LIFE Project Number

LIFE08 ENV/S/000271

Final Report

WEBAP - Wave Energized Baltic Aeration Pump

2014

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Data Project

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Data Beneficiary

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KTH

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LIST OF KEY-WORDS AND ABBREVIATIONS

- IVL – Swedish Environmental Research Institute (Sweden)
- WEBAP – Wave Energized Baltic Aeration Pump
- KTH – Royal Institute of Technology (Kungl tekniska Högskolan, Sweden)
- UAA – University Aalborg (Denmark)
- LIFE+ – EU’s funding instrument for the environment
- WGS-84 - World Geodetic System, reference coordinate system LCA – Life Cycle Assessment
- LCC – Life Cycle Cost

1 EXECUTIVE SUMMARY

The WEBAP project aimed at demonstrating a cost-effective wave-powered device, entitled the "Wave Energized Baltic Aeration Pump (WEBAP)", which may help to mitigate the problem of oxygen depletion ("hypoxia") in coastal zones and open seas. The project has gained much attention in both the involved project partner member states and Europe. This final report describes the various actions that were implemented during the project lifetime, their successful completions, problems encountered during the project implementation and how they were dealt with. The WEBAP project was started in January 2010 and the project activities ended in September 2013.

As this final report covers the whole project period, it can only provide an overview of the various activities and achievements. There are a number of other project reports that cover the progress of the project at various stages and detailed information about specific topics. The various reports are mentioned at relevant places in this final report and can be provided upon request and if no sensitive information is included. The reader may also consider a more scientific report on the project available on the project webpage www.webap.ivl.se or on the IVL homepage www.ivl.se; B2130 "WEBAP - Vågdriven syrepump för Östersjön".

The final report marks the closing of the LIFE+ project LIFE08 ENV/S/000271, WEBAP - Wave Energized Baltic Aeration Pump.

Results achieved as compared to what was planned in the project proposal

The project activities were successfully implemented throughout the whole project period as they were planned in the project description. Necessary adaptations and amendments were early dealt with and the project management and activities adjusted to changes. The project management structure facilitated a close collaboration between the different groups and with help of the proper election of collaboration partners, all tasks that were planned could be realized during the project lifetime. This also includes additional tasks that became necessary during the project e.g. as a results of force majeure. The contribution and commitment of the main and the associated beneficiaries, and the involved collaboration partners permitted to overcome all challenges that appeared during the project. The direct and close contact between project members and the coordination by the project manager were key items that made the successful implementation of all activities possible.

The main objectives of the project was: "*the demonstration of a cost-effective wave-powered device, entitled the "Wave Energized Baltic Aeration Pump (WEBAP)" that mitigates the problem of oxygen depletion ("hypoxia") in coastal zones and open seas.*". The project beneficiaries conclude that this objective has been achieved by the project activities. The project has moreover developed and demonstrated a cost-effective electrically-powered aeration pump for the use in marine environments without enough wave energy accessible. Further, the project substantially improved the knowledge about the current situation in the Baltic Sea regarding hypoxia and the phosphorous dynamics.

Recalling the expected results as stated in the project description, it can be said that these expected results remain after the successful demonstration of the WEBAP-concept. The WEBAP-system will significantly improve the situation in marine environments suffering from hypoxic conditions. The implementation of oxygen pumps is expected to lead to enhanced ventilation/mixing of hypoxic bottom water layers with the following primary quantitative environmental results (compared to present situation):

A. Increased oxygen levels in hypoxic deep-water layers to at least 2 mg/l.
B. Significantly decreased phosphorus concentrations in the bottom water due to a decrease in the phosphorus leakage from bottom sediment by 50% in anoxic waters and eventually phosphorus binding when more aerobic conditions occur.

Further, secondary effects will be:

- Recovery of benthic animals and deep-water living fish.
- Less algal bloom during summer months.
- Improved water quality and increased catches of high quality fish.
- Restoration of natural marine ecosystems, including natural habitats.
- Halting the loss of biodiversity.

A full-scale implementation of the technology would be possible in many of the more than 400 hypoxic marine environments worldwide. For the Baltic region the implementation would provide a significant improvement of the environmental state of the Baltic Sea. A full-scale implementation of the WEBAP-system and the transfer to other areas worldwide can lead to economic growth and increase Europe's competitiveness in this field on the world market.

The WEBAP-project has succeeded with it planned activities. Moreover, the project did not only demonstrate the initial solution of a wave-powered oxygen pump but it also brought up an alternative technical solution for applications in areas where the wave conditions do not allow for wave-powered oxygenation. Further, activities initiated by the WEBAP-project created further enhancements of the original approach and even new technologies that broaden the field of implementation of artificial oxygenation of oxygen-depleted marine environments.

The WEBAP-project as also identified some of the relevant failure factors of which one is the need for a successful integration and acceptance of oxygenation activities with other interests of marine environments such as fishery, transport, recreation etc. Also technical constraints or hinder have been brought up. The further development of technical details in a full-scale application can be named as one.

The intention of this demonstration project has not only been to demonstrate a sound technical solution for an environmental problem, but it also intended to create enough information to implement that solution in a full-scale basis. This includes the availability of knowledge for the construction of oxygen pumps that are realistic and economic feasibility, and that also understand all limiting factors. The project prepared for a commercial application that is available for society as a method to mitigate oxygen depleted bottom waters.

2 GENERAL

2.1 Beneficiary and associated beneficiaries

2.1.1 Main Beneficiary - IVL Swedish Environmental Research Institute

IVL Swedish Environmental Research Institute is an independent research body that since 1966 has been involved in the development and demonstration of solutions to environmental problems on behalf of the business sector and the community. IVL deals with environmental issues from a holistic perspective with the aim of contributing to sustainable growth. IVL has a long experience in coordinating both national and international projects (e.g. FP6 and FP7) and has a strong competence in demonstrating and full-scale implementation of environmental technology solutions in Sweden and Europe.

IVL Swedish Environmental Research Institute has a long and strong tradition on developing and conducting research and demonstration project within the field of water pollution, ecosystem restoration and environmental technologies. IVL is one of the leading R&D organisations within applied research on environmental topics worldwide, having a high rank on Conducted European Research projects and several national and international projects. IVL has considerable contacts and various active networks on an international level. IVL was pioneering in approach to water and water resources management of the EC's Water framework directive. IVL works to support the implementation and the management of water resources according to the principles of sustainable development, with consideration of the economic and social, as well as environmental, tradeoffs. Our teams have a long history of working with water issues. In fact, IVL's reputation was founded on this research area. IVL is actively involved in stakeholder dialogue in the development of tools and methods through dissemination of our knowledge through publications, seminars and workshops via IVL Knowledge. The experience gained in these fields served as a strong foundation for this demonstration project.

2.1.2 Associated Beneficiary - Royal Institute of Technology (KTH)

KTH has extensive experience in running demonstration projects mainly in connection with demonstration projects based on KTH intern research. KTH has also been involved in a number of external demonstration projects. The size of the current demonstration objects with KTH as a main partner range from mini-scale steam-power units to highly advanced research and development plants for municipal wastewater purification. KTH is responsible for one third of Sweden's capacity for technical research and is the country's largest organiser of technical/engineering education at university level. KTH education and research covers a broad spectrum – from natural sciences to all branches of engineering plus architecture, industrial economics, urban planning, work science and environmental technology. In addition to the research at KTH schools there are a large number of national and local competence centres located at KTH, as well as research programmes financed by various research foundations. KTH is one of the highest ranked technical universities in Sweden and well recognised worldwide, with several international researchers and training programmes. KTH has several contacts in and collaboration project all over Europe and is e.g. involved in some 200 EU projects. One of KTH's focuses has been on water quality and quantity dynamics in natural and engineered systems. The interaction of marine environments with anthropogenic inputs, the development of tools for predictive modelling and efficient use of monitoring data for integrated water resources management, scenario analysis and hydrological /hydraulic design, are included in the research and teaching. Uncertainty and/or risk assessment related to water quality and quantity changes are considered in most of the on-going projects. The research within the Dept. of Land and Water Resources Engineering includes for example the one of the most urgent environmental issues in the Baltic Sea: eutrophication, excessive algal blooms and hypoxia. Hydrodynamic studies of the applicability of temporal engineered mitigation measures to the Baltic Sea and location studies are performed.

2.1.3 Associated Beneficiary - Municipality of Simrishamn

Simrishamn is a main centre for the Swedish fishing fleet in the Baltic Sea. Nearly one-fifth of the total cod catch from the Baltic Sea in 2007 was in Simrishamn, and the same was the case for other catches like herring. The fishing industry has always been important for Simrishamn and the surrounding communities. There is, however, a fisheries decline, especially along the east coast of Sweden, due to overcapacity and declining stocks. Declining stocks are partly explained by low-oxygen area in the Hanö bay, which is part of the southern Baltic Sea outside the coasts of Simrishamn. Therefore, the Municipality of Simrishamn is focusing on various actions that will help to restore the water quality of the Baltic Sea in general and the Hanö Bay in particularly. Simrishamn includes access to one of Sweden's largest fishing ports and immediate access to the Baltic Sea. There is a strong presence of high technology companies and easy access to transport and logistics networks. The municipality of Simrishamn shares common concerns about problems that are affecting the Baltic Sea and the impact they would have on biodiversity and natural habitats as well as industries such as tourism and fisheries. Issues such as the overuse of fertilisers causing eutrophication, algal blooms and oxygen depletion, the increase shipping and associated risk of accidents, high concentrations of chemical pollutants, the introduction of alien species and coastal erosion. The Municipality of Simrishamn is member of KIMO, an international association of Local Authorities and associated organisations, which was formally founded in Esbjerg, Denmark, in August 1990 to work towards cleaning up pollution in the North Sea. Simrishamn municipality has taken the initiative to launch KIMO Baltic Sea to promote municipal cooperation around the Baltic Sea. KIMO Baltic Sea is co-ordinated by the Municipality of Simrishamn and includes among others KIMO International Baltic Forum.

2.2 Description of project management

The Project Management Group was managed by the Project Coordinator/Manager Dr Christian Baresel, IVL Swedish Environmental research Institute. The project manager was directly responsible for the daily operations in the project, as well as overseeing the project’s long-term progress. As such, the project coordinator was responsible for project planning and scheduling, internal and external reporting and documentation, as well as for contractual matters and accounting. The manager was also responsible for preparation, organisation and coordination of Steering Group meetings as well as for all communication with the European Commission and the monitoring team. The project coordinator followed-up the technical activities carried out in the actions and examined the performance of the project, i.e. reviewed technical aspects and results, inspected and examined prototype system, evaluated documentations, controlled parameters, initiated measurements. In number meetings, the Management Group discussed and decided on various tasks and enquires from the steering and reference groups.

The Steering Group met 2-3 times per year to decide and follow up the various tasks, make decisions on the overall project development, fulfilment of project objectives, budget and financing. This group has also been involved in organising seminars and conferences.

The Reference group advised the project in the preparatory stages of the project such as on selecting methods and evaluation tools. It provided input on technical aspects from a scientific, end-user and construction point of view. The group was further used for continuous input regarding results from the demonstration, monitoring and evaluation actions of the project.

