario 1	5,6	**2**	133,1	**2**
Scenario 2	4,5	**3**	106,9	**3**
Scenario 3	-1,5	8	-34,8	8
Combination 1	3,3	**4**	78,2	**5**
Combination 2	2,2	6	52,9	6
Combination 3	1,3	7	30,4	7
WWTPs - Finland	3,3	**5**	106,8	**4**
WWTPs -St. Petersburg	7,0	**1**	229,2	**1**

Starting with annual net benefits, the ranking is evident: reducing phosphorus in the Russian WWTPs produces highest annual net benefits, pure pumping scenarios 1 and 2 become next and combination 1 outperforms the reduction in the Finnish WWTPs but only by 0.03 million Euros. Rolling over the net benefits helps us to take into account the difference in time spans, actually, the longer time span of WWTP investment. The ranking changes slightly: now nutrient reduction in the Finnish WWTP.s outperforms Combination 1 and obtains the fourth place.

Based on the rankings and the fact that pure scenarios 1 and 2 are less realistic than combinations, we make the following conclusion: *Under current abatement level and costs in WWTPs, reduction of external loads produces higher annual net benefits than oxygenating anoxic bottoms in semi-closed coastal areas by pumping*.

We also note that once 95-97% abatement rate is achieved also in St. Petersburg, the only really cheap source to reduce nutrients in external source is nitrogen. Its abatement can be increased up to 90% with low fairly marginal costs (Hautakangas et al. 2012), because in the short-run reducing phosphorus from agriculture is fairly expensive (unlike in the long-run). Therefore, we also suggest an additional conclusion: *When pumping is regarded as a means of reducing eutrophication, pumping may obtain an important role in cost-efficient policy in semi-closed coastal areas once the marginal abatement costs in external sources increase and exceed the unit (and marginal) costs of pumping*. The size of the unit abatement costs of pumping depends on two factors: achieved reduction and annualized costs of pumping. Costs decrease when we learn more of pumping and develop more efficient equipments.

This section analyzed pumping as a means of reducing nutrients in a similar fashion as load reductions in external sources. Next we switch the angle of analysis and examine the role of pumping as a means of speeding recovery of the Baltic Sea.

6.4.3 Desirability of oxygenation as a means of speeding the recovery of the Baltic Sea

In this section we assume that the littoral countries are truly willing to reduce nutrient loads from external sources by the amounts allocated to them in the Baltic Sea Action Plan but a very long time horizon is needed before these reductions translate into the targeted reductions in eutrophication. Thus, we examine whether the benefits from a faster recovery exceed the costs of pumping. The natural regional scale of analysis is that of sub-basins of the Baltic Sea. Therefore, we examine pumping at the regional scale of the Gulf of Finland. Drawing on previous section, we examine separately pumping in the anoxic coastal waters of Gulf of Finland. We then use the Baltic Sea model simulations from Chapter 5 to examine net benefit of pumping in the anoxic deep areas of the Gulf of Finland. Recall, that simulations showed no impacts for pumping the open anoxic shallow areas of the Gulf of Finland, thus, we need to analyze this case here. In all calculations we use the WTP estimates for pumping reported in Table 6-8 and the pumping costs developed in the previous section.

6.4.3.1 The Gulf of Finland: Anoxic Coastal areas

Drawing on nutrient reductions and costs of *Tables 6-19 - 6-21*, we collect the net benefits of pumping for faster recovery under all scenarios *Table 6-25*. Because the WTP measures are expressed in terms of phosphorus, we re-express nutrient reductions in P-equivalents (DIN reduction divided by 7.2). Given that the choice of the interest rate does not crucially change the results, we present results only for the case of 4% interest rate.

Table 6-25. Net benefits of different pumping scenarios (4% real interest rate).

	Phosphorus	**Present value of net benefits 20 years**		
	equivalents	**WTP Min**	**MTP Mean**	**WTP Max**
Scenario 1	**ton**	**M€**	**M€**	**M€**
min	128	22,3	36,1	50,0
mean	140	30,2	45,4	60,5
max	143	38,1	54,5	71,0
Scenario 2	**ton**	**M€**	**M€**	**M€**
min	89	13,2	22,9	32,5
mean	108	25,7	37,4	49,1
max	128	38,2	52,0	65,8
Scenario 3	**ton**	**M€**	**M€**	**M€**
min	-11	-17,7	-18,9	-20,1
mean	-8	-16,0	-16,9	-17,7
max	-5	-14,2	-14,8	-15,4
Combination 1	**ton**	**M€**	**M€**	**M€**
min	74	7,8	15,7	23,7
mean	87	16,4	25,8	35,3
max	100	25,1	35,9	46,8
Combination 2	**ton**	**M€**	**M€**	**M€**
min	53	1,8	7,5	13,2
mean	65	9,5	16,5	23,5
max	77	17,2	25,5	33,8
Combination 3	**ton**	**M€**	**M€**	**M€**
min	36	-3,3	0,5	4,4
mean	46	3,0	8,0	12,9
max	56	9,4	15,4	21,4

