Wetland Oxelösund, Sweden - the first five years of operation

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Abstract

Wetland Oxelösund (23 ha) was established in 1993 to remove nitrogen from wastewater before discharge to the Baltic Sea. Since it was the first full-scale wetland for nitrogen removal in pre-treated municipal wastewater in Scandinavia, an elaborate monitoring program was tied to the operation of the wetland. The basic monitoring was primarily aimed at mass-balance calculations to estimate removal of nitrogen, phosphorus and BOD. In addition, studies were made concerning: removal processes for nitrogen and phosphorus, removal of indicator microorganisms and hygienic risk assessment, vegetation and birdlife development, and economic valuation of the wetland. In this paper we describe the wetland system and summarize the results from the first five years of operation (1994-1998).

1 Introduction

During the 1980s, recurrent algal blooms and spread of oxygen deficiency in the water and sediments at the bottom of the Baltic Sea called attention to the eutrophication of this brackish enclosed coastal sea (Nixon [12]). The load of nutrients, especially nitrogen, was identified as an important component of the eutrophication process (Granéli et al. [6]). In order to decrease the discharge of nitrogen to the Baltic Sea, the Swedish authorities decided that all large-scale wastewater treatment plants (>10 000 person equivalents) situated along or near the coastline should remove at least 50% of incoming nitrogen (Swedish EPA [13]).

For the town of Oxelösund (12 500 inhabitants, 1993) at the Swedish Baltic Sea coast, reaching the nitrogen removal requirement meant large investments. The town's wastewater treatment plant was equipped only with mechanical and chemical treatment for removal of BOD and phosphorus. Adding a conventional biological nitrification-denitrification step would amount to approximately SEK 150 per kg nitrogen removed. This should be compared with the cost of achieving nitrogen removal in a treatment plant with an existing biological step, approximately SEK 30-50 per kg of nitrogen removed (Swedish EPA [13]).

Primarily to avoid the large investment, the municipality decided to apply for a permit to utilize surface-flow wetland technology for nitrogen removal from the pre-treated wastewater. The ability of surface-flow wetlands to remove nitrogen from wastewater has been demonstrated in natural as well as man-made systems (e.g. Knight et al. [11]). Often, however, the primary goal of treatment wetlands has been the removal of total suspended solids (TSS) and organic matter (BOD), with ammonium oxidation only as a secondary objective (Knight [10]). Therefore, it might be argued that the design loads have in many cases been too high to leave enough oxygen for substantial nitrification to take place. Another factor of importance is the loading schedule. While most surface-flow wetlands have been continuously loaded, intermittent filling and emptying might be a more efficient regime in order to improve nitrification and other treatment processes. It was therefore assumed that the potential for removal of wastewater nitrogen in wetlands might be greater than what several experiments have shown, given that the BOD load is low and that the wetland system is designed and operated for intermittent filling and emptying (Wittgren & Tobiason [15]).

Since Wetland Oxelösund was the first full-scale wetland for nitrogen removal from pre-treated wastewater in Scandinavia, the Swedish EPA and Oxelösund municipality together invested SEK 2.5 million in a monitoring program scheduled for the period 1993-1998 (Wittgren et al. [17]). In this paper we describe the wetland system and summarize the results from the first five years of operation (1994-1998).

2 Site description

The surface-flow wetland was constructed during the winter and spring of 1993 on the Brannäs peninsula adjacent to the town of Oxelösund in south-eastern Sweden. The wetland system consists mainly of five ponds, where a southern (S1-S2) and a northern (N1-N2) branch run in parallel, with a final common pond (SN3) (Fig. 1). The ponds are intermittently filled and emptied, with a cycle length of one week. During such a cycle, ponds S1 and N1 fill alternately during 3- and 4-day periods, respectively. These ponds are then emptied to S2 and N2, which alternately discharge to the constantly "full" final SN3 pond. The goal of intermittent operation is to create conditions that alternately promote nitrification of ammonium adsorbed to sediments and plant surfaces (emptied ponds), and denitrification of formed nitrate (filled ponds). Another asset of intermittent operation is that hydraulic short-circuiting is minimized. Filling and emptying are regulated manually with sluices at the outlets of the ponds.

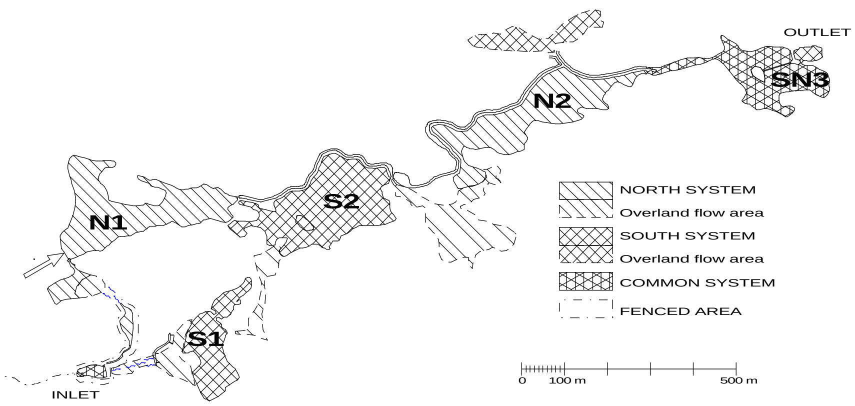

Figure 1: Map of the wetland system in Oxelösund. The arrow indicates the inlet to the northern system during 1993-97.