Collaboration partners and stakeholders actively contributed to the planning and implementation of various tasks during the planning and construction period. They further contributed to varying extends to the selection of methods and evaluation tools.

2.3 Organigramme of the project team and the project management structure

The project management established in the WEBAP project was run in a structure consisting of three cornerstones: Project Management Group, Steering Group and Reference Group. The main responsible Project Coordinator of the WEBAP project was Christian Baresel, with experience of leading demonstration projects. The Project Coordinator was together with main responsible personnel of the associated project beneficiaries the Royal Institute of Technology KTH and the Municipality of Simrishamn form the Project Management Group. The project management spanned the entire project period. The Project Coordinator worked in close collaboration with all other involved persons secured the successful accomplishment of project management objectives and results, deliverables and milestones.

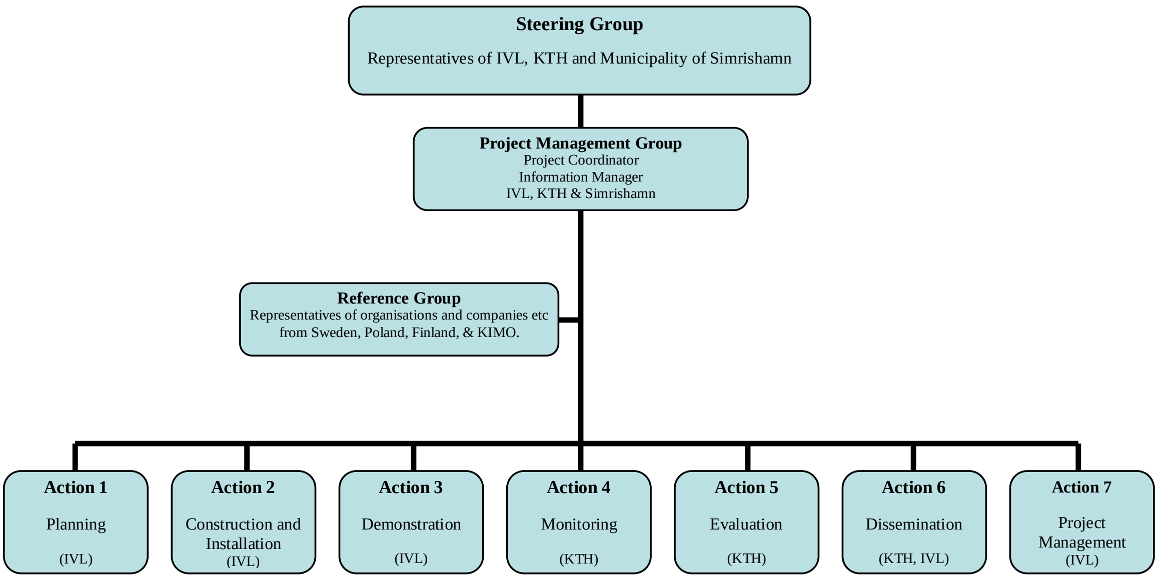

Figure 2.1. Organigramme of the project management structure.

2.4 Delivered reports since the start of the project

The project delivered a number of different reports. These reports contained information about the state of implementation of the project including the financial situation, and whether the project was on track towards achieving its objectives or whether there were serious delays and/or obstacles.

The Inception and Progress reports also included the partnership agreement, which describes the technical and financial participation of the project partners in the project according to the LIFE+ Guidelines to Partnership agreements. Further, deliverables and reports that have been produced during the project can be seen in Table 2.1).

Table 2.1. Project deliverables.

Name of the Deliverable	Code of the associated action	Part of	Date
D1.1: Report on technical specifications and plan for the construction of the test plants.	Action 1	Inception report	30/09/2010
D1.2: Short summary report on methods and evaluation tools selected.	Action 1	Inception report	30/09/2010
D1.3: Short summary report on water basin tests.	Action 1	Progress report	30/11/2010
D2.1: Summary report on the delivery and setup of the prototype plants.	Action 2	Midterm report	30/08/2011
D3.1: Intermediate report on demonstration plant operation	Action 3	Progress Report II	31/12/2012
D3.2: Final report on demonstration plant operation	Action 3	Final report	30/09/2013
D4.1: Intermediate monitoring report on data collected from the demonstration units.	Action 4	Progress Report II	31/12/2012
D4.2: Final monitoring report on data collected from the demonstration units.	Action 4	Final report	30/09/2013
D5.1: Technical, environmental and economic evaluation report.	Action 5	Final report	30/09/2013
D5.2: Evaluation report of results during the demonstration	Action 5	Final report	30/09/2013
D6.1: Communication plan	Action 6	Inception report	30/09/2010
D6.2: Notice boards	Action 6	Progress report	30/11/2010
D6.3: Updated Communication plan	Action 6	Progress Report II	31/12/2012
D6.4: White paper	Action 6	Final report	30/09/2013
D6.5: After-LIFE Communication plan.	Action 6	Final report	30/09/2013

3 IMPLEMENTATION AND RESULTS

The project aimed to demonstrate a cost-effective aeration pump that could help to mitigate the problem of oxygen depletion (hypoxia i.e. when dissolved oxygen becomes reduced in concentration to a point detrimental to aquatic organisms living in the system) in coastal zones and open seas. The focus was on technical solutions to achieve a transport of oxygen-rich surface water to hypoxic water layers. It is hoped that the associated enhanced mixing of water layers will increase the oxygen levels in hypoxic waters and will decrease the phosphorus concentrations due to lesser leaking from bottom sediment.

3.1 Actions

Project implementation was done through seven (7) complementary actions, all aiming at reaching for the objectives of the project.

3.1.1 Action 1: Planning

The objective of Action 1 was to perform all necessary planning and technical preparation for the following Actions (mainly 2-5). This was achieved by following actions:

- A partnership agreement was accepted and signed by all beneficiaries.
- Responsibilities between suppliers and assigners were defined where possible.
- Agreements on technical specifications and signed contracts with suppliers of equipment, with technical consultant companies etc. were signed.
- The final technical specifications of the demonstration units including the choice of material and size were performed.
- The behaviour of the demonstration and test plants was simulated.
- The demonstration project gained the support of all relevant authorities and obtained all necessary approvals.
- Evaluation methods were discussed and agreed upon. Delivery D1.2 provides information about methods and evaluation tools selected. This includes all parameters that require evaluation (concentrations of oxygen, phosphorous, pH and several relevant pollutants in the water and sediment, bottom flora and fauna) and describes test methods used (simplified LCA, LCC, and others to be defined in the plan). (Note that methods may have been adjusted or completed if necessary due to findings during the demonstration period.)
- The project team adjusted the number of collaboration partner in order to provide the best "value for money" and expertise for the various actions of the project.

Based on the initial design of the wave-powered oxygen pump, Aalborg University completed basin tests with a scale model (1:25) to *(i)* validate the concept itself; *(ii)* estimation the pump efficiency for ordinary wave conditions in the Baltic Sea; *(iii)* estimate the behaviour/movement of the unit during extreme wave conditions; and *(iv)* estimate mooring forces during extreme wave conditions.

The various task of Action 1 were completed as planned in the project plan and its objectives were achieved. See Table 2.1 for a deliverables of this action.

Related and active deliveries and more (see Table 2.1*):*

- D1.1: Report on technical specifications and plan for the construction of the pilots.
- D1.2: Short summary report on methods and evaluation tools selected.
- D1.3: Short summary report on water basin tests.

3.1.2 Action 2: Construction and Installation

The objective of Action 2 was to prepare the demonstration facilities and assemble the WEBAP prototypes, including test running and fine-tuning of the systems. The wave-powered demonstration unit WEBAP I was launched and installed in September/November 2010. Once the demonstration pump was in place, the initial adjustment and optimisation of the pump to the local conditions was started. Unfortunately, due to problems caused by exceptional heavy winter conditions and force majeure, the demonstration had to be halted and the pump towed back into the harbour. Immediately after the ice at the towing site had melted, inspections and reparations of the unit were started. WEBAP I was reinstalled as soon as all necessary works were finalized. The unit was again adapted and optimised to the local conditions. Gathered experiences from the first launch were of great help for the second launch and a number of enhancements to the installation procedure were implemented. More information about the successful installation and tuning of the pump to local conditions can be found in "*D2.1 Summary report on the delivery and setup of the prototype plants*".

During the initial construction phase, results and findings from the basin tests have been used to adapt the construction to expected loads and stresses, and to optimise the construction design. The results of these basin tests were provided as the deliverable "*D1.3 Short summary report on water basin tests*".

The construction of the second demonstration unit was finalised in 2010 but the launch had to be postponed. The reason for this was, as for the wave-powered unit, the early and exceptional heavy start of the winter with ice formation at the test site, which prevented any installation works. However, the electricity-powered demonstration unit was launched and installed shortly after the ice cover disappeared, on April 14 2011. More information about the successful installation and tuning of the pump to local conditions can be found in "*D2.1 Summary report on the delivery and setup of the prototype plants*".

3.1.2.1 WEBAP I – Wave-powered oxygen pump

The wave-powered oxygen pump uses local energy in the form of surface waves to supply oxygen to the deep water. The plants can be likened to a floating breakwater ("wave-plane") where the breaking waves takes in oxygen-rich surface water into a basin inside the wavebreaker. The level difference between the basin and the surrounding sea implies that the oxygen-rich water is pumped down to the depth of the water.

The pilot plant consisted of a 17-ton steel structure 13.5 m wide and 7 m long where the width is counted parallel to the wave crests. The front part consists of an inclined plane at about 20-30 degrees. Behind this, a 3m wide basin with an outlet that was connected to a 72 m long vertical pipe was situated. The special anchorage of the unit allowed a free rotation to utilize pumping at all wave directions. The principle is the same as that used for the Danish wave-power project Wave Dragon (http://www.wavedragon.net/). A crucial difference however is that the WEBAP-pilot strives to maximize the flow through the tube to the deep bottom waters and not the flow to produce high dense energy.

Figure 3.1. Preparation and delivery of the wave-powered prototype (left) and monitoring equipment (right, here wave buoy).

WEBAP I was equipped with pressure sensors in each outer corner, in each corner of the inside basin, two force sensors connected to the anchorage and an accelerometer in the rear of the module. In addition, the module was equipped with two flow meters. None of these did however work satisfactory. A separate wave-meter was installed in connection to the module (see Figure 3.1).

3.1.2.2 WEBAP II – Electrical oxygen pump

The design of the electrical pump oxygen focused on the ability to control the flow of pumped water in order to facilitate a comprehensive evaluation of WEBAP system. With the project also created not only a robust and safe installation but also an alternative to wave-powered oxygen pumps in areas where wave conditions are not sufficient. The result was a pump with high efficiency, but with low power consumption. As a direct power connection to land lines was not possible, a diesel-powered generator was producing the electricity required.

The pilot plant consisted of a 2.5 m banana leaf pump with a power of 5 kW. The pump was mounted some meters below the water surface with water intake and a vertical pipe with an outlet at 95m depth transported the oxygen-rich surface water to the deep-water layers. The float on the water surface carried all necessary equipment such as generator, fuel tank, control systems and safety equipment.