Table 6-25 shows positive net present values (net benefits) for pumping under scenarios 1 and 2 and in all combinations. Dividing the mean figures by 20 years shows that the average annual net benefits range from almost zero (combination 3) to 2.75 million Euros (Scenario 1, WTP max). The figures are rather modest, though. Moreover, focusing on the more realistic combinations 1-3, we find that they are further decreased: while the maximum average annual net benefit is 2.3 million Euros, the mean is as low as 1,3 million Euros.

As *Figures 6-5a* and *6-5b* suggest, anoxic coastal areas are in many cases more open than our experiment sites. Thus, pumping may be more challenging along than coastal line than in the experiment sites. This may decrease efficiency of pumping, which shows up in increased pumping costs. Therefore we ask: what happens to net benefits if costs of pumping turn out to be higher than used in *Table 6-25*? To make net benefits of all scenarios negative or equal to zero at most would require 16 times higher costs and increasing costs by a factor 5 would make most means negative or zero but the largest mean of Combination 1 would be zero when costs are increase by a factor 10. Thus, we conclude that the results of positive net benefits are, in fact, a fairly robust finding.

Based on these figures our conclusion is as follows: *Pumping in the anoxic coastal areas of the Gulf of Finland provides positive net benefits and desirable provided it truly speeds up the recovery of the coastal areas of the Gulf of Finland.*

6.4.3.2 Gulf of Finland: Anoxic Deep Open Sea areas

We next examine the net benefits of pumping for faster recovery of the Gulf of Finland Deep. The required pumping capacity and obtained phosphorus reduction is taken from in the Baltic Sea simulation model presented section 5. According to the Baltic Sea model simulations, the pumped area is 120 km^2 and pumping takes place within a year. The basic description of pumping capacity is recapitulated in Table 6-26 The upper part of the table represents the simulation data and the lower part transforms the capacities to standard Mixox pumps.

Table 6-26. Simulation model for the Gulf of Finland Deep

Baltic Sea model	capacity indicator
Number of the model pumps	90
Total pump rate	27000m3 s-1
Flow per pump	300m3 s-1
Flow m^3 per pump day-1	25 920 000
Scaling to Mixox pumps	
Mixox capacity day-1	82 000
Number of 19 Mixox pump sets	1 497

As table 6-26 shows, the “super pumps” used in simulations would require roughly 1500 sets of 19 standard Mixox pumps. To scale the high capacity to a more realistic level, we assume that benefits are obtained gradually during 10 years pumping and remain constant thereafter for the remaining 10 years. This assumption scales the number on pump sets to 150 to be used in the analysis. We use the pumping costs of Table 6-19. However, we acknowledge that the pumping costs are plausibly higher in the high seas than in the relatively closed local pumping sites. Therefore, we also define the highest critical cost level which makes the pumping break-even, that is, the net benefits equal to zero.

Table 6-27 condenses the net benefits of pumping for a faster recovery for the range of WTP estimates. The first column gives the simulated phosphorus retention under high and low impacts of pumping; we distinguish between two cases. The minimum retention is the same for both cases and defined using an assumption that oxygenation leads to retention of 0.5 g P m^{-2}. Maximum values differ; in Case 1 the max retention is based on Stigebrandt and Gustafsson (2007) (3 g P m^{-2}) and Case 2 is based on the linear model presented in Conley et al. (2002, Figure 4a).

Table 6-27 Present value of net benefits from pumping the anoxic Gulf of Finland Deep.

	P reduction tons	**Net benefits Min WTP (M€)**	**Net benefits Mean WTP (M€)**	**Net benefits Max WTP (M€)**
Case 1. High				
min	60	-142,3	-137,5	-132,7
mean	210	-70,3	-53,5	-36,7
max	360	**1,7**	**30,6**	**59,4**
Case 2. Low				
min	60	-142	-137	-133
mean	155	-75	-59	-43
max	250	-51	-31	-11

Results in Table 6-27 show the net benefits depend on both the estimated retention and the range of WTP estimates. Using the mean values of both variables imply simply negative net benefits. Only the highest retention estimate in Case 1 gives positive net benefits. Thus, the case for pumping the anoxic Gulf of Finland Deep is not especially encouraging under the standard Mixox pumping technology and costs. How much higher the costs can be to warrant zero net benefits for the most optimistic cases? Increasing pumping costs by 34% makes the highest net benefits zero. This means that the annual pumping costs per pump would increase by 1532 Euros, which is not entirely unrealistic in the challenging open sea conditions. Less than 20% increase in costs is needed to make net benefits zero under the mean WTP estimate.