The system of ponds, canals and overflow areas cover approximately 23 ha, and calculations in this paper are based on this area. However, the area covered with water is sometimes smaller, due mainly to channeling in the overflow areas (Fig. 1). The effective area is presumably between 18 and 23 ha, and use of the latter should thus give conservative values for areal performance. The design flow is 6 000 m^3 day^{-1} of pretreated wastewater from the Oxelösund wastewater treatment plant. The water level amplitude between “empty” (the ponds are rarely completely emptied) and full ponds varies from 0.6 to 1.5 m between the different ponds. The hydraulic retention time in the wetland is approximately eight days.

During the period 1993 to 1996, the parallel branches had separate inlets where the water was treated in stone filters constructed from iron-blast furnace slag. The N1 stone filter was situated immediately adjacent to the N1 pond, while effluent traveled (and still does) approximately 200 m through forest between the S1 stone filter and the S1 pond. In order to improve the treatment results and hygiene safety, the wetland was reconstructed in 1997 and the inlets were co-ordinated to a common site where the southern inlet used to be. At the same time, the stone-filters were replaced by a sedimentation pond. To connect the new inlet with the northern system, a series of shallow ponds and overland flow areas were constructed. This increased the area of the wetland system to approximately 24 ha.

The wetland is loaded with pretreated wastewater, which is pumped 2 km through underground piping from the wastewater treatment plant (WWTP). Pretreatment consists of mechanical treatment and chemical precipitation with aluminum sulfate in the WWTP.

The wetland is situated in a clay-covered depression, reaching towards the Baltic Sea. The slope of the depression is less than 0.5‰, except for the steeper inlet area. Geologically, the area is a typical Swedish coastal landscape with thin clay sediments overlaying glacial till and bedrock. Prior to wetland establishment, the area was dominated by abandoned arable land and mixed forests. Some parts had become waterlogged, due to lack of maintenance of the drainage system, and were covered with wet meadow or wetland plants. The final pond, SN3, differed from the other four since it was, and still is, occupied to approximately 50% by a reed-covered peat bog. The catchment area has been estimated to 103 ha, including the wetland system, and is characterized by uninhabited spruce, pine, birch and oak forest.

Construction work involved cutting trees, excavating channels and dikes, constructing trails and stone filters, and building wooden footbridges and control gates, including an outlet weir for flow measurements. Additionally, the establishment of vegetation adapted to the special wetland conditions was a major part of the construction work. This had to be done since little natural wetland vegetation existed in the area and rapid coverage by macrophytes was desired to prevent microalgal blooms.

3 Establishment of vegetation

The plant establishment was divided into structure- and diversity-promoting establishment. The structure-promoting establishment aimed at rapid creation of a vegetation cover with species assumed to promote nitrogen removal and wildlife habitats. In the upper part of the system, the ambition was to establish plant communities with hard stem species, e.g. reed (*Phragmites australis*) and sedges (*Carex* spp.), serving to increase the surface area for nitrifying bacteria to attach to. In the lower part of the system, more edible species were desired, such as cattail (*Typha* spp.) and reed sweetgrass (*Glyceria maxima*), serving as energy sources for denitrifying bacteria.

For wildlife habitat creation, plants producing grains or seeds were desired. For this purpose, bulrush (*Scirpus lacustris*) and some large growing species of sedge (e.g. *Carex riparia*) were introduced as a part of the structure-promoting establishment.

The major part of the plant establishment was performed during late April to early May 1993. Three different methods were used for the structure-promoting establishment: (1) broadcast sowing of seeds of common reed, cattail and rushes, (2) transferring of soil/root/shoot clumps of different species of sedges and reed sweetgrass, and (3) transferring of whole plants of some floating and submerged species. A fourth ”method” may be mentioned: activation of the local seedbank by inundation of the soil.

The diversity-promoting establishment was performed during the summer of 1993 and the spring of 1994. Species such as *Iris pseudacorus*, *Calla palustris* and *Nymphaea* spp. were introduced from nearby wetland sites.

4 Basic monitoring

The flow of treated wastewater piped to the wetland from the WWTP was measured continuously with an inductive flow meter. At the outlet of the wetland, the flow through a rectangular weir was automatically calculated from continuous water level measurements (1994-97) or measurements taken with a pressure head level recorder (1997-98). Some errors in the outflow measurements were observed during 1994 and 1995. These measurements were therefore adjusted using a water balance model, HBV (Bergström [1]), with the inflow of wastewater and daily temperature and precipitation measurements as input data.

