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Stochastic multi-objective performance optimization of an in-stream woodchip denitrifying bioreactor

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ABSTRACT

Woodchip denitrifying bioreactors (WDBs) that target filtration of nitrate from farm drainage water are gaining recognition as a tool for tackling the issue of diffuse nitrate pollution from agricultural landscapes. Whilst the hydraulic regime and concentration of nitrate in the drainage water constitute two fundamental environmental variables that determine the size of a denitrifying bioreactor, the issue of over- or under-treatment of water that might otherwise promote undesirable pollution swapping phenomena and construction costs also need to be factored into the overall design process. Conventional methods for optimizing the design of denitrifying bioreactors generally rely on deterministic models, even though many of the design parameters are not known with confidence. In this work we apply an alternative design philosophy and demonstrate how the bioreactor design process can be improved through application of stochastic methods. The design aspect of an 'in-stream' WDB planned for installation on a farm in New Zealand is structured as a multi-objective performance optimization problem that is solved in a stochastic framework, using freely available open source tools. Uncertainty considerations regarding values of physical parameters that govern bioreactor performance are incorporated into the assessment, from which a Pareto set of optimal designs was obtained. A 75 m long bioreactor of 1.5 m height was selected as the preferred choice from the optimal set of design solutions. Assuming a 10-year operational life, it is predicted the cost of nitrate removal by the planned denitrifying bioreactor will be NZ$9.70/kg-N (approx.US$6.60/kg-N).

1. Introduction

Nitrate pollution of surface water systems from farming activities is a global environmental problem (UN, 2011). A woodchip denitrifying bioreactor (WDB) represents a low-key, passive water treatment system designed to filter excess agricultural nitrate from waterways that is gaining recognition as a tool for tackling the issue of diffuse nitrate pollution from agricultural landscapes (e.g. Gold et al., 2013). In essence, a WDB comprises a mass of woodchip placed in the ground through which drainage water contaminated with nitrate is routed. WDBs are effectively packed-bed reactors, sited to intercept land drainage on the farm, before it discharges to a natural waterway. The woodchip is the reactive component of a WDB. It serves as a carbon food source for mixed consortia of facultative denitrifying bacteria living within the reactor system. The denitrifying organisms metabolize aqueous nitrate entering the reactor, converting it to innocuous di-nitrogen gas, via a step-wise reductive reaction process.

The concepts of WDBs have been successfully demonstrated in North America and Europe (Schipper et al., 2010; Christianson et al., 2012a; Fenton et al., 2014). Recently, within the major US agricultural states of Iowa, Illinois and Minnesota, they have been included within official nutrient reduction strategies (USDA, 2015; Christianson and Schipper, 2016). Being passive treatment systems, operating in agricultural landscapes, the performance of WDBs is inherently variable and controlled by many natural environmental conditions relating to: climate, hydrology and land-use. The scale of any individual reactor must be tailored to fit within the constraints imposed by individual site conditions.

The hydraulic regime and concentration of nitrate in the drainage water are two key variables at any site to which a reactor size must be scaled. As with any packed-bed reactor, the objective is to optimize the hydraulic residence time of treatment water passing through the system. In the case of denitrifying bioreactors, over- or under-treatment results in undesirable redox-sensitive pollution swapping phenomena. For example, under-treatment results in production of N_2O greenhouse gas. On the other hand, an extensively long hydraulic residence time can promote sulphate-reduction and formation of undesirable odorous and toxic sulphide gas, also methanogenesis, i.e. production of methane

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– again, a greenhouse gas (e.g. Schipper et al., 2010). Whilst idealistic to treat 100% of the nitrate flux carried in a drain, it is generally impracticable to do so. Instead, some compromise must be sought, between bioreactor size, cost and nitrogen removal efficiency.

There are very few studies that have examined the long-term performance of woodchip denitrifying bioreactor systems. Nonetheless, evidence is that the initial reactivity of woodchip drops off very rapidly, due to leaching of volatile components from the wood in the early stages. After this initial leaching event, the reactivity declines at a much reduced rate and whilst it may be a gross simplification of the kinetics of denitrification reactions, nitrate removal in woodchip bioreactors can be simulated with a zero-order reaction rate (Robertson, 2010). The permeability of the woodchip declines over time also (Cameron and Schipper, 2012). Decomposition of the wood however is relatively slow, provided it is kept saturated such that anoxic conditions can prevail. Prognosis is that denitrifying bioreactors constructed with woodchip have a useful operational life of around 10 years, if not longer (Moorman et al., 2010; Christianson et al., 2012b; Gold et al., 2013).

