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Free water surface wetlands for wastewater treatment in Sweden – nitrogen and phosphorus removal

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Abstract

In South Sweden, free water surface wetlands have been built to treat wastewater from municipal wastewater treatment plants. Commonly, nitrogen removal has been the prime aim, though a significant removal of tot-P and BOD_7 has been observed. In this study, performance data for 3 – 8 years from four large (20 – 28 ha) FWS wetlands have been evaluated. Two of them receive effluent from WWTP with only mechanical and chemical treatment. At the other two, the wastewater has also been treated biologically resulting in lower concentrations of BOD_7 and $NH4^+$-N.

The wetlands performed satisfactorily and removed 0.7 - 1.5 ton N ha^{-1} yr^{-1} as an average for the time period investigated, with loads between 1.7 and 6.3 ton N ha^{-1} yr^{-1}. Treatment capacity depended on the pre-treatment of the water, as reflected in the k_{20}-values for N removal (first order area based model). In the wetlands with no biological pre-treatment, the k_{20}-values were 0.61 and 1.1 m $month^{-1}$, whereas for the other two they were 1.7 and 2.5 m $month^{-1}$. P removal varied between 10 and 41 kg ha^{-1} yr^{-1}, and was related to differences in loads, P speciation and to the internal cycling of P in the wetlands.

Keywords
Chemical precipitation; FWS wetlands; nitrogen removal; phosphorus removal; wetland design

INTRODUCTION

During the 1990´s, a lot of effort has been undertaken in the Scandinavian countries to reduce the load of nitrogen to coastal waters. Free water surface (FWS) wetlands are perceived as a cost-efficient method of achieving nitrogen removal in both wastewater and water draining from agricultural areas. A number of wetlands have for example been constructed in the 90´s with the main aim of removing nitrogen from wastewater treated in conventional wastewater treatment plants (WWTP). Design and operation conditions vary considerably between the wetlands, but satisfactorily results for nitrogen removal have been achieved already in the first years of operation (Andersson et al., 2000; Linde & Alsbro, 2000).

Considerable efforts have been put on developing design models for treatment wetlands, and a common approach has been the use of first order kinetics and a plug flow assumption (Kadlec & Knight 1996). Arheimer & Wittgren (2002) used data from 8 small wetlands receiving non-point source effluents and found a considerable variation in performance, as estimated by the first order volume based rate coefficient. Generally, it is thought that the performance of wetlands receiving sewage at a fairly constant load is more predictable than for wetlands receiving water from non-point sources with varying flows and concentrations. However, the use of the simple first order rate model with plug flow assumption has demonstrated a considerable variation in treatment capacity of wastewater treatment wetlands (Kadlec & Knight, 1996). For example, the mean k_{20} value for nitrogen removal in FWS wetlands was 22 m yr^{-1}, but it spanned from 0.6 to

50 m yr^{-1}. As our understanding of the nature of wetlands has grown, more and more emphasis has been put on the importance of wetland hydraulics for the treatment results and the simple model based on plug flow assumption has been increasingly criticized (*e.g.* Kadlec, 1999b). The importance of designing wetlands to achieve as high hydraulic efficiencies as possible is now recognized. A better description of the hydraulic properties of treatment wetlands will certainly contribute to better design models.

Apart from the hydraulic properties, some of the variation in performance results for different wetlands can also be attributed to ecosystem characteristics. Kadlec (1999a) using data from various treatment wetlands pointed out the cyclic nature of wetland nutrient processing, and that temperature alone does not account for this seasonal changes. Plant species and growth patterns are certainly an important component of such cycles due to the direct nutrient uptake. But the plant community composition and growth dynamics also have important indirect effect through photosynthesis, biomass death and decomposition, which have profound impact on the physical and chemical environment in a wetland. Significant differences in nitrogen removal between wetland dominated by different plant species have been demonstrated (Bachand & Horne, 2000). Thus a better understanding of the quantitative impact of plant community composition on overall wetland nutrient removal capacity is much needed.

