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Quantifying the contribution of tile drainage to basin-scale water yield using analytical and numerical models

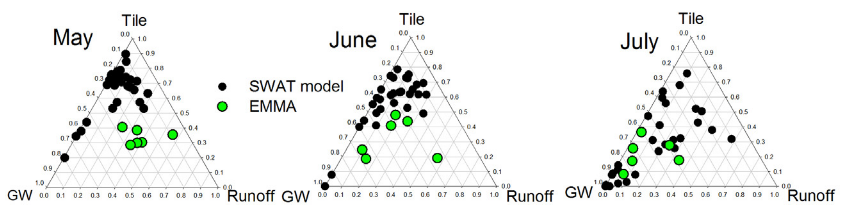
Keith E. Schilling [a,*], Philip W. Gassman [b], Antonio Arenas-Amado [c], Christopher S. Jones [c], Jeff Arnold [d]

[a] Iowa Geological Survey, University of Iowa, Iowa City, IA, United States of America
[b] Center for Agricultural and Rural Development, Iowa State University, Ames, IA, United States of America
[c] IIHR-Hydroscience & Engineering, University of Iowa, Iowa City, IA, United States of America
[d] Grassland Soil and Water Research Laboratory, USDA-ARS, Temple, TX, United States of America

HIGHLIGHTS

- Discharge from subsurface drainage tiles comprises a substantial fraction of water yields in intensely-drained watersheds
- Contributions from tile drainage to basin-scale water yields were detectable beyond 16,000 km^2
- A better understanding of water sources contributing to river discharge is needed for mitigation and control strategies.

GRAPHICAL ABSTRACT



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ABSTRACT

The Des Moines Lobe (DML) of north-central Iowa has been artificially drained by subsurface drains and surface ditches to provide some of the most productive agricultural land in the world. Herein we report on the use of end-member mixing analysis (EMMA) models and the numerical model Soil and Water Assessment Tool (SWAT) to quantify the contribution of tile drainage to basin-scale water yields at various scales within the 2370 km^2 Boone River watershed (BRW), a subbasin within the Des Moines River watershed. EMMA and SWAT methods suggested that tile drainage provided approximately 46 to 54% of annual discharge in the Boone River and during the March to June period, accounted for a majority of flow in the river. In the BRW subbasin of Lyons Creek, approximately 66% of the annual flow was sourced from tile drainage. Within the DML region, tile drainage contributes to basin-scale water yields at scales ranging from 40 to 16,000 km^2, with downstream effects diminishing with increasing watershed size. Developing a better understanding of water sources contributing to river discharge is needed if mitigation and control strategies are going to be successfully targeted to reduce downstream nutrient export.

1. Introduction

Production of row crops of corn and soybeans in the United States (U.S.) is concentrated in the Corn Belt, a region of highly productive, glacially-derived soils covering large portions of many states including Iowa, Minnesota, Illinois, Indiana and Ohio (McLellan et al., 2015). Excessive loss of nitrogen and phosphorus from this region is contributing to severe nutrient enrichment of rivers and streams at local and regional scales, with impacts observed in the Gulf of Mexico (USEPA, 2013; Jones et al., 2018b). A major factor contributing to this nutrient loss is the presence of artificial drainage systems to drain excess water from wet, prairie soils for improved crop production (Schilling et al., 2012).

The recently-glaciated Des Moines Lobe (DML) of central Iowa contains some of the most productive agricultural land in the world. This

* Corresponding author.
E-mail address: keith-schilling@uiowa.edu (K.E. Schilling).

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area reflects the southernmost extent of Wisconsin-age glaciation that occurred approximately 12,000 years ago (Prior, 1991). The disintegrating glacier left behind a flat till plain dominated by wet prairie and poorly drained wetlands and swamps that were once considered “unfit for human habitation” (Kanwar et al., 1983). From the late 1880's to early 1900's, artificial drainage in the form of subsurface drains and surface ditches were installed to drain the land for crop production. In many areas of the DML, drainage districts were formed by landowners to facilitate coordinated drainage over large areas for the purpose of “improving lands for agriculture” (McCorvie and Lant, 1993) which resulted in an estimated reduction of DML wetlands of 95% to 99% (Miller et al., 2009). By the late 1920's over 2.5 million hectares of Iowa were part of drainage districts and today they number >3000 (Schilling et al., 2012). The practice of tile drainage continues today as drainage systems are continually expanded and upgraded (McIsaac and Hu, 2004). In recent decades farmers have installed pattern tile systems that lower the water table across farmed fields in a systematic manner (Cook and Pecinovsky, 2006). Overall, crop productivity in many of Iowa's agricultural lands, especially those with hydric soils found in the DML, can be maximized only when drainage is present (Wheaton, 1977).

The magnitude of the effects of tile drainage on changing streamflow conditions in the Midwest has been the subject of considerable debate (Gupta et al., 2015; Belmont et al., 2016; Foufoula-Georgiou et al., 2016; Schilling, 2016; Dingbao, 2016; Schottler et al., 2014) and is not the focus of this study. It is recognized that historical changes in streamflow in the glaciated Midwest across the 20th Century have been influenced by the combined effects of climate, changing land cover and expansion of artificial drainage (e.g., Schilling and Libra, 2003; Zhang and Schilling, 2006; Schilling et al., 2008; Lenhart et al., 2011; Frans et al., 2013; Xue et al., 2013; Kelly et al., 2017). Our study is instead focused on assessing the contribution of tile drainage to watershed-scale water yield within the context of the current agricultural cropping system. Land use patterns have remained relatively stable in many intensely cropped areas within the U.S. Corn Belt region during the past few decades (Jones and Schilling, 2011) and the extent of tile drainage has likely reached its maximum in the central Midwest. Schilling et al. (2015) considered maximum tile drainage density in central Iowa to be approximately 0.04 m^{-1}, equivalent to approximately 400 m of drainage per ha.

