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Non-linear hydraulic properties of woodchips necessary to design denitrification beds

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ABSTRACT

Denitrification beds are being used to reduce the transport of water-soluble nitrate via subsurface drainage systems to surface water. Only recently has the non-linearity of water flow through woodchips been ascertained. To successfully design and model denitrification beds with optimum nitrate removal, a better understanding of flow in denitrification beds is needed. The main objectives of this study were to characterize the hydraulic properties of old degraded woodchips and provide a better understanding of the factors affecting flow. To achieve this goal, we conducted constant-head column experiments using old woodchips that were excavated from a four-year old denitrification bed near Willmar, Minnesota, USA. For Izbash's equation, the non-Darcy exponent (n) ranged from 0.76 to 0.87 that indicates post-linear regime, and the permeability coefficient (M_{10}) at 10°C ranged from 0.9 to 2.6 cm s^{-1}. For Forchheimer's equation, the intrinsic permeability of 5.6×10^{-5} cm^2 and ω constant of 0.40 (at drainable porosity of 0.41) closely resembled the in-situ properties found in a previous study. Forchheimer's equation was better than that of Izbash's for describing water flow through old woodchips, and the coefficients of the former provided stronger correlations with drainable porosity. The strong correlation between intrinsic permeability and drainable porosity showed that woodchip compaction is an important factor affecting water flow through woodchips. Furthermore, we demonstrated the importance of temperature effects on woodchip hydraulics. In conclusion, the hydraulic properties of old woodchips should be characterized using a non-Darcy equation to help design efficient systems with optimum nitrate removal.

1. Introduction

Agricultural subsurface drainage facilitates the removal of excess water from the soil profile to provide soil aeration, timely field operations, and reduce surface erosion. While subsurface drainage helps improve crop production, it can also transport some nitrate to surface water from organic matter mineralization as well as from nitrogen fertilizers used to produce crops. Elevated concentrations of nitrate in surface water can contribute to hypoxia and toxin production from harmful algal blooms (USEPA, 2013; Horst et al., 2014; Harke and Gobler, 2015). Denitrifying bioreactors are one approach for removing nitrate from water by providing a carbon source for the biological transformation (i.e., denitrification) of nitrate into di-nitrogen gas. One type of a denitrifying bioreactor is a denitrification bed (also known as a woodchip bioreactor) that can reduce nitrate concentration from subsurface drainage water (Schipper et al., 2010; Bednarek et al., 2014). In denitrification beds (hereafter referred to as bed), woodchips have been commonly used as the carbon medium.

Accurate characterization of hydraulic properties of woodchips is vital for the successful design and modeling of beds to achieve optimum nitrate removal. The design guideline of beds in the Midwest USA has been developed based on the hydraulic properties of woodchips assuming Darcian flow (USDA NRCS, 2015). However, Ghane et al. (2014) showed overestimation of the peak flow rate of a bed using Darcy's law under field conditions, which in turn, results in underestimation of the actual hydraulic retention time at the peak flow rate of the bed. As a result, bed designs can be overly long and have undersized width according to the non-Darcy flow component of the bed model in Ghane et al. (2015). Beds that are too long increase the potential for undesirable consequences when nitrate concentration is depleted within the bed, i.e., reduction of sulfate to hydrogen sulfide and inorganic mercury to methylmercury (Shih et al., 2011). Therefore, there is a need for characterizing water flow through woodchips using the governing

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flow equation in laboratory column experiments, so the results can be used to adjust bed design guidelines, and in turn, provide systems that are more efficient.

For many years, water flow through woodchips was assumed to follow Darcy's law in laboratory experiments without validation of linear flow (Chun et al., 2009; Cameron and Schipper, 2010; Leverenz et al., 2010; Schmidt and Clark, 2013; Krause Camilo et al., 2013; Subroy et al., 2014; Goodwin et al., 2015). These studies reported a range of woodchip hydraulic conductivities from 0.01 to 54 cm s^{-1}. Leverenz et al. (2010) calculated one of the highest woodchip hydraulic conductivities ever reported (i.e., 54 cm s^{-1}). However, the related work by Hopes (2010) presents evidence that suggests their reported value is too high.

Darcy's law has also been used to provide a rough estimate of hydraulic conductivity in the field based on assumptions and without validation of linear flow (Van Driel et al., 2006; Robertson et al., 2009; Robertson and Merkley, 2009). In one of these studies, Robertson et al. (2009) found a wide range of hydraulic conductivities from 0.3 to 5 cm s^{-1} for a bed assuming 90% of the water flows through the coarse woodchips for the first two years and 100% from year two to seven. David et al. (2016) attempted to determine the in-situ hydraulic conductivity of woodchips in a bed, but they encountered a non-linear relationship between specific discharge and hydraulic gradient that did not allow them to determine a definite in-situ hydraulic conductivity based on Darcy's law. More recently, Krause Camilo (2016) reported a hydraulic conductivity of 10 cm s^{-1} for a mixture of bark mulch chips and straw in a pilot-scale bed based on Darcy's law and without validation of linear flow.