Aim of the study

The purpose of this paper is to evaluate the nitrogen and phosphorus removal performance of four large (20 – 28 ha) FWS wetlands receiving effluent from conventional WWTP with varying degree of pretreatment. Since a lot of literature information exist on first order rate constants from various parts of the world, this simple model has been used for comparative purposes. Results are compared and discussed in view of differences in design, plant cover and wastewater pretreatment.

METHODS

Four wetlands situated in South Sweden were selected for this study. Those were, in order from south to north, Magle in Hässlehom, the wetland in Oxelösund, Ekeby in Eskilstuna and Alhagen in Nynäshamn, south of the capital Stockholm. Two of the wetlands, Magle and Ekeby, receive wastewater that has been treated both biologically and chemically, whereas the other two receive effluent from a WWTP with only chemical treatment and settling. Consequently, the inflow water to the latter wetlands contains more BOD_7 and NH_4^+-N than for the other two (Table 1).

Magle wetland was constructed in 1995 with the prime aim to reduce the P load to the downstream eutrophic lake. It consists of an inflow basin from which the water is distributed to four parallel basins and subsequently collected in an outflow channel, in total a wet area of 20 ha. The average depth is 0.5 m but each basin is subdivided in three sections starting with a deeper part to redistribute the water and favor anaerobic conditions and denitrification. A more detailed description is found in Kallner and Wittgren (2001). Most of the wetland basins are dominated by the submerged macrophytes *Elodea candensis* and *Myriophyllum spicatum*, mixed with large stands of filamentous green algae.

Oxelösund wetland was created in 1993 and has been described in detail by Andersson et al. 2001 and Wittgren & Tobiason, 1995. Briefly, it covers 23 ha and consists of two parallel systems (South and North) with two basins each, emptying to a joint final basin which is always flooded. Each system is currently filled up during 2 –3 days followed by draining during an equal time period to ensure utilization of the whole wetland area and to favor nitrification followed by denitrification. All basins are dominated by emergent macrophytes, mainly *Typha latifolia*. In deeper sections and in the channels connecting the basins, large stands of submerged plants such as *Elodea canadensis* and *Potamogeton sp*. are found.

Ekeby wetland has been in operation since 1999, and is operated from May to December each year. From an inlet channel, the effluent from the WWTP is distributed to five parallel basins and subsequently to a collecting channel from which the water is distributed to another set of three parallel basins (Linde & Alsbro, 2000). The flooded area covers 28 ha with a mean depth of 1 m. About 20 % of the basins have been covered by emergent macrophytes, e.g. *Glyceria maxima* and *Typha sp*., with various submerged species and filamentous algae in the remaining areas.

Wetland Alhagen was constructed in 1997 and covers 28 ha including an overland flow area. From an inflow basin, the water is alternately fed to two parallel ponds with fluctuating water levels. After passing through two wetland basins in series, the water is intermittently (2 d intervals) distributed to a 2 ha overland flow area from which it is collected in a collection pond and passes through a channel to two shallow fens, where it is mixed with stormwater and flows to the Baltic Sea (Andersson & Kallner Bastviken, 2002). During 1999 – 2001, the wetland received wastewater only in April – December each year. In the first wetlands, the plant community is dominated by emergent species such as *Phragmites australis*, *Typha sp.* and *Carex riparia*. Downstream the overland flow area, large stands of *Elodea canadensis* and *Ceratophyllum demersum* are observed. In the final wetland, various *Carex* species are predominant.

Data on water flow and quality were obtained from the monitoring programs of the respective municipalities or companies operating the wetlands. Water flow has been measured both at the inlet and outlet of the wetlands, except Ekeby where the outflow has been set equal to inflow. Water samples for quality analyses have been collected weekly or biweekly.

Table 1. Inflow water quality and hydraulic loads of four large FWS treatment wetlands in South Sweden (n.d. = not determined). Data from Andersson & Kallner Bastviken, 2002.