Figure 3.2. Launching of the main float and the pump-house.

Summarised, the delivery and installation of the two demonstration units i.e., Action 2, was delayed with approximately 6 months.

Related and active deliveries and more (see Table 2.1*):*

- D2.1 Summary report on the delivery and setup of the prototype plants.

3.1.3 Action 3: Demonstration

The objective of Action 3 was the complete demonstration of the operation and performance of the WEBAP prototype through tests at the two complementary test sites in the Baltic Sea. One location (Hanöbukten) was used for the demonstration of the working principle in the real environment, i.e. a real wave climate and no clear separation from the open sea. Another location (Kanholmsfjärden) was utilized to demonstrate the actual effect of the pump on hypoxic bottom water layers. Because there was not sufficient wave energy available at the second site, an artificial power-supply was required for this pump. In order to enable a meaningful evaluation of the pumps, the demonstration was planned to last for at least one year. In total the demonstration period for the two pilots lasted for more than 2 years during October 2010 to April 2013.

This action started in October 2010 after the first installation of the demonstration unit WEBAP I was finalised. It was halted for the winter because of extreme weather conditions and continued after reinstalling WEBAP I and launching WEBAP II in April 2011. The exact locations of the two demonstration units in the Hanöbukten and Kanholmsfjärden were as followed.

- Hanöbukten: N 55 36.71 and E 14 51.61 (WGS-84)
- Kanholmsfjärden: N 59 20.147 and E 18 46.207 (WGS-84)

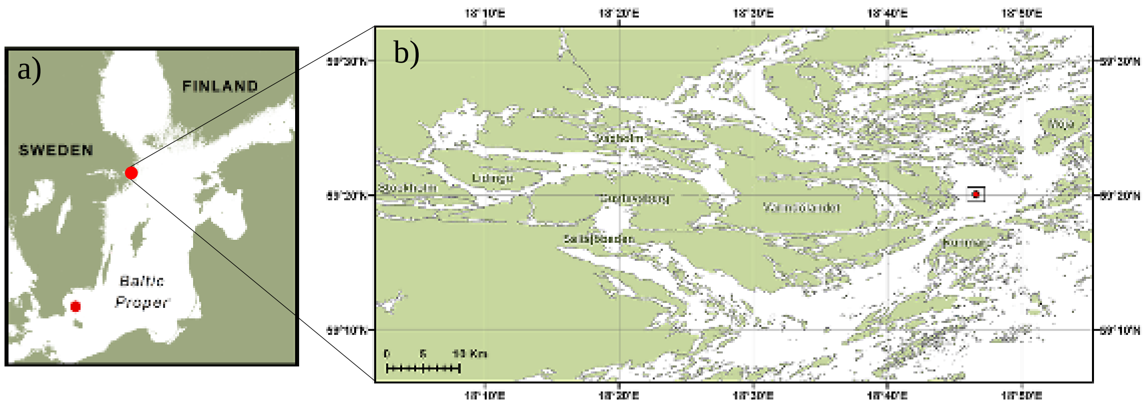

Figure 3.3. Map of the Baltic Sea with the study area Hanöbuktens and the study area Kanholmsfjärden in the Stockholm archipelago.

As descripted in the previous section, the wave-powered demonstration pump was launched and installed in September/November 2010. Once the demonstration pump was in place, the initial adjustment and optimisation of the pump to the local conditions was started. Unfortunately, due to problems caused by exceptional heavy winter conditions and force majeure, the demonstration had to be halted and the pump towed back into the harbour.

In addition, the launch of WEBAP II, the electricity-powered demonstration unit, had to be postponed. However, WEBAP II was launched and installed on April 14 2011. With that, the demonstration period was initiated and first results were included in the reporting.

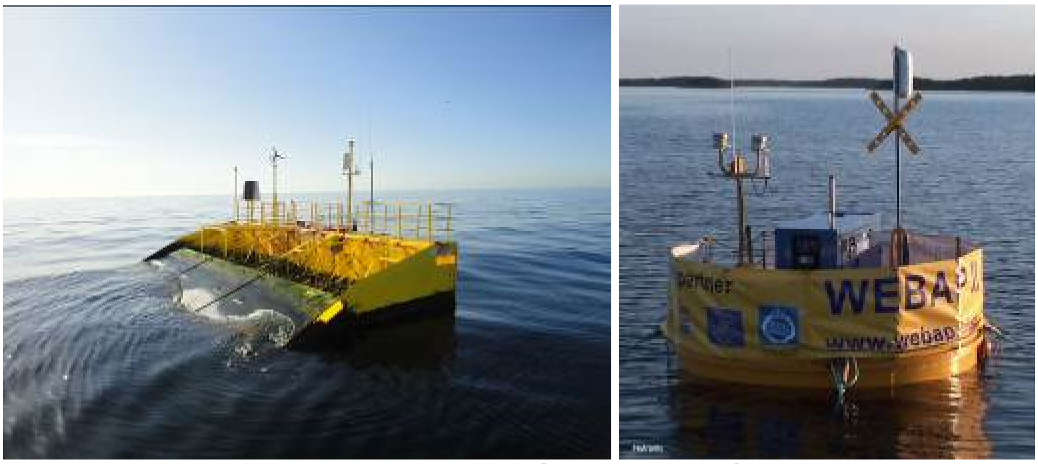

Figure 3.4. Demonstration pilots WEBAP I and II.

The demonstration phase was finished with the de-installation of WEBAP I and WEBAP II in April 2013 and October 2012, respectively. After de-installation WEBAP I was recycled. This was because the pilot was specifically constructed to demonstrate the WEBAP-principle which it did. Therefore it was found that there would be no further use for that pilot but only costs. WEBAP II was saved for eventual further use in research-related activities.

Despite the problems and delays due to the outside causes described, the objectives of this action were achieved.

Related and active deliveries and more (see Table 2.1*):*

- D3.1: Intermediate report on demonstration plant operation
- D3.2: Final report on demonstration plant operation after 1- year operation.

3.1.4 Action 4: Monitoring

The objective of Action 4 was to monitor the proposed WEBAP prototype and the overall project (Action 1-7) with the aim to ensure efficient and successful demonstration of the innovative technology. During this phase, the environmental status and conditions at the two demonstration sites were documented using certain indicators such as concentrations of oxygen, phosphorous, pH and several relevant pollutants in the water and sediment, bottom flora and fauna. These indicators were then used to evaluate the concrete effects of the proposed demonstration pumps at the two sites (see section 3.1.5).

Monitoring the effect of the WEBAP prototypes implies that the initial status and conditions at the two demonstration locations was investigated in a number of monitoring campaigns carried out in during May to September 2010. Both water and sediment samples were collected, relevant indicators were measured at the sites and laboratory tests with the samples were carried out. Information and data from these campaigns was used to finalise the selection of methods and evaluation tools that relate to environmental monitoring of the WEBAP prototypes.

Besides earlier field expedition, repeating sampling campaigns were performed during the project period where sediment and water samples were collected. The main aim of these campaigns was to examine environmental conditions around the site for the demonstration units including the phosphorus chemistry of the sediments. Sediment cores and profiles of oxygen, temperature and salinity in the water column were collected at all locations.

Sediments were analyzed for different phosphorus fractions, concentrations of manganese and iron, water content and organic content. Sediment surface characteristics from the different stations were monitored.

Figure 3.5. Monitoring actions including sediment sampling and analyses.

Concentration profiles of different phosphorus fractions allow us to see how oxygenation implies considerably less mobile phosphorus was found in the anoxic sites. A possible implication is hence that oxygenation may remove phosphorus from the water column and bind up to 2 $g \times m^{-2}$.

Concentration profiles of different phosphorus fractions allowed us to calculate the amount of potentially mobile/bioavailable phosphorus in each station. A general finding was that oxidized sediments on average contained more potentially mobile phosphorus ($>2\ g \times m^{-2}$) while considerably less mobile phosphorus was found in the anoxic sites. Very low or zero concentrations of mobile P were found near the site proposed for the wave energized pump, probably explained by the low redox potential. There is more work to be done before any final conclusions may be drawn. However, we notice very low or zero concentrations of mobile P near the site proposed for the wave energized pump, probably explained by anoxic bottom water. A possible implication is hence that oxygenation may remove phosphorus from the water column and bind up to 2 $g \times m^{-2}$.

The dataset collected from offshore Baltic proper in 2010 have been compiled and evaluated. A scientific manuscript has been published in Air, Soil and Water Research.

The study area located in Kanholmsfjärden Bay and adjacent coastal areas have been visited several times during the project period. The water salinity, temperature and oxygen concentration were measured online in the field using a SEBA KLL-Q2 CTD-device complemented with an optical oxygen sensor. Water samples from each station and depth level were collected with a Ruttner sampler and stored cold in plastic bottles. When returning to the laboratory a part of the sampling volume (normally 1 liter) was filtered through a 0.45 µm Whatman GF/C glass micro fibre filter for later analysis of suspended particulate matter (SPM) and suspended organic matter (LOI). Filters used for suspended matter analysis had been dried at 550° C and pre-weighed. Another part of the sampling volume (normally 500 ml) was filtered through a 0.45 µm Whatman cellulose acetate filter for later analysis of particulate phosphorus. The filtrate was saved as well as the remaining unfiltered water volume. The chemical analyses were performed at Erken Laboratory, Uppsala University. The analyses were performed according to Swedish standard methods, SS EN 872:2005 for SPM, SS-EN 15169:2007 (modified for water) for LOI, SS-EN ISO 6878:2005 for DIP, SS 02 81 27 for TP and SS-EN ISO 15681-1:2005 for PP respectively.

The sampling stations in Kanholmsfjärden and surrounding bays were revisited several times. Sediment and water samples were taken and sent to laboratories for analyses of levels of phosphorus (P), iron (Fe), manganese (Mn) and cadmium (Cd). Moreover, triplicate benthic samples were taken around the lowest depth of bioturbation registered in 2010 samplings campaign. These samples will be analysed on the distribution of macrozoobenthos.

Monitoring of the overall WEBAP project was performed during the whole project period. The main monitoring reports that are produced at least every nine months were used as indicators and sources for verification of the project objective. This include inter alia: technical specifications of prototype system, signed contracts with suppliers, evaluation criteria, correct installation of prototype plants, demonstration, monitoring and evaluation reports, communication plan for dissemination, number and quality of materials for dissemination etc.

In the study area located in Kanholmsfjärden Bay and adjacent coastal areas, additional campaigns after the de-installation of the pump were performed.

Action 4 was completed in the first quarter of 2013.

Related and active deliveries and more (see Table 2.1*):*

- D4.1: Intermediate monitoring report on data collected from the demonstration units.
- D4.2: Final monitoring report on data collected from the demonstration units.

3.1.5 Action 5: Evaluation

The objective of Action 5 was the evaluation of the WEBAP prototype with the aim to validate that the technology is ready for full-scale implementation in the Baltic Sea and other European aquatic systems suffering from oxygen depletion (i.e. hypoxia). The evaluation includes technical and economic aspects as well as potential optimisations and improvements of the WEBAP-technology.

