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Hydrologic impacts of subsurface drainage at the field scale: Climate, landscape and anthropogenic controls

Brandon P. Sloan[a,1], Nandita B. Basu[b,*], Ricardo Mantilla[a]

[a] IIHR-Hydroscience and Engineering, University of Iowa, C. Maxwell Stanley Hydraulics Laboratory, Iowa City, IA 52242, United States
[b] Civil and Environmental Engineering, and Earth and Environmental Sciences, University of Waterloo, 200 University Avenue West, Waterloo, ON N2L 3G1, United States

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ABSTRACT

Installation of subsurface drainage systems is one of the most common modifications of the agricultural landscape, and while it is well accepted that these systems alter the hydrologic regime, the nature and magnitude of such alterations remains poorly understood. We explore the impact of drainage systems using the field-scale model DRAINMOD and rainfall and soils data for Iowa. Our objective is to understand how climate, landscape and anthropogenic controls modify the hydrological response at the field scale. We show that drainage systems do not significantly alter the annual peak flows (Q_P). This is because Q_P is typically generated by the largest storms of the year for which the additional soil storage created by the drains does not significantly alter the total quick-flow volume of water entering the streams, and thus the hydrograph peaks. We identify a threshold storm size (~6 cm/day for Iowa) beyond which tiles have minimal impact on the peak flow. Effects are apparent, however, for peak flows generated by other storms in which the percent of peak flow reduction is a function of the storm size and the antecedent moisture conditions. The effect of the drains on runoff production is further investigated using the daily Flashiness Index (FI). For soils with high hydraulic conductivity (K), tile drains increase the FI due to faster flow routing through subsurface drains, while for soils with low K, drainage decreases flashiness due to availability of increased soil storage that reduces surface runoff. We conclude that tile drains homogenize spatial patterns in hydrologic response by minimizing response differences between soil types. Furthermore, we investigate the effects of tile spacing and show that the FI decreases with an increase in drain spacing up to an optimal spacing (S_M), beyond which FI increases with greater spacing. The FI-S_M relationship was found to be a function of soil type and rainfall intensity, with the U-shaped behavior more apparent for low K soils and high rainfall intensity.

1. Introduction

Artificial drainage of soils using subsurface tile drains and surface ditches is a commonly used agricultural practice to increase crop productivity in poorly drained, but highly productive soils (Zucker and Brown, 1998). Subsurface drainage involves installing a network of drainpipes, typically 1–2 m below the land surface that routes the infiltrated water, in excess of the gravitational water (field capacity water content), into surface drainage ditches, which eventually flow into the stream network. Tile drains maintain the water table at a depth of 1–2 m below the ground surface, thus allowing the crop root system to thrive, and preventing excess water from inhibiting crop growth, as long as the capacity of the drainage system is not exceeded. Large-scale agricultural drainage has been practiced in many parts of the world, including the US, Northwestern Europe and Asia (Lennartz et al., 2011). More than 30% of agricultural soils in the Midwestern US are drained, while the estimates are even higher in the UK (60.9%), Netherlands (65.2%), Denmark (51.4%) and Finland (91%) (Goudie, 2000). The spatial extent of this landscape modification underscores the importance of studying these systems and understanding how they have altered the hydrologic regime.

It is well recognized that proliferation of artificial drainage has led to severe environmental impacts, including loss of wetland and floodplain ecosystems, and alteration of the streamflow regime (that in turn affects stream morphology), instream and riparian

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* Corresponding author
E-mail address: nandita.basu@uwaterloo.ca (N.B. Basu).

[1] Current address: Short Elliott Hendrickson Inc., 3535 Vadnais Center Drive, St. Paul, MN 55110, United States.

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habitats, nutrient cycles and biota (Blann et al., 2009; Thompson, 2002). However, despite this widespread knowledge, use of subsurface drainage is increasing in many agricultural regions, motivated by economic (increase in corn prices) and climatic (increase in high intensity rain events) factors. While most of the installation of subsurface drainage in the Midwestern US occurred in the late 1800s and early 1900s (Miller et al., 2009), enhancement of the drainage network is now being triggered by the need to replace aging infrastructure. Concurrent with increase in drainage, there has been increasing concern regarding how drainage systems impact streamflow fluctuations and water quality. Specifically, following the major floods in Iowa that led to large property loss and millions of dollars in economic loss (Des Moines Register, 2010; Barnes and Eash, 2012), as well as studies suggesting an increased frequency of flooding in the Midwest (Mallakpour and Villarini, 2015), there has been growing concern regarding the role of tiles in altering flood peaks.

Despite decades of research on subsurface drainage, there remains significant controversy regarding the impact of these drains on catchment hydrology. While some researchers argue that drainage systems reduce runoff by draining the soils before a precipitation event which increases subsurface moisture storage, others contend that tile drains increase flows by accelerating soil water movement through the subsurface into ditches and streams (Wiskow and van der Ploeg, 2003). An extensive review on this subject by Robinson and Rycroft (1999) and Robinson (1990) demonstrated that tiles can indeed both increase and decrease peak flows, and that the dominant behavior is a function of a complex interplay of landscape, climate and management controls. Apart from these reviews in the late 1900s, few studies have explored the effect of drainage on peak flows, and most studies on tile drainage have focused on how drains have altered water quality (Lemke et al., 2011). However, as discussed above, more and more agricultural areas are being tiled, which makes it critical to study the effects of tiling on watershed hydrology.