The basic monitoring program during 1994-95 included flow proportional sampling at the WWTP outlet, and weekly grab sampling at the outlet from the wetland. The daily flow proportional samples from the WWTP outlet were pooled to create weekly “operation cycle” samples before analysis of total N,

NH_4^+-N and total P. Biological oxygen demand, BOD_7, was analyzed in a fresh day sample once weekly. Initially, NO_3^--N was also analyzed, but was found to occur only in trace amounts. The grab samples at the wetland outlet were taken during peak flows, when water from S2 or N2 was released to SN3. The samples were analyzed for total-N, NH_4^+-N, NO_3^--N, total-P and BOD_7. Repeated grab samples taken within peaks showed virtually constant values for the variables analyzed.

During 1996-98, samples were taken in the same manner, but only every second week, and were analyzed for the components listed above. All samples were analyzed at an accredited laboratory, mostly according to Swedish Standards. The results from the basic monitoring are summarized in Table 1.

Table 1: Annual average flows and concentrations (with standard deviations) at the inlet and outlet of Wetland Oxelösund, 1994-98.

Variable		1994	1995	1996	1997	1998
Water flow	In	4 013	5 628	5 455	4 604	4 891
(m^3 d^{-1})	Out	4 309	5 957	4 875	3 978	4 025
Total N	In	21.5 (4.7)	22.7 (5.2)	22.3 (4.4)	25.2 (5.2)	22.7 (4.3)
(mg l^{-1})	Out	12.9 (3.5)	14.2 (4.2)	15.3 (5.1)	15.0 (4.0)	14.6 (4.0)
NH_4^+-N	In	17.2 (5.1)	18.0 (5.7)	17.1 (3.9)	17.7 (5.3)	15.0 (5.5)
(mg l^{-1})	Out	11.3 (3.8)	11.3 (4.0)	12.0 (5.1)	11.9 (4.3)	11.6 (4.2)
NO_3^--N	In	n.d.	n.d.	n.d.	n.d.	n.d.
(mg l^{-1})	Out	0.4 (0.4)	0.8 (0.6)	0.5 (0.5)	0.8 (0.8)	0.4 (0.3)
Total P	In	431 (265)	323 (235)	272 (160)	350 (254)	526 (345)
(µg l^{-1})	Out	59 (36)	32 (19)	50 (43)	39 (20)	44 (45)
BOD_7	In	29.5 (13.9)	17.8 (7.4)	17.8 (9.2)	22.0 (6.5)	25.9 (6.4)
(mg l^{-1})	Out	4.8 (5.0)	4.0 (1.8)	4.9 (3.1)	4.0 (1.6)	3.8 (1.4)

n.d. = not determined

The basic monitoring was aimed primarily at mass-balance calculations to estimate removal of nitrogen, phosphorus and BOD in the wetland (see next section). In addition, studies were made concerning: removal processes for nitrogen and phosphorus, removal of indicator microorganisms and hygienic risk assessment, vegetation and birdlife development, and economic valuation of the wetland. Monitoring efforts associated with these studies are briefly described in each of the following sections, respectively.

5 Removal of nitrogen, phosphorus and BOD

At the planning stage, a preliminary nitrogen budget for the town of Oxelösund was made. During an average year, a total amount of 65 tons of nitrogen was estimated to reach the WWTP from the connected households and industries. To achieve the required 50% nitrogen removal, at least 32 tons of nitrogen would have to be removed from the wastewater. Approximately 10 tons of nitrogen were being removed in the mechanical and chemical steps in the WWTP. The wetland would therefore have to remove 22 additional tons, or approximately 960 kg N ha^{-1} $year^{-1}$, before discharge to the Baltic Sea.

During the monitoring period, 1994-98, the amount of incoming nitrogen to the WWTP was somewhat smaller than expected, mainly due to a decreasing population in Oxelösund. The relative nitrogen removal was steadily around 17% in the WWTP, whereas the removal in the wetland increased in both absolute and relative terms (Fig. 2 and Table 2).