This action was for the most part taken place after the successful demonstration of the WEBAP prototypes. However, the project team started to use collected data for modelling and up-scaling calculations already during the demonstration period. This included the devolvement and use of models for a full-scale application of the wave-powered oxygenation pump in the Gotland bay and Hanöbukten but also the simulation long-term effects of oxygenation by using the electrical unit in Kanholmsfjärden.

The following sections provide an overview of the various evaluation actions performed. The pumping capacity was evaluated using the data collected during the demonstration period. Furthermore, the evaluation of the environmental and economic performance of the proposed technique was done by simplified LCA and LCC modelling.

3.1.5.1 Pumping capacity

For the calculations of the flow for the WEBAP I pilot measured and modeled wave data was used. For some periods overlapping data was available that could be used for calibration of the calculated data. For the entire measurement period the mean of the flow was then determined. In a few cases, a more detailed analysis has been made which also takes into account the module vertical acceleration. These calculations yielded a slightly greater flow. The method and more results of the analysis and a comparison are provided in *D5.2 Evaluation report of results during the demonstration.*

The figure below summarizes the results of the analyses. From the diagram, it becomes clear that both - as expected - there is a minimum level of wave height that provides a flow and partly because there is a fairly clear correlation between flow and wave height. There also appears to be a maximum mean flow.

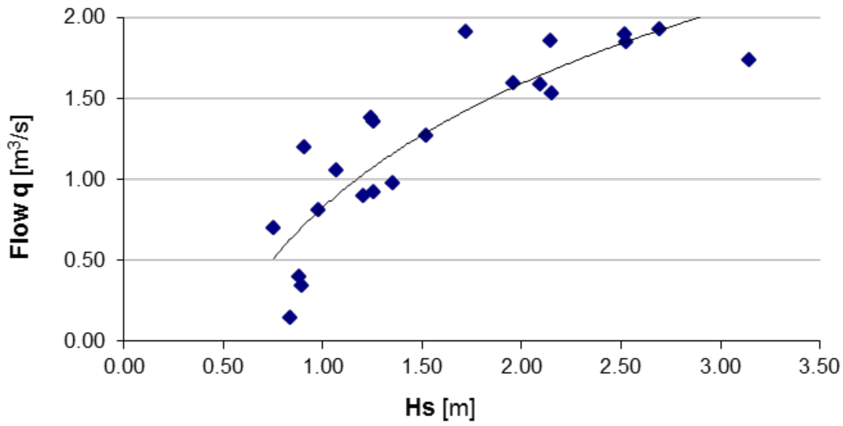

Figure 3.6. Calculated average flows in the WEBAP I pilot as a function of significant wave height Hs.

Observations at the rough sea suggest that the demonstration unit WEBAP I worked as intended but that it “rides” the waves, which is significantly reducing its efficiency. This is caused by the limitation if pilot unit dimensions that are compared to the wave lengths much smaller.

For the calculations of the electrical pump WEBAP II direct flow measurements from the pilot and the assumption that the flow is evenly distributed over the tube diameter due to the technical design of the pump was used. Calculated flows were also compared with theoretical calculations from the manufacturer. WEBAP II most operated at 80% of its capacity for most of the time. This corresponded to a power consumption of the aggregate of 10-11 kWh. The measured flow rates ranged from 0.2 to 0.4 m/s, which gives an estimated rate of 1-2 m^3/s, these measurements were made at a temperature in surface waters of 17 degrees. At lower altitudes (intake positioned deeper) and thus lower temperature differences between surface and deep water, the pump efficiency increased.

Calculations of the expected capacity of a full-scale WEBAP plant were not possible but it can med assumed that an installation with dimensions that correspond at least to typical wave characteristics would avoid the problem of “wave riding” and thus increase the pumping capacity per meter wave crest.

3.1.5.2 Estimating the pool of mobile phosphorus in offshore soft sediments of the Baltic Proper

Twelve sediment cores were collected in the Baltic Proper between 61 m and 175 m water depth and a number of phosphorus fractions were analyzed. Integrating the concentrations over the depth profiles, the amounts of mobile phosphorus were estimated in each core. The results were presented in the scientific journal Air, Soil and Water Research (2012:5 1–13).

It was found that sediments below the redox cline in the Baltic Proper contained small amounts of mobile phosphorus. The total amount of mobile phosphorus in the entire Baltic Proper sediments below 65 m water depth was estimated to between 55,000 tonnes and 156,000 tonnes or between less than 10% to around 25% of the phosphate in the system (water plus sediments). This represents the maximum amount of phosphorus that could possibly be released to the water column from these areas. We argue that the most reasonable estimate of the pool of mobile phosphorus in the sediments is the lower number.

The amounts of mobile phosphorus in sediment cores with oxidized surface layers were higher compared with sediment cores with reduced surfaces, indicating that there is a potential phosphorus-binding capacity in sediments below the redox cline if oxic conditions improved. Oxygenation of the Baltic Proper bottom water between 65 m and 100 m could probably remove around 100,000 tonnes of phosphorus from the water column and reduce phosphorus concentrations in the deep water by on average 30 mg/m^3, which would possibly be felt also in the surface water.

3.1.5.3 Comparing mobile phosphorus content in soft sediments from two sub-systems of the Baltic Sea

The role of sediments in the phosphorus (P) dynamics of the Baltic Sea is often highlighted. The impact of the sediments on the water column is strictly limited by the amount of potentially mobile P in the sediments. During 2012 we performed detailed measurements of different P forms with different mobility in ten sediment cores from two Baltic Sea sub-systems. The results were presented at the ASLO Aquatic Sciences Meeting, New Orleans 17-23 February, 2013. A scientific manuscript has also been submitted to the journal Plos One.

One sub-system is characterized by anoxic conditions in the bottom waters overlying the accumulation sediments, whereas the bottom waters of the other sub-system are generally oxidized which is also reflected in the sediments. Integrating the sediment concentrations over the depth profiles, amounts of mobile phosphorus were estimated in each core.

Average mobile P content in the sediments of the oxidized basin was found to be an order of magnitude higher than in the anoxic basin. By contrast, the bottom waters of the anoxic basin contained dramatically higher P concentrations indicating that the available mobile P was largely present above the sediments. Organic P was also much more abundant in the oxidized sediments challenging the hypothesis that biodegradation is slower under anoxic conditions.

3.1.5.4 Oxygen concentrations in water

Figure 3.7 shows oxygen concentrations in the bottom waters (100 meters depth) in Kanholmsfjärden near the WEBAP II pilot during the project. It is noted that relatively soon after the pump been put into continuously operation an oxygenation of bottom waters occurs. However, measurements in adjacent bays with similar bathymetry showed increased oxygen levels in the same period. Therefore, it was concluded that the improved oxygen levels may mainly be explained by the natural inflow of oxygen-rich water, but it cannot be excluded that the pumping also had a positive impact.

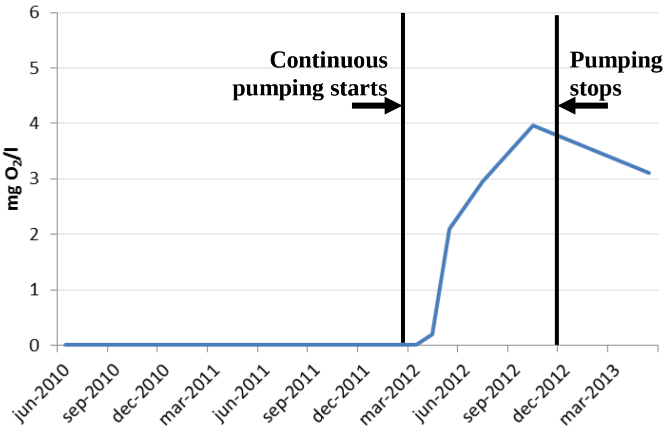

Figure 3.7. Oxygen concentration (mg/l) June 2010-May 2013in the bottom water in Kanholmsfjärden adjacent to the WEBAP II pilot.

3.1.5.5 Phosphor concentrations in water

Figure 3.8 shows total phosphorus concentration in the bottom waters (100 meters depth) and surface water (5 m) in Kanholmsfjärden near the WEBAP II pilot during the project period. It is noted that relatively soon after the bottom water gets oxygenated phosphorus concentration decreased from 250 mg/l to about 70 g/l. However, no significant change in phosphorus concentration in the surface water was observed. This contradicts fears that oxygenation disturb existing stratifications and thus initially lead to increased levels of phosphorus in surface waters as a result of phosphorus-rich bottom water would move to the surface. The ultimate aim of oxygenation is that phosphorus concentrations shall decrease also in surface waters, which would lead to a reduced primary production in the photic zone.

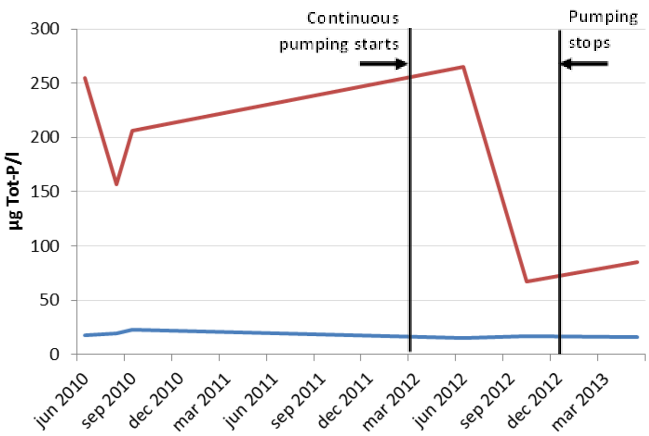

Figure 3.8. Total phosphorus (mg/l) June 2010 - May 2013 in the bottom water (red) and surface water (blue) in Kanholmsfjärden adjacent to the WEBAP II pilot.

3.1.5.6 Bottom fauna distribution

Repeating observations and analyses at two sampling stations in Kanholmsfjärden during 2010, 2011 and 2012 showed relatively small differences in the bottom fauna distribution. The oxygenation that occurred had obviously not worked long enough to affect the sediments. Observation in other oxygenated coastal regions however, indicated a colonization of benthic invertebrates in previously anoxic bottoms after three years of oxygenation.

3.1.5.7 Cadmium concentrations in oxic and hypoxic environments

One of the concerns raised against large-scale oxygenation is that this would lead to increased contaminant concentrations in water and biota, e.g. because redox-sensitive metals would go into solution at oxidized conditions. There are a number of studies that show that this is not the case in areas where oxygen depletion is abated (mostly naturally). There are therefore no observations to suggest that improved oxygen conditions would lead to problems linked to the release of environmentally harmful substances. Also in our project this problematic was addressed. Figure 3.9 shows measured levels in Kanholmsfjärden before and after the deep water oxygenation. Concentrations after oxygenation were approximately a factor of 3 lower.

