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A three-stage experimental constructed wetland for treatment of domestic sewage: First 2 years of operation

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ABSTRACT

Hybrid constructed wetland systems have recently been used to treat wastewaters where high demand for removal of ammonia is required. However, these systems have not been used too often for small on-site treatment systems. This is because in many countries ammonia is not limited in the discharge from small systems. Hybrid systems have a great potential to reduce both ammonia and nitrate concentrations at the same time. In our study we employed a three-stage constructed wetland system consisting of saturated vertical-flow (VF) bed (2.5 m^2, planted with *Phragmites australis*), free-drained VF bed (1.5 m^2, planted with *P. australis*) and horizontal-flow (HF) bed (6 m^2, planted with *Phalaris arundinacea*) in series. All wetlands were originally filled with crushed rock (4–8 mm). However, nitrification was achieved only after the crushed rock was replaced with sand (0–4 mm) in the free-drain wetland. Also, original size of crushed rock proved to be too vulnerable to clogging and therefore, in the first wetlands the upper 40 cm was replaced by coarser fraction of crushed rock (16–32 mm) before the second year of operation started. The system was fed with mechanically pretreated municipal wastewater and the total daily flow was divided into two batches 12 h apart. The evaluation of the results from the period 2007 to 2008 indicated that such a system has a great potential for oxidation of ammonia and reduction of nitrate. The ammonia was substantially reduced in the free-drained VF bed and nitrate was effectively reduced in the final HF bed. The inflow mean NH_4-N concentration of 29.9 mg/l was reduced to 6.5 mg/l with the average removal efficiency of 78.3%. At the same time the average nitrate-N concentration rose from 0.5 to only 2.7 mg/l at the outflow. Removal of BOD_5 and COD amounted to 94.5% and 84.4%, respectively, with respective average outflow concentrations of 10 and 50 mg/l. Phosphorus was removed efficiently despite the fact that the system was not aimed at P removal and therefore no special media were used. Phosphorus removal amounted in 2008 to 65.4%, but the average outflow concentration of 1.8 mg/l is still high. The results of the present study indicate very efficient performance of the hybrid constructed wetlands, but optimal loading parameters still need to be adjusted. The capital cost of the experimental system is comparable to the conventional on-site treatment plant but the operations and maintenance costs are about one third of the conventional plant.

1. Introduction

For on-site treatment of domestic wastewater sub-surface horizontal (HF) or vertical-flow (VF) constructed wetlands are commonly used. Both systems performed well in terms of organics and suspended solids. However, the removal of total nitrogen is very low (Vymazal, 2007; Vymazal and Kröpfelová, 2008). HF systems do not oxidize ammonia, while VF systems do so but release high concentrations of nitrate because VF systems do not denitrify. Hybrid systems which can solve these problems have not been used too often for small on-site treatment systems (Vymazal and Kröpfelová, 2008). VF systems may reduce high nitrate concentrations using the recirculation to the previous treatment units, which are usually anoxic or anaerobic.

However, in the 1990s, there was a growing demand for removing ammonia nitrogen and also total nitrogen from on-site systems. As single-stage constructed wetlands were not able to provide this requirement, there has been a growing interest in hybrid systems (also sometimes called combined systems). Hybrid systems used to comprise most frequently VF and HF systems arranged in a staged

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Table 1
Filtration media composition in three periods between April 2007 and December 2008. Crushed rock was granodioride, an intrusive igneous rock similar to granite, but contains more plagioclase ($NaAlSi_3O_8$ to $CaAl_2Si_2O_8$) than potassium feldspar (orthoclase $KAlSi_3O_8$).

Period	1st stage	2nd stage	3rd stage
14.4.–16.8.2007	Crushed rock 4–8 mm	Crushed rock 4–8 mm	Crushed rock 4–8 mm
20.8.–27.11.2007	Crushed rock 4–8 mm	Sand 1–4 mm	Crushed rock 4–8 mm
20.5.–23.12.2008	Crushed rock 16–32 mm (upper 40 cm) 4–8 mm (bottom 60 cm)	Sand (replacement) 1–4 mm	Crushed rock 4–8 mm

manner, however, all types of constructed wetlands could be combined (Vymazal, 2005). In hybrid systems, the advantages of various systems can be combined to complement each other. It is possible to produce an effluent low in BOD, which is fully nitrified and highly denitrified and hence has much lower total-N outflow concentrations (Cooper, 1999, 2001).

