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Dual permeability modeling of tile drain management influences on hydrologic and nutrient transport characteristics in macroporous soil

Steven K. Frey [a,b,*], Hyoun-Tae Hwang [b], Young-Jin Park [b], Syed I. Hussain [a,c], Natalie Gottschall [a], Mark Edwards [a], David R. Lapen [a]

[a] *Agriculture and Agri-Food Canada, 960 Carling Drive, Ottawa, Ontario K1A 0C8, Canada*
[b] *Aquanty Inc., 564 Weber Street North, Waterloo, Ontario N2L 5C6, Canada*
[c] *University of Waterloo, Department of Earth and Env. Sciences, 200 University Ave. W., Waterloo, Ontario, Canada*

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SUMMARY

Tile drainage management is considered a beneficial management practice (BMP) for reducing nutrient loads in surface water. In this study, 2-dimensional dual permeability models were developed to simulate flow and transport following liquid swine manure and rhodamine WT (strongly sorbing) tracer application on macroporous clay loam soils under controlled (CD) and free drainage (FD) tile management. Dominant flow and transport characteristics were successfully replicated, including higher and more continuous tile discharge and lower peak rhodamine WT concentrations in FD tile effluent; in relation to CD, where discharge was intermittent, peak rhodamine concentrations higher, and mass exchange from macropores into the soil matrix greater. Explicit representation of preferential flow was essential, as macropores transmitted >98% of surface infiltration, tile flow, and tile solute loads for both FD and CD. Incorporating an active 3rd type lower boundary condition that facilitated groundwater interaction was imperative for simulating CD, as the higher (relative to FD) water table enhanced water and soluble nutrient movement from the soil profile into deeper groundwater. Scenario analysis revealed that in conditions where slight upwards hydraulic gradients exist beneath tiles, groundwater upwelling can influence the concentration of surface derived solutes in tile effluent under FD conditions; whereas the higher and flatter CD water table can restrict groundwater upwelling. Results show that while CD can reduce tile discharge, it can also lead to an increase in surface-application derived nutrient concentrations in tile effluent and hence surface water receptors, and it can promote NO_3 loading into groundwater. This study demonstrates dual permeability modeling as a tool for increasing the conceptual understanding of tile drainage BMPs.

1. Introduction

Tile drains are an integral component of the agricultural landscape in many parts of North America and Europe. While necessary to support crop production, it is well known that tile drains can serve as conduits for the rapid transmission of a broad range of contaminants from the soil profile to surface water receptors, including nutrients, pesticides, pharmaceutical and personal care products, and pathogenic microorganisms (Skaggs et al., 1994; Lapen et al., 2008a, 2008b; Blann et al., 2009; Frey et al., 2015). In North America, effluent from tile drains is widely regarded to be a principle source of nutrient loading to many surface water bodies suffering from eutrophication, including the Gulf of Mexico and Lake Erie (Mitsch et al., 2001; David et al., 2010; Royer et al., 2006). Because of the large scale deleterious impact that tile drainage can have on surface water resources, there are currently widespread efforts to investigate beneficial management practices (BMPs) that can help mitigate the environmental consequences (Dinnes et al., 2002; Drury et al., 2014; Schipper et al., 2010; Strock et al., 2010; Woli et al., 2010; Jaynes and Isenhart, 2014; Wilkes et al., 2014; Sunohara et al., 2015).

One of the most promising tile drain BMPs is controlled tile drainage (CD), which is a system for physically restricting tile discharge with adjustable gates or valves housed in edge-of-field inline control structures (Gilliam et al., 1979; Evans et al., 1995; Wesström et al., 2003; Skaggs et al., 2010). For structures using the adjustable stopgate approach (Fig. 1), adjustment of the elevation of the stopgates can control the distance between the ground

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* Corresponding author at: Aquanty Inc., 564 Weber Street North, Waterloo, Ontario N2L 5C6, Canada. Tel.: +1 519 279 1080.
E-mail address: sfrey@aquanty.com (S.K. Frey).