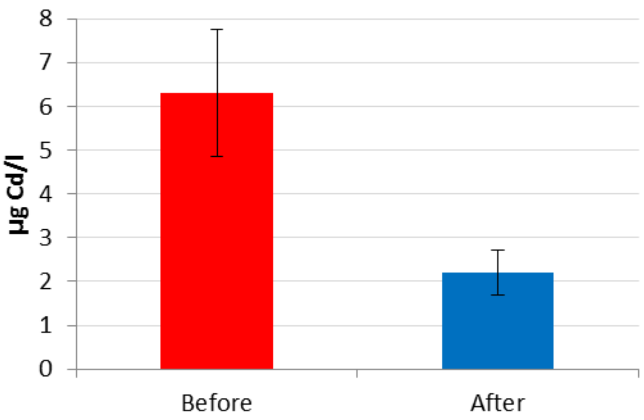

Figure 3.9. Cadmium concentrations in Kanholmsfjärden surface and deep water before (n = 4) and after (n = 2) oxygenation.

3.1.5.8 Toxicity tests

In order to elucidate the instantaneous toxicity that might occur during oxidation of reduced sediment and elemental sulphur (S8) is formed, toxicity tests were conducted in the laboratory where three ubiquitous Baltic Animal species were exposed in an aquarium for 24 hours. Oxygen-rich surface water was pumped down to an anoxic bottom with reduced sediment. A dozen individuals from each group of these animals were collected from the test location Kanholmsfjärden in September 2010. After exposure to the oxidation of the sediment the animal recovery was followed up during a period of 7 days after which they were returned to the Baltic. Both mobility and activity was studied. When the exposure was stopped the oxygen saturation in bottom waters had increased to between 50 and 70%.

3.1.5.9 Model study of pumping activities in the Baltic Sea (Hanöbukten and Gotlandsdjupet)

By employing a numerical 3D-model (AS3D) of the Baltic circulation, the impact on the stratification of down-pumping surface water in the vicinity of the location of the pump has been simulated and analyzed using oceanographic forcing data for the year 2004. In order to obtain a noticeable impact, a pumping capacity amounting to 25 m^3/s was chosen. This value is about one order of magnitude higher than for the pilot version of the Wave Energized Baltic Aeration Pump (WEBAP), currently deployed in Hanöbukten in the southern Baltic.

An outspoken ambition has been to mimic the pumping conditions of the pilot version as closely as possible, exempting its 10-fold increased capacity and its slight positional offset to a location farther offshore than that which corresponds to the depth of the actual deployment site.

The interleaving of the plume — assumed in the model to be discharged at a depth of 80 m — has been modeled following the established theory augmented with the assumption that the down-pumped surface water is replaced by an incoming long surface wave towards the WEBAP platform. Conservation of volume demands that on the interleaving level an equal volume rate will flow out horizontally. This flow in the model is symmetrically superimposed on the naturally occurring fluxes. Vertical entrainment of the rising buoyant plume in the depth interval between the discharge and the interleaving level will be the primary cause of the alteration of the stratification in the water column where the WEBAP is located. Since alteration and foremost lowering of the deeper density interfaces has been the major cause of biological concern, the unit σ_t (i.e. deviation from the reference density of 1000 kg/m^3) has been chosen as the basis for the evaluation.

The focus of the first part of this study has been the relative alteration of the stratification with and without a WEBAP stationed in Hanöbukten, and the results are graphically presented for a set of three representative but non-encompassing horizontal and vertical cross-sections in the near-field of the pump. These relative changes have been found to be modest, and only on one occasion (March 2004) was there a +1% relative aberration in $\sigma_{t.}$

In order to perform a more encompassing comparison from a spatial point of view, the average density of the different layers from the surface to the bottom has been calculated in concentric horizontal slices departing from the site of the pump. A more frequent temporal basis for the analysis has been obtained by extending the analyzed periods to comprise the middle and the end of each month. This provides 24 time slices for which the average density differences with regard to depth of the model layers and radial distance to the pump have been calculated. These contour diagrams show that the minimum and maximum values of the absolute σ_t-differences are restrained to the interval of –0.10 to +0.05 kg/m^3. As the lowest surface water density corresponds to 5 kg/m^3 (occurring during late spring), this means that the statistical average (over the entire near-field) relative aberration of σ_t is well within a bracket of –2% to +1%.

An analogous analysis of an array consisting of 40 such WEBAPs — all with 25 m^3/s pumping capacity — deployed in an equidistant array east of Gotland show that the impact on the density stratification in these open waters is small — in regard to differences to unaffected conditions less than 0.5%. After five years of pumping at the collective rate (1000 m^3/s) for the array of pumps, the concentration of WEBAP-aerated water has increased to 1–3 % for a substantial part of the Baltic Proper intermediary depths.

With continued pumping under the same assumed conditions (constant pumping and only loss through water exiting the Baltic through the Danish straits), it will take about 35 years from the start of the pumping activities before the tracer concentration reaches a 1:5 dilution (corresponding to approx. 2 mLO_2/L) that covers large parts of the bottom area on intermediary depth east of Gotland.

3.1.5.10 Model study of pumping activities in Stockholm middle center archipelago (Kanholmsfjärden)

By employing a numerical model based on discrete hydraulically coupled basins (**CouBa**) of the Stockholm archipelago, the impact of down-pumping surface water on the aeration and stratification of the basin where the pump was deployed has been simulated. This together with the spreading of the aerated water in the mid archipelago has been analyzed for the time period 1993 through 2004. A pumping capacity of 4 m^3/s was chosen in accordance with the in situ pumping that has been going on intermittently since 2011 in Kanholmsfjärden.

With the **CouBa** model approach combined with the implemented theory of plume interleaving, it is found that with water drawn from 5 m depth and discharged at 100 m, the yearly averaged interleaving level falls in the bracket of 50 to 70 m, i.e. as a temporal average above the measured position of the redox cline located at 70 m depth. However, the inherent model uncertainty can be appreciated to amount to ±10 m and on occasion aerated water penetrates down to the bottom. The inherent model limitation of permitting persistent interleaving of numerous tiny layers has been mitigated by superposing two cases with the pumped layers merged both to adjacent layers upward and downward.

This result is not particularly sensitive to the scale length corresponding to the nozzle diameter of the vertical tube of the down-pumped aerated water (2.5 m) or a scale length (1.5 m) that also takes into consideration the horizontal screen at the end of the tube. This screen directs the out-flowing pumped water in a horizontal direction.

The results are presented as yearly averages of the 12 consecutive years, contour diagrams (time of year vs. depth with daily resolution) of the relative concentration of tracer-marked water that has passed the pump. This is not restrained to Kanholmsfjärden, but is also shown for a selection of basins distributed throughout the central mid part of the Stockholm archipelago. The minimal dilution of pumped water is obviously at Kanholmsfjärden, but Möja Söderfjärd displays a quite similar tracer concentration development. These two basins are hydraulically strongly coupled because of the broad and deep strait (90-m sill) connecting them. In all other basins in the archipelago presence of water that has passed the pump can be detected at a much higher dilution.

In these two coupled basins the minimal horizontally averaged dilution is found to be about 1% (or a dilution 1:100). In the vicinity of the discharge tube it can be inferred that the dilution is close to the primary dilution of the plume that varies between 10 and 20 times depending on the stratification. The interleaved modeled plume is instantaneously spread to the entire layer volume of its depth interval. In the real basin there is a gradient formed as the internal wave slowly progresses under constant vertical mixing out from the discharge point. The model thus exaggerates the horizontal dilution in the near-field by an order of magnitude. Since the pump is deployed at a deep plateau with 50-m isopleths nearby, it is likely that a sufficient oxygen supply could hypothetically tip the sediments from being anoxic if the redox cline should be higher than today’s 70-m depth.

The impact of the pumping activities on the temperature, salinity and density distribution in the other basins in the mid archipelago have been assessed by comparison with an analogous model run, with the only differing factor being that pumping was not performed. It is found that – as a yearly average – the alteration of the density stratification is mainly confined to the two major coupled basins. The pumping is also found to alter the net strait exchange flows in a small but systematic way.

Analysis of accessible measured temperature, salinity and oxygen concentration data cannot ascertain whether the bottom water in Kanholmsfjärden basin during the period 2012-05-16 and 2012-07-05 was oxygenated by inflowing bottom water from adjacent basins or by down-pumping of aerated surface water. Same data cannot, however, rule out that the WEBAP-pumping may have provided a beneficiary contribution to this end.

3.1.5.11 Climate impact and life cycle cost assessment

A *simplified* life cycle assessment and life cycle cost estimation, that covered the most important steps of the life cycles, were done for the oxygenation pumps and precipitation techniques.

Four techniques to remove phosphorus in or into the Baltic Sea were investigated in six scenarios. Three scenarios was oxygen pumping into the sea with the secondary effect of phosphorus turnover and removal, either by the WEBAP I, wave-energized aeration pump, or by an electric pump (WEBAP II, diesel aggregate off shore, or electricity near shore). Three scenarios consisted of precipitation, either in wastewater treatment plants (WWTP) or by spreading of treatment chemical in the sea.

The goal was to compare climate impact and costs for several P-removing techniques, taking into account materials production, transports, operation and maintenance of these. No consideration was taken to end-of-life treatment of the techniques since it was outside the scope of the study. However, the precipitation from the chemical treatment techniques was assumed safely taken care of, and the pumps used for materials recycling by end-of-life.

Removal of 1 kg of phosphorus was chosen as the basis for comparison (functional unit). Emissions from materials and chemicals production, as well as transports and energy use were normalized to removal of 1 kg P. All costs were also normalized to removal of 1 kg phosphorus

Climate impact was calculated as Global Warming Potential (GWP), expressed as kg CO_2-eq (Figure 3.10). Costs were calculated and expressed in SEK (Figure 3.11).

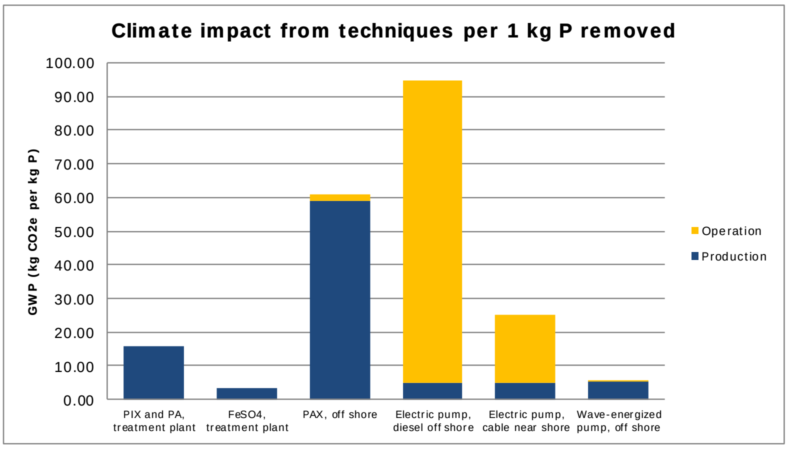

Figure 3.10. Climate impact from the different techniques.

For production of techniques, PAX has by far the largest climate impact. Impacts from fuel use or electricity production are the largest share of the electric pump's life cycle. The wave-energized pump can compete with impacts from FeSO4 treatment, and is efficient regarding removal of P during lifetime.