Many of these systems are derived from original hybrid systems developed by Seidel at the Max Planck Institute in Krefeld, Germany. The process is known as the Seidel system, the Krefeld system or the Max Planck Institute Process (MPIP) (Seidel, 1965, 1976, 1978). The design consisted of two stages of several parallel VF beds ("filtration beds") followed by 2 or 3 HF beds ("elimination beds") in series. The VF stages were usually planted with *Phragmites australis*, whereas the HF stages contained a number of other emergent macrophytes, including *Iris*, *Schoenoplectus* (*Scirpus*), *Sparganium*, *Carex*, *Typha* and *Acorus*. The VF beds were loaded with pretreated wastewater for 1–2 days, and were then allowed to dry out for 4–8 days. The thin crust of solids that forms on top of the VF beds is mineralized during the rest period.

In the early 1980s, several hybrid systems of Seidel's type were built in France with the systems at Saint Bohaire and Frolois being the best described (Boutin, 1987; Vuillot and Boutin, 1987; Lienard et al., 1990, 1998). A similar system was built in 1987 in the United Kingdom at Oaklands Park (Burka and Lawrence, 1990). In the 1990s and the early 2000s, VF-HF systems were built in many countries, e.g., Slovenia (Urbanc-Berčič and Bulc, 1994; Bulc, 2006), Norway (Mæhlum and Stålnacke, 1999), USA (House and Broome, 2000), Austria (Mitterer-Reichmann, 2002), Ireland (O'Hogain, 2003), France (Reeb and Werckmann, 2005), Belgium (Lesage, 2006), Japan (Kato et al., 2006), Estonia (Öövel et al., 2007), Thailand (Kantawanichkul and Neamkam, 2003), for domestic but also other types of wastewater.

In the mid-1990s, Johansen and Brix (1996) introduced a HF–VF hybrid system with a large HF bed placed first and a small VF bed as the second stage. In this system nitrification takes place in the vertical-flow stage at the end of the process sequence. If nitrate removal is needed, it is then necessary to pump the effluent back to the front end of the system where denitrification can take place in the less aerobic horizontal-flow bed using the raw feed as a source of carbon needed for denitrification (Brix et al., 2003). Similar systems were built also in other countries, such as Nepal (Laber et al., 1999) or Mexico (Belmont et al., 2004).

In the Czech Republic, only constructed wetlands with horizontal sub-surface flow have been used so far (Vymazal, 2002, 2006). The expected more stringent discharge limits for ammonia nitrogen in the near future led to the evaluation of hybrid constructed wetlands under field conditions. The purpose of this study was to evaluate performance of a three-stage experimental system consisting of saturated VF bed, free-drain VF bed and HF bed in series with special focus on removal of nitrogen. The inclusion of the first saturated stage should improve denitrification and therefore the whole system should also provide low inflow concentrations of total nitrogen.

2. Methods

2.1. Experimental set-up

The experimental system (Fig. 1) was built at the Třeboň Wastewater Treatment Plant (8000 PE). Mechanically pretreated wastewater from the municipal treatment plant is pumped twice a day into the first circular vertical filter made of polypropylene (surface area of 2.54 m^2) planted with Common reed (*P. australis*). The filtration substrate is 100 cm deep and water is kept about 5 cm below the surface using the standpipe in the outflow shaft (Fig. 1). This arrangement makes the filter predominantly anaerobic.

The second rectangular filter made also of polypropylene (1.2 m × 1.3 m, area of 1.56 m^2, depth 0.8 m,) is a "typical" free-drain vertical constructed wetland planted with Common reed (*P. australis*). The filtration material is 70 cm deep. The water drains into a sump and from there it is pumped partially to a horizontal subsurface flow bed (8.0 m × 0.75 m, surface area 6 m^2, depth 0.7 m) planted with Reed canarygrass (*Phalaris arundinacea*) and partially recycled to the first wetland (Fig. 1). The recycle starts to operate when the water level in the sump reaches certain level which is indicated by a floater. The pumping cycle runs about 10 min and it runs three times a day on average depending on the water level in the sump from the previous cycle.

The rationale behind the experimental set-up was based on the idea of high removal of both ammonia-N and nitrate nitrogen. The combination of a free-drain vertical wetland and a horizontal-flow wetland has already been used (see Section 1). The first saturated wetland was included in the treatment system in order to enhance denitrification and thus removal of nitrate.

2.2. Filtration materials

The composition of filtration materials is shown in Table 1. In the beginning, all the wetlands were filled with crushed stones (4–8 mm, porosity 44%). However, because of inability of the second free-drain constructed wetland to achieve nitrification, on August 20, 2007, after 4 month of operation, the crushed rock was replaced with sand (1–4 mm, porosity 33%). At the end of 2007, the first wetland got clogged (about on November 20) due to organic and hydraulic overloading and, in addition, the wastewater overflowed without any treatment into the free-drain wetland causing serious percolation problems as well. Therefore, before the experiment was started in 2008, the top 40 cm in the first wetland was replaced with coarse crushed rock (16–32 mm, porosity 50%) and the sand in free-drain wetland was completely replaced. Because of