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Resilience of carbon and nitrogen removal due to aeration interruption in aerated treatment wetlands

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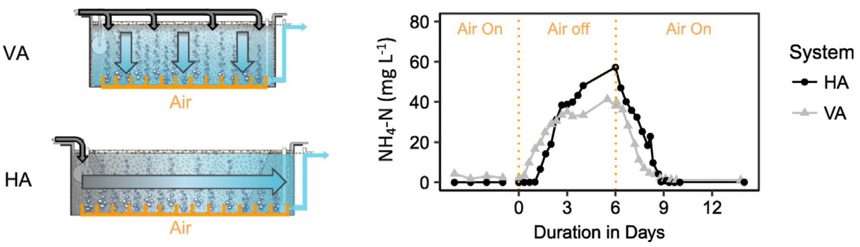
HIGHLIGHTS

- Air pump failure in two different designs was simulated during warm and cold weather.
- Recovery of treatment performance for both designs was 3–4 d during warm weather.
- Lower temperature during cold weather ($T_{water} < 10$ °C) prolonged recovery time.
- Pore water quality patterns depended on aerated wetland design.

GRAPHICAL ABSTRACT



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ABSTRACT

Treatment wetlands have long been used for domestic and industrial wastewater treatment. In recent decades, treatment wetland technology has evolved and now includes intensified designs such as aerated treatment wetlands. Aerated treatment wetlands are particularly dependent on aeration, which requires reliable air pumps and, in most cases, electricity. Whether aerated treatment wetlands are resilient to disturbances such as an aeration interruption is currently not well known.

In order to investigate this knowledge gap, we carried out a pilot-scale experiment on one aerated horizontal flow wetland and one aerated vertical flow wetland under warm ($T_{water} > 17$ °C) and cold ($T_{water} < 10$ °C) weather conditions. Both wetlands were monitored before, during and after an aeration interruption of 6 d by taking grab samples of the influent and effluent, as well as pore water. The resilience of organic carbon and nitrogen removal processes in the aerated treatment wetlands depended on system design (horizontal or vertical flow) and water temperature. Organic carbon and nitrogen removal for both systems severely deteriorated after 4–5 d of aeration interruption, resulting in effluent water quality similar to that expected from a conventional horizontal sub-surface flow treatment wetland. Both experimental aerated treatment wetlands recovered their initial treatment performance within 3–4 d at $T_{water} > 17$ °C (warm weather) and within 6–8 d (horizontal flow system) and 4–5 d (vertical flow system) at $T_{water} < 10$ °C (cold weather). In the vertical flow system, DOC, DN and NH_4-N removal were less affected by low water temperatures, however, the decrease of DN removal in the vertical flow aerated wetland at $T_{water} > 17$ °C was twice as high as in the horizontal flow aerated wetland. The quick recovery of treatment performance highlights the benefits of aerated treatment wetlands as resilient wastewater treatment technologies.

Abbreviations: CSTR, continuous-stirred-tank-reactor; DO, dissolved oxygen; DOC, soluble organic carbon; DN, soluble nitrogen; d, days; EC, electric conductivity; HA, aerated horizontal sub-surface flow wetland; nHRT, nominal hydraulic retention time; ORP, redox potential; T_{water}, water temperature; t_R, recovery time; VA, aerated vertical sub-surface flow wetland.

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1. Introduction

The release of untreated and/or non-adequately treated wastewater still poses a threat to the protection of groundwater and natural waterways, especially in rural areas of less developed and semi-arid countries (WWAP, 2017). In such areas centralized sewer systems are often not feasible from an engineering or economical standpoint (Maurer et al., 2005; Engin and Demir, 2006). An interesting alternative to centralized wastewater treatment can be found in a decentralized approach using treatment wetlands (Zhang et al., 2014). In recent decades, treatment wetland technology has expanded to include more engineered or intensified designs such as aerated treatment wetlands (Ilyas and Masih, 2017). Aerated treatment wetlands provide high levels of treatment for organic carbon, nitrogen and pathogens. Opposed to completely passive treatment wetland designs, aerated treatment wetlands use pumps that move air within the system thereby reducing the system footprint but requiring a power source for operation (Ilyas and Masih, 2017). How does an aerated treatment wetland respond during and after a power disruption or air pump failure? The resilience of aerated treatment wetland technology is not well known.

In general, the resilience of a wastewater treatment system can be defined as the ability to maintain treatment performance during a disturbance or to recover initial treatment performance within a given time after a disturbance (Cuppens et al., 2012). However, theoretical concepts and metrics of resilience are still a widely disputed topic in the literature (Holling, 1973, 1996; Bruneau et al., 2003; Cuppens et al., 2012; Thorén, 2014). In a recent review, Juan-García et al. (2017) highlighted the importance of resilience in wastewater treatment, but reported that few publications directly address the topic of resilience.

The resilience of aerated treatment wetlands may be affected by a number of factors. Here, two factors (wetland design and temperature) are considered in detail. Wetland design can be classified in two main types, horizontal and vertical flow. These two designs are reported to exhibit different hydraulic characteristics: aerated vertical flow systems show hydraulic characteristics similar to one continuous-stirred-tank-reactor (CSTR) compared to three to four CSTRs in an aerated horizontal flow design (Boog, 2013; Boog et al., 2014). The wetland design controls the hydraulics and the wetland functioning, but may also affect resilience. Temperature has an influence on microbial processes in treatment wetlands in general (Kadlec and Wallace, 2009) and thus, may have a potential effect on the resilience of aerated treatment wetlands.