Our objective in this paper is to better our understanding of the impact of tile drains on the hydrologic regime using the field-scale model DRAINMOD (Skaggs, 1981). DRAINMOD is one of the most widely used hydrologic models to simulate subsurface drainage by calculating surface runoff, infiltration, evapotranspiration, subsurface drainage and seepage from the soil profile (Singh et al., 2006). Specifically, we will explore how rainfall, soil type and anthropogenic factors control the relationship between agricultural drainage and hydrologic flows. We focus our analysis on the state of Iowa; however, the simulation results and methodology are applicable to similar conditions in the Midwest and other parts of the world.

2. Methods

2.1. DRAINMOD

The field-scale model DRAINMOD was used to simulate the effects of landscape (soil-type and surface storage), climate and anthropogenic or management factors on the hydrologic response of drained fields. DRAINMOD has been utilized in many studies over the past 30 years to explore a range of issues, from hydrologic impacts to nutrient loading, and it is a well-accepted approach for describing field-scale behavior (Skaggs, 1981; Singh et al., 2006; Skaggs et al., 2012). Recently, Singh et al. (2006) calibrated and validated a DRAINMOD model on Iowa State University's experimental plots near Gilmore City for two common Iowa soils: Webster and Canisteo. Tile flow was collected at these 0.05 ha field plots with 7.6 m tile spacing, a tile incision depth of 1.06 m, and a continuous corn rotation (Webster) or a corn-soybean rotation (Canisteo soil). The model was calibrated using monthly tile flow data from 1990 to 1993 and validated with data from 1994 to 2003, with Nash-Sutcliffe model efficiency coefficients of 0.89 and 0.56 over the calibration and validation periods, respectively (Singh et al., 2006). The study used the Iowa Soil Properties and Interpretations Database (ISPAID) Version 7.0 and the pedotransfer function ROSETTA to predict the soil hydraulic parameters that are necessary inputs to DRAINMOD. The vertical and lateral saturated hydraulic conductivities, and the parameter α, which controls the relationship between the water table depth and the volume drained, were used for calibration. The calibrated Webster model is the baseline for our field-scale analysis.

2.2. Metrics for analyzing hydrologic response

We used hydrographs, mean annual peak discharge Q_P (mm/h), the Richard–Baker Flashiness Index (FI) and the flow duration curve (FDC) as metrics for analyzing the hydrologic response. The hydrologic response that we investigate is the ditch flow out of the tile-drained field, which is the sum of the surface runoff, tile flow and lateral seepage. The flow duration curves were estimated using the mean daily flow data (mm/h), as recommended by the USGS (Searcy, 1959). The Richard-Baker Flashiness Index, which is a measure of flow oscillations relative to the total flow and is a good indicator of how quickly a system responds to a hydrologic input (Deelstra and Iital, 2008), is defined as,

$$\mathrm{FI} = \frac{\sum_{i=1}^{n} |q_i - q_{i-1}|}{\sum_{i=1}^{n} q_i} \tag{1}$$

where, q_i and, q_{i-1} are the mean daily flow (mm/h) on day i and day i-1, respectively, and n is the total number of time steps. For the Q_P and FI metrics, the difference between drained and undrained fields was evaluated at a significance level of 0.05 by calculating the statistic (p-value) for the one-tailed t-test assuming unknown and unequal variances in the program R.

2.3. Model simulations: parameters and design scenarios

The calibrated model was used as a diagnostic tool to explore the effects of (1) soil type, (2) surface storage, (3) rainfall patterns, and (4) drainage designs typical to Iowa on the hydrologic response. The parameters relevant to these four groups of simulations are described in this section.

2.3.1. Effect of soil type

We used the USDA-NRCS Digital General Soil Map of the United States (STATSGO2) to determine the main soil types across Iowa as silt clay loam, loam, and silt loam (K = 11, 12, and 18 cm/day). Furthermore, in order to capture the effect of end member soil types, clay, silt, and sand (K = 15, 44, and 643 cm/day) were also analyzed. The hydraulic parameters for these soil textural classes required by DRAINMOD were estimated using the pedotransfer function ROSETTA (USDA, 2005). The saturated lateral hydraulic conductivity (K_L) was assumed to be 1.4 times the vertical hydraulic conductivity K_V (Singh et al., 2006).

Hourly precipitation and daily minimum and maximum temperature data were obtained from the NOAA National Climatic Data Center (NCDC) for Iowa City, Iowa (COOP #134101) for 1981–2010. Potential Evapotranspiration (PET) adjustment factors were left unchanged from the calibrated values. The surface storage magnitude of 1.25 cm was also left unchanged from the calibrated values (Singh et al., 2006). Drainage spacing was assumed to be equal to 20 m, and drains were placed at a depth of 1 m below the ground surface based on typical values found in the Iowa Drainage Guide (Iowa State University Extension and Outreach, 2012). Depth to the