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Nitrification cessation and recovery in an aerated saturated vertical subsurface flow treatment wetland: Field studies and microscale biofilm modeling

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HIGHLIGHTS

- Loss of nitrification in aerated treatment wetlands was investigated and modeled.
- DO was depleted 12 h after aeration was switched off.
- Effluent NO_3-N was observed up to 48 h after aeration was switched off.
- Modeling indicates mass transport in biofilm is important in pollutant removal.
- Time for nitrification establishment is 10–20 times longer than for recovery.

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ABSTRACT

In aerated treatment wetlands, oxygen availability is not a limiting factor in sustaining a high level of nitrification in wastewater treatment. In the case of an air blower failure, nitrification would cease, potentially causing adverse effects to the nitrifying bacteria. A field trial was completed investigating nitrification loss when aeration is switched off, and the system recovery rate after the aeration is switched back on. Loss of dissolved oxygen was observed to be more rapid than loss of nitrification. Nitrate was observed in the effluent long after the aeration was switched off (48 h+). A complementary modeling study predicted nitrate diffusion out of biofilm over a 48 h period. After two weeks of no aeration in the established system, nitrification recovered within two days, whereas nitrification establishment in a new system was previously observed to require 20–45 days. These results suggest that once established resident nitrifying microbial communities are quite robust.

1. Introduction

The nitrification capability of passive subsurface flow treatment wetlands is limited by the availability of oxygen (Kadlec and Wallace, 2009). Artificially aerating wetlands ensures that oxygen availability is no longer a limiting factor in achieving nitrification. Aerated wetland systems have been installed in both horizontal subsurface flow and saturated vertical flow configurations (Ouellet-Plamondon et al., 2006; Nivala et al., 2007, 2013; Maltais-Landry et al., 2009; Murphy and Cooper, 2011), with 40 full scale systems now installed in the UK and more than 200 systems worldwide. Aeration is delivered into a network of tubes at the base of the bed via a mechanical blower to enable air to be forced through the bed media to increase the rate of oxygen transfer. Oxygen transfer rates for aerated wetlands have been shown to be 10–100 fold higher than for traditional (non-aerated) horizontal subsurface flow wetland designs (Kadlec and Wallace, 2009). Effluent dissolved oxygen concentrations at or near saturation (>10 mg/L) have been observed in continuously aerated horizontal subsurface flow wetlands (Boog, 2013), which is also supported by the extremely low concentrations of ammonium nitrogen and

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carbonaceous compound concentrations reported for this wetland design (Nivala et al., 2013).

Aerated wetlands can be designed to operate with intermittent aeration to minimize power use (Murphy et al., 2012), provide maximum aeration at peak loads by operating the blowers as a duty/assist (Murphy et al., 2015), or to optimize total nitrogen (TN) removal (Boog et al., 2014). Total nitrogen removal rates vary with treatment wetland design. Classical subsurface flow wetlands are known to be limited in their capacity to remove TN. Horizontal subsurface flow (HSSF) wetlands are reported to have an average TN mass removal rate average, 0.75 g/m^2 d (N = 123 systems) whereas TN removal in vertical subsurface flow (VF) systems is very low due to the fact that organic nitrogen and ammonia nitrogen are oxidized and exported from the system as nitrate and nitrite (Kadlec and Wallace, 2009). In comparison, aerated vertical flow wetlands have been shown to have significantly higher removal rates under both permanent aeration and intermittent aeration, with TN removal rates of 3.8 and 4.3 g/m^2 d, respectively (Boog et al., 2014). This represents a 5-fold increase in TN removal over traditional wetland designs.

In vertical flow aerated treatment wetlands, an intermittent aeration regime results in a steady-state microbial community where both aerobic and anaerobically controlled reactions can take place. However, a sudden and extended loss of aeration could have negative impacts on the predominantly aerobic microbial population, and therefore, the treatment performance of the system. Such a loss of aeration could be reasonably expected during blower failures and maintenance periods.

To date, there have been no microbiologically focused studies investigating either the cessation or recovery of nitrification in treatment wetlands based on aeration intensity. An exhaustive investigation would require spatial sampling of biofilm based microbial communities over the temporal period of the study. Destructive sampling of treatment wetlands enables spatial analysis of biofilm and can yield a large amount of information (Weber and Legge, 2013), however it is only possible where further use of the treatment wetland is not required. Excluding lab-based studies designed specifically for this purpose, the destructive nature of biofilm sampling limits the ability for treatment wetland researchers to perform such studies with respect to fully operational systems. Recent studies have shown that informative spatial sampling can be accomplished in operational treatment wetlands (Button et al., 2015), however this requires for the original design to include for spatial sampling devices, something which is often not in the budget or thought of as an objective when designing operational treatment wetland systems.