Wetland	Magle	Ekeby	Oxelösund	Alhagen
Time period	1995 – 2001	1999 - 2001	1994 – 2001	1999 - 2001
Total wet area, ha	20	28	23	28
Hydraulic load, mm d^{-1}	57	155	21	17
Detention time, d	7 – 8	6 – 7	8	14
	mg L^{-1}			
BOD_7	2.4	5.2	22	38
Tot-P	0.15	0.23	0.40	0.37
PO_4^{3-}-P	0.11	0.12	n.d.	n.d.
Tot-N	20	20	23	37
NH_4^+-N	6	5	17	37

RESULTS AND DISCUSSION

The four wetlands received quite different hydraulic loads with the wetlands treating the wastewater with highest concentrations of nutrients receiving the lowest loads (Table 1). Because of design features, the detention time in wetland Alhagen was almost double that in wetland Oxelösund despite the similar hydraulic load. Ekeby wetland received the highest loads of all wetlands, but because of its depth, the detention time was almost the same as in Magle wetland.

Phosphorus and BOD_7 removal

BOD_7 removal was constant and stable over the years in all wetlands, with mean concentrations in the outflow varying between 3.9 (Oxelösund), 4.7 (Ekeby) and 4.8 (Alhagen and Magle). No significant temperature dependency was observed in the data series (see also Andersson *et al.*, 2000). The concentrations in Magle were actually increasing from inlet to outlet, suggesting that the background concentration of BOD_7 in Swedish treatment wetlands would be 4 – 5 mg L^{-1}.

All the four wetlands had an efficient removal of tot-P, varying from 10 – 41 kg ha^{-1} yr^{-1} (Table 2) with the concentrations in the outflow well below the required levels (0.3 or 0.5 mg L^{-1}). The relative efficiency varied between the wetlands, with Magle removing about 30 % of the load and Oxelösund removing up to 90 %. This was mainly related to the difference in inflow concentrations and composition, with Oxelösund and Alhagen receiving water richer in tot-P, but also to different internal processes dominating the removal. In a study of Oxelösund wetland, it was shown that the main part of the inflow phosphorus settled close to the inlet of the wetland (Gunnarsson, 1997; Andersson *et al.*, 2000), and it is likely that this was also the case for wetland Alhagen receiving wastewater of similar quality. A recent short-term tracer study in Ekeby wetland indicated that also in this wetland a substantial fraction of P in suspended solids in the inflow water accumulated in the bed sediment in the first shallow zone at the inlet. It is likely that the phosphorus precipitation continues in the wetland with residues of the chemicals used in the WWTP. The use of precipitation chemicals based on Al would be preferable since that reduces the risk for P being released again from the sediments.

Table 2. Concentrations in outlet water, and removal of tot-P and tot-N in four large FWS treatment wetlands in South Sweden. Data from Andersson & Kallner Bastviken, 2002.

Wetland	Magle	Ekeby	Oxelösund	Alhagen
Time period	1995-2001	1999-2001	1994-2001	1999-2001
	mg L^{-1}			
Tot-P in outflow	0.11	0.10	0.04	0.12
Tot-N in outflow	14	15	15	11
	kg ha^{-1} yr^{-1}			
Tot-P load	33	77	30	17
Tot-P removal	10	41	27	12
Tot-N load	4200	6300[1]	1700	1600[1]
Tot-N removal	1200	1500[1]	700	1100[1]

[1]Annual load and removal has been calculated for the operation period only.

In contrast, Magle wetland receives water which has been filtered in the WWTP and contains predominately PO_4^{3-}- P (Table 1). Thus, the removal depends entirely on internal cycling of P in the wetland, where uptake in filamentous algae and submerged plants account for an important part during the growing season. Plant harvesting biannually is thought to be an important management strategy to maintain the P removal capacity of the wetland. Interestingly, the P removal in Magle was 1 g m^2 yr^{-1}, which has been suggested to be the loading threshold level below which the outflow P concentrations can remain very low (Richardson et al. 1997). According to these authors, the long-term accumulation rate (due to organic matter accumulation) is exceeded when the load is higher. Since only part of the added P can be stored via sediment accretion, the rest remains in the water phase and outflow concentrations remain elevated. In fact, data from Magle wetland may support this hypothesis.