While there are no universally agreed design standards or performance criteria for WDB systems, a code of practice (605-CPS-1) published by the USDA (2015) specifies treatment of 15–20% of peak flow as a treatment objective for individual WDBs instrumented on subsurface (tile) drains. To help operators conform to this code, Cooke and Bell (2014) have developed a protocol and interactive mathematical routine for informing the design of subsurface WDBs that targets USA tile-drain settings. The routine can optimize the size of a bioreactor to simultaneously satisfy any combination of flow, residence time and performance constraints. Bioreactor costs are automatically calculated and provided as a model output. Whilst a useful application for optimizing the design of WDBs, the models assumed by Cooke and Bell (2014) are deterministic, and the routine does not factor in uncertainty in model predictions. So far as we can tell, all WDBs described in the published literature have so far been designed using deterministic models to predict bioreactor performance, even though many of the values of parameters that determine reactor performance are highly uncertain and likely to change with time. In this paper we describe how we have optimized the design of an 'in-stream' (or 'in-ditch') WDB similar to the type field-demonstrated by Robertson and Merkley (2009), Pfannerstill et al. (2016) and Christianson et al. (2016), using a stochastic multi-objective performance optimization approach. Unlike any previous WDB design examples, we factor in uncertainty considerations regarding values of physical parameters that govern bioreactor performance. The mathematical method is demonstrated for a pilot WDB being planned for a farm in New Zealand, where information on drain flows and nitrate concentrations are limited. How this uncertainty is encapsulated in the predictive modelling exercise is described.

2. Reaction processes mathematical model

Fig. 1 shows the physical concept of an in-stream bioreactor. The sealed woodchip bioreactor is emplaced within the channel of a drain that conveys nitrate-laden water. A portion of flow within the drain is diverted through the confined bioreactor that acts as a constant carbon food source for resident bacteria that facilitate oxidation-reduction (redox) reactions. Microbes living at the head of the reactor first consume any dissolved oxygen in the influent water through aerobic respiration. Deeper within the reactor, consortia of facultative anaerobic denitrifying organisms convert nitrate to di-nitrogen gas via a sequence of redox reactions. Whilst a gross simplification of the true reaction kinetics, we assume denitrification rates in woodchip bioreactors can be modelled assuming a linear zero-order reaction rate (Robertson, 2010; Schipper et al., 2010; Schmidt and Clark, 2013).

Assuming zero-order reaction kinetics, the nitrate mass removal ΔM rate by the reactor can be expressed as

$$\Delta M = kV_A \tag{1}$$

where k is the treatment rate of the bioreactor medium and V_A the active reactor volume, which is a function of the geometric design and the inlet and outlet head. Nitrate mass removal is subject to the limiting condition

$$\Delta M \leq C_D Q_R \tag{2}$$

In Eq. (2) Q_R is the flow through the reactor and is limited by the available flow rate in the drain (Q_D) and the reactors through flow capacity. C_D is the nitrate concentration in the drain water that is subject to treatment. Both C_D and Q_D are time variable; subject to both systematic and irregular fluctuations.

Assuming uniform flow conditions in the reactor and that Darcy's law is applicable, flow through the reactor can be expressed in terms of the hydraulic conductivity of the reactor media (K), the hydraulic gradient ($\Delta h/L$) and the active cross sectional area (A_R). Then Q_R becomes

$$Q_R = min\left\{Q_D, \frac{K\Delta h}{L}A_R\right\} \tag{3}$$

while the reactor outflow nitrate concentration is given by

$$C_R = \frac{Q_R C_D - \Delta M}{Q_R} \tag{4}$$

Neither k in Eq. (1), or K in Eq. (3), which define the respective reactive and hydraulic properties of an in-stream woodchip bioreactor, are constant. Instead, their values decay over time due to biodegradation of the organic matter and siltation effects (Robertson and Merkley, 2009; Moorman et al., 2010). It is worthy to note that whilst porosity is a physical property of woodchip, it does not explicitly feature in the mathematical problem as we have formulated it here, but is implicit to the parameters V_A, K and k.

Removal rate k is also temperature dependent. This dependency commonly described by (e.g. Cameron and Schipper, 2010)

$$k = k_0 Q_{10}^{\frac{T-T_0}{10}} \tag{5}$$

where k_0 is the treatment rate at temperature T_0, and Q_{10} is the temperature coefficient, quantifying the reactivity rate change for 10 °C change in temperature.

If temperature T is assumed to follow a seasonal trend and is

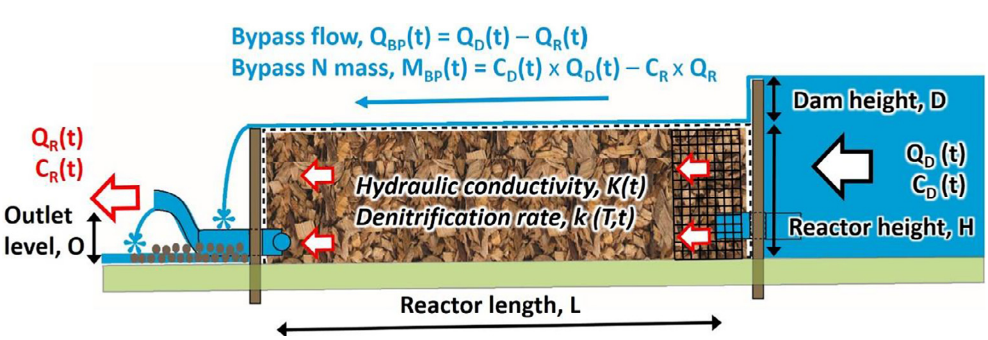

Fig. 1. Schematic design of the in-stream WDB planned at Barkers Creek, New Zealand. The woodchip-filled reactor is a sealed unit, lined with EPDM rubber. Drain water enters the reactor and flows through woodchip-filled gabion baskets that act as serviceable sediment traps/pre-filters, before passing through more woodchip that fuels denitrification reactions. Drain flows that the WDB cannot handle spill over the bioreactor and bypass any treatment.