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# Effects of vegetation and hydraulic load on seasonal nitrate removal in treatment wetlands

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ABSTRACT

Optimising nitrate removal and identifying critical factors for nitrate removal in wetlands is an important environmental task in the effort to achieve better surface water quality. In this study, eighteen free water surface wetlands with similar shape and size (22 $m^2$ each) received groundwater with a high nitrate-N concentration (about 11 mg $l^{-1}$). The effects of two hydraulic loads, 0.13 m $d^{-1}$ and 0.39 m $d^{-1}$, and three vegetation types – emergent, submersed and freely developing vegetation – on the nitrate-N removal were investigated through mass inflow and outflow measurements.

No significant difference in nitrate removal between the different hydraulic loads could be detected. Significantly higher area-specific nitrate removal and first-order area-based rate coefficients were found in the basins with emergent vegetation, with no difference between the basins with submersed and freely developing vegetation. The nitrate-N removal increased as the wetlands matured and the vegetation grew denser, emphasizing the role of dense emergent vegetation for nitrate removal at high nitrate concentrations.



## 1. Introduction

Constructed wetlands are frequently established to reduce the nitrate transport from diffuse sources to the sea. Besides changes in agricultural management, wetlands are thought to be cost-efficient measures to reduce the nitrate transport (e.g. Turner et al., 1999; Prato and Hey, 2006). But the efficiency of the nitrate removal in wetlands is variable (Kadlec, 2005) and difficult to accurately predict. Several model approaches have been used to describe the fate of nitrate in a wetland (e.g. Arheimer and Wittgren, 2002; Braskerud, 2002; Kadlec, 2005), but none is generally applicable as a good predictive model. To better predict and optimise wetland performance in the effort to achieve better water quality, identifying critical factors that limit nitrate removal in wetlands is an important task.

Denitrification is the main process that removes nitrate from the water in wetlands. It is a bacterial process where nitrate is transformed to nitrous oxide and dinitrogen gas by denitrifying bacteria. Denitrification occurs in anaerobic conditions, in the presence of nitrate and organic carbon. The bacteria are favoured by high temperature and attachment surfaces. Plants can supply denitrifying bacteria with organic carbon and suitable attachment surfaces (Weisner et al., 1994). They also promote the development of anaerobic conditions through litter accumulation and decomposition, which would favour denitrification. The presence of plants has been shown to enhance nitrate removal in field studies (Bachand and Horne, 2000). Toet et al. (2005b) found a higher nitrogen removal in wetland compartments with emergent plants than in those with submersed plants. Results from microcosm studies have shown that the potential for denitrification is specific for different plant species (Bastviken et al., 2005, 2007). In those studies, the denitrifying capacity in intact sediment cores from stands of *Glyceria maxima* and *Typha latifolia* were higher than for the submersed plant *Potamogeton pectinatus* in one wetland. On the other hand, the potential denitrification in intact sediment cores from stands of the submersed plant *Elodea canadensis* was higher than for *T. latifolia* and *Phragmites australis* in another wetland. Significant seasonal differences in the potential for denitrification were also observed (Bastviken et al., 2007).

Other factors that are critical for the wetland water treatment performance are the water flow and residence time. With a high hydraulic load, the denitrifying bacteria receive large amounts of nitrate. Studies have shown that wetlands receiving high hydraulic loads remove larger amounts of nitrate (kg $ha^{-1}$ $year^{-1}$) than those with low loads of water containing similar nitrate concentrations (Fleischer et al., 1994; Kadlec, 2005). Kadlec (2005) suggested that

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the nitrate removal per area is highest when the hydraulic load is so high that the difference between the inlet and outlet concentrations is minimal. In such situations, the precision in the analyses of total nitrogen and nitrate concentrations may be of significant importance for the observed removal when based on measurements of mass in- and outflow.

On the other hand, high hydraulic loads may also have a negative impact on the nitrate removal (Raisin and Mitchell, 1995; Spieles and Mitsch, 2000), e.g. through oxygenation of the sediment surface and resuspension of organic material. High oxygen concentrations would restrict denitrification to occur in the upper sediments rather than on plants, litter and other surface structures in the water column. Resuspension of organic material might result in substrate limitations for the denitrifying bacteria. Such occasional negative effects on the nitrate removal can have a very large influence on the annual removal balance (Spieles and Mitsch, 2000). Thus, it is important to identify the critical residence time, or hydraulic load, to obtain substantial nitrate removal. Arheimer and Wittgren (2002) suggested a critical mean residence time of 2 days to ensure a significant annual nitrogen removal in Swedish wetlands, based on inflow and outflow data from wetlands receiving hydraulic loads of 0.26–6.8 m d$^{-1}$. Braskerud (2002) observed no, or insignificant, nitrate removal in wetlands receiving hydraulic loads higher than 1.7 m d$^{-1}$. Similarly, Toet et al. (2005a) found positive total nitrogen and nitrate removal in wetland compartments with a residence time of 0.8 days, whereas the results with 0.3 days residence time were more variable with observations of both significant and insignificant nitrogen removal. Furthermore, the effect of hydraulic load may differ between wetlands depending on e.g. the dominant plant community and the shape of the basin, as those factors can affect the hydraulic efficiency of wetlands (Persson and Wittgren, 2003; Kjellin et al., 2007).