When comparing the two wetlands receiving wastewater with the highest concentrations, Oxelösund and Alhagen, a larger variation in the outflow concentrations was observed in the outflow from Alhagen with higher concentrations in the middle of the growing season (fig. 1). This might be attributed to a release of stored P from the sediments in the last wetlands as anaerobic conditions might develop during the warm season.

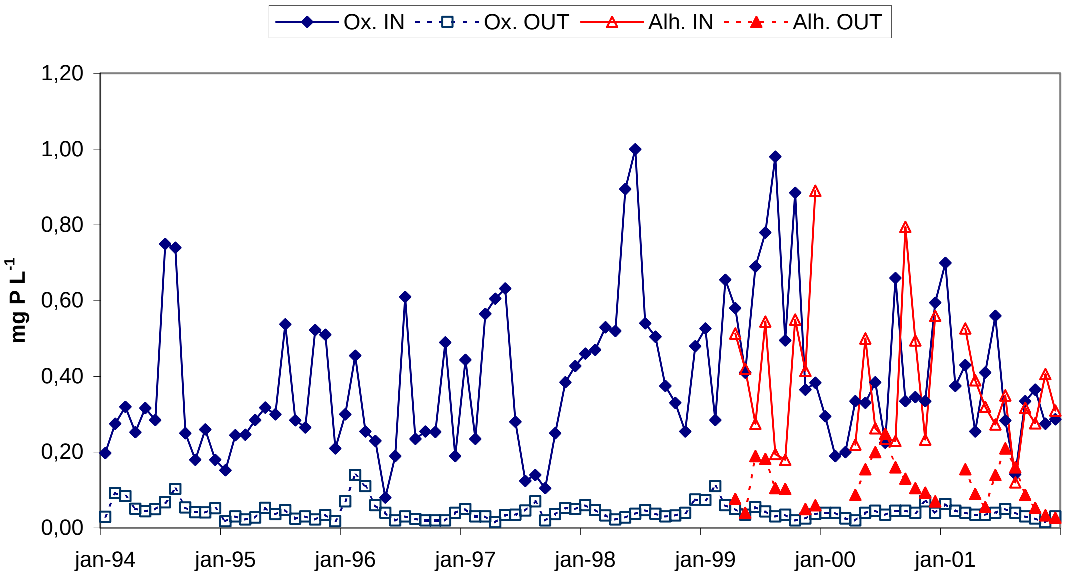

Figure 1. Inflow and outflow concentrations of tot-P in the FWS wetlands in Oxelösund and Alhagen, Nynäshamn, receiving chemically treated municipal wastewater.

Nitrogen removal

Concentrations of tot-N in the outflow from the four wetlands were 15 mg L^{-1} or below, which is the demand from authorities in Sweden. The area specific removal was highest in the Magle and Ekeby wetlands, which also received the highest loads of nitrogen and water containing predominantly nitrate-N which favor denitrification (Table 2). In Magle and Oxelösund which are operated throughout the year a clear seasonal variation was observed (Fig. 2; Andersson et al. 2000). Part of the differences in nitrogen removal between the wetlands can be attributed to different inflow concentrations and hydraulic loads. To eliminate some of those effects and facilitate an evaluation of the inherent nitrogen removal capacity of the different wetlands, a first order area based equation with temperature correction was adapted to the data sets (Kadlec & Knight, 1996):

$$\frac{C_{out}}{C_{in}} = e^{\left(-\frac{k \cdot A}{Q}\right)} \qquad \text{and} \qquad k = k_{20} \cdot 1.08^{(T-20)}$$

where C_{in} and C_{out} are the mean annual concentrations of inflow and outflow (mg L^{-1}), A is the wetland area (m^2), Q is the mean water flow (m^3 yr^{-1} or m^3 $month^{-1}$), k is the rate coefficient (in m yr^{-1} or m $month^{-1}$), k_{20} is the temperature corrected rate coefficient (in m yr^{-1} or m $month^{-1}$) and T is the air temperature (^{o}C).