Our conclusion for pumping in the Gulf of Finland Deep can, therefore, be expressed as follows: *Pumping in the high seas of the Gulf of Finland is not desirable under current pumping technology.*

Given that the simulation model produced a clear phosphorus reduction, the social desirability of pumping depends much on pumping technology and citizens’ valuation. Improved pumping rate, advances in the maintenance of equipment and electricity supply in the challenging open sea areas is a key variable. Technology can be improved and experimenting more speeds up the technological development. Our conclusion is based on the current knowledge and is, therefore, subject to changes both in technology and citizens’ valuation of recovery. More research on efficient pumping technology, design and energy use is needed for more comprehensive conclusion.

Conclusions and recommendations

We applied the social cost-benefit analysis to examine the social desirability of pumping drawing on two alternative approaches to social benefits of pumping. The first approach regarded pumping *as an additional means of reducing eutrophication* giving pumping a similar status as actions to reduce loads from external sources. The second approach regards pumping as a complementary instrument to reductions of external loads, *a means of speeding up the recovery of the Baltic Sea* assuming that countries are willing to implement the Baltic Sea Action Plan.

1. Pumping as *an additional means of reducing eutrophication* as a local and regional option in the anoxic coastal areas of the Gulf of Finland.

Local scale: closed inner archipelago. Pumping in experiment site Lännerstasundet produced positive net benefits. Pumping in Sandöfjärden failed but increasing pumping capacity in the idealized case of Sandöfjärden produced positive net benefits. A comparison to external sources suggests that *in closed sites, such as Lännerstasundet, pumping is a local policy option*. This conclusion can be extended more open sites, such as Sandöfjärden, but the outcomes of pumping are more risky because of larger influence of the water mass movements from the open sea especially during winter time.

Regional scale: coastal anoxic areas. We generalized results from the three experiment sites models to anoxic sites of the Gulf of Finland using three scenarios (Optimistic, Idealized and Pessimistic) and their success-failure combinations. Optimistic and Idealized scenarios produced positive net benefits, and scenario 3 negative benefits. In the success-failure combinations the positive net benefits were reduced to almost a half. A comparison to reductions of external loads in the Finnish and Russian WWTPs locating in the Gulf of Finland shows that reduction of external loads still produces higher annual net benefits than oxygenating anoxic bottoms by pumping in semi-closed coastal areas.

We conclude, therefore, that *reducing loads from external source is the preferred option and pumping is not desirable under current cost structure*. However, we also suggest that pumping of oxygen-rich water may become an important role in cost-efficient policy once the marginal abatement costs in external sources increase and exceed the unit (and marginal) costs of pumping.

2. Pumping *a means of speeding up the recovery of the Baltic Sea* at the regional scale, anoxic bottom in coastal and deep areas of the Gulf of Finland.

Coastal anoxic areas. Pumping of the anoxic bottoms in coast of the Gulf of Finland provides in most cases positive net benefits. This result is fairly robust. **Anoxic areas in open sea**. Pumping the deep anoxic bottoms of the Gulf of Finland Deep produces positive net benefits only under the most optimistic assumptions.

We conclude, therefore, that while *pumping is desirable in the coastal areas to speed recovery, it is not desirable in the open sea areas, similar to the Gulf of Finland*.

As the simulations show that pumping reduces phosphorus, the desirability of pumping depends on the efficiency of pumping, ability to meet challenges associated with maintenance and supply of electricity in the open seas. Therefore, our conclusion is subject to changes both in technology and citizens' valuation of recovery. More research on efficient pumping technology, design and energy use is needed for more comprehensive conclusion.

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7 Main results, conclusions and recommendations

7.1. Effects of oxygenation on the status of the pilot sites

7.1.1 The pilot sites and oxygenation methodology

Artificial bottom water ventilation by oxygenation pumping was chosen as the test method to study the possibilities to counteract anoxia and benthic release of nutrients in coastal marine conditions in the Baltic Sea. The method is very energy-effective compared with pumping of oxygen or air, and it has been used in Finnish lakes since the 1980s, as well as in the estuarine Pojo Bay, western Gulf of Finland in the mid 1990s. PROPPEN is the first comprehensive study of this methodology in the Baltic Sea with intensive – partly automatic – monitoring before, during and after oxygenation pumping events.

