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Hydraulic characterization and optimization of total nitrogen removal in an aerated vertical subsurface flow treatment wetland

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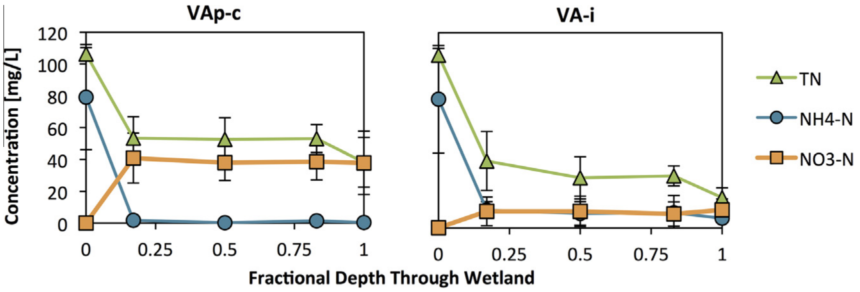
HIGHLIGHTS

- Intermittent aeration improved TN (+30%) and NO_3-N removal (+70%).
- Intermittent aeration resulted in 78% TN mass removal at a loading of 8.5 g TN/m^2 d.
- Hydraulics for the aerated vertical flow wetlands systems were similar to one CSTR.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, a side-by-side comparison of two pilot-scale vertical subsurface flow constructed wetlands (6.2 m^2 × 0.85 m, $q_i = 95$ L/m^2 d, $\tau_n = 3.5$ d) handling primary treated domestic sewage was conducted. One system (VA-i) was set to intermittent aeration while the other was aerated continuously (VAp-c). Intermittent aeration was provided to VA-i in an 8 h on/4 h off pattern. The intermittently aerated wetland, VA-i, was observed to have 70% less nitrate nitrogen mass outflow than the continuously aerated wetland, VAp-c. Intermittent aeration was shown to increase treatment performance for TN while saving 33% of running energy cost for aeration. Parallel tracer experiments in the two wetlands showed hydraulic characteristics similar to one Continuously Stirred Tank Reactor (CSTR). Intermittent aeration did not significantly affect the hydraulic functioning of the system. Hydraulic efficiencies were 78% for VAp-c and 76% for VA-i.

1. Introduction

Constructed wetlands (CW) have been proven as suitable technology for decentralized sewage treatment and can also be used in groundwater protection zones or for providing water for reuse in agriculture and landscaping. The insufficient supply of oxygen is often cited as a limiting factor for removal of carbonaceous and nitrogenous compounds in conventional subsurface flow wetland designs (Maltais-Landry et al., 2009; Nivala et al., 2013a). In the last decade, treatment wetlands with active aeration have gained attention because they are capable of improving the removal of key pollutants such as organic carbon, nitrogen and pathogens (Dong et al., 2012; Nivala et al., 2007; Ouellet-Plamondon et al., 2006; Headley et al., 2013). Aerated wetlands enhance the treatment capacity of a wetland system, which can result in a smaller system footprint and thus reduced capital construction costs (Wallace et al., 2006; Zhang et al., 2010). Aerated wetland systems are suitable for use in cold climates, provide stable treatment

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performance year-round, and are thought to be less susceptible to clogging (Nivala et al., 2007; Ouellet-Plamondon et al., 2006). When continuous aeration is applied to a wetland system, an aerobic environment dominates and high levels of nitrification can be achieved. However, subsequent denitrification is limited due to the prevailing aerobic conditions.

The classical nitrification–denitrification microbial pathway is reported to be responsible for a significant portion of nitrogen removal in treatment wetlands (Hu et al., 2012). Other nitrogen removal pathways, such as plant uptake, ammonia adsorption, anaerobic ammonia oxidation (ANAMMOX), heterotrophic ammonia oxidation and aerobic denitrification can play a role in treatment wetland systems, but usually only to a limited extent. The use of intermittent aeration (aerated and non-aerated phases) may facilitate the creation of aerobic and anoxic conditions inside the treatment wetland, improving denitrification and overall nitrogen removal (Zhang et al., 2010). Recent studies report enhanced nitrogen removal by the use of intermittent aeration in constructed wetlands handling polluted river water (Dong et al., 2012), artificial sewage in a laboratory (Fan et al., 2012, 2013a; Liu et al., 2013) as well as pilot-scale experiments (Fan et al., 2013b). Foladori et al. (2013) conducted a pilot-scale experiment using an intermittently aerated vertical flow (VF) wetland to treat domestic sewage. However, to date no studies have directly compared continuously aerated and intermittently aerated wetland systems operating under the same wastewater loading and environmental conditions.

Wetland hydraulics in aerated horizontal flow wetlands can be influenced by aeration and level of water saturation. There is currently little information about hydraulic behavior of aerated vertical flow wetlands in the literature. Wallace et al. (2006) reports the hydraulic behavior of an aerated vertical flow pilot-scale system similar to one Continuously Stirred Tank Reactor (CSTR).

This paper focuses on a pilot-scale experiment consisting of two aerated vertical flow constructed wetlands treating real domestic wastewater. Treatment performance for organic carbon and nitrogen were evaluated in a side-by-side comparison of a continuously and an intermittently aerated saturated VF wetland to in order assess the effect of intermittent aeration. Oxygen consumption rates and wetland hydraulics were also investigated.