Modeling studies can be informative when carefully thought out and designed for express purposes. There have been a number of recent modeling studies of varying complexity conducted for various purposes (Meyer et al., 2015; Samsó and Garcia, 2013; Langergraber and Šimùnek, 2012; Mburu et al., 2012). One of the most microbiologically focused models is that of Rajabzadeh et al. (2015) where biofilm dynamics and the interactions of biofilm growth and detachment with hydrology, water treatment and solute transport was assembled and validated using lab-scale data. This model was able to predict pore scale volumetric changes and the resulting system dynamics over a 280 day period using a Computational Fluid Dynamics (CFD) approach with a high resolution discretization. Although complex TW models such as those found in Meyer et al. (2015) and the model of Rajabzadeh et al. (2015) exist, they do not include microscale modelling of nutrient (or other pollutant) diffusion into and out of the biofilm attached to the bed media. Although identified as important, there has been no attempt to model the diffusion of pollutants into and out of treatment wetland biofilm, the resulting microbiological reactions, and subsequent diffusion of reaction products back through the biofilm into the bulk water. This process is fundamental to the transformation and treatment of pollutants in treatment wetlands and could provide insight into full-scale system treatment performance and dynamics under changing conditions such as aeration intensity.

A field trial was carried out at a pilot scale aerated wetland in Rugeley, UK. The trial was designed to emulate an electricity supply failure. During such an event, the treatment wetland would receive no external air input (later referred to as a "crash test"). The study was designed in order to determine the time at which nitrification ceases after the aeration is switched off, and the rate at which the system recovers after the aeration is switched back on. Due to the well-documented temperature sensitivity of nitrifying bacteria in the literature (Hwang and Oleszkiewicz, 2007; Kadlec and Reddy, 2001; Wang and Li, 2015), the crash test was conducted under both summer and winter conditions.

The specific objectives of this study were to (1) investigate the dynamics of nitrification loss and recovery in a pilot-scale vertical flow aerated wetland, under both summer and winter conditions; (2) to simulate diffusion and reaction of nitrogen species into and out of the biofilm using microscale modeling; and (3) to compare nitrification recovery of an existing aerated treatment wetland system to the establishment of nitrification in a newly built system.

2. Methods

2.1. Site and system description

The 10 m^2 pilot-scale saturated vertical flow wetland system was built in January 2011. The bed measures 1.6 m wide by 6.4 m long and is filled with 8–16 mm rounded gravel to a depth of 1 m, and has an integrated aeration system that was designed according to Wallace (2001). The pilot-scale aerated wetland is part of a full-scale treatment wetland system serving a trading estate (a compound of 10 small businesses, including rainwater from roof runoff) that produces an average of flow of 5 m^3/d with a population equivalent of 44. Primary treatment is achieved in a septic tank and effluent is then pumped to a holding tank. A proportion of effluent from the holding tank is subsequently pumped on to the surface of the pilot-scale aerated wetland bed five times a day for a fixed period, resulting in a hydraulic loading rate of 200 L/m^2. The pilot-scale system has a nominal hydraulic retention time (HRT) of approximately two days. The aeration in the bed is operated continuously (24 h/d). Effluent from the wetland flows out of the collection pipework and directly into a pump sump, which is then emptied using a float switch that is triggered after two inlet doses (approximately every 10 h). Fig. 1 shows a photo and schematic of the pilot-scale system.

2.2. Experimental methods

2.2.1. Sampling and analysis

The first crash test was conducted from September 9–25, 2013, and the second was conducted from January 7–29, 2014. Each test comprised of bi-hourly effluent monitoring for 48 h immediately after switching the aeration off, followed by two weeks of operation with no aeration. After the blower was switched back on, bi-hourly effluent samples were collected for another 48 h.

An Aquacell P2 auto-sampler containing 24 one-liter bottles was set up to collect samples directly from inside the collection pipe at the outlet of the bed (Fig. 1). For a period of 48 h, the auto-sampler took 250 mL samples every 30 min before switching to the next bottle. Dissolved oxygen and water temperature measurements were taken every 15 min using a Hach Lange HQ40d DO probe positioned near the collection pipework in the pump well. Inlet flow measurements were recorded as total daily flow using a paddle wheel flow meter.