Two pilot coastal sites were selected for the study: the basin of Sandöfjärden in the outer archipelago of the western Gulf of Finland and the eastern sub-basin of Lännerstasundet in the inner archipelago off Stockholm. These water areas vary highly regarding to hydrodynamic and geomorphologic conditions; the variability of such features play a key role in the control of deep water and benthic oxygen conditions of coastal waters. Though both areas are subject to anoxia, they differ both regarding to physical dimensions and to flow and mixing conditions due to differences in stratification of the water masses.

Sandöfjärden has suffered from seasonal summertime anoxia at least since the 1990s. Since 2000, when regular monitoring of the basin was initiated, total anoxia of the deepest part of the basin has been observed every summer in July-September. The density stratification of the area is in a high extent caused by the existence of seasonal thermocline (vertical jump layer in temperature stratification). The salinity difference between surface and deep layers is relatively small, usually from 0.2 to 0.3 psu, thereby generally affecting the density gradient less than the thermocline. In **Lännerstasundet** the anoxia is semi-permanent. Continuous anoxic periods of 2 to 3 years have often been recorded in the western basin of Lännerstasundet since the intensive monitoring was started there in 1992. Distinct salinity stratification exists in both sub-basins due to continuous fresh water inflow from Lake Mälaren into the Stockholm archipelago. The salinity difference between surface and bottom waters is about 2 psu. The halocline forms a pycnocline that usually prevents natural oxygenation of the deeper water masses and the bottom.

In Sandöfjärden the maximum daily pumping efficiency was 520 000 to 600 000 m^3d^{-1}, while in Lännerstasundet it was about 82 000 m^3d^{-1}. Relative to the hypoxic/anoxic volume of deep water, the pumping efficiency of Lännerstasundet was 4 to 5 times that of Sandöfjärden. In Sandöfjärden all the experiments were performed between May and October, i.e. during typical summertime stratification in temperature. In the other seasons deep water oxygen conditions are always good due to wind-induced and convective vertical mixing. In Lännerstasundet oxygenation was tested also in December, 2009, when salinity stratification alone restricted mixing between oxic surface and anoxic deep water layers.

Technically the experiments were carried out mostly according to the original plans and without substantial problems. The Mixox-pumping devices used, as well as assembling, anchoring and electricity systems originally planned for lake conditions, worked generally well under conditions of inner coastal waters. For outer archipelago waters (Sandöfjärden) more massive arrangements would have been helpful. Metal corrosion affected some of the pumps and wires, and caused a few delays. Antifouling paint was necessary for the oxygenation pumps due to bay barnacles and filamentous algae, which otherwise would have reduced the water intake of the pumps.

7.1.2 Direct and indirect effects of oxygenation in the pilot sites

In Lännerstasundet oxygenation clearly improved near-bottom oxygen conditions and removed a part of the nutrients from water column and decreased benthic nutrient release. The positive effects were observed within a week after the pumping was switched on. In summer 2010 the oxic conditions prevailed several months after the pumping period (~3 weeks), because oxygen-containing water from the neighboring basins could enter the basin and replaced and mixed with the "old" deep water thanks to the changes in hydrographic conditions due to the pumping. In other words, in Lännerstasundet it is evident that high pumping rate, together with ambient strong density stratification and limited contact with surrounding sub-pycnocline waters, makes the oxygenation more effective than in the other pilot site. In Sandöfjärden clearly lower relative pumping rate was used, density stratification was weaker, and the topography does not easily allow inflows of oxygen-rich water from the neighboring areas into the deep anoxic part of the basin.

Despite that oxic conditions were established in Lännerstasundet, a significant recolonalization of benthic fauna was not observed in the area; the oxic periods were obviously too short for this. Additionally, oxygen concentration around 2 to 4 mg l^{-1} is still low for most benthic animals.

Of the two pilot sites the original (unmanipulated) oxygen conditions are much better in Sandöfjärden, because effective vertical mixing takes place every year approximately from October to April, when there is no thermocline. Thus, the period of anoxia in the area is relatively short, only 2 to 3 months annually; concentrations of hydrogen sulphide (H_2S) are much lower than in Lännerstasundet. Despite this, oxygenation could not prevent the formation of anoxia in late July/early August in Sandöfjärden. After near-bottom oxygen was consumed, a rapid release of benthic nutrients took place. In September phosphate content in the deep water was on the same level than in the previous years when no oxygenation was carried out. The ammonium content was even higher in the case of oxygenation, probably due to warming of the sediment surface layer caused by the pumping.