Only recently has the non-linearity of water flow for fresh (Feyereisen and Christianson, 2015) and old woodchips (Ghane et al., 2014) been ascertained in laboratory column experiments. Thus, reports of woodchip hydraulic properties using the governing non-linear flow equation are scarce. Therefore, a need exists to determine the hydraulic properties of woodchips for non-Darcy flow in laboratory column experiments. In particular, old woodchip properties are of great importance because they represent the woodchips that have been under natural conditions in a bed, and they have been found to have different properties than fresh woodchips (Robertson, 2010; Ghane et al., 2014). While laboratory experiments have ascertained the non-linearity of water flow through woodchips, this has not been shown in a bed under field conditions. Therefore, there is a need for graphical evaluation of the non-linearity of water flow through a bed in a field experiment.

Drainable porosity (specific yield) is an important property of woodchips, which can be used instead of effective porosity to calculate the actual hydraulic retention time (*HRT*) when the latter is unavailable from tracer testing. However, there are only a few laboratory column studies that have calculated the drainable porosity of old woodchips. Ghane et al. (2014) calculated drainable porosities of 0.37–0.39 for the two-year, two-month old woodchips, and Robertson (2010) calculated a value of 0.46 for seven-year old woodchips when draining the water for 1 h. Some studies have assumed much higher values (i.e., 0.70) for woodchip beds under field conditions (Bell et al., 2015; Rambags et al., 2016). Therefore, there is a need for more experiments to obtain better estimates of drainable porosity of old woodchips.

Temperature is another important parameter in woodchip hydraulics. Temperature effect on soil hydraulic properties is well known (Gao and Shao, 2015), but this effect for water flow through woodchip media has never been shown previously. Some studies have accounted for the effect of temperature on woodchip hydraulic conductivity (Ghane et al., 2014; Feyereisen and Christianson, 2015), and some studies have not (Van Driel et al., 2006; Chun et al., 2009; Robertson et al., 2009; Robertson and Merkley, 2009; Cameron and Schipper, 2010; Schmidt and Clark, 2013; David et al., 2016). Those that did not account for this effect could have had temperature as a confounding variable affecting specific discharge, and thereby, affecting hydraulic conductivity. Therefore, there is a need to evaluate the effect of temperature on hydraulic properties of woodchips.

Although hydraulic properties of old woodchips are essential to the design and modeling of beds, we found only one study that had reported those values while validating the Darcian flow. In that study, Ghane et al. (2014) reported the first laboratory and in-situ hydraulic properties of old woodchips using Forchheimer's equation. A review of the literature shows that there is a need to better understand the non-Darcian flow, and determine the hydraulic properties of old woodchips using other flow equations such as Izbash's law, for which, to our knowledge, has never been investigated for woodchips in its entirety.

The objectives of this study were to (1) graphically evaluate Darcy's law for water flow through old woodchips in a permeameter and in a bed under field conditions, (2) determine the hydraulic properties (i.e., flow coefficients and drainable porosity) of old woodchips, (3) compare the performance of Forchheimer's equation to that of Izbash's in describing the flow, (4) determine the error of ignoring the non-Darcy flow, and (5) evaluate the effect of temperature on hydraulic properties. The practical importance of this study is that it provides essential information that is required to design efficient denitrification beds in which undesirable consequences are minimized.

2. Theory

2.1. Pre-linear, linear, and post-linear flow

The theory of water flow through porous media is fundamental to a wide range of disciplines. Basak (1977b) identified three main zones for water flow through porous media for a range of hydraulic gradients (Fig. 1). These zones are pre-linear, linear and post-linear zones. The former occurs when water flows through porous media at very low velocities. For this zone, specific discharge (apparent velocity) is not proportional to hydraulic gradient. For the linear zone, water velocity is low, so specific discharge is proportional to hydraulic gradient. In this zone, soil scientists commonly apply Darcy's (1856) law for water flow through soils.

For the post-linear zone, the linear relationship between specific discharge and hydraulic gradient does not exist due to the high water velocities in the porous media (Basak, 1977a). In this zone, the increase in specific discharge is proportionally smaller than the increase in hydraulic gradient. This is because inertial forces

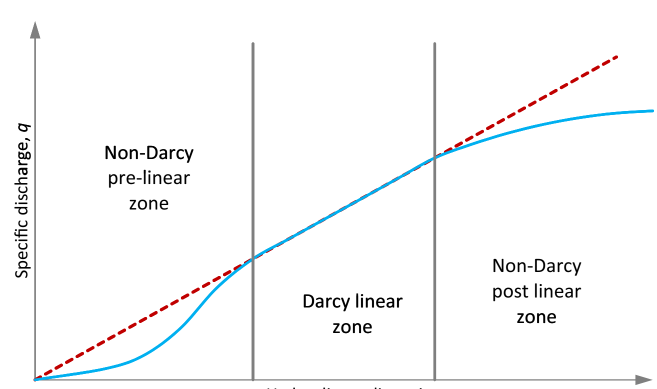

Fig. 1. Diagram of the three main zones for water flow through porous media. The dotted line represents Darcian flow (modified from Basak, 1977b).

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