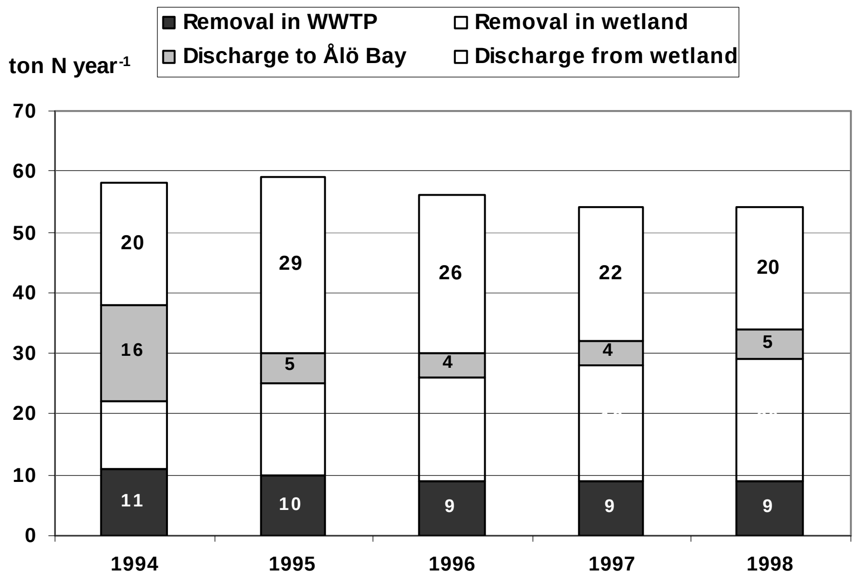

Figure 2: Nitrogen budgets for Oxelösund municipal wastewater treatment facility, 1994-98. The diagram illustrates removal of total nitrogen in the WWTP and the wetland, as well as discharge from the wetland and direct discharge from the WWTP to the old receiving water, the Ålö Bay.

Table 2: Removal of nitrogen in Wetland Oxelösund, 1994-98, as calculated from inlet and outlet data, and as obtained from regression analysis. In the 'Calculated' case, the relative removal in relation to inlet load is also shown.

Year	Tot-N removal (kg ha^{-1} yr^{-1})		
	Calculated	Regression	Difference
1994	493 (37 %)	582	-89
1995	665 (35 %)	661	4
1996	738 (40 %)	621	118
1997	835 (46 %)	705	130
1998	834 (48 %)	648	186

The data was further analyzed by regression, with the objective of finding out whether the increase in removal could be explained in terms of loads or temperature conditions, or if other explanations were more likely.

In the regression analysis, first-order area-based removal to a background concentration was assumed:

$$ln[(C_{out}-C^*)/(C_{in}-C^*)] = - k_{aT} * A/Q \qquad (1)$$

with temperature dependence according to the modified Arrhenius equation:

$$k_{aT} = k_{a20} * Q^{(T-20)} \qquad (2)$$

where

C_{in} = Tot-N concentration in wastewater inflow [mg l^{-1}]
C_{out} = Tot-N concentration in outflow from the wetland (flow-adjusted to inflow of wastewater) [mg l^{-1}]
C^* = background concentration of Tot-N [mg l^{-1}] = 1,5 mg l^{-1} (Kadlec & Knight [8])
A = wetland area [m^2] = 230 000 m^2
Q = inflow of wastewater [m^3 d^{-1}]
k_{aT} = areal rate coefficient at temperature T [m d^{-1}]
Q = temperature coefficient [dimensionless]
T = temperature [^oC]

After rearrangement and introduction of logarithms, eqns (1) and (2) were combined into a linear equation:

$$log[(Q/A) * ln[(C_{in}-C*)/(C_{out}-C*)]] = \\ = log[k_{a20}] + log[Q] * (T-20) \qquad (3)$$

where k_{a20} and Q could be calculated from the regression coefficients to 0.021 m d^{-1} and 1.07, respectively, with an explained variance of $R^2 = 0.23$. As indicated by the temperature coefficient, removal of nitrogen varied with the season (Fig. 3).

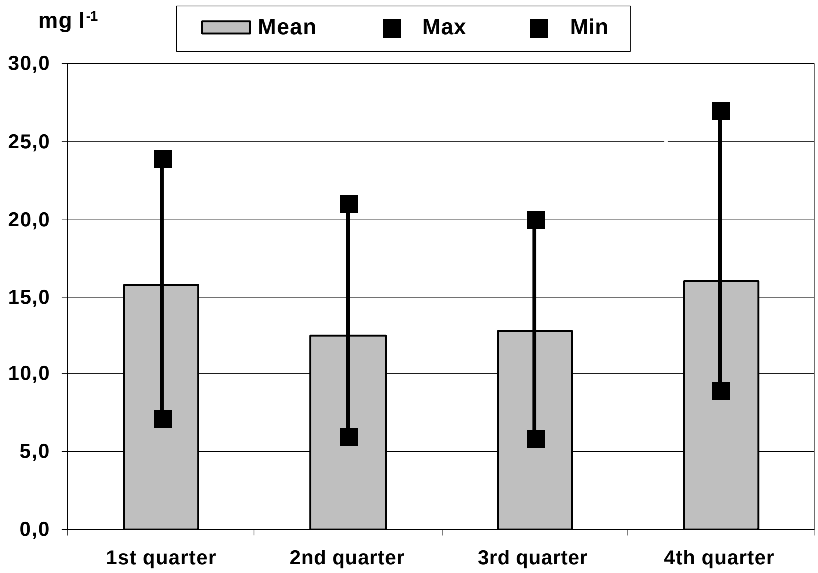

Figure 3: Average seasonal concentrations of total nitrogen in outgoing water from Wetland Oxelösund during 1994-98.