7.1.3 Advantages and disadvantages of oxygenation: the critical controlling factors

The results of PROPPEN's experiments highlight the importance of the following factors that control the effects of pumping oxygenation:

- Topography and hydrographic (physical) conditions, especially stratification, of the coastal area under restoration
- Relative oxygenation efficiency (pumping flow rate/ anoxic deep water volume)
- Deep water temperature

Physical and geomorphologic conditions of the basin, as well as conditions and water exchange at the sills between the basin and surrounding water areas, play a crucial role from the viewpoint of benefits of artificial oxygenation. The oxygenation can have both direct and indirect effects on oxygen conditions. In the case of relatively high pumping rate compared with small water volume

(Lännerstasundet), the oxygenation is able to create oxic conditions in the deep water even if a high hydrogen sulphide ("negative oxygen") concentration prevails before the pumping. On the other hand pumping decreases to some extent oxygen concentrations in the lower pycnocline, due to upward entrainment of the pumped water mixed with anoxic deep water.

The pumping decreases the density of deep water. This may increase inflow of water from neighboring basins. In case that inflowing water of a neighboring basin is denser than the deep water of the basin under oxygenation, it can penetrate into and replace the old near-bottom water. This indirect effect on oxygen conditions depends strongly on local morphometry, especially the sill depth, density stratification and naturally also on oxygen conditions of neighboring basins.

Increased pumping intensity brings more oxygen into the deep water layers, but at the same time increases oxygen consumption due to warming and increased availability of oxygen for microbial respiration; in case the sediment surface becomes anoxic despite oxygenation, release of nutrients from the sediment is rapid, as was found in Sandöfjärden. There the option that remained without testing was the alternative that the full capacity pumping would not be started until in late summer when the oxygen level had already decreased to 2-3 mg l^{-1}. In this case the deep water would still be cold, and the consumption of oxygen would have been considerably smaller.

Considerable negative effects due to the oxygenation – like harmful algal blooms or upwelling of nutrients caused by weakening or total break-down of the pycnocline – were not recorded in either of the study areas. However, in Sandöfjärden the ammonium content of near-bottom water rose in late summers 2010 and 2011 probably due to an efficient release from the sediment due to warming of sediment by pumping.

7.2 Cost-efficiency and cost-benefits of oxygenation

Social cost-benefit analysis and cost-efficiency analysis was applied to examine the social desirability of pumping from two alternative angles. First, oxygenation was treated *as an additional means of reducing eutrophication* giving, thus, pumping a similar status as actions to reduce loads from external sources. Second, pumping was regarded as a complementary instrument to reductions of external loads, *a means of speeding up the recovery of the Baltic Sea* assuming that countries are willing to implement the Baltic Sea Action Plan. Calculations are based on changes in nutrients affecting eutrophication, without giving any weight on the effects of pumping on oxygen conditions as such.

1. Oxygenation as *an additional means of reducing nutrients* was examined as a local and regional option in the anoxic coastal areas of the Gulf of Finland.

Oxygenation at the local scale. For individual experiment sites, pumping in Lännerstasundet produced positive net benefits, which most likely cannot be exceeded by reductions in external sources unless extremely high costs are paid. The pumping capacity in Sandofjärden was undersized and produced negative net benefits. A hypothetical pumping in Sandofjärden with three times higher pumping efficiency than applied in practice was estimated to reduce nutrient and, therefore, produced positive net benefits. Therefore, our conclusion is that in closed inner archipelago sites such as Lännerstasundet pumping is a local policy option to improve the water quality. This conclusion can be extended to more open sites, like Sandofjärden, but the outcomes are more risky and largely dependent on the conditions of both the basin itself and water exchange with the neighboring sea areas.

Oxygenation at the coastal scale. We generalized the results from the pilot sites for the Finnish coastal water areas of the Gulf of Finland, for which an average anoxic bottom area of approximately 185 km^2 was estimated. By linear extrapolation three scenarios where developed. Scenario 1**.** *Optimistic*: is based on the measured nutrient reduction obtained in Lännerstasundet; Scenario 2. *Idealized*: is based on the estimated hypothetical reduction in Sandofjärden with the increased amount of pumps; and Scenario 3. *Pessimistic*: is based on the measured negative reduction in Sandofjärden with the applied (undersized) pumping efficiency. Also, a more realistic combination of the scenarios was examined by postulating alternative success and failure – combinations. Annual net benefits of each case were compared to those of reducing nutrient from external sources in selected Finnish and Russian waste water treatment plants (WWTPs) located by the Gulf of Finland.