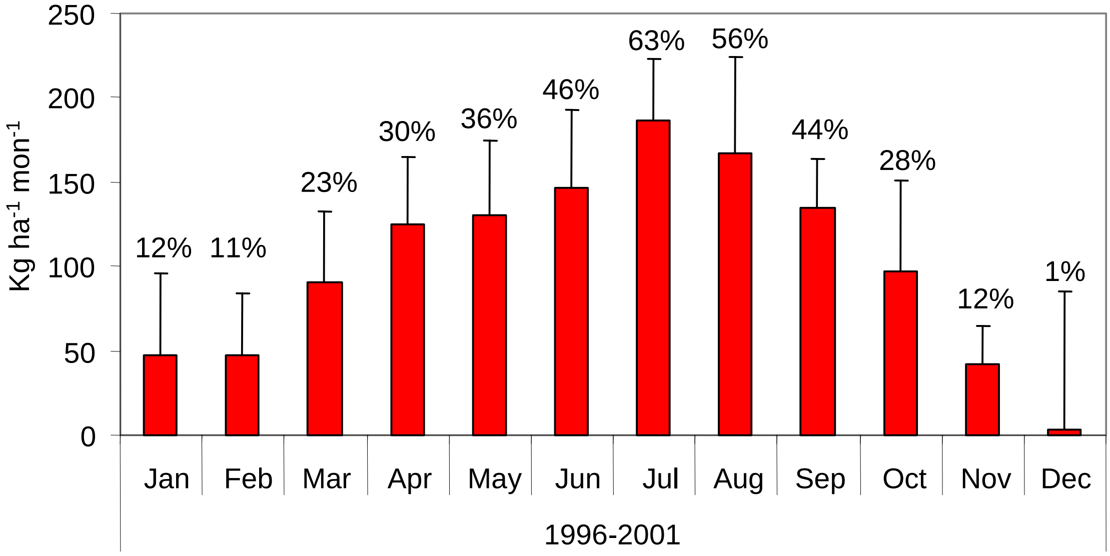

Figure 2. Seasonal variation in area specific and relative tot-N removal in the FWS wetland Magle receiving biological and chemically pretreated wastewater from Hässleholm municipal wastewater treatment plant. Error bars denote std error. (From Andersson & Kallner Bastviken, 2002).

Further, to be able to compare the wetland nitrogen removal rate coefficients, only the period May – October was used, when all wetlands had been in operation. Clearly, Ekeby had a higher removal constant than Magle, and Alhagen had a higher removal coefficient than Oxelösund (Table 3).

Table 3. Rate removal coefficients (m month^{-1}) using the first order area based temperature dependent model for nitrogen removal in four FWS treatment wetlands in South Sweden. Data for the months May – October have been used.

Wetland	Magle	Ekeby	Oxelösund	Alhagen
Time period	1995 – 2001	1999 – 2001	1994 – 2001	1999 - 2001
Rate coefficient, k_{20}	1.7	2.5	0.61	1.1

The higher removal rate in Ekeby *versus* Magle may be related to a higher hydraulic efficiency in Ekeby. A tracer study in Magle revealed hydraulic short-comings with dead zones and shortcircuiting in one of the basins studied (Persson, in press). Similar misplacements of islands can not be observed in Ekeby wetland suggesting that it might have a better hydraulic efficiency. Another contributing factor can be the fact that Ekeby is a deeper wetland, which favor development of anaerobic zones. In addition, oxygenation of the water column through photosynthesis may counteract denitrification processes during a large part of the year in the shallow basins in Magle wetland. The plants are also regularly harvested, which means that organic matter that would be an important energy source for denitrifying bacteria is removed. In Ekeby, there were proportionally larger areas with emergent macrophytes and they were not harvested. Hence there was potentially more organic matter available for the denitrifying bacteria. Other studies have shown that denitrification in wetlands receiving high loads of nitrate can indeed be limited by the availability of organic matter (Kozub and Liehr, 1999).