The trend in the difference between calculated removal and removal obtained from regression analysis (Table 2) indicates that differences in load or temperature were not a reason for the calculated increase in removal over the five years.

The improvement during the later years, comparing 1997-98 with 1996, may be explained by the reconstruction at the inlets, although only partly during

1997, when the reconstruction was done. The most apparent change over the years, however, was the development of the vegetation. The increase in removal efficiency might therefore be a result of increasing macrophyte production and litter accumulation, which could have increased the surface area suitable for cation exchange and nitrification of NH_4^+. We considered this as a likely explanation since the absence of nitrate in the inflow, and the low concentrations in the outflow, strongly suggested that nitrification was the limiting step for nitrogen removal. Consequently, we did experiments to study the potential for nitrification in more detail (discussed further in the next section).

The rate coefficient (k_{a20} = 0.021 m d^{-1}) obtained from regression is of limited interest since the equation used (eqn (1)) did not take into account, e.g., the particular hydrological regime of the Oxelösund wetland, but rather assumed plug flow conditions, which were obviously not at hand. For the purpose of analyzing the suspected trend in annual nitrogen removal, this simplification was considered fair. For a more detailed analysis of the data, however, we made a model which took the hydrological regime into account, and also included different nitrogen transformation processes (Kallner & Wittgren [9]).

The amount of incoming phosphorus to the WWTP during 1994 was 8.7 tons. In 1998 it had decreased to 7.1 tons, due to both a decreasing population and increased use of non-phosphate detergents. The removal efficiency in the WWTP was approximately 90%, and the phosphorus load on the wetland averaged only 29 kg ha^{-1} $year^{-1}$ during 1994-98. The removal in the wetland averaged 25 kg ha^{-1} $year^{-1}$ which brought concentrations in outgoing water (Table 1) down to values far below the limit of 0.5 mg l^{-1} set by the authorities.

A large fraction of BOD in raw wastewater was removed in the WWTP, and additional removal took place in the wetland (Fig. 4). The amount of incoming BOD to the treatment plant gradually decreased, as a consequence of the decreasing population in Oxelösund. The observed increase in amount during 1998 is probably due to an artefact; in 1994-97 analyses were done on fresh samples but in 1998 frozen samples were used. The relative removal efficiency of the WWTP was, however, relatively constant at approximately 80%.

During 1994-1998, the annual load of BOD to the wetland averaged 1 700 kg ha^{-1} $year^{-1}$ and the removal in the wetland averaged 1 400 kg ha^{-1} $year^{-1}$. As for phosphorus, the wetland brought concentrations in outgoing water (Table 1) down to values well below the discharge limit set for the Oxelösund municipal treatment facility: 15 mg l^{-1} as an average for a quarter of a year. The wetland removal of BOD did not show significant temperature dependence (Wittgren & Mæhlum [14]), but some seasonal variations did occur due to high loads of organic matter in snowmelt from the catchment area.

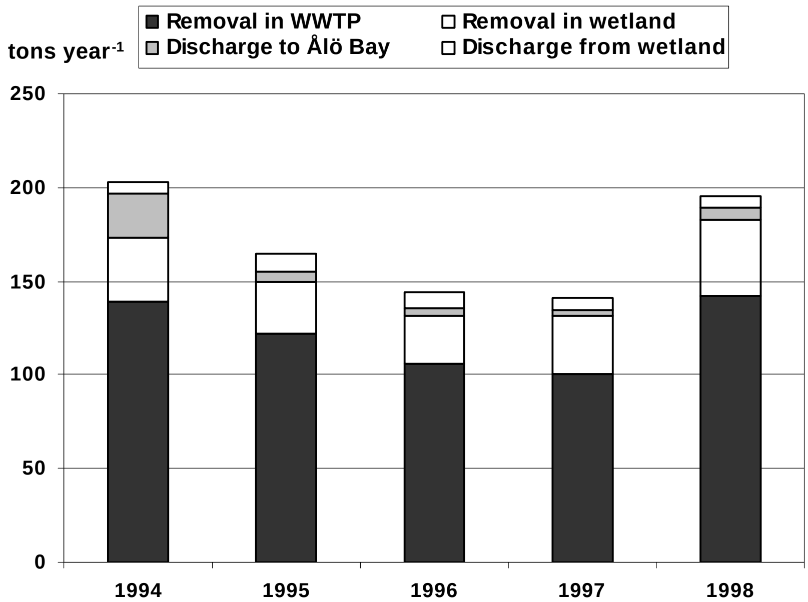

Figure 4: BOD budgets for Oxelösund municipal wastewater treatment facility 1994-98. The diagram illustrates removal of BOD_7 in the WWTP and the wetland, as well as discharge from the wetland and direct discharge from the WWTP to the old receiving water, the Ålö Bay.