The purpose of this study was to investigate the effect of two critical factors, hydraulic load and vegetation type, on *in situ* nitrate removal. Two major hypotheses were tested: (1) significant nitrate removal would not be achieved at residence times below 2 days. (2) Nitrate removal will differ among the vegetation types, with highest removal in wetlands with emergent plants followed by submersed plants. Two different water flows and three different vegetation types (3 replicates) were used in 18 pilot scale wetland basins.

## 2. Methods

### 2.1. Site description

The study was performed in pilot-scale wetlands in Plönninge near Halmstad, Sweden (56°43′45″N, 12°43′33″E). The system was constructed in 2002 on heavy clay soil that was former agricultural land. It consisted of 18 wetland basins, that were dug out 1 m down to the mineral soil, with a rectangular shape, an area of 16 m$^2$ (2 m × 8 m) at the bottom and 40 m$^2$ at the ground surface and a side slope of about 1:1. During this study, the water surface area was set to about 22 m$^2$ with a mean water depth of 0.4 m in all wetlands. The experimental setup during this study was two different flows and three different vegetation types, which resulted in 3 replicate basins for each treatment.

Two different plant communities (emergent and submersed) were established in the wetland basins during May 2003, while one-third of the basins were left unplanted in order to achieve freely developing vegetation. In the basins with emergent vegetation, *P. australis* (Trin.), *G. maxima* (Hartm.) and *Phalaris arundinacea* (L.) were established. The basins with submersed vegetation were planted with *E. canadensis* (Rich.), *Myriophyllum alterniflorum* (DC.) and *Ceratophyllum demersum* (L.), and those also remained the dominant species. From 2004 to 2006, the remaining basins were gradually colonized by algae and higher plants, and were dominated by *Alopecurus geniculatus* (L.), *Agrostis gigantea* (Roth.) and *T. latifolia* (L.). The plant cover was investigated during late summer in 2004 and 2005, when the coverage of emergent and submersed vegetation was visually estimated in 10 equal subdivisions of each wetland basin, and expressed in percentage of the total basin area. The coverage of filamentous algae was estimated by counting the subdivisions in which more than 50% of the area was covered with algae.

Water samples were collected once every week or once every other week, usually in the morning. At the same time the water temperature in the outflow water of each basin was measured, and those values were used as estimates of the daily mean temperature in the analyses of temperature dependency (see below). The inflow water was groundwater with a pH of 6.5, distributed through three different pipes, and the water flows were adjusted using gate valves fitted on each inlet pipe. Flows were set to 2 l min$^{-1}$ and 6 l min$^{-1}$, which resulted in hydraulic loads of 0.13 m d$^{-1}$ and 0.39 m d$^{-1}$, equal to theoretical residence times of 3 and 1 days, respectively. The outflow of water was measured manually with a bucket and a stop watch at every sampling occasion and the inflow was adjusted if the water flow differed by more than 10% from the desired flow. Precipitation was measured continuously on site, but during some periods precipitation data were collected from a nearby meteorological station. The nitrogen concentration in the incoming water was dominated by nitrate as the water contained about 11 mg l$^{-1}$ total nitrogen and 11 mg l$^{-1}$ nitrate-N, with a mean ammonium-N concentration of only 10 μg l$^{-1}$. Phosphorus occurred as phosphate-P, and had a mean concentration of 8 μg l$^{-1}$. All analyses were performed spectrophotometrically with Flow injection analysis, using a modification of the method ISO 13395 as suggested by Tecator (Application Note 5201 and 5202). The water temperature in the individual basins varied between 0 °C in winter to 22 °C in summer.

### 2.2. Data and calculations

Measured water flows were used in the calculations of nitrogen removal and first-order area-based rate coefficients. Because of the high hydraulic loads, the influence of evapotranspiration was considered insignificant for the calculations, and the inflow was assumed to be equal to the outflow. On some occasions, values of water flows were missing in the data set, and at these occasions a flow of 2 l min$^{-1}$ and 6 l min$^{-1}$ was assumed for low and high hydraulic load, respectively. The water flows were sometimes affected by events with high precipitation preceding the sampling. At extreme precipitation events, some basins received more water than others due to surface runoff from the surrounding land. Since the experiment was set up as a two factor study, i.e. exclusively focusing on the effect of two hydraulic loads and three vegetation types, large deviations from the intended hydraulic load would introduce undesired variation in the treatment (the hydraulic load factor) and consequently in the results. To account for this, sampling occasions have been excluded from the data set when the inflow nitrate concentrations were diluted with more than 0.5 mg l$^{-1}$ (about 4.5%). Further, the concentrations in samples with a dilution of 0.1–0.5 mg l$^{-1}$ (about 1–4.5%) of the inflow nitrate concentrations have been recalculated to account for precipitation. As a result, 37% of the sampling occasions were excluded from the data set to avoid uncertain recalculations when the dilution was high, and 47 occasions remained.

The inflow concentration of total nitrogen was measured at the three inlet pipes. In the calculations, the median value of these three was used. Since the source of water was groundwater with a relatively constant nitrogen content, occasional concentration