When comparing the two wetlands receiving wastewater rich in ammonium, there is a striking difference between the two, with a 50 % higher removal rate constant in Alhagen. Despite the relatively low load, wetland Alhagen removed almost as much nitrogen per area as Magle wetland, and reached a record 70 % relative removal for the operational period. Oxelösund removed only about 40 % of the same load. Apart from one quarter in 2000, the wetland provided more than 50 % removal of nitrogen with little seasonal changes (Fig. 3), contrasting to what has been observed in other wetlands (e.g. Kallner & Wittgren, 2001; Andersson et al., 2000).

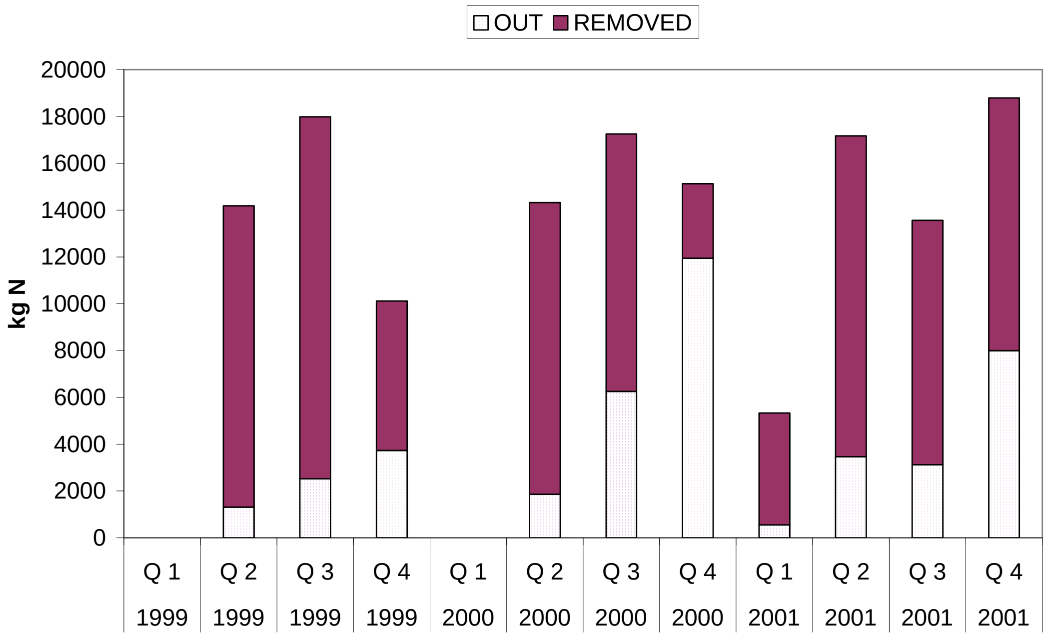

Figure 3. Quarterly load, removal and outflow of tot-N at wetland Alhagen, Nynäshamn, receiving chemically treated municipal wastewater. Total area of the wetland system is 28 ha. The data for quarter 1 in 2001 are from March only.

One hypothetical explanation for this is that the 2 ha overland flow area contributed to the higher removal in Alhagen by promoting efficient nitrification. In a summer study, it was shown that the concentrations of NH_4^+-N in the water had dropped by about 8 mg L^{-1} after passing that area (af Petersens, 1999). In addition, campaign measurements have shown that most of the BOD_7 is reduced in the first two wetland basins and that oxygen concentrations increases rapidly in the subsequent overland flow area. Along with this, there is commonly an increase in NO_3^--N concentrations suggesting on-going nitrification (unpublished data). Since nitrification is the rate limiting process in the system, increased nitrification will support a high overall tot-N removal.

CONCLUSIONS

The removal capacity of nitrogen and phosphorus depended on pre-treatment, load, and wetland specfic factors such as hydraulic efficiency, oxygen concentrations and organic matter (which in turn depend on depth, design and vegetation). We conclude that FWS wetlands can successfully treat wastewater from municipal wastewater treatment plants and that these factors are important to consider when constructing such wetlands.

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