6 Removal processes for nitrogen and phosphorus

Results from the first year of operation indicated that nitrification was a limiting step for nitrogen removal in the wetland (Wittgren & Tobiason [15]). A lack of suitable surfaces for cation exchange and nitrification of NH_4^+ was suggested as a possible reason. Plant litter provides a large fraction of the suitable surface area in emergent macrophyte wetlands, and scarcity of decaying plant matter in newly created surface-flow wetlands could thus limit coupled cation exchange and nitrification. It might also be the case that specific macrophyte species, e.g. *Typha latifolia*, which were particularly dominant during the first years of operation, are not suitable substrates for attachment of nitrifying bacteria.

In June 1996, a study was made to investigate possible species-related differences in cation exchange capacity (CEC) and potential nitrification at surfaces of emergent macrophyte litter (Eriksson & Andersson [4]). Litter from four different plant species, *Scirpus sylvaticus* L., *Carex rostrata* Stokes., *Equisetum fluviatile* L. and *Typha latifolia* L. was sampled in pond S2 and measured for CEC and potential NH_4^+ and NO_2^- oxidation.

The results showed that both CEC and nitrification were highest at surfaces of *S. sylvaticus* and *C. rostrata*. On the other hand, *E. fluviatile* showed both the lowest CEC and the lowest nitrification. Although CEC at the litter surfaces was not directly correlated to the activity of the nitrifying bacteria, the results indicated that CEC may have beneficial effects on the nitrification process. For *T. latifolia*, relatively high CEC but low potential nitrification indicated that litter from this species was not a good substrate for nitrifiers. This may be due to a low amount of nitrifiers, owing to competition from heterotrophic bacteria, using the easily decomposable *T. latifolia* as an energy source (Eriksson & Andersson [4]). Hence, a proper selection and management of emergent macrophytes may enhance NH_4^+ removal efficiency in wastewater treatment wetlands.

To gain more information about phosphorus retention - where phosphorus had been retained and in which forms - samples from the wetland sediments were taken in the autumn of 1996 (Gunnarsson [5]). A chemical fractionation method was used to analyze the sediment samples.

The investigations showed that the main part of the incoming phosphorus was deposited at the inlet of the wetland. As much as 97% of the wastewater phosphorus content was in particulate form, and the most dominant fraction in sediment samples close to the inlet was aluminum-bound phosphorus, which had its origin in the chemical treatment of phosphorus with aluminum sulfate in the WWTP (Gunnarsson [5]). A peak of iron-bound phosphorus was found in the inlet of the pond N2; at the outlet from the last pond, SN3, calcium-bound phosphorus was the dominating fraction in sediments.

Sedimentation and accumulation of sediments rich in phosphorus was restricted to a relatively small area close to the inlet. At the inlet of pond N1, the concentration of phosphorus in the sediment was approximately 45 mg P (g ash-free dry weight)$^{-1}$, comparable with the concentrations found in sludge from the chemical precipitation step in the WWTP. To avoid resuspension of phosphorus, regeneration of the sedimentation area was recommended. This would also generate fresh sorption sites for phosphorus. Partly as a consequence of the study, the wetland inlet was reconstructed in 1997, as described above, with the addition of a common sedimentation pond at the inlet from which sludge is removed annually.

7 Removal of indicator organisms and hygienic risk assessment

The hygienic aspects on the use of constructed wetlands for wastewater treatment are similar to those for conventional treatment plants or discharge from such facilities. In a treatment wetland, however, the wastewater is more or less undiluted. As the wetland in Oxelösund is meant to attract both wildlife and visitors, there is a larger risk of exposure to pathogens than in most conventional facilities. The possible transmission of infections to and by wildlife, as well as potential public health implications, is thus of concern. For these reasons two studies were performed in the Oxelösund wetland, where occurrence and removal of indicator microorganisms in both sediments and the open water bodies were analyzed (Wittgren et al. [16], 1996; Carlander [2]).

Factors reducing pathogens in wetlands are not well documented and are based mainly on occurrence of coliform bacteria (Carlander [2]). In Oxelösund, fecal indicator bacteria such as presumptive *E. coli* and fecal streptococci, as well as highly resistant spores of sulfate-reducing Clostridia, were analyzed. As a viral indicator, somatic coliphages were included (Wittgren et al. [16]. The results from the studies made by Wittgren et al. [16] and Carlander [2] both indicated efficient removal of fecal indicator microorganisms from the inlet to the outlet of the wetland, in particular for *E. coli* and fecal streptococci.

Removal of sulfate-reducing clostridia and somatic coliphages was less efficient (Fig. 5). The survival of indicator organisms is generally higher at low water temperatures. However, results from November 1995 and 1997 showed no significant decrease in reduction when compared with the results from the summer period. This indicated that sorption and sedimentation might be more important than biological processes for removal of microorganisms from the water body (Carlander [2]).