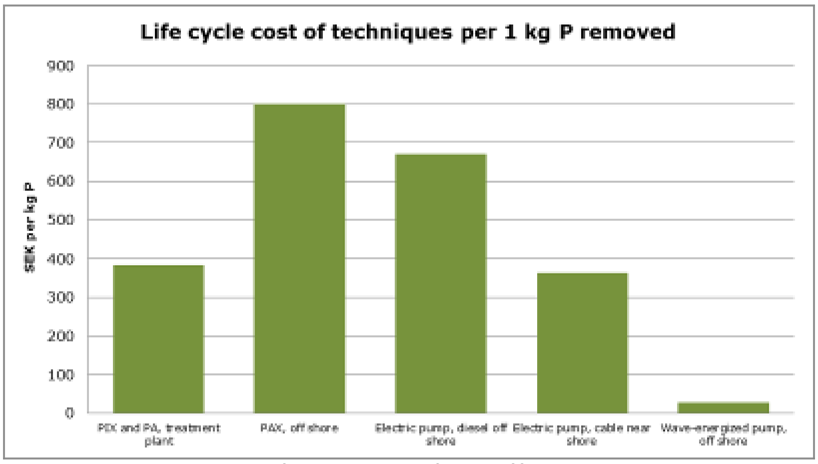

Figure 3.11. Life cycle cost of the different techniques.

The results for the costs follow mainly the same distribution as climate impact (except for a switch in ranking between PAX off shore and electric pump diesel off shore). The wave-energized pump has very low life cycle cost compared to other techniques, which means efficient P removal for the money invested.

It is important to note that the techniques differ in their potential. For the Swedish case, removal of phosphorus in all major treatment plants is already performed with a maximum efficiency, and further removal of phosphorus can be complicated, or very costly. For example, to use extra sand filters to remove additional phosphorus, the marginal cost would be 4600 SEK/kg P. The pumps however, have a more unlimited potential since a large number of pumps can pump as much oxygen-rich sea water as there is at the sea surface (not without cost or climate impact though).

It is also a difference between focuses of the treatments. The plant-based treatments aims for eliminating inflow of phosphorus to the Baltic Sea, while the pumps focus on fixing a problem caused by phosphorus inflow. Therefore these techniques could be used in concert. The pumps could be useful for a period of time to re-oxygenize the Baltic Sea, while efficient P removal in treatment plants must continue so as not to cause oxygen depletion again.

Also note that if end-of-life treatment of the techniques were included, the climate impact and costs may look different. There could also be other environmental issues related to treatment of precipitate, or materials recycling of construction material.

Conclusively, the large offshore wave-driven pump WEBAP I, has in this estimation shown to be competitive with other techniques regarding climate impact and costs. It could therefore be a realistic option for phosphorus remediation of the Baltic Sea.

3.1.5.12 Up-scaling of the technology and costs

Calculations of pump efficiency for wave-powered WEPAB show a relatively significant flow with a mean of 0.34 $m^3/(s\ m)$ even if assuming uncertainty interval ranging between 50 - 90 %. However, a challenge for full-scale systems is assimilate the vast energy present during storms (which corresponds to the 90% percentile) while also being effective at more normal wave conditions. The performed demonstration and monitoring as well as related activities can be used for the further development.

Wave-powered oxygen pumps

As already mentioned, results from the project indicate that full-scale pumps needs to have a certain minimum size that depends on the current wave parameters in the region of application. This is necessary to prevent the pump from riding the waves. Further, the slope and freeboard has to be adjusted for each wave characteristic. This would increase pump efficiency and reduce stresses on the anchorage and the vertical pipe. In addition, also the water intake principle can be improved without significant changes in costs. The cost of oxygen pumps can be divided into different parts: manufacturing, installation, de-installation, maintenance and operation. In contrast to the demonstration units used in this project, there is no need for measurement equipment on the module itself. Each module must be equipped with offshore safety marking. Some things can be improved based on experience from the prototypes, e.g. the pipe connection and anchorage. Since the size of a full-scale oxygen pump is not defined cost calculation was based on the pilot plant WEBAP I with a width of 14 m. The production would amount to around 1-1.2 MSEK. Considering the production of multiple devices would reduce unit costs significantly (Table 3.1).

Table 3.1. Simplified calculation of unit production costs as well as assumed life of 10 years and discount rate of 4%.

Produced unit	Investment SEK	Capital cost SEK/yr
1	1 200 000	147 000
10	700 000	86 000
100	407 000	50 000
1000	237 000	29 150
Mean for 1000	309 000	38 000

This cost can be compared to the module's efficiency which would likely much higher for a full-scale plant than for the used prototype because of an improved efficiency by avoiding “riding the waves”, a rougher wave climate in the open sea and with regard to constructive improvements.

Several suggestions for improvement of WEBAP concept and design have come up during the project, both the project itself and third parties. One of these is to utilize even small waves by adding the intake just below the water surface and using the pressure difference as a control parameter. When an overpressure due to the incoming wave crest occurs outside the valves the water rises inside the basin. When the pressure at wave trough becomes bigger on the inside, the valves closes and the water flows down through the tube.

The fact that the wave-powered oxygen pumps of type WEBAP I would be more effective when they are built with large dimensions opens for another option to combine oxygen pump with other offshore structures.

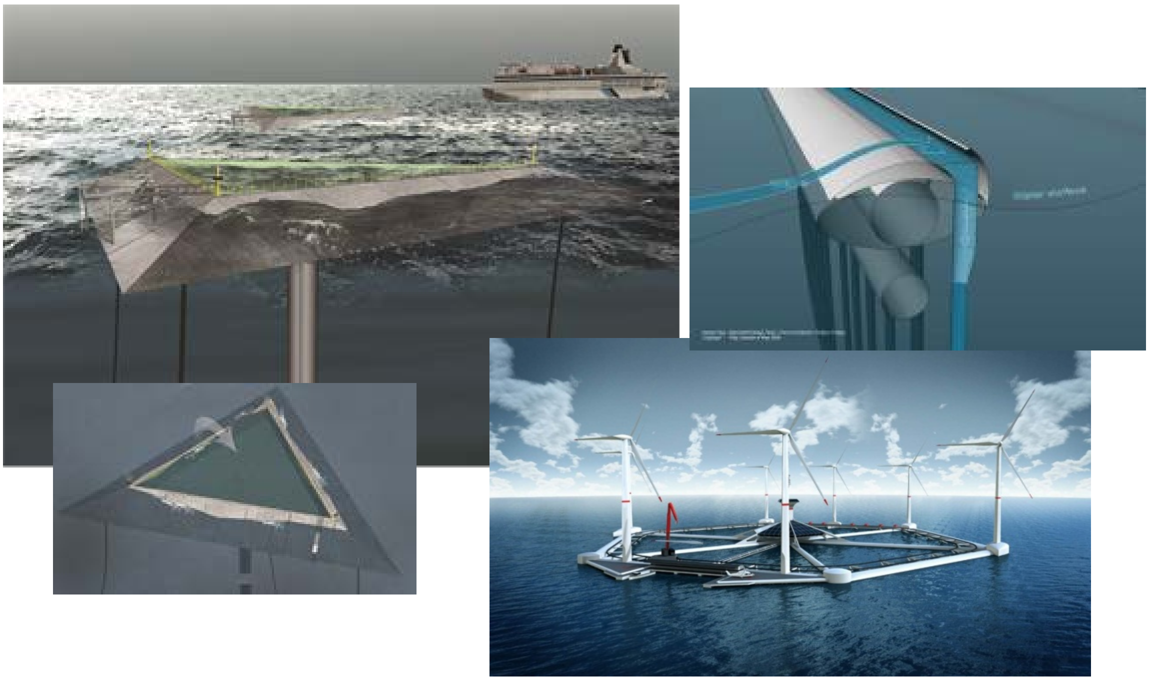

Figure 3.12. Concept of a possible full-scale application and design of WEBAP I as an independent unit or in combination with other offshore structures (here Hexicon offshore wind; www.hexicon.eu).

Electrical driven oxygen pumps

For areas without access to the waves, the electric oxygen pump consisting of one or more modules can be the only alternative. The electric oxygen pump WEBAP II contains apart from the tube mostly standard components and a full-scale plant would thus consist of similar parts. Cost analysis can therefore largely based on the existing pilot plant although a full-scale plant should be operated preferably with green electricity, biofuels, biogas, biodiesel, ethanol, etc. Figure 3.13 shows a possible full-scale facility consisting of three pumps of the same type as used for the prototype, a simple control system and working platform that enables service year round and protects the structure from ice. When using standard components for example floating pontoons etc. such a full-scale plant would, based on estimations from companies that have been involved and constructed the prototype, cost about 700 -800 kSEK. However, in contrast to wave-powered oxygen pumps a larger operational cost for electricity or biofuel and service of pumps is required. On the other hand, a stable and controllable pumping can be achieved.

Figure 3.13. Concept of a possible full-scale application and design of WEBAP II - Electric oxygen pump with three pumps in combination.

CoreOceanPump – Another approach of the Wave-powered oxygen pump

The pump is a development of the company Inovacor AB and can be seen as a further development of WEBAP concept, which combines the advantages of WEBAP I and II. Although this pump makes use of wave power as WEBAP I it utilises wave energy with the help of a moving float that follows the wave motion. The pump is based on a new pump technology DAPP (Dynamic Adaptive Piston Pump) that originates in a basic discovery about the real heart pumping and control functions, and that is very resource efficient. Even at small waves (~ 10cm) a flow is generated by the pump. In the same manner as WEBAP II it allows to take in water from different depths. Other benefits which have been tested during pilot tests are that the vertical pipe does not follow the movement of the float but is fixed providing an even more robust design. The anchorage is centred in the structure, which reduces wear and tear on the pump.

The development of this type oxygen pump was initiated by WEBAP activities and a side-development of an on-going compact wave energy project www.corpowerocean.com. The pump has a very high efficiency and created a continuous flow. Up-scaling calculations and cost calculations from the wave power project indicates that the production of a standard unit for 3-5 m^3/sec and 0.05 bar pressure, and 100 meters depth requires an average power of about 25 kW and peak power of over 100 kW. Investment cost including installation of such a unit should be less than 500 kSEK. The design of the pipe is the most uncertain cost item. At 50 % utilization over a year around 80 km^3 of surface water can be pumped down to the anoxic bottoms. At smaller difference between surface water intake and water outlet can more than double this amount.