Under current abatement level and costs in WWTPs in St. Petersburg, reduction of external loads produces higher annual net benefits than oxygenating anoxic bottoms by pumping in semi-closed coastal water areas. Therefore, reducing loads from external sources is the preferred option and pumping is not desirable under current cost structure. However, in the overall ranking, pumping occupied the second and third place. This reflects the fact that once the 95-97% abatement rate in phosphorus reduction is achieved also in St. Petersburg, the only economically feasible source to reduce nutrients in external point sources is nitrogen. Its abatement can be increased in WWTPs up to 90% with fairly low marginal costs. Also, agriculture provides economical options to reduce nitrogen. Reducing phosphorus from agriculture is expensive in the short-run but economical in the long-run. Thus, pumping of oxygen-rich water can obtain an important role in cost-efficient policy once the marginal abatement costs for external sources increase and exceed the unit (and marginal) costs of pumping.

2. Oxygenation as a means of speeding up the recovery of the Baltic Sea was examined the regional scale: i) the anoxic bottoms in the coastal, and ii) deep areas of the Gulf of Finland.

The role of oxygenation as a way of promoting the recovery of the Baltic Sea was examined at two regional scales: anoxic coastal and deep open sea areas of the Gulf of Finland. While the analysis of the anoxic coastal areas was based on the above linear extrapolation of results in the experiment sites, the analysis of the anoxic deep areas of the Gulf of Finland was based on the Baltic Sea Model simulations. As simulations showed no proper impacts (and therefore zero benefits) of oxygenation in the shallow open areas of the Gulf of Finland, this case was omitted from the economic analysis.

Coastal anoxic areas. Oxygenation of anoxic bottoms at the coast of the Gulf of Finland provided in most cases positive net benefits. Moreover, this result is was fairly robust to changes in pumping costs. Therefore, the conclusion is that oxygenation of anoxic coastal bottoms is socially desirable under current technology and citizens' valuation of recovery.

Anoxic areas in open sea. Simulations suggested alternative cases for the economic analysis of oxygenating the deep anoxic bottoms based on two alternative upper limits of the expected nutrient retention. Despite challenges of pumping in deep open areas of the Gulf of Finland, they applied the same pumping costs as in the experimental coastal sites. In reality, the pumping costs are more likely higher. Pumping into the deep anoxic bottoms of the Gulf of Finland Deep produces negative net benefits for the mean values of both cases analyzed. Positive net benefits occur only under the most optimistic assumptions.

Finally, the desirability of oxygenation in open sea areas depends on the estimated retention of phosphorus, efficiency of pumping, ability to meet the challenges associated with the maintenance of equipment and supply of electricity in the open seas. Therefore, our conclusions on oxygenation are subject to changes in all three variables: retention, technology and citizens' valuation of recovery. Most importantly, more research on efficient pumping technology, design and energy use is needed for more comprehensive conclusions, especially, in the Baltic Proper.

7.3 Risks related to oxygenation in different scales

The risk perception survey finds that as the scale of oxygenation pumping increases from small to large, people are:

i) more concerned about the potential ecological risks, and

ii) less willing to accept the risks and uncertainties of pumping for the prospects of a faster recovery of the Baltic Sea .

Across several dimensions, the Swedish sample appears as the most risk averse and the Finnish sample as the least risk averse towards potential ecological risks and uncertainties involved with oxygenation pumping.

We only find partial evidence that the level of risk (high vs. low risk) is a determinant for the stated opinions. In relation to concerns towards pumping, we find evidence of this in the Finnish sample at all three scales (small, medium, large) of pumping and at small-scale pumping in the Swedish sample. We also find evidence of risk sensitivity in the Lithuanian sample at all three scales of pumping with regard to willingness to accept risks of pumping for a faster recovery of the Baltic Sea.

Where the opposite is the case (i.e. no risk level sensitivity), people react to the scale of pumping and they do *not* let the differences in information (high vs. low risk) have a statistically significant impact on their answers. We interpret this as an indication that for these people, pumping appears so worrying that the scaleof pumping and not the level of risk associated determine their concerns and willingness to accept pumping.

Still, between 27 to 38% of people across Finland, Sweden and Lithuania state they would be willing to accept high risks associated with pumping for the prospects of a faster recovery of the marine environment. This gives an indication that around one third of the populations in the three countries find the state of the Baltic Sea so severe that they would be willing to accept even high risks induced by oxygenation pumping for a faster recovery.