In addition to the indicator microorganism studies, hygienic risk was addressed by monitoring of pigs and Highland Cattle held in an enclosed area bordering the wetland, with the wetland as the sole drinking water source. In October and November 1995, two pigs were held in a 0.5 ha area bordering the channel between pond S2 and SN3. The pigs were fed with conventional fodder. Feces samples were taken on two occasions and after the pigs were slaughtered, autopsies were carried out at the Swedish National Veterinary Institute (SVA).

During the summer of 1996, three pigs and three head of Highland Cattle were kept in the same area. Feces samples were taken repeatedly and in October autopsies were carried out on the pigs at SVA. In addition, feces from two roe deer killed adjacent to the wetland was analyzed in January 1996.

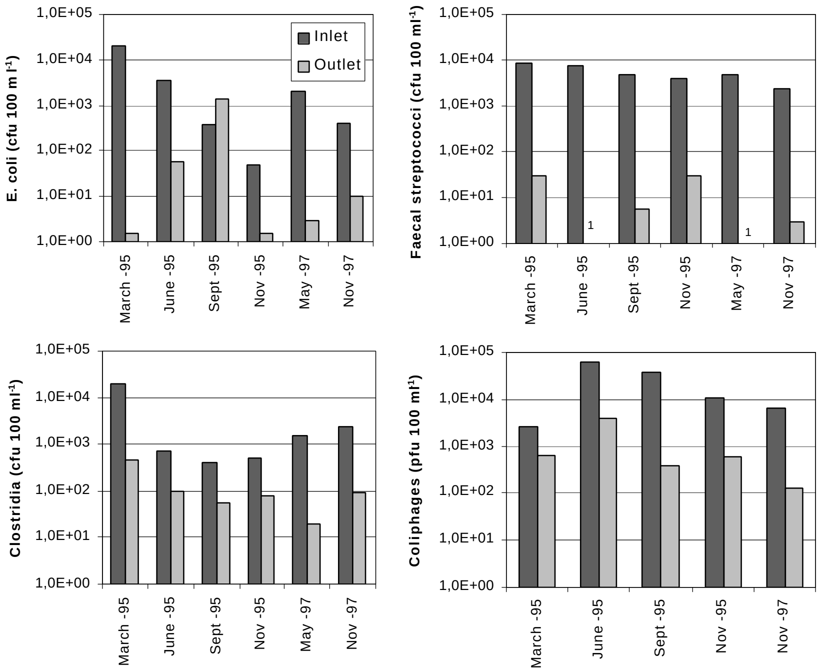

Figure 5: Removal of indicator microorganisms in Wetland Oxelösund, based on Wittgren et al. [16] and Carlander [2]. Dark gray bars represent concentrations in incoming water to pond N1 and light gray bars concentrations in outgoing water in pond SN3. The high concentration of *E. coli* in pond SN3 in September 1995 was probably due to contamination of samples by swan feces.

Neither the pigs nor the cattle showed any health disturbances during or after the pasture seasons. Also, both the analyses of the feces and the autopsies showed that the animals were in good health. The analyses of the feces from the roe deer showed normal levels of coccicidia and intestinal parasites and no salmonella. The only suspected negative health effect of the treated wastewater was the discovery of intestinal parasites, *Endamoebidae* spp*.*, in the pigs. It is possible that this infection (usually not pathogenic for humans and pigs) could have come from the treated wastewater in the wetland.

8 Observations of vegetation and birdlife development

The vegetation development was monitored both quantitatively and qualitatively. Only qualitative observations are reported here since the quantitative results have not yet been evaluated. The development of the birdlife in the wetland was monitored during 1994-96.

As a result of the broadcast sowing of seeds during the first season, cattail (*Typha latifolia*) emerged in all impounded areas where the soil had been left bare after the construction work. Germinating seeds of common reed (*Phragmites australis*), on the other hand, were very weak in their early stages. Practically all reeds died off during the first season as a consequence of drying, flooding or competition from other species. Dense reed-stands that currently cover some areas, especially in pond S1, are the offspring of shoots that were cultivated from seeds in a greenhouse.

Spreading of wild picked seeds from different species resulted in extensive stands of *Typha angustifolia*, *Iris pseudacorus*, *Scirpus lacustris* and *Carex pseudocyperus*.

Transfer of soil/root/shot clumps was successful, but only when the clumps were spread on bare soil, i.e., where the soil had been prepared by tilling and flooding. A prerequisite for success was that the soil clumps were protected from drying by a balanced filling and emptying of the ponds during the establishment period. With regard to the soil clumps, species belonging to a mature wetland ecosystem were introduced, such as some small sedges, rushes and *Ranunculus* species. The *Glyceria maxima* introduced in pond N2, also by means of soil clumps, rapidly formed a dense mat of vegetation.

In addition to the vegetation that resulted from the active structure-promoting establishment, it was interesting to observe the growth of plants that very likely had their origin in dormant diaspores of the soil. Even in the fields which had been used for agricultural purposes for at least the last 50 years, species such as *Juncus bufonius*, *Juncus effusus* and *Alisma plantago-aquatica* started to grow.