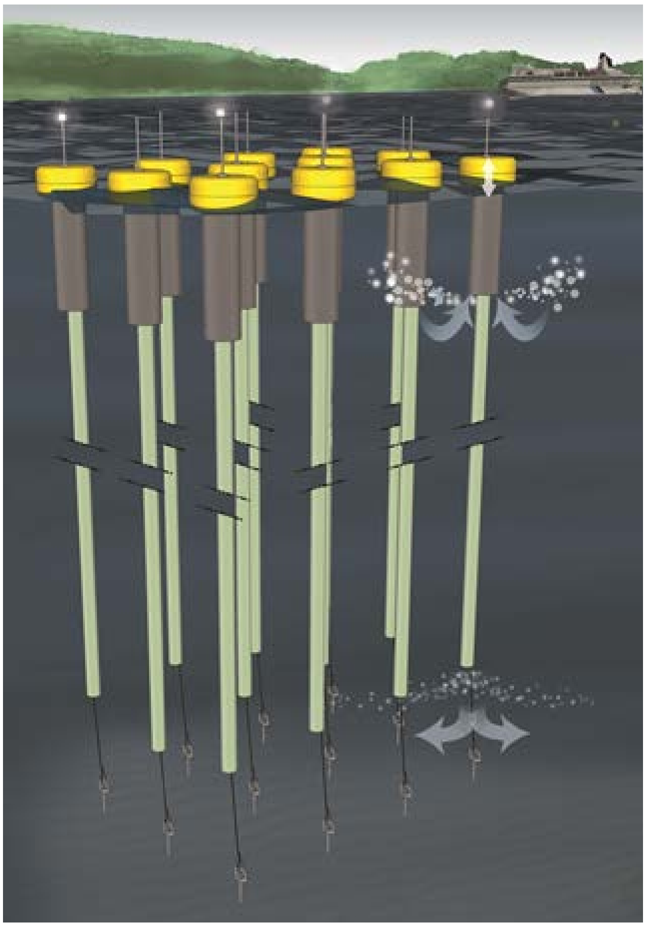

Figure 3.14. Concept of a possible full-scale application and design of CoreOceanPump.

The various tasks of Action 5 were completed as planned according to the updated project schedule and its objectives were achieved.

Related and active deliveries and more (see Table 2.1*):*

- D5.1: Technical, environmental and economic evaluation report.
- D5.2: Evaluation report of results during the demonstration

3.1.6 Action 6: Dissemination

The objective of Action 6 was to ensure a wide dissemination of results and encourage an exploitation of results via various means to the identified target group/end-users across the EU. Further, the objectives included to provide sufficient technical information on the performance of the technology to other relevant parties and raise public awareness about the WEBAP-system via media.

The dissemination action involved a continuous updating of information about the project via the project homepage on www.webap.ivl.se. Further, following dissemination activities, were performed during the project period:

- Continuously updated project web site: www.webap.ivl.se
- Continuously updated Facebook site: Wave-Energized-Baltic-Aeration-Pump-Webap

- A number of seminars and workshops
- Freely accessible WEBAP-exhibition at Marint Centrum in Simrishamn
- Press event in May 2012 with field trip to the unit WEBAP I
- Information material about the project and obtained results created (Swedish and English version, including 2 roll-ups, several brochures)
- Continuously updated project notice boards
- Over 20 articles/notes in national and local press, and specialised press, e.g. Svenska Dagbladet, Sydsvenskan, YstadAllehanda, Miljörapporten, NyTeknik
- Several TV news/reportage and radio news/reportage e.g. TV-news "Sydnytt", "Rapport", Swedish Scientific Radio P1 "KLOTET" Swedish Radio P4 Kristianstad.
- A number of seminars and workshops / Participation at conferences
    - ASLO Aquatic Sciences Meeting, New Orleans 17-23 February, 2013
    - State of the environment conference, May 2013
    - Baltic Sea Workshop/conference at KTH with national and international scientists/researchers about oxygenation, September 02, 2010.
    - Workshop at the Swedish EPA on November 9, 2010
    - 8 Workshops at the Marin centre in Simrishamn during 2010 and 2013
    - Seminar in Stockholm for 40 environmental experts/researchers in August 2011
    - Seminar in Gothenburg for 50 environmental experts/researchers in August 2011
    - Etc.
- Site visits in relation to press events
- Establishment of an After-LIFE+ Communication Plan
- Layman's report (English and Swedish)
- White Paper
- A research report
- WEBAP-Multimedia presentation
- Interactive project portal
- Etc.

Furthermore, the dataset collected from offshore Baltic proper were compiled and evaluated. A scientific manuscript has been prepared and submitted to Journal of Marine Systems.

Action 6 also included the preparation of a large international event that informed all stakeholders with focus on problem-owners and decision makers about the need and possibility for actions in order to save the ecosystem Baltic Sea. This event involved a number of partners from around the Baltic Sea.

The project resulted in a number of external reports on pilot plants, basin tests, data collection, simulations etc. The following list includes independent publications presented at conferences or considered as separate publications.

- Alongi Skenhall, S, Baresel, C., Karlsson, M. & Ek, M., 2013. Climate impact and life cycle cost assessment of wave-energized aeration pump -Performance of oxygenation and comparison with other techniques for removal of phosphorus from the Baltic Sea. Technical report IVL Swedish Environmental Research Institute 2013-05-14, 7 p.

- Baresel, C., Malmaeus, M., Engqvist, A., Alongi Skenhall, S., Carstens, C., Viktor, T., Malm, J., Claeson, L., Cvetcovic, V., Ekengren, Ö., Karlsson, M. (red), 2013. WEBAP - Vågdriven syrepump för Östersjön. IVL Swedish Environmental Research Institute, B2130, Stockholm.
- Carstens, C., Baresel, C., Destouni, G. & Cvetkovic, V., 2013. Reducing Hypoxia in the Baltic Sea through the Wawe-powered Baltic Aeration Pump (WEBAP) ASLO Aquatic Sciences Meeting, New Orleans 17-23 February, 2013. Abstract ID: 11306.
- Engqvist, A., 2012a. Kommentar till konstaterad syresättning av Kanholmsfjärden. PM 2012-05-31, 2 sid.
- Engqvist, A., 2012b. Model computation of the impact on the density stratification and on the aeration enhancement in the Stockholm archipelago by forced down-pumping of surface water in Kanholmsfjärden. Aythya AB rapport, 24 sid.
- Engqvist, A., 2012c. Analys av syresättning av Kanholmsfjärdens bottenvatten 2012. Aythya AB rapport, 5 sid.
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Action 6 was completed as planned in the updated project schedule and its objectives were achieved.

Related and active deliveries and more (see Annexes):

- D6.1: Communication plan
- D6.2: Notice boards
- D6.3: Updated Communication plan
- D6.4: White paper
- D6.5: After-LIFE Communication plan.

3.1.7 Action 7: Project Management

The objective of Action 7 was to coordinate the WEBAP project and ensure partner cooperation and involvement in order to maintain continuity in the work throughout the project period and delivery of the defined tasks together with the project reports. The project management was based on quick and efficient decision-making for optimum harmonization of actions. IVL also secured reduction of the “carbon footprint” from the project during its implementation.

The project management included a number of telephone or video meetings for the various tasks that the project management group had to work with. This comprises management of beneficiaries, subcontractors and collaboration partners. The project management created a solid and thought-out fundament for the whole project period. This embraced both cooperation and involvement of all relevant stakeholders and partners.

The Project Coordinator had together with all other involved persons of the Project Management Group and by support by the Steering Group and Reference Group worked to secure a successful accomplishment of project management objectives and results, deliverables and milestones.

However, during the whole project additional and unexpected resources had to be provided to the communication and update with Astrale monitors. As the project team had to deal with new monitors several times during the project periods, a number of extra meetings and discussions had to be managed and considered in the project budget in order to update and inform every new monitor. What the project team expected or would have been wished for was a continuous and stable support by the monitoring team. Despite this, the project team and all monitors that have worked with the project experienced a good collaboration.

Action 7 was completed as planned in the project schedule and its objectives will be achieved with the final submit of the report.

4 PROBLEMS ENCOUNTERED

As the project aimed at the demonstration of a new technique, problems and difficulties have been encountered during the whole project period. During the design and construction of the pilots, these problems or difficulties were mainly of technical nature or caused by delays in the equipment delivery. Such issues have partly been foreseen in the project planning and their implications for actions in the project were therefore of minor nature.

One of the problems encountered and reported on in the first status report was the delay of the planned basin tests because the initially assigned partner could not carry out the test as discussed. This however was experienced as an advantage as also findings during the construction could be tested in the basin.

During the planned demonstration period, the project was forced to stop the launch and installation of the second pilot due unforeseen and exceptional weather conditions. The winter 2010/2011 was one of the coldest winter ever with e.g. the coldest November and December in 100 years. The early and strong winter begin did not only imply difficulties in the communication and power-supply with the already launched wave-powered pilot due to the freezing-over of such equipment, it further forced the project team to postpone the launch of the pilot WEBAP II in Kanholmsfjärden to after the winter due to thick ice formation at the test site. Please note that the pilot WEBAP II in Kanholmsfjärden was successfully launched on April 14 2011, only 1 week after the ice cover vanished.

Another problem encountered was the breakdown of the anchorage of the wave-powered device after one month of successful demonstration. As this breakdown happened at a time with now external loads, i.e. wind, waved etc., on the device also this problem is classified as a force majeure. The pilot had to be towed to the harbour and due to heavy icing there too; reparation could only be stated right after Easter and have been finalised during June 2011. The wave-powered pump WEBAP I was successfully re-launched on July 12 2011 right after reparation works had been finalized. The unit has been in operation since then without any major observed problems.

Other observed problems include failure of measurement equipment and other electrical devises. This is partly explained due to the new application field with minor or no experience at the involved companies. Measuring the vertical flow in the pumps is for instance not a trivial task but requires the adaptation of existing equipment or development of new tools to accomplish. Therefore, it is natural that problems occur. The project was however able to solve most of the problems with help of the various collaboration partners.

As the WEBAP project encountered a number of difficulties and problems that disrupted the project they have to be considered by the full-scale implementations. The main challenges can be divided into technical challenges related to the actual construction and pump efficiency, and conflicts associated with oxygenation due to conflicts of interest.

One of the biggest problems was the pipe connections to the demonstration units and to the diffuser at the seabed. In both installations, a PVC tube with very strong strength was used. Other options need to be investigated. The most realistic option is PE pipes as used at oil platforms in the North Sea. Even rubber has been tested in another project, but this material is addressed with the problems too. The handling of the pipe in the launching and uninstallation of oxygen pumps are one of the most important aspects for selection of pipe materials and design.

In addition, the diffuser at the end of the tube may need further development as there are different ideas on how the mixing of oxygen-rich surface water provides the greatest effect. Large openings to the sides with low flow velocities as used in this project or nozzles that increase the speed of the outflowing water significantly but may have negative effects on the pump efficiency.

Baltic Sea water is used by many actors. Therefore, interests of many groups need to be considered by the full-scale implementation of oxygen pumps. Although oxygen pumps aimed at improving the state of the sea by increasing the oxygen content and by reducing the phosphorus in the water and therefore secure the reproduction of fish and the quality of coastal areas, the project has shown that short-term interests can disturb a successful implementation. The installation of pilot plants required a large number of permits and approvals from, among others Transport Agencies, Maritime Administration, the Swedish Armed Forces, Professional Fisherman's Association, county administrative boards, societies etc. Despite this, and a rigorous safety marking both demonstration units were damaged by other vessels, both fishing, leisure boats, etc. The wave buoy was hit and damaged several times; mainly trawlers that did not respect the safety distance.

Another important aspect is the placement of oxygen pumps outside the main vessel paths. The Baltic Sea is one of the most navigated seas in the world.