A noteworthy finding is that for 50% of the samples in the three countries, pumping ranks at the lower end of a ranking of concerns about impacts of human activities in and around the Baltic Sea. This is far behind chemical accidents, hazardous substances, and oil transportation, which in all three countries rank as ‘very concerning’. In Finland, all three scales of pumping rank as ‘not especially concerning’. In Sweden, large-scale pumping at high risk and in Lithuania, low and high risks of large-scale pumping rank as ‘somewhat concerning’. All lower scales of pumping rank as ‘not especially concerning’.

In relation to the conditions under which pumping should be allowed or not to proceed, we find a strong preference for requiring that benefits outweigh costs and risks in the Finnish and Lithuanian sample (44% to 59%) and less so in the Swedish sample (37 to 39%). Across all countries, similar shares of people agree that pumping should be undertaken only if risks can be shown to be minimal (25 to 32%). More people in the Swedish sample compared to the other two countries require that pumping should only be undertaken on a coastal scale to minimize risks (ca. 9%) or that large scale pumping should not be undertaken under any circumstance (13 to 16%).

As a part of the PROPPEN project, a risk assessment study was conducted concerning the possibility of up-scaling Mixox oxygenation pumping to the open sea areas of the Gulf of Finland and/or the Baltic Proper (Gotland Deep). It became evident that the mechanisms of nutrient reactions and cycles versus the potential remediation method by oxygenation pumping must be carefully surveyed before any decisions on the remediation techniques and actions.

One of the key findings was that no impacts of the highest risk category (catastrophe) could be foreseen. However, several very likely or likely and major or significant risks were identified. The most prominent risks related to the up-scaling concerned issues like public resistance and regulatory obstacles due to international EIA, conflicting research and experimental data, as well as lack of permanent impact and cost-efficiency of oxygenation. Additionally risks of changing water circulation, stratification and salinity, warming of deep waters and causing temporary increase in eutrophication were foreseen. Additionally up-scaling of the Mixox method was considered to pose some risks in technical feasibility, e.g. related with energy supply and corrosion-proof materials. Regulatory risk concerning habitat changes was also recognized.

7.4 General applicability of the method in different coastal and open sea scales

Results of the coastal experiments indicate that oxygenation pumping is able to improve oxygen conditions, remove nutrients and decrease sediment nutrient release in certain kind of coastal water areas through both direct and indirect effects. However, there is no straightforward answer to the question of the general applicability of the studied oxygenation method. Based on the results of the present study, the factors which evidently favor positive results of oxygenation pumping are:

- Sufficient relative pumping efficiency compared to deep water volume
- Favorable basin topography (deep sills, high deep water volume/ sediment area –ratio)
- Sill topography and stratification which allow inflows of oxygen-rich water into the deep basin under pumping

Also in cases, where benefits from a purely ecological point of view seem to be evident and risks are considered to be under control, it's finally cost-efficiency, cost benefits and political decisions that determine the outcome.

Our results from Lännerstasundet’s eastern sub-basin suggest that in **relatively small archipelago basins** with semi-persistent salinity stratification, strong enough pumping efficiency is able to rapidly oxygenate near-bottom waters. Strong density stratification enables high pumping efficiency related to volume of the basin without the break-down of density stratification. Large vertical density gradient favors indirect positive effects of pumping by making easier inflows of oxic water from the neighboring basins. Deep water nutrient concentrations decrease as a result of oxygenation pumping partly due to removal of nutrients and decreased sediment release, and partly due to dilution. It should be noted, that at the same time when improving near-bottom oxygen conditions, the method decreases oxygen concentrations in the lower part of pycnocline (combined thermo-/halocline). In small coastal basins located near urban areas, the electricity demand and the maintenance of the technical systems are relatively small and cheap to resolve.

In larger **archipelago basins,** the applicability of the method seems to depend decisively on local conditions. An area like Sandöfjärden in the present study is very challenging – contrary to expectations when choosing the area. In this kind of semi-enclosed areas, there is a risk that improvements remain small. Even disadvantages are possible, as was observed when warming caused by the pumping increased sediment release of ammonium. However, in coastal areas the risk for permanent harmful effects is very low.

It remained open, whether a stronger, short-term oxygenation (less warming) under mid-summer conditions would have produced more beneficial results. In coastal basins with more open connections (deeper sills) with the neighboring basins and the open sea, inflows of oxygen- rich water from the neighboring basin could be initiated more easily, and one could assume that positive results would be possible to reach even with similar relative pumping efficiency than used in Sandöfjärden.