Since the cattail stands became very dominating, efforts to hold them back were tested during the third year of operation. Crushing of the root systems, using a tractor, turned out to be an effective method of diminishing the cattail stands. In areas not accessible for heavy vehicles, cutting the stems below the water table turned out to be a successful method for favoring other wetland species. A self-regulating mechanism was also observed after some years of operation, when an insect, the bulrush wainscot (*Nonagria typhae*), infected the cattails. As a consequence of both artificial and natural stress, the previously uniform stands of cattails gave room to other species, especially *Carex riparia* and bulrush (*Scirpus lacustris*).

Submerged plant communities were much simpler to introduce than the emergent vegetation. In channels and ponds, *Elodea canadensis, Potamogeton filiformis* and other *Potamogeton* species rapidly developed from small amounts of introduced “mother plants”. Spontaneous establishment of seeds transferred by birds was probably also an important part of the development of the now quite diverse submerged vegetation. The introduction of flowering or in other aspects special species, for example *Stratiotes aloides, Sagittaria sagittifolia, Calla palustris* and different species of *Nuphar* has promoted variety and diversity.

The development of the birdlife in the wetland during 1994-1996 showed an increase in both numbers of breeding pairs and number of species (Hägermark & Martinsson [7]). The birds breeding in the wetland were common species typical of natural wetlands in Sweden. Lack of larger open waters probably makes the wetland less valuable for more demanding birds such as waders. The occurrence of, for example, garganey (*Anas querquedula*) in recent years indicates that the wetland has developed into a valuable site for some rarer birds too.

9 Valuation of the wetland and effects on recreation

In 1994 a study was made to measure the societal value of the wetland in Oxelösund using the contingent valuation (CV) method (Cravener [3]). As a prerequisite for use of this method, a hypothetical market for the environmental good in question is set up, creating an incentive for consumers to reveal their preferences. In a survey consumers are then asked for their willingness to pay (WTP) for the ecological services provided, or how much compensation they would request for an improvement or degradation in the quality (willingness to accept, WTA) of the environmental services from, in this case, the wetland.

The study in Oxelösund was primarily aimed at secondary benefits of the wetland, e.g., increased possibilities for recreation and increased biodiversity, rather than its function as a nitrogen sink. Therefore, a scenario was suggested where the wetland did not fulfil the nitrogen removal requirements, and its existence was threatened. The citizens of Oxelösund were then asked how much they would be willing to pay to preserve the wetland.

The results showed that the average citizen was willing to pay SEK 170-370 as a single-time payment to preserve the wetland and its plant and animal life. This corresponded to approximately SEK 1.7-3.7 million for the whole town, based on a population of 10 000. This willingness to pay may be compared to the costs for construction of the wetland, approximately SEK 2.7 million (excluding the pipe from the WWTP to the wetland, for which costs amounted to SEK 2.3 million). The contingent valuation method, however, has some weaknesses, with the hypothetical situation perhaps being the most important one, since in reality the consumer does not have to pay for the ecological services (Cravener [3]).

When constructed, the wetland soon became an attraction as an example of a new approach to wastewater management. A large number of environmental professionals and politicians have visited the wetland, and it has also been used for education of school children. Most local people, however, come to the wetland for recreation. An investigation among the resident people in Oxelösund showed that the wetland is a popular site for excursions.

10 Conclusions

Nitrogen removal in Wetland Oxelösund has improved throughout the first five years of operation and the treatment facility as a whole, including the wastewater treatment plant, now fulfils the 50% nitrogen removal requirements. In comparison with preliminary international design criteria, however, the nitrogen removal appears to be quite low and it is obvious that the nitrification process is the limiting step.

One of the factors that influence nitrification, the availability of suitable surfaces for cation exchange and nitrification, has been studied in some detail. The study indicated that the accumulation of plant litter and the gradual change in vegetation composition during the first years after establishment probably played a role in the increased nitrogen removal. Vegetation design, i.e., choosing species able to promote different biological processes, should therefore be considered an important part of the planning and design process.

The observations on phosphorus removal has led to the conclusion that wetlands, when used as a complement to conventional treatment plants, can be used for process optimization and decreased operation costs. Efficient secondary sedimentation takes place in the sedimentation pond of the wetland, and when sludge is removed from the pond it can easily be treated in low-technology sludge stabilization ponds adjacent to the wetland. This has decreased the overall energy consumption of the treatment facility in Oxelösund.

Monitoring showed efficient removal of some indicator organisms, and pigs and Highland cattle kept adjacent to the wetland showed no health disturbances. These were positive results, but hygienic issues still have to be taken seriously, especially when a treatment wetland is intended for and, as is the case in Oxelösund, actually used for recreation. Zoning based on hygienic criteria may be a feasible strategy. The reconstruction of the inlet in 1997, when the inlet and the associated sedimentation pond was located to an area not accessible to the public, was a first measure towards adopting such a strategy.

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