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Numerical investigation of the spatial scale and time dependency of tile drainage contribution to stream flow

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SUMMARY

Tile drainage systems are pervasive in the Central U.S., significantly altering the hydrologic system. The purpose of this study was to assess the effects of tile drainage systems on streamflow. A physically based coupled hydrologic model was applied to a 45 km^2 agricultural Iowa watershed. Tile drainage was incorporated though an equivalent porous medium approach, calibrated though numerical experimentation. Experimental results indicated that a significant increase in hydraulic conductivity of the equivalent medium layer was needed to achieve agreement in total outflow with an explicit numerical representation of a tiled system. Watershed scale analysis derived the tile drainage contribution to stream flow (Q_T/Q) from a numerical tracer driven analysis of instream surface water. During precipitation events tile drainage represented 30% of stream flow, whereas during intervals between precipitations events, 61% of stream flow originated from the tile system. A division of event and non-event periods produced strong correlations between Q_T/Q and drainage area, positive for events, and negative for non-events. The addition of precipitation into the system acted to saturate near surface soils, increase lateral soil water movement, and dilute the relatively stable instream tile flow. Increased intensity precipitation translated the Q_T/Q relationship downward in a consistent manner. In non-event durations, flat upland areas contributed large contributions of tile flow, diluted by larger groundwater (non-tile) contribution to stream flow in the downstream steeper portion of the watershed. Study results provide new insights on the spatiotemporal response of tile drainage to precipitation and contributions of tile drainage to streamflow at a watershed scale, with results having important implications for nitrate transport.

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1. Introduction

Subsurface tile drainage significantly alters flow pathways within hydrologic systems (Eidem et al., 1999; Hansen et al., 2013; Hirt et al., 2011; King et al., 2014; Macrae et al., 2007; Rozemeijer et al., 2010b; Schilling et al., 2012; Singh et al., 2006; Stamm et al., 2002; van den Eertwegh et al., 2006; van der Velde et al., 2010), improving conditions for agricultural productivity by providing a fast flow route for excess water though subsurface pipe networks. Tile drainage has been shown to increase baseflow (Schilling et al., 2012; Schilling and Libra, 2003), reduce groundwater travel times (Schilling and Helmers, 2008; Schilling et al., 2012, 2015), increase annual flow volume (Blann et al., 2009; Haitjema, 1995; Magner et al., 2004), and increase instream nitrate concentrations (Blann et al., 2009; Jaynes et al., 2001; Rozemeijer et al., 2010b; Skaggs et al., 1994; van den Eertwegh et al., 2006). The impact of subsurface drainage on baseflows can vary based on soil characteristics (Blann et al., 2009; Skaggs et al., 1994), with drainage systems reducing groundwater recharge and lowering water table levels and subsequently reducing baseflow under some conditions (Blann et al., 2009; Bryant et al., 1987). Subsurface drainage is used extensively throughout the agriculturally dominated central U.S. to drain more than 37% of the soils (Zucker and Brown, 1998). The dominance of row crop agriculture and heavy soil types in central Iowa has led to a wide distribution of tile drainage.

Studies investigating the hydrologic impact of tile drains at the field and small catchment scale have indicated a wide range of tile drainage contribution to stream flow (Carluer and De Marsily, 2004; Eastman et al., 2010; Hirt et al., 2011; King et al., 2014; Macrae et al., 2007; Sims et al., 1998; van den Eertwegh et al., 2006; van der Velde et al., 2010). Catchment analyses have reported tile drainage contribution to stream flow ranging from 0–90% (3 km^2) (Macrae et al., 2007), and 30–61% (4 km^2) (King et al., 2014) varying with season. At field locations without surface flow measurements, tile flow represented 10–79% of volumetric precipitation (De Schepper et al., 2015; Eastman et al., 2010; Kladivko et al., 2004; Logan et al., 1980; Sands et al., 2008). Tile

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discharge contribution to stream flow has been strongly correlated with the size of the contributing drainage area, noting a direct relationship to total upstream drained area (King et al., 2014; van der Velde et al., 2010). Further research is needed on the impact of tile drainage contribution to hydrologic flow processes at the watershed scale (Eidem et al., 1999; King et al., 2014; Macrae et al., 2007; Schilling et al., 2012). Monitoring campaigns thus far have been limited to field and small catchments, as it becomes increasingly impractical to complete similar studies over larger areas. The knowledge gap at increasing spatial scales is often investigated with numerical models.

Numerical modeling of coupled surface–subsurface systems provides insight into the effects of tile drainage on various hydrologic processes. Hydrograph recession, base flow, travel times, flood-frequency analyses, and stream flow response (De Schepper et al., 2015; Hofer et al., 2011; Rahman et al., 2014; van der Velde et al., 2010) have been investigated through various modeling approaches. Numerous methods have been applied to simulate tile drainage flow at the watershed scale.

The first of which divides a watershed into representative subcatchments, modeling each subcatchment with a detailed field scale model such as DRAINMOD (Skaggs, 1982). Streamflow is calculated based simplified topographic based routing (Ale et al., 2012; Northcott et al., 2002). Field scale simulations in the form of DRAINMOD offer increased temporal detail in hydrologic variables and processes, prior to, during, and after events. These simulations retain high levels of local complexity, but often lose the ability to investigate streamflow and similar variables at larger scales.