In the **outmost coastal waters** where the pumped water must be taken from the warm surface layer (in summer) benefits of the method seem to be small. Additionally, these areas quite seldom suffer from anoxia.

The model simulations suggest that deep water ventilation by oxygenation pumping could improve oxygen conditions of deep waters in **open sea areas** of the Gulf of Finland and in the Baltic Proper, where the pumped water could be taken from the cold intermediate layer between the thermocline and halocline, i.e. without warming up the deep waters. Model simulations were carried out with high pumping capacities during a five month running period. In practice pumping rate would be much lower and pumping time much longer. The simulation results suggest that a significant reduction of hypoxic water area ($O_2 < 2$ mgl^{-1}) can be obtained in the central Baltic Sea. It should be stressed that the simulated reduction of hypoxic bottom water area does not transfer directly to a reduction of anoxic sediment area because of the very complex physical and biogeochemical processes at the sediment-water interface which are not considered in the model simulations. However, the simulations suggest that flow dynamics around the oxygenation sites in general increases the bottom water oxygen concentration and reduces oxygen concentration higher up in the water column below the halocline.

Model simulations were performed with high pumping efficiencies of the order of 10^4 to 10^5 m^3/s during a 5 month period in a relatively high resolution (3.7 km x 3.7 km) three-dimensional model covering the whole Baltic Sea. The simulations performed with high pumping efficiencies were applied to roughly estimate the long-term (up to tens of years) effects with much lower pumping efficiencies. The performed model simulations, as well as the results of Lännerstasundet, give indication on possibilities to improve near-bottom oxygen conditions also in open sea conditions. However, large uncertainties still remain on long-term direct and indirect effects, e.g. on stratification, water exchange with the North Sea, and sediment nutrient storage and its stability.

According to the risk analysis on up-scaling the pumping to larger open sea scales, the possibility that oxygenation would have no permanent impact on oxygen conditions were evaluated as a major and very likely risk. The possibility that large scale oxygenation would not be cost-efficient was assessed as a major and likely risk. In addition to economic and technical risks, large scale deep water ventilation in the open Baltic Sea would affect physical, biogeochemical and biological status of the Baltic Sea. However, oxygenation should not cause adverse effects or decisively change the unique nature of the Baltic Sea ecosystem. In order to manage these risks, oxygenation applications in outer coastal and open sea conditions would in practice proceed step by step from smaller to larger units by learning from the experiences of the former step. Large scale open sea oxygenation would also require an international Environmental Impact Assessment (EIA) process.

Attitudes of the general public appear to be less critical than the views of interviewed experts or the participants of the risk assessment session. According to the risk perception survey the respondents assessed large-scale oxygenation pumping as “somewhat concern” at highest. About one third of the populations in Finland, Sweden and Lithuania find the state of the Baltic Sea so severe that they would be willing to accept even high risks induced by oxygenation pumping for a faster recovery.

7.5 Recommendations

Artificial oxygenation may offer an applicable and cost-efficient method to counteract oxygen deficiency and its consequences especially for sheltered coastal water areas. Particularly water areas, where local eutrophying load is small, or reduced to such a low level that reducing external loading is not cost-efficient anymore, may benefit from oxygenation. However, local morphological and hydrodynamic conditions largely govern the applicability of the method, and need to be studied before practical actions are plausible. Additionally, at least during pilot phases of oxygenation, intensive monitoring is needed to study its effects both on oxygen conditions and factors indicating the status of the ecosystem under restoration.

Oxygenation pumping in offshore coastal waters and the open sea would require large investments both regarding development of proper technology and the construction and maintenance of facilities in practice. Our present knowledge on ecological, socio-economic and technical prerequisites and consequences is not sufficient for the implementation of such investments even in a larger coastal scale. More scientific information is needed in the first place on physical and ecological factors, but also on technical, political, and socio-economic questions related to artificial oxygenation of the Baltic Sea.

The experimental results of PROPPEN are based on the studies from relatively sheltered inner archipelago basins. Also the presently available technology for artificial oxygenation is suitable for lakes and sheltered inner coastal waters, and not for marine coastal or open sea conditions. In order to produce more precise information about the availability and ecological effects of oxygenation for more open waters, pilot studies should be continued in representative study areas showing various kind of hydrodynamic and geomorphologic conditions, and also including thorough studies on fisheries, nutrient cycling and algal dynamics. This would also require development work of oxygenation technology, especially concerning pumping design, availability and supply of electrical power, assembling and mooring techniques of pumping facilities, and counteracting corrosion of materials.