5 EVALUATION

The described actions of the WEBAP project consist of an immense work performed by the project beneficiaries and their collaboration partners. This work and what it has accomplished is further briefly evaluated in the following sections.

5.1 Project implementation

The project activities were successfully implemented throughout the whole project period. Necessary adaptations and amendments were early dealt with and the project management and activities adjusted to changes. The project management structure facilitated a close collaboration between the different groups and with help of the proper election of collaboration partners, all tasks that were planned could be realized during the project lifetime. This also includes additional tasks that became necessary during the project e.g. as a results of force majeure. The contribution and commitment of the main and the associated beneficiaries, and the involved collaboration partner permitted to overcome all challenges that appeared during the project. The direct and close contact between project members and the coordination by the project manager were key items that made the successful implementation of all activities possible.

5.2 Technical and commercial application

The intention of this demonstration project has not only been to demonstrate a sound technical solution for an environmental problem, but it also intended to create enough information to implement that solution in a full-scale basis. This includes the availability of knowledge for the construction of oxygen pumps that are realistic and economic feasibility, and that also understand all limiting factors. As the problem of oxygen-depleted marine environments is a problem owned by the whole society, the demonstrated technology will never be a product profitable product in the sense that it generates a profit in monetary terms. However, the project prepared for a commercial application that is available for society as a method to mitigate dead bottom waters.

5.3 Success and failures

The WEBAP-project has succeeded with its planned activities. Moreover, the project did not only demonstrate the initial solution of a wave-powered oxygen pump but it also brought up an alternative technical solution for applications in areas where the wave conditions do not allow for wave-powered oxygenation. Further, activities initiated by the WEBAP-project created further enhancements of the original approach and even new technologies that broaden the field of implementation of artificial oxygenation of oxygen-depleted marine environments.

The WEBAP-project as also identified some of the relevant failure factors of which one is the need for a successful integration and acceptance of oxygenation activities with other interests of marine environments such as fishery, transport, recreation etc. Also technical constraints or hinder have been brought up. The further development of technical details in a full-scale application can be named as one.

Measuring the effect and thus quantify the impact of oxygenation pumps on the environment is an impossible task due to several reasons. First, marine ecosystems are highly heterogeneous and complex systems that contain processes that by today have not fully been understood, as for example the internal phosphorous kinetics. The overlapping and interaction of artificial oxygenation and natural events imply that a certain attribution to one or the other is a difficult task. This is clearly illustrated by the demonstration tests in the Stockholm

Archipelago. However, a complete and unbiased quantification of the effect of artificial oxygenation would not even be possible with an extensive online monitoring program that covers the surrounding of an oxygen pump. This also includes long-term implications of oxygenation. Issues related to that could not be worked with within this project as the time frame did not allow for long-term measurements and follow up.

5.4 Comparison against the project-objectives

To assess the extent to which the WEBAP project has met its stated goals and objectives the main objectives of the project has to be recalled: "*The main objective of the proposed project is the demonstration of a cost-effective wave-powered device, entitled the "Wave Energized Baltic Aeration Pump (WEBAP)" that mitigates the problem of oxygen depletion ("hypoxia") in coastal zones and open seas.*".

The project beneficiaries conclude that this objective has been achieved by the project activities. The project has moreover developed and demonstrated a cost-effective electrically-powered aeration pump for the use in marine environments without enough wave energy accessible. Further, the project substantially improved the knowledge about the current situation in the Baltic Sea regarding hypoxia and the phosphorous dynamics.

Recalling the expected results as stated in the project description, it can be said that these expected results remain after the successful demonstration of the WEBAP-concept. The WEBAP-system will significantly improve the situation in marine environments suffering from hypoxic conditions. The implementation of oxygen pumps is expected to lead to enhanced ventilation/mixing of hypoxic bottom water layers with the following primary quantitative environmental results (compared to present situation):

A. Increased oxygen levels in hypoxic deep-water layers to at least 2 mg/l.
B. Significantly decreased phosphorus concentrations in the bottom water due to a decrease in the phosphorus leakage from bottom sediment by 50% in anoxic waters and eventually phosphorus binding when more aerobic conditions occur.

Further, secondary effects will be:

- Recovery of benthic animals and deep-water living fish.
- Less algal bloom during summer months.
- Improved water quality and increased catches of high quality fish.
- Restoration of natural marine ecosystems, including natural habitats.
- Halting the loss of biodiversity.

A full-scale implementation of the technology would be possible in many of the more than 400 hypoxic marine environments worldwide. For the Baltic region, the implementation would provide a significant improvement of the environmental state of the Baltic Sea. A full-scale implementation of the WEBAP-system and the transfer to other areas worldwide can lead to economic growth and increase Europe's competitiveness in this field on the world market.

5.5 Effectiveness of dissemination activities

Dissemination activities by the project included and include (as stated in the After LIFE communication plan) a wide range of actions using variety of information materials and channels. The effectiveness of these activities could directly be measured by the interest of different targeted groups in the information provided. This includes that e.g. information brochures were fast distributed, large audience in project seminars or presentations, a high number of visitors at the WEBAP-exhibition, feedback (both written and in meetings) after articles in the press etc.

The project judges the dissemination activities as successful also because the topic of hypoxia has been more frequent on the agenda and discussions about possible mitigation measures have been extend from professional groups to policymakers and the public since the project started. The project further has created a number of interests and activities that illustrate the effectiveness of the planned dissemination activities.

6 IMPACT

Project beneficiaries and the associated collaboration partners have seen a significant change in the presence of the environmental issue targeted by the project. Not only has the number of activities to investigate the spread and seriousness of the problem with hypoxia increased but also the general awareness. The need and possibility to take actions to prevent further negative impacts has been realised and publicly discussed. Many authorities are actively supporting projects in order to get more information about future strategies.

Other teams started to work with similar approaches. This implies that various technologies are tested all with the aim of reducing the negative impact of oxygen depletion in deep-water layers. Various collaborations with companies, authorities and research groups have been initiated since the start of the project. Students from different parts of the world ask to contribute to the project or to use the project results for own and further studies.

To impacts that are more indirect the growing interest from construction companies seeking various ways to optimise a possible future manufacturing and combinations with other offshore installation may be named. Many actions outside the framework of the WEBAP project show the impact of the project even so it may be difficult to lead back single activities to the current project.

Further development of the initial WEBAP-design will bring up new ideas, reduce costs and increase overall awareness.

Outside LIFE: Actions outside the LIFE project but complementary to the project

Main activities outside the framework of the WEBAP LIFE+ project include the data collection and processing within other marine ecosystem related projects and activities. This comprises activities by the beneficiaries but also by third parties that were willing to share data with the project team.

The SEABED project, a Central Baltic INTERREG IV A project administered by Åbo Akademi University, Finland (Turku), aimed to "*improve the situation in the Baltic Sea by creating tools for the management of the eutrophied archipelago areas with a special focus on the quantification of the internal load of phosphorus.*" Furthermore, the project looked at scenarios for the effects of climate change and eco-engineering measures in the Baltic Sea region. This was partly accomplished by using existing data and new data from field studies, data that could also be used within WEBAP.

In a joint project between the foundations of Ångpanneföreningen (ÅF) and IVL the cost-efficiency and resource consumption of different remedial actions to mitigate eutrophication within the coastal zone of the Baltic Sea were studied. A mass balance model was applied to identify phosphorus sources, for one Baltic coastal area outside the city of Gävle. Results from the WEBAP-project were incorporated in the analysis.

Another significant work has been performed during the development and test of a pilot unit of the CoreOceanPump – Another approach of the Wave-powered oxygen pump. Even so, initiated by the on-going WEBAP project, the work on that oxygenation pump was not included in the current project.

7 THE FUTURE: CONTINUATION OF THE PROJECT AND REMAINING THREATS

The following section provides a brief analysis of long-term benefits with the demonstrated WEBAP-approach and its full-scale implementation.

Environmental benefits of the demonstrated approach are described as a significantly improvement of the situation in marine environments suffering from hypoxic conditions. This can be measured in different terms as for example the increase of oxygen concentrations in deep water layers, the decrease of mobile phosphorous in deep waters. This will, on a long-term, decrease algae bloom during summer months, recover benthic animals and deep-water living fish, improve water quality and increased catches of high quality fish, restore natural marine ecosystems, including natural habitats and halt the loss of biodiversity. Those are important benefits compared to the current state of the large areas in the Baltic Sea and more than 400 known marine environments around the world.

An improved oxygen situation in the Baltic Sea, or any other of suffering marine environments, would not only imply favourable effects on the ecosystem but would also have positive effects on tourism and the fishery. The reproduction of fish is disturbed by low oxygen concentrations, and the mitigation of hypoxia has thus a significant impact on how fishery is developing in the future. In addition, tourism is depending on balanced marine environments, as tourists will choose destinations with good water quality. Many communities along the Baltic Sea coast are however, depending on tourism for economic survival.

From a technical perspective, the presented approach may be the most resource efficient measure to mitigate hypoxia and thus it helps to reduce emissions, energy use and use of other resources.

The WEBAP implementation would contribute to enhanced water quality. It is in line with national annual priorities for Sweden as well as Swedish environmental objectives that include “a balanced marine environment, flourishing coastal areas and archipelagos”. With the aim to enhance the oxygen situation in the coastal and/or open seas, oxidation may contribute to the fulfilment of the Water Framework Directive (Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy”). It contributes to the objective of protecting and enhancing the status of aquatic ecosystems by enhancing the restoration of self-purifying biogeochemical processes.

The WEBAP project directly targeted the council directive concerning Thematic Strategy on the Protection and Conservation of the Marine Environment (COM(2005)504 final), especially as it proposes the implementation of mitigation measures that need to be taken in order to achieve or maintain good environmental status (Article 13). With its potential to reduce the negative impacts of nutrient loads to the Baltic Sea, an implementation will also contribute to the fulfilment of the HELCOM Convention ("Convention on the protection of the marine environment of the Baltic Sea area, 1992, Helsinki Convention). Further, potential water quality improvement in coastal waters and open seas are directly related to the Directive on Bathing Water (76/160/EEC) which sets cleanliness standards for bathing water.

The successful implementation would also help to adapt of the EU economy and society, nature and biodiversity, water resources and human health to the adverse impacts of climate change. While the main objective of the project is on mitigation measures of hypoxia in marine environments the project also falls within the scope of the European Environment & Health Action Plan 2004-2010 (COM(2004) 416) as the proposed technique will help to protect and control areas intended for recreational uses, particularly bathing.

The demonstrated technology may be implemented in many of the more than 400 hypoxic marine environments worldwide. Such an implementation of the WEBAP-system and the transfer to other areas worldwide could lead to economic growth and increase Europe's competitiveness in this field on the world market.

The project beneficiaries and many of the collaboration partner that were involved in the project already plan on follow up actions to continue the implementation of the demonstrated WEBAP approach on a larger scale and the monitoring of ecological effects over a longer period of several years. The main obstacles for this are the political understanding and willingness to take the lead. The dissemination efforts and material during the final period of the WEBAP project and activities as planned in the After-LIFE communication plan will help to overcome this hinders.