The resilience of treatment wetlands to shock loads or operational malfunctions has been addressed in very few studies (Zapater et al., 2011; Dotro et al., 2012; Butterworth et al., 2016). To the best of our knowledge, only one publication deals with resilience in aerated treatment wetlands (Murphy et al., 2016), which highlights an important research gap. Murphy et al. (2016) reported the resilience of nitrification due to a two–week–long aeration interruption in a full-scale aerated horizontal flow wetland. However, this study only investigated one aerated wetland design, and the question remains whether aerated vertical flow systems are resilient against aeration interruption and to which degree. Furthermore, the resilience of organic carbon removal in aerated treatment wetlands has not yet been investigated. The internal system behavior during transition from aerated to non-aerated phases has also not been reported in the literature; this information could reveal fundamental insights into the functioning of aerated treatment wetlands.

To address these open questions, this study investigates the resilience of organic carbon and nitrogen removal due to aeration interruption in aerated treatment wetlands. The goal of this paper is to assess the potential effect(s) of (1) system design (aerated horizontal or aerated vertical flow), and (2) temperature on the resilience of aerated treatment wetlands, and, (3) to investigate the spatio-temporal system behavior during the transition from aerated to non-aerated phases. To investigate the effect of system design and temperature, pilot-scale experiments including one horizontal and one vertical sub-surface flow aerated wetland were carried out under warm and cold weather conditions. To study the associated spatial dynamics, samples of the influent, effluent and pore water were taken over the course of the experiments.

2. Materials and methods

2.1. Experimental methods

2.1.1. Site and system description

The pilot-scale experiments were carried out at the UFZ Ecotechnology Research Facility at Langenreichenbach, Germany. Two unplanted aerated sub-surface flow treatment wetlands were used as experimental units: a saturated horizontal flow system (HA) and a saturated vertical down-flow system (VA). Previous studies (Nivala et al., 2013b; Boog, 2013; Boog et al., 2014) at the site did not find significant differences in mass removal of bulk organic carbon and nitrogen between the two unplanted systems and planted replicates. This validated the use of unplanted systems to further investigate the resilience of organic carbon and nitrogen removal in aerated treatment wetlands. A detailed description of the experimental site and the two wetlands can be found in Nivala et al. (2013a). Basically, the horizontal flow system measured 4.7 m in length, 1.2 m in width with saturated depth of 1.0 m. The vertical flow system measured 2.7 m in length, 2.4 m in width with a saturated depth of 0.85 m. Both wetlands were filled with gravel (8–16 mm) as the main filter media. Coarse gravel (16–32 mm) was used as filter media in the influent and effluent zones for HA. Both systems were continuously aerated (24 h d^{-1}) through a network of drip irrigation tubing installed along the wetland bottom according to Wallace (2001). Air was provided by electric diaphragm pumps: one pump (Mistral 4000, Aqua Medic) for VA at an air flow rate of approximately 1.6 m^3 h^{-1} and three pumps (Mistral 2000, Aqua Medic, two at the front and one in the back) for HA at flow rates of approximately 1.2 m^3 h^{-1} (first half) and 1.0 m^3 h^{-1} (second half). The two systems were loaded with domestic wastewater that was pretreated in a septic tank with a nominal hydraulic retention time (nHRT) of 3.5 d. The design loading rate of both wetlands was 576 L d^{-1}, resulting in an areal specific loading rate of 102 mm d^{-1} for the horizontal flow, and 95 mm d^{-1} in case of the vertical flow system. Wastewater was dosed every 30 min for HA and every hour for VA.

Both systems were established in September 2009 and started operation in June 2010. The aeration modes were changed between August 2012 and July 2014: the horizontal flow system was switched to a wind-powered air pump (Boog et al., 2016) and the vertical flow system to intermittent electric aeration (Boog et al., 2014). In August 2014, aeration in both systems was switched back to continuous electric aeration. It is noted here that the wind-driven aeration in the horizontal flow (HA) system turned out to be insufficient; the system became overloaded during that time which induced clogging of the aeration system (Boog et al., 2016). In autumn 2014, HA was drained and filled with clean water while compressed air at a pressure of 5 bar was injected into the aeration system in order to clean the clogged aeration orifices. Despite this, the system was at stable performance before the start of this study.

2.1.2. Experimental design

Two experimental series were carried out: one series during warm weather ($T_{water} > 17$ °C, June–August 2015) and one series during cold weather conditions ($T_{water} < 10$ °C, January–February 2016). Each series contained an experiment on the horizontal (HA) and the vertical flow (VA) aerated wetland. The warm weather experiments were conducted in series (first HA then VA) due to limitations in the number of available sensors and auto-samplers. The cold weather experiments were conducted side-by-side. Both systems were monitored during a four to six-week baseline phase to assess baseline performance, a six-day interruption phase without aeration and an eight–day recovery phase after restarting aeration. During the baseline phase, grab sampling of influent

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