The specific objectives of this study were: (1) to evaluate pollutant removal and oxygen consumption in a continuously and an intermittently aerated pilot-scale VF wetland over one full year of operation; (2) to investigate pollutant removal inside the two treatment systems; and (3) to conduct tracer testing in order to asses effect of aeration on residence time distribution.

2. Methods

2.1. Site and system description

The experiment was carried out at the Ecotechnology Research Facility of the Helmholtz Center for Environmental Research (UFZ) in Langenreichenbach, Germany as described in detail by Nivala et al. (2013a). Two aerated pilot-scale VF wetlands ($6.2\ m^2 \times 0.85\ m$, $q_i = 95\ L/m^2\ d$, $\tau_n = 3.5\ d$) treating primary settled domestic sewage have been used in this study. One system was unplanted (VA) and the other was planted with *Phragmites australis* (VAp). The treatment wetlands were constructed in 2009 and VAp was planted in September 2009 with healthy *P. australis* (five plants per square meter). After a watering and fertilizing period until June 2010, the systems started operation. Plants had not been harvested and were fully established after the second growing season in 2011 when monitoring for the first period of this study was started.

Gravel (8–16 mm) was used as main media in both systems which were saturated and loaded hourly (additional details shown in Table 1). Wastewater was distributed to the top of the wetland cell with a network of pipes and collected by a drainage system on the wetland bottom (exact dimensions are provided in Nivala et al., 2013a). Each system has internal sampling tees at three different depths, corresponding to the upper, middle and lower third of the water column. The aeration system was installed on the wetland bottom and designed according to Wallace (2001). Aeration was provided to each bed by a 35 W diaphragm pump. Actual airflow to each wetland cell was measured to be $2.2\ m^3/h$ using a rotameter and a differential pressure manometer (Prandtl sensor).

The two treatment wetlands were monitored from 2011 to 2012 (1st period) and from 2012 to 2013 (2nd period). During the 1st period, both wetlands were aerated continuously; therefore the abbreviations VAp-c (planted wetland with continuous aeration) and VA-c (unplanted wetland with continuous aeration) are used. During the 2nd period, the unplanted wetland was aerated intermittently (abbreviated as VA-i) and the planted wetland remained continuously aerated (abbreviated as VAp-c). Intermittent aeration in VA-i was provided in a pattern of 8 h on/4 h off. After the first monitoring period, the pretreatment system was extended with an additional septic tank in order to meet the wastewater demand of the entire research site.

2.2. Experimental methods

2.2.1. Sampling and water quality analysis

Both systems were sampled from 2011 to 2013 and internal water quality profiles were taken three times during August–November 2012 (2nd period) for: five-day carbonaceous biochemical oxygen demand ($CBOD_5$) (DIN 38409 H52, *WTW OxiTOP®*), total organic carbon (TOC) (DIN EN 1484, *Shimadzu TOC-VCSN*), total nitrogen (TN) (DIN EN 12660, *Shimadzu TNM-1*), ammonia nitrogen (NH_4-N) (DIN 38 406 E5, *Eppendorf EPOS ANALYZER 5060*), nitrate nitrogen (NO_3-N) (DIN 38 405 D9, *Eppendorf EPOS ANALYZER 5060*), nitrite nitrogen (NO_2-N) (DIN 38 405 D10, *Eppendorf EPOS ANALYZER 5060*), dissolved oxygen (DO) (*WTW Multi 350i*) and redox potential (*WTW Multi 350i*). TOC and TN analyses were conducted on the supernatant of the settled samples. TKN was calculated from water quality data. VA-i was routinely sampled during the end of the 8-h aeration phase. In order to assess the potential for diurnal fluctuation of effluent concentration in VA-i, two 24 h-monitoring sessions were conducted. Effluent samples were taken every 2 h directly from the wetland outlet standpipe by an auto-sampler. Samples were stored at 4 °C in the auto-sampler. At each sampling event, biofilm particles and solids attached to the standing pipe were released and mixed within the sample due to the priming step of the auto-sampling procedure. Before analyzing TOC and TN according to the methods previously defined, samples were settled for 30 min to exclude this distortion.

2.2.2. Tracer study

In November 2012 (2nd period) a fluorescein tracer study was conducted using the impulse method in accordance to Kadlec and Wallace (2009) and Headley and Kadlec (2007). A defined mass of fluorescein (255 mg as 10.2 g/L solution into a 25 L loading event) was added as a pulse injection into the distribution manifold of each wetland. Fluorescein concentrations were measured online by the *NORDANTEC CYCLOPS-7* fluorescence sensor.

A tanks-in-series model has often been used to analyze the retention time distribution (RTD) of treatment wetlands (Chazarenc et al., 2003; Giraldi et al., 2009; Seeger et al., 2013). According to Headley and Kadlec (2007) and Kadlec and Wallace (2009) the sum of square errors (SSQE) between experimental data and a best-fit gamma distribution model were minimized with the Solver™ function in Microsoft Excel and transformed into a dimensionless form in order to calculate the number of tanks in series (NTIS), the mean tracer retention time, and hydraulic efficiency