Watershed scale models (SWAT, HSPF, HEC-HMS, etc.) output stream flow timing and peak characteristics but much of the important detail is lost through aggregation of time to days and months, and space to increasingly large subcatchments. The second approach applies SWAT (Arnold et al., 1998) or similar conceptual modeling platform to represent heterogeneities over a large range of spatial scales. Simplified modeling algorithms which incorporate tile drainage, route water out of hydrologic subbasins into stream links and out of the system (Green et al., 2006; Kiesel et al., 2010; Rahman et al., 2014). MIKE-SHE (Refsgaard et al., 1995) and MODFLOW (McDonald and Harbaugh, 1988) offer increasingly complex alternatives, simulating tile drainage systems as a head dependent boundary conditions within a complex 3-D subsurface, based on user input drain depth and conductance terms.

The most complex numerical models incorporate a fully coupled 3-D subsurface, 2-D surface, and 1-D tile flow into hydrologic simulations, such as Hydrogeosphere (HGS) (De Schepper et al., 2015; Rozemeijer et al., 2010a) as reviewed by Hansen et al. (2013). Adding a realistic representation of tile drainage into numerical models is important to investigate subsurface flow pathways (Kiesel et al., 2010). The complex fully coupled system offers detailed insights into the hydrologic system, such as groundwater–surface water interaction, variable flow route contributions, and travel times, which other approaches may miss. With the added numerical burden of these complex systems, approximate methods have been tested to represent tile drainage impacts. Carlier et al. (2007) presented an equivalent medium approach, where regularly spaced drainage systems were represented by a highly permeable subsurface layer. Rozemeijer et al. (2010a) applied this approach as a boundary condition to an internal explicit drain tile representation. De Schepper et al. (2015) compared numerous simplifications to tile drainage representation at the subcatchment scale, finding that an equivalent medium approach was able to represent surface outflow and subsurface hydraulic heads adequately. De Schepper et al. (2015) noted a significant increase in computation speed derived from a reduced mesh resolution, and simplified internal boundary conditions.

The goal of this study was to investigate two main concepts: (1) Estimate equivalent porous medium parameters to represent tile drainage for watershed scale simulations using field scale numerical experimentation. Without field scale tile drainage data, an explicit representation of field tiles was used as a calibration target. (2) Quantify the impact tile drainage has on stream flows during events, and during intra-event periods and analyze how these patterns vary with spatial scale. To accomplish these goals, we provided a combined methodology of tile drainage application at the watershed scale, and tracer based flow route contribution. HGS was applied to a watershed dominated by tile drained agriculture. An annual meteorological time series was chosen to force the numerical model, expanding on previous studies focused on single events. Event and non-event time periods were investigated independently to determine the spatiotemporal dependency of tile drainage contribution to surface flow.

2. Methodology

2.1. Study area

The focus of this study was the Beaver Creek Watershed (BCW), a 45 km^2 catchment, located in the agriculturally dominated central U.S. Land use in the BCW is predominantly row crop agriculture (corn and soybeans), constituting 72% of the catchment (Fig. 1). The remaining land is a mix of grasslands in the south

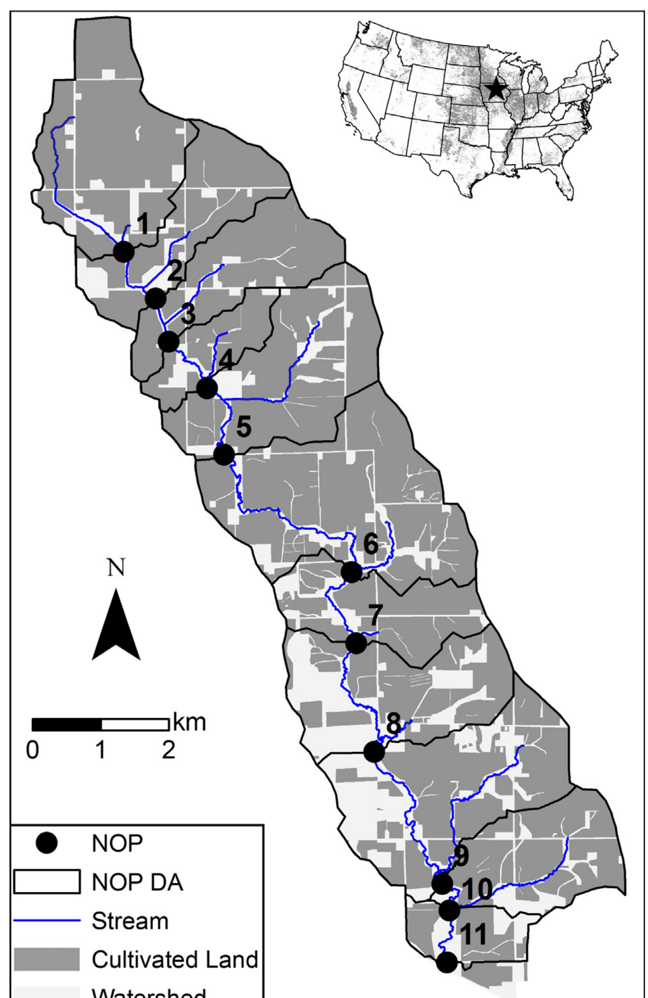

Fig. 1. BCW location and agricultural land classification (FSA, 2013). Numerical Observation Points (NOP) labeled from upstream to downstream.

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