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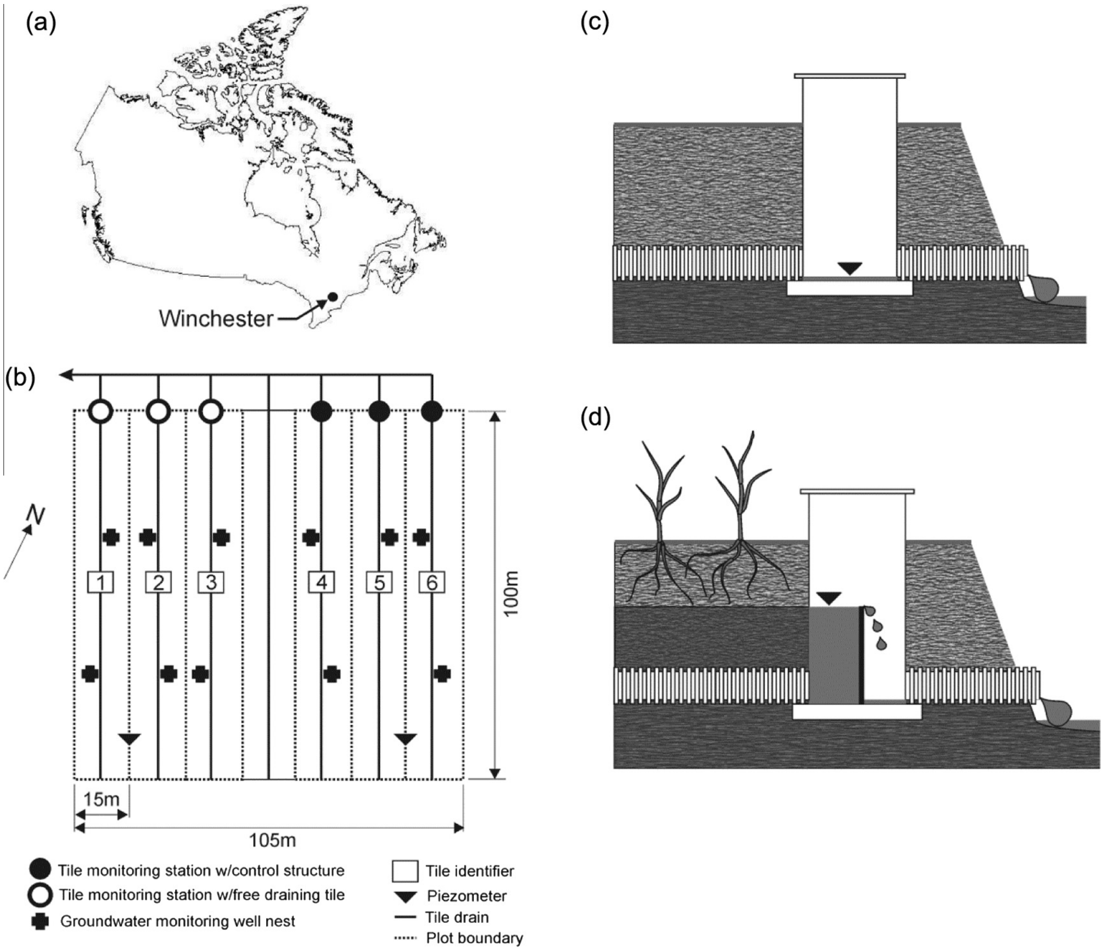

Fig. 1. (a) Geographical location of the Winchester field research site within Canada; (b) schematic layout of the six tile drained test plots and associated instrumentation; and cross section perspective of an inline control structure configured for (c) free drainage, and (d) controlled drainage (during overflow) scenarios (from Frey et al., 2015).

surface and the tile drain discharge point, which allows CD to be used for water table control. Previous research has shown that CD can be very effective for reducing tile discharge volume, and that on an annualized basis, there is often a reduction in nitrate loads that is proportional to the reduction in discharge (Wesström and Messing, 2007; Skaggs et al., 2010; Sunohara et al., 2015). It has been estimated that approximately 30 million acres of crop land across the Upper Midwest United States are suitable for CD (Natural Resources Conservation Service), and that such an en masse implementation could have a marked impact on nitrate loads in the Mississippi River (Jaynes et al., 2010). There has also been recent research that has shown CD may be an effective practice for reducing phosphorus loading at watershed scales (Sunohara et al., 2015).

Although CD is widely regarded for its ability to reduce surface water nitrate loads in tile drained landscapes, it is a BMP with some potentially deleterious side effects. By raising the water table, vertical hydraulic gradients can also increase, which can then increase the movement of nitrate laden waters into the groundwater flow system (Skaggs et al., 2010). Furthermore, the higher water table can also promote the mobilization of phosphorus from within the soil profile (Valero et al., 2007) and an increase in nutrient laden surface runoff (Skaggs et al., 2010; Tan and Zhang, 2011; Ball-Coelho et al., 2012). In order to fully understand the implications of CD for both surface water and groundwater resources, and to optimize its implementation, there must be a solid quantitative understanding of the physical and chemical processes that drive flow and transport in both free drainage (FD) and CD conditions. For example, Frey et al. (2013, 2015) showed experimentally that CD did not significantly reduce nutrient and pharmaceutical loads over a one month period following a mid-October liquid swine manure application on a macroporous clay loam. Reasons for these findings are not entirely clear but the underlying processes have important implications for how CD might be managed for both agronomic and environmental targets.

Our understanding of complex soil physical processes is often supported by modeling, and while CD has not yet been subject to extensive numerical modeling analysis, the DRAINMOD model (Youssef et al., 2005), which uses analytical solutions to solve for infiltration and tile drain discharge, has been used to investigate drainage water management related operational strategies (Ale et al., 2010), nitrate reduction strategies (Luo et al., 2010; Ale et al., 2012a), and watershed scale hydrologic characteristics (Ale et al., 2012b). In contrast, traditional FD has been studied extensively from a process-based numerical modeling perspective (Gerke and Köhne, 2004; Haws et al., 2005; Gardenas et al., 2006; Gerke et al., 2007, 2013); and it is now well recognized that in order to investigate flow and transport in structured tile drained soils, the influence of preferential flow needs to be considered explicitly (Vogel et al., 2000; Köhne et al., 2006). For such applications, dual permeability, Richards equation based models have been shown to perform well for applications involving flow,