In non-tiled landscapes, direct precipitation inputs, surface runoff and groundwater seepage as baseflow provide the main pathways for water movement into a stream. However, in drained areas, tiles provide an additional pathway for water transport and it is difficult to separate the tile contribution from the other water sources (Blann et al., 2009). In some studies, unit discharge from tile drainage sites has been scaled up to the watershed to estimate tile contributions (e.g., Ikenberry et al., 2014; King et al., 2015). King et al. (2015) reported that tile drainage accounted for 56% of the annual watershed discharge over an eight-year period in a small Ohio watershed consisting predominantly of silt and clay loam soils (Alfisols Order). Likewise, other smaller watershed (<4 km^2) studies have reported tile drainage contribution to stream flow ranging from 0% to 90% (Macrae et al., 2007), and 30% to 61% (King et al., 2014). End member mixing analysis (EMMA) models have also been used to estimate tile contributions to river discharge at the timescale of a single storm event (Schilling and Helmers, 2008b; Tiemeyer et al., 2008; Tomer et al., 2010; Smith et al., 2015). At a longer time scale, Arenas-Amado et al. (2017) used a mixing model to estimate the contributions of quick flow, groundwater, and tile drainage to streamflow for an eight-month period in a northeast Iowa watershed. They reported that tile drainage accounted for 15–43% of streamflow from April to November.

Numerical models are often used to provide insights into tile drainage impacts on watershed hydrology. Modeling using a detailed field model such as DRAINMOD (Skaggs, 1982), can offer increased temporal detail in assessing tile drainage impacts during rainfall events. Sloan et al. (2016) used DRAINMOD to investigate the effects of drainage tiles on peak flows, reporting that tiles reduced peak flows below a rainfall threshold of 5–6 cm but had no impact on peak flows above this level. More complex numerical models incorporate fully coupled surface and subsurface processes into hydrologic simulations and these models can provide a more realistic representation of tile drainage (De Schepper et al., 2015; Rozemeijer et al., 2010; Thomas et al., 2016). For example, using the model Hydrogeosphere (HGS), Thomas et al. (2016) investigated the impacts of tile drainage on streamflow at a watershed scale and reported that tile drainage represented 30% of streamflow during storm runoff events but 61% during intervals between precipitation events. However, these complex coupled models often require detailed parameterization, or simplification in the use of an equivalent porous medium to simulate tile layers (De Schepper et al., 2015; Rozemeijer et al., 2010; Thomas et al., 2016) and tend to be computationally intensive. Other numerical models such as MIKE-SHE (Refsgaard, 1995) and MODFLOW (McDonald and Harbaugh, 1988) simulate tile drainage as head-dependent boundary conditions.

At a watershed scale, the Soil and Water Assessment Tool (SWAT) ecohydrological model (Arnold et al., 1998; Williams et al., 2008; Arnold et al., 2012b) has been applied for an extensive variety of water resource problems across the globe for systems ranging from small research plots, to river basins that drain multiple countries and entire continents (Gassman et al., 2007, 2014a, 2014b; Bressiani et al., 2015; Gassman and Wang, 2015; Krysanova and White, 2015). Algorithms for simulating tile drains were first introduced in SWAT version 98.1 (SWAT98.1; Gassman and Wang, 2015), which were further improved in research described by Du et al. (2005, 2006) and Green et al. (2006) and were ultimately incorporated in SWAT version 2005 (SWAT2005; Gassman et al., 2007; Gassman and Wang, 2015). Alternative tile drainage algorithms that were developed on the basis of the physically-based Hooghoudt and Kirkham tile drain equations have also been grafted into more recent SWAT version 2012 (SWAT2012) codes (Moriasi et al., 2012, 2013). At present, over 50 studies have been documented that incorporate tile drain representation in SWAT (CARD, 2018), many of which have been performed in the U.S. Corn Belt region (e.g., Du et al., 2005, 2006; Green et al., 2006; Jha et al., 2007, 2010; Schilling et al., 2008, 2014a, 2014b; Schilling and Wolter, 2009; Moriasi et al., 2012, 2013; Yen et al., 2015; Gassman et al., 2017a; Ikenberry et al., 2017; Panagopoulos et al., 2015;Valcu-Lisman et al., 2017).

In this paper, we report on two different approaches to quantify the contribution of tile drainage to basin-scale water yields in an intensively-drained DML watershed located in north-central Iowa. Using EMMA analyses and the numerical model SWAT, we focused our investigation at two different scales within the same watershed. At a smaller scale, we assessed tile drainage discharge from three large drainage district tile outlets into a 42 km^2 subbasin, whereas at a larger scale, we evaluated cumulative tile drainage contributions to the larger 2370 km^2 receiving river. By combining multiple approaches and reporting results using end-member ternary diagrams, we demonstrate that tile drainage is a significant component of the annual and seasonal water yield in intensively-drained basins at a variety of spatial scales. Ultimately, developing a better understanding of water sources contributing to river discharge is critical if mitigation and control strategies are going to be successfully targeted to reduce downstream nutrient export.

2. Methods and materials

2.1. Site description

The Boone River watershed (BRW) drains 2370 km^2 from six counties in north-central Iowa (Fig. 1). Considered an eight-digit hydrologic unit code (HUC8) watershed (USGS, 2013), the BRW has been divided into approximately 30 HUC12 subwatersheds located in the DML. Dominant soils include the Canisteo-Nicollet-Webster soil association (Mollisols order)

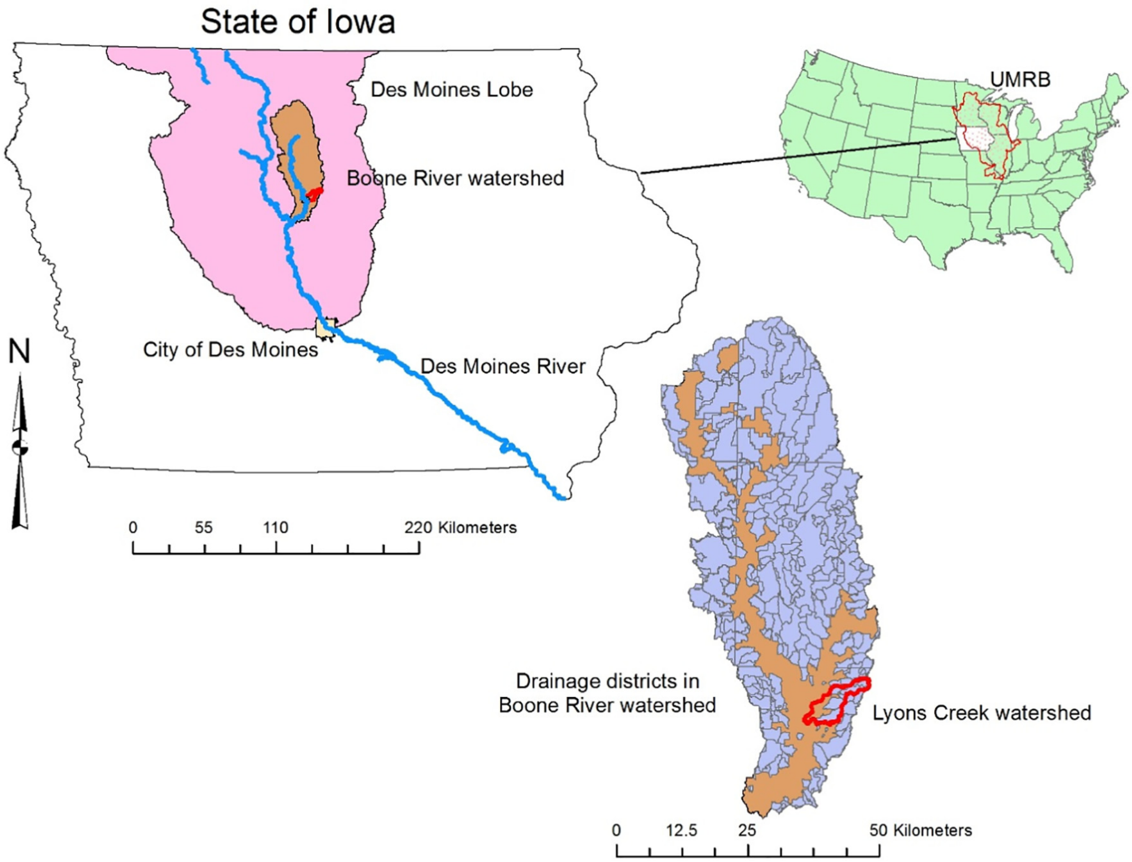

Fig. 1. Location of Lyons Creek and Boone River watersheds within the Des Moines Lobe region of Iowa. Three drainage districts and associated infrastructure within Lyons Creek watershed are shown. The Des Moines River drains into the Upper Mississippi River Basin (UMRB shown in inset map).

consisting of silty and loamy soils formed in glacial till and wetlands (Schilling et al., 2013). Land use in the watershed is dominated by corn (48.5%) and soybean (41.4%) production (total row crop is 89.9%), with minor land uses including pasture, Conservation Reserve Program (CRP) lands and other grasslands (5.4%), woodland (2.6%), urban areas (2.0%) and water/wetlands (<0.1%) (Gassman et al., 2017b). Nearly 60% of the BRW soils have been mapped as "poorly drained" and over 75% of soils are characterized as "hydric" or "partially hydric" (Gassman et al., 2017b).

To achieve such cropping intensity in the flat and poorly drained landscape of the DML, much of the BRW has been artificially drained using a network of subsurface drainage tiles and surface ditches. The BRW contains dozens of organized drainage districts (Fig. 1) which are quasi-governmental entities incorporated in the Iowa Constitution that are tasked with managing tile infrastructure in the respective drainage district (McCorvie and Lant, 1993). While the extent of the drainage district infrastructure is known, the extent of tile drainage within individual cropped fields is uncertain (Schilling et al., 2015). Typical drain depth is approximately 1.2 m (Gassman et al., 2017a) and spacing in typical DML soil associations in Iowa is 24–30 m (Singh et al., 2006). Within the BRW, our study also focused on the 42 km^2 Lyons Creek watershed (LCW) that drains into the Boone River near the town of Webster City (Fig. 1). Land cover in LCW is similar to the BRW and is dominated by corn and soybean production (84%).

2.2. Methods

2.2.1. Discharge data

Daily streamflow in the Boone River for the 1984–2013 period was obtained from the USGS gaging station near Webster City (ID = 05481000) located approximately 7 km downstream of the mouth of Lyons Creek (Fig. 1). Precipitation measured at a station in Webster City is available on line from the Iowa Environmental Mesonet (https://mesonet.agron.iastate.edu/).

2.2.2. EMMA

Chemical and isotopic tracers (i.e., Ca, Mg, Na cations, Cl^-, NO_3, electrical conductivity) are typically used in EMMA to evaluate sources of water contributing to stream runoff (e.g., Barthold et al., 2011; Christophersen and Hooper, 1992). By linearly mixing conservative tracers, hydrographs of streams can be separated into two or more components provided the different sources have sufficiently different compositions for different contributing water sources.

In our study, EMMA was conducted using a combination of stream discharge data and high frequency measurements of nitrate-nitrogen (nitrate) concentrations collected at the USGS Boone River gaging station near Webster City (Fig. 1). A Hach Nitratax sc plus sensor, installed at the Webster City site in 2012, quantifies nitrate + nitrite by measuring absorbance at 210 nm with background correction 350 nm for turbidity and organic matter, and has a measurement range of approximately 0.1–25 mg/L with an accuracy of +/−3% of the measured value. Nitrate concentrations are typically measured every 15 min from approximately April to November each year of operation. For this study, we compiled the 15 min data as daily averages for the 2012 to 2017 period.

Daily Boone River nitrate concentrations together with daily discharge measured at the gaging site were used to perform an EMMA-based assessment on the contribution of groundwater, tile and surface water runoff. The goal of the EMMA investigation was to evaluate the maximum and minimum contribution of tile drainage to Boone River discharge.

End-member quantification was accomplished by solving a system of linear equations:

$$Q_{BR} = Q_{gw} + Q_t + Q_{surf} \quad (1)$$

$$Q_{Bf} = Q_{gw} + Q_t \quad (2)$$

$$Q_{BR}C_{BR} = Q_{gw}C_{gw} + Q_tC_t + Q_{surf}\,C_{surf} \quad (3)$$

where the Q represents flow, Bf baseflow (digital filtering method; Eq. (1)), C nitrate concentration, and BR stands for Boone River. Sub-indices gw, t and surf stand for groundwater, tile, and surface runoff, respectively.

For Eq. 3, representative nitrate concentration values were selected for the three end-members from predetermined acceptable ranges. The nitrate concentration ranges were determined based on literature review, analysis of in-stream measured concentrations, and communications with watershed stakeholders. Surface water runoff nitrate concentrations in Iowa are approximately 1–2 mg/L (Cambardella et al., 1999; Zhou et al., 2014) and for this study we used values between 0.5 and 2.5 mg/L for scenarios. Groundwater nitrate concentrations discharging into the Boone River are unknown but we assume that they are <10 mg/L since shallow groundwater nitrate concentrations in the DML tend to be low in private wells. Schilling (2017) reported mean nitrate concentrations from approximately 1 to 9 mg/L in 34 central Iowa wells <9 m deep. Likewise, Kross et al. (1993) reported that 94% of private wells in north-central Iowa had nitrate concentrations <10 mg/L. Arenas-Amado et al. (2017) considered a suitable range of groundwater nitrate concentrations to be approximately 2–4 mg/L in an EMMA study conducted in northeast Iowa. Herein, we assumed that the end-member groundwater nitrate concentrations varied between 2 and 10 mg/L. For tile drainage, we assumed that nitrate concentrations ranged from 10 to 30 mg/L based on monitoring data provided by the Iowa Soybean Association. This concentration range is representative of typical nitrate values discharged from field and drainage district tiles in Iowa (e.g., Ikenberry et al., 2014; Lawlor et al., 2008; Tomer et al., 2003).

The system of linear equations (Eqs. (1)–(3)) was solved repeatedly (>50,000 times), using nitrate concentrations for the three end-members randomly chosen from the predetermined ranges to find the set of nitrate concentrations that predicted both the maximum and minimum contribution of tile drainage to BRW discharge. The analysis was conducted for the April to October period during 2012 to 2017 when Nitratax sensor data were available. This time period coincides with the active period of tile drainage flows in the BRW drainage districts (Schilling et al., 2013).

2.2.3. SWAT model

The current SWAT codes incorporate a mix of physical and empirical functions to depict simulated systems and represent over 30 years of model development (Gassman et al., 2007; Williams et al., 2008; Arnold et al., 2012b; Gassman and Wang, 2015). SWAT can be executed for continuous watershed-scale simulations for any time period, pending available data, which are typically executed on a daily time step although sub-daily time step simulations are also possible. The delineation of a watershed in SWAT is performed by subdividing the simulated region into multiple subwatersheds, which are then usually further divided into Hydrologic Response Units (HRUs). The HRUs are characterized by homogeneous land use, management, topographic and soil data, and are represented as "lumped areas" in SWAT (i.e., are not spatially defined in a subwatershed). Hydrologic and pollutant dynamics are first simulated at the HRU level; the HRU flow and pollutant outputs are then aggregated within a given subwatershed and subsequently routed through channels, impoundments and potentially other features to the watershed outlet. The model consists of several components including climate, hydrology, crop and plant growth, pollutant cycling and transport, and management. Further details regarding SWAT theory and inputs are provided in Neitsch et al. (2011) and Arnold et al. (2012a).

2.2.3.1. Key algorithm choices. The SWAT modeling approach used in this study is based directly on immediate predecessor studies (Gassman et al., 2017a; Valcu-Lisman et al., 2017) including the following two algorithms: (1) runoff curve number (RCN) approach computed as a function of evapotranspiration (ET), and (2) the original empirical tile drainage method. Current versions of SWAT feature multiple RCN options (Gassman et al., 2017a) or the Green-Ampt method (Green and Ampt, 1911) for simulating the partitioning of precipitation between surface runoff and infiltration (Neitsch et al., 2011). The ET-based RCN approach requires the use of a plant ET curve number coefficient (CNCOEF) as described in Kannan et al. (2008), Neitsch et al. (2011) and Williams et al. (2012), and resulted in improved results in several previous studies versus the traditional RCN approach that is based on soil moisture accounting (Green et al., 2006; Kannan et al., 2008; Gassman, 2008; Yen et al., 2015; Ikenberry et al., 2017). Tile drainage effects were computed using the original empirical tile drainage method which includes the following parameters: tile drain depth, the time required to drain the soil to field capacity, lateral flow time, drain tile lag time and an impervious layer depth (Du et al., 2005, 2006; Green et al., 2006; Neitsch et al., 2011).

2.2.3.2. SWAT calibration and validation. The input data, model structure and calibration process for the BRW SWAT application are described in depth in several previous studies (Gassman, 2008; Gassman et al., 2017a, 2017b; Valcu et al., 2016; Valcu-Lisman et al., 2017). The overall baseline SWAT testing process included evaluation of crop yields, streamflow, and pollutant transport, which incorporated aspects of protocols proposed by Nair et al. (2011) and Arnold et al. (2012b, 2015). Key aspects of the hydrologic simulation method and testing process are reviewed here to provide an overview of how the relatively flat, heavily tile-drained BRW cropland landscapes were represented in SWAT.

The BRW was subdivided into 30 subwatersheds, which were further delineated by a total of 2212 HRUs, to perform the SWAT simulations. The tile drain depth was set at 1200 mm, which is consistent with other several other previous SWAT studies performed in the region (Jha et al., 2007, 2010; Schilling and Wolter, 2009) and it was assumed that all cropland <2% in slope was managed with tile drains. A 30-year (1984 to 2013) simulation period was chosen to perform the SWAT BRW streamflow testing, which was evaluated per a 15-year (1999 to 2013) calibration period, 15-year (1984 to 1998) validation period and overall 30-year simulation period (1984 to 2013). Each of the three simulation periods was preceded by a two-year initialization period. The streamflow comparisons were performed by comparing predicted streamflows with measured streamflows at a U.S. Geological Survey (USGS) flow gauge located just south of Webster City (Fig. 1). The accuracy of the simulated streamflows relative to corresponding measured streamflows was determined on the basis of graphical comparisons and coefficient of determination (R^2) and Nash-Sutcliffe efficiency (NSE) statistics (Krause et al., 2005), which have been used extensively to assess SWAT statistical accuracy (e.g., Gassman et al., 2007, 2014a, 2014b; Bressiani et al., 2015). Criteria for assessing the success of ecohydrological model results have been suggested by Moriasi et al. (2007, 2015) which include the following NSE and R^2 thresholds for satisfactory replication of measured daily, monthly or annual streamflows: R^2 values > 0.60 and NSE > 0.50. The data for the annual and monthly comparisons are aggregated from the simulated or measured daily streamflow data.

2.2.4. Data analysis

Daily discharge and baseflow were compiled as monthly and annual totals and converted to water yield by dividing by watershed area.

Water yields quantified for groundwater, tile drainage and surface runoff components were summed and assumed to represent 100% of the flow discharging to the Boone River. In the case of hydrograph separation, this method was only capable of separating flows into groundwater and surface runoff components. For EMMA and SWAT outputs, ternary plots were used to graphically depict the fractions of the three components contributing to the total water yield. While common to many physical sciences, use of ternary plots in hydrologic analysis has not been widely explored. For this study, the ternary plots provide a convenient methodology to show differences among the different approaches, timeframes and scales in the relative proportion of major flow components contributing to discharge in a heavily-tiled watershed.

3. Results

3.1. EMMA

The EMMA algorithm was used to identify concentrations of groundwater, tile drainage and surface runoff that satisfied the two scenario conditions within the specified concentration ranges. For the maximum tile drainage scenario, groundwater, tile drainage and surface runoff nitrate concentrations were 2 mg/L, 24 mg/L and 1 mg/L, respectively. For the minimum tile drainage scenario, the concentrations were 10 mg/L, 30 mg/L and 2.5 mg/L, respectively. Tile nitrate concentrations of 24 and 30 mg/L best satisfied the maximum and minimum tile flow contributions to Boone River discharge.

The EMMA results showed that the contribution of tile drainage to Boone River discharge (Q_T) represented between 31 and 53% of streamflow for the maximum scenario and 19 to 37% for the minimum scenario for the six-year period (Fig. 2). Overall, the average tile drainage contribution was 45.6% and 29.5% for *max* and *min* scenarios, respectively, and the three-component flow separation for both scenarios plots in the central region of the ternary graph (Fig. 3). The average surface runoff component was the same for both scenarios (30.7%) despite differences in starting end member concentrations, indicating that contributions from tile and groundwater sources were highly related with one or the other dominating the subsurface discharge signal. For the time max scenario, the groundwater contribution was 23.7% whereas for the minimum scenario the groundwater contribution was 39.9%.

On a monthly basis, the tile contribution to water yields varies across the season (Fig. 4). A greater proportion of tile flow contributes to water yield in May and June for both max and min scenarios (~39 to 63%) and the contribution decreases in late summer and early fall (Table 1). The range of monthly tile drainage contribution is tightly clustered in May and June but variability increases substantially during the July–September period (Fig. 4).

3.2. SWAT modeling

3.2.1. Calibration and validation

Table 2 lists the parameter definitions (and units), parameter names, default values or recommended ranges and final values for the parameters that were adjusted as part of the calibration process. The final value for the CNCOEF value (Table 2) was determined via a sensitivity analysis that is described in Gassman et al. (2017b). A sensitivity analysis is also described in Gassman et al. (2017b) regarding the depth to impervious layer (DEP_IMP) parameter (Table 2), which revealed that there was very little effect on the SWAT output for DEP_IMP values that ranged between 1200 and 2500 mm.

Graphical comparisons of simulated versus measured aggregated annual and monthly streamflows are shown Figs. 5 and 6, respectively. The predicted annual streamflows tended to underpredict the measured streamflows during the first decade of the simulation period (Fig. 5). However, the reverse pattern can be discerned during the majority of the final simulated decade. Overall, the long-term estimated 30-year average streamflow was nearly identical to the corresponding measured streamflow. The predicted monthly streamflows also accurately tracked the majority of measured streamflows across the 30-year simulation period (Fig. 6). Some under prediction of peak monthly flows occurred in several years (e.g., 1984, 1986, 1993, 1997, 2010 and 2013), a phenomenon that has been documented in previous SWAT studies (Gassman et al., 2014b).

The statistical results of the evaluations for the comparisons of the predicted versus measured annual, monthly and daily streamflows are presented in Table 2 for the three simulation periods. The R^2 and NSE statistical results ≥0.75 and ranged between 0.94 and 0.98, 0.91 to

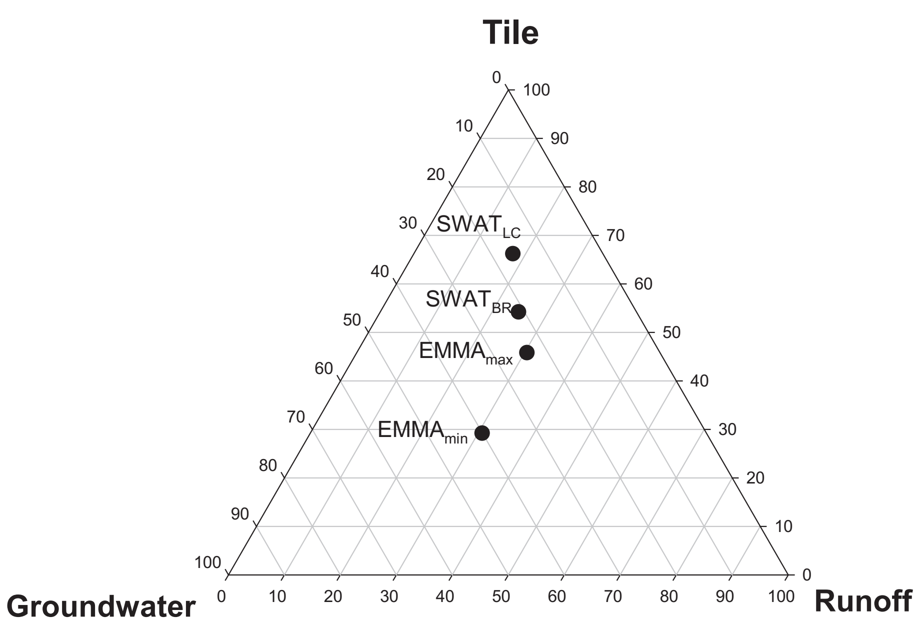

Fig. 2. Ternary diagram of the relative contribution of surface runoff, tile drainage and groundwater (GW) evaluated using end-member mixing analysis (EMMA) for maximum and minimum tile contributions and SWAT model for the Boone River ($SWAT_{BR}$) and Lyons Creek ($SWAT_{LC}$). Data length for each method was variable and results are based on the overall average for the method.

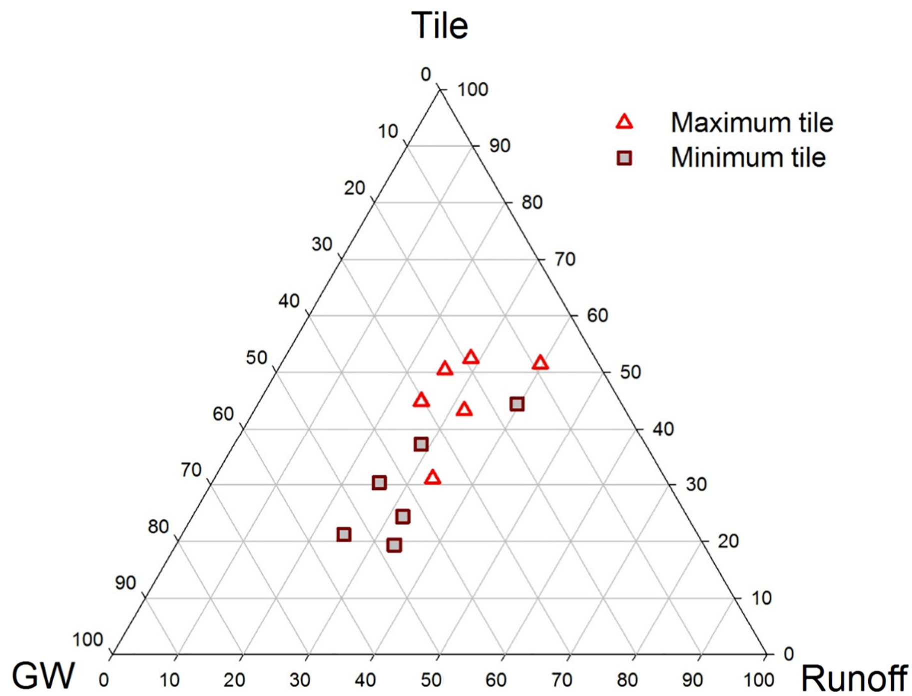

Fig. 3. Ternary diagram of the relative contribution of annual (2012–2017) surface runoff, tile drainage and groundwater (GW) for maximum and minimum EMMA tile drainage scenarios.

0.95 and 0.75 to 0.82 for the annual, monthly and daily streamflow comparisons. These results are more than adequate based on the ecohydrological modeling criteria suggested by Moriasi et al. (2007, 2015). The statistical results also show that the common practice of temporally subdividing a SWAT simulation into calibration and validation periods (Arnold et al., 2012b; Gassman et al., 2007, 2014b; Nair

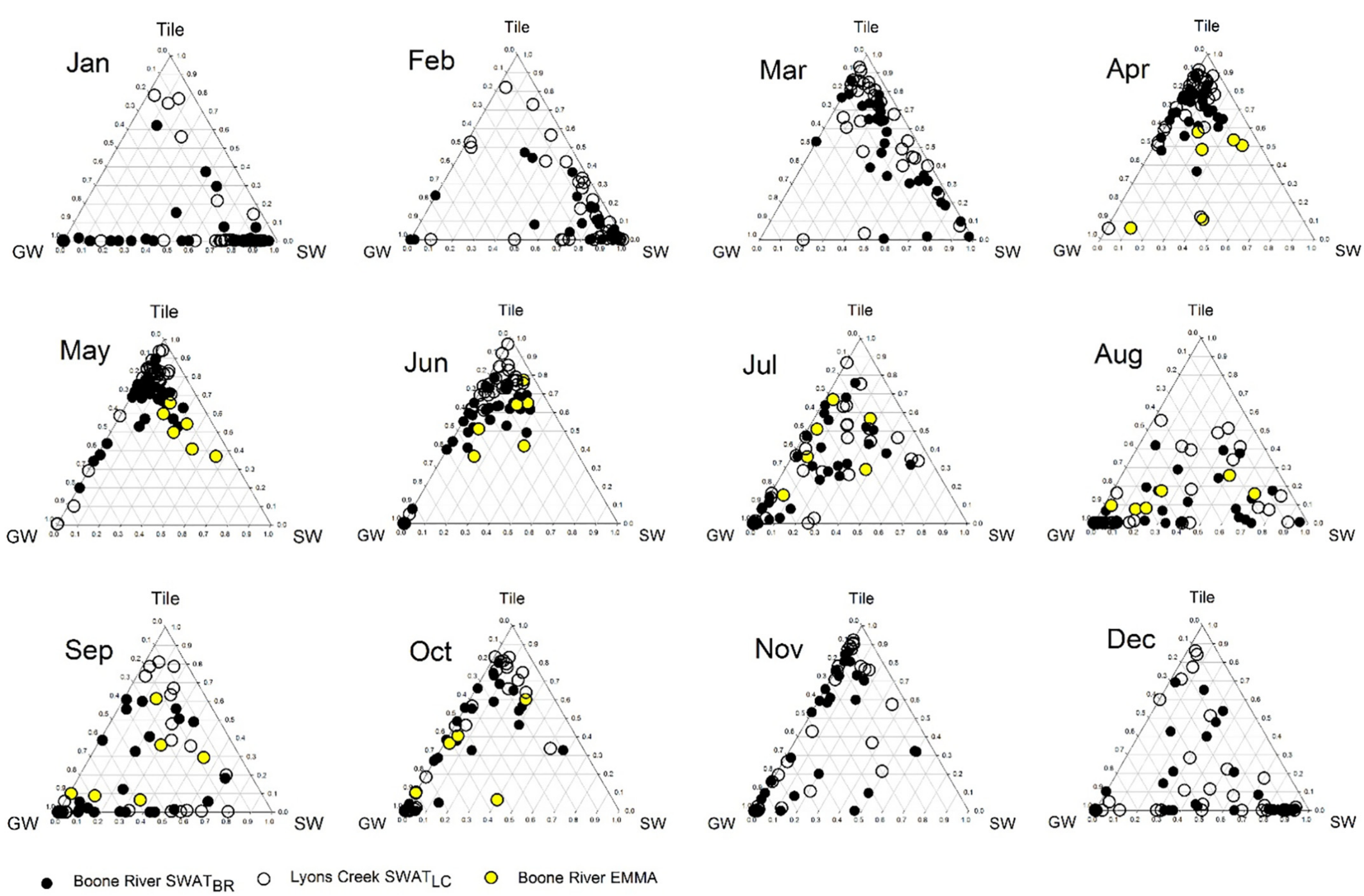

Fig. 4. Ternary diagram of the monthly relative contribution of surface runoff, tile drainage and groundwater (GW) evaluated using end-member mixing analysis (EMMA) for maximum tile contributions and SWAT model for the Boone River ($SWAT_{BR}$) and Lyons Creek ($SWAT_{LC}$).

Table 1
Summary of monthly mean tile drainage contribution to total streamflow (in percent).

Method	Where applied	All years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
EMMA	max	45.6				50.6	47.2	62.9	47.6	19.5	32.2	45.6		
	min	29.5				31.3	38.8	45.2	26.0	12.3	16.1	17.9		
SWAT	Boone	53.7	5.5	9.7	47.4	69.8	65.4	57.1	29.6	9.3	16.3	34.8	38.1	13.3
	Lyons	65.8	10.8	19.8	61.4	72.8	71.3	67.8	29.9	12.6	19.7	35.0	40.9	18.0

et al., 2011) had a negligible impact on the streamflow results relative to simply simulating the entire 30-year period.

3.2.2. Annual and monthly water yields

Annual water yields for runoff, groundwater and tile drainage were extracted from the calibrated SWAT model for the Boone River watershed and the Lyons Creek subbasin (Fig. 7). Contributions from tile drainage in the Boone River ranged from approximately 30 to 70% and averaged 53.7% for the 30-year simulation period. Compared to tile water yields, the annual contribution from groundwater varied within a relatively narrow range (~20–25%), whereas the range of variation for runoff was similar to tiles (Fig. 7). In the subbasin Lyons Creek, the fraction of annual water yield from tile drainage was approximately 10% higher than the Boone River (Fig. 7) and it averaged 65.8% for the 30-year simulation period (Table 1). The annual contribution from runoff was similar between the Boone River and Lyons Creek, but in this case, increasing tile drainage was mainly offset by a reduction in groundwater discharge. Overall, the mean annual contribution of tile drainage to basin-scale water yield decreased from approximately 66 to 54% from the heavily-tiled Lyons Creek subbasin to the larger Boone River (Fig. 2).

At a monthly scale, the source water contribution to water yield was variable (Fig. 4). February water yields were largely supplied by surface runoff, but contributions from tile drainage dominated monthly water yields from March to June in both the Boone River and Lyons Creek. Average tile water yields exceeded 60–70% at both spatial scales in the late spring and early summer period. From July to September flows were more evenly distributed across the three end-members, whereas in October and November, water yields were largely comprised of both groundwater and tile discharge. Groundwater contributions increased from July through December and tile drainage accounted for approximately 35 to 40% of streamflow in October and November (Table 3).

3.2.3. Sensitivity analysis

At the scale of the Boone River, water yields estimated using SWAT were closely related to the partitioning between tile drainage and runoff. We evaluated the sensitivity of this partitioning to the choice of CNCOEFF in the SWAT model. The CNCOEFF was changed from 0.75 (Table 3) to either 0.85 or 0.65 and the results indicated the annual contribution of tile drainage could be either decreased or increased, respectively. At a CNCOEFF of 0.85, long-term average runoff increased from 25 to 31% and tile drainage decreased from 54 to 49%. At a CNCOEFF of 0.65, tile drainage increased from 54 to 59% and runoff decreased from 25 to 19%. Both sensitivity scenarios included an annual groundwater contribution of approximately 20–22%. The results indicated that the estimated contribution of tile drainage to Boone River discharge could be modified to some degree based on the selection of the CNCOEFF. However, considering the range of CNCOEFF values evaluated in this study, results consistently suggest tile drainage contributions in excess of ~50% in the Boone River.

4. Discussion

4.1. Contribution of tile drainage to BRW water yields

In this study, EMMA and SWAT were used to separate the contribution of tile drainage discharge to water yields in the Boone River watershed. The two highly disparate methods produced similar contributions, with tile drainage providing an average 46 ($EMMA_{max}$) to 54% (SWAT) of the discharge in the Boone River. It is important to note that the EMMA results were focused only on the months of April to October and for a much shorter time period (six years) than the SWAT modeling (30 years). However, both the annual and monthly tile drainage yields of both methods followed similar patterns (Fig. 4).

The results from the BRW are consistent with other heavily tiled regions in the Midwest where tile drainage often accounts for one-half the

Table 2
Calibrated hydrologic parameters for the BRW baseline simulations[a,b].

Definition of adjusted SWAT parameter	SWAT parameter name	Default value or recommended range	Final calibrated value
Curve number calculation method (0 versus 1)	ICN	0	1
Plant ET curve number coefficient	CNCOEF	0.5–2.0[c]	0.75
Soil evaporation compensation factor	ESCO	0.95	0.91
Depth to subsurface drain (mm)	DDRAIN[d]	–	1200
Depth to impervious layer in soil profile (mm)	DEP_IMP	0.0	1200[e]
Time to drain soil to field capacity (hours)	TDRAIN[d]	–	24
Drain tile lag time (hours)	GDRAIN[d]	–	48
Surface runoff lag	SURLAG	4.0	0.5
Delay time for aquifer recharge (days)	GW_DELAY[f]	–	30
Baseflow recession constant	ALPHA_BF	0.1–0.3; 0.9–1.0[g]	0.9
Threshold water level in shallow aquifer for base flow (mm)	GWQMN[f]	–	0
Revap coefficient	GW_REVAP	0.02–20.0	0.02
Threshold water level in shallow aquifer for revap (mm)	REVAPMN[f]	–	2
Aquifer percolation coefficient	RCHRG_DP	0.0–1.0	0

[a] The tabulated information reported here was originally reported in Gassman et al. (2017b).
[b] Definitions, parameter names, and defaults/ranges are reported in Arnold et al. (2012a).
[c] The CNCOEF value is set to 0.0 if ICN = 0.
[d] Optional inputs for SWAT; default values are not given in the documentation.
[e] The depth to the imperious layer of 1200 mm was used only for cropland areas that are tile drained.
[f] Required inputs for SWAT; default values are not given in the documentation.
[g] The range of 0.1 to 0.3 are typical for systems with slow response to recharge versus 0.9 to 1.0 for systems with rapid response to recharge.

Table 3
Statistical results for the streamflow calibration, validation and entire simulation period at the outlet of the Boone River watershed[a].

Model testing phase	Time period	Annual		Monthly		Daily	
		R^2	NSE	R^2	NSE	R^2	NSE
Calibration (15-year)	1999–2013	0.97	0.93	0.91	0.93	0.77	0.75
Validation (15-year)	1984–1998	0.98	0.95	0.94	0.96	0.82	0.81
Entire duration (30-year)	1984–2013	0.95	0.95	0.92	0.92	0.79	0.78

[a] This table is adapted from Table 3 in Valcu-Lisman et al. (2017) and was also reported in Gassman et al. (2017b).

annual watershed discharge. King et al. (2015) reported that subsurface tile flow contributed 37% to 74% of discharge with an 8-year average of 56% in a 389 ha subwatershed of Upper Big Walnut Creek in Ohio. Macrae et al. (2007) estimated that 42% of the basin annual discharge originated from drainage tiles in a 3 km^2 watershed in Ontario. Arenas-Amado et al. (2017) and Thomas et al. (2016) estimated that tile drainage accounted for 15–43% and 39% of streamflow in two northeast Iowa watersheds, respectively, whereas Schilling and Helmers (2008a) reported that tile drainage (as baseflow) accounted for 60 to 80% of flow from a heavily-tiled central Iowa watershed. However, a unique aspect of our study is the much larger size of the BRW relative to other watershed studies, and we find it is rather astounding to report that ~50% of the annual flow in the river draining 2370 km^2 can be sourced to discharge from subsurface tile drainage. While the flow contribution from tile drainage may be large at first glance, it is important to recall that the topography of the recently-glaciated BRW is mostly flat and that the pre-settlement hydrology was once dominated by wet prairie and standing water in poorly drained prairie potholes and wetlands (Miller et al., 2009). Today, in contrast, if we assume a tile drainage density of 0.04 m^{-1} for intensive drainage on DML crop ground (Schilling et al., 2015), there could be on the order of 85,000,000 m of subsurface tile draining row crop lands in the BRW. Hence, the flow contribution from tile drainage would be consistent with its likely extent in the watershed and the change in hydrology from a watershed that naturally stored and infiltrated water to one that drains and sheds water (Menzel, 1983).

The tile drainage contribution to discharge in the BRW exhibited pronounced seasonality. During the March to June period, tile drainage accounted for a majority of monthly flow and flow fractions clustered at the apex of the ternary plot (Fig. 4). The March to June period is recognized as a dominant period of tile drainage discharge in the central Midwest due to snowmelt, increased spring precipitation and low evapotranspiration (Ikenberry et al., 2014; Eastman et al., 2010; Schilling and Helmers, 2008a; Randall and Goss, 2008). In contrast, in the eastern Corn-Belt, the majority of tile discharge normally occurs between November and March (Kladivko et al., 2004; King et al., 2014). In Iowa, the water table in cropped fields of the DML tends to rapidly rise in the spring and remain elevated through June and then fall in the mid-summer and fall (Schilling et al., 2018; Khan and Fenton, 1994). During the growing season, crop water uptake from corn and soybean crops reduces soil moisture and lowers water table levels below typical tile depths (Logsdon et al., 2010; Schilling et al., 2018). Eastman et al. (2010) similarly reported a reduction in both discharge and tile drainage during the growing season in Quebec, Canada. After crop senescence in early fall, soil moisture conditions are typically replenished with precipitation recharge and tiles often resume flowing in October and November. On average, tiles contributed approximately 30–40% of discharge in both Lyons Creek and Boone River during these two months.

4.2. Scaling in tile drainage contribution to watershed-scale discharge

The contribution of tile drainage to annual discharge was higher in the Lyons Creek subbasin versus the larger BRW (Fig. 7). The Lyons Creek flows are dominated by discharge from the three drainage districts tile mains (Fig. 1), and tile drainage contributes approximately 12% more discharge in the 42 km^2 Lyons Creek watershed compared to the 2370 km^2 BRW (Table 3).

The scaling relation of tile drainage contribution to drainage area can be expanded to include the 16,175 km^2 Des Moines River watershed above the City of Des Moines. The Des Moines River was the subject of Total Maximum Daily Load (TMDL) assessment for the nitrate impairment of the drinking water source for the City of Des Moines (Schilling and Wolter, 2009). Using a SWAT modeling framework similar to the Boone River SWAT model, results from a 13-year simulation period (1994–2006) indicated that tile drainage accounted for 32% of the annual discharge in the Des Moines watershed. Including these results with the Lyons Creek and Boone River output suggests that the contribution of tile drainage to annual water yield remains detectable in larger basins but the effects diminish with increasing scale (Fig. 8a). The three basins evaluated in this study are all located within the DML landform region and the scaling relation can be fit very well with an exponential curve ($R^2 = 0.98$). Hence, the results suggest that tile drainage is contributing to basin-scale water yields at scales ranging from 40 to 16,000 km^2 within the heavily-tiled region of central Iowa.

We can further extend the downstream effects of tile drainage to the 492,000 km^2 Upper Mississippi River Basin (UMRB) (Fig. 8b). Panagopoulos et al. (2015) developed a SWAT model of the UMRB and Ohio-Tennessee river basins using the same basic framework as reported herein. Output from the UMRB portion of the model calibrated for the USGS gauge at Grafton, Illinois suggested that tile flow contributed 17% of the discharge for the basin at this location (Panagopoulos et al., 2015). The best fit curve for the scaling relation that includes the DML watersheds and the UMRB is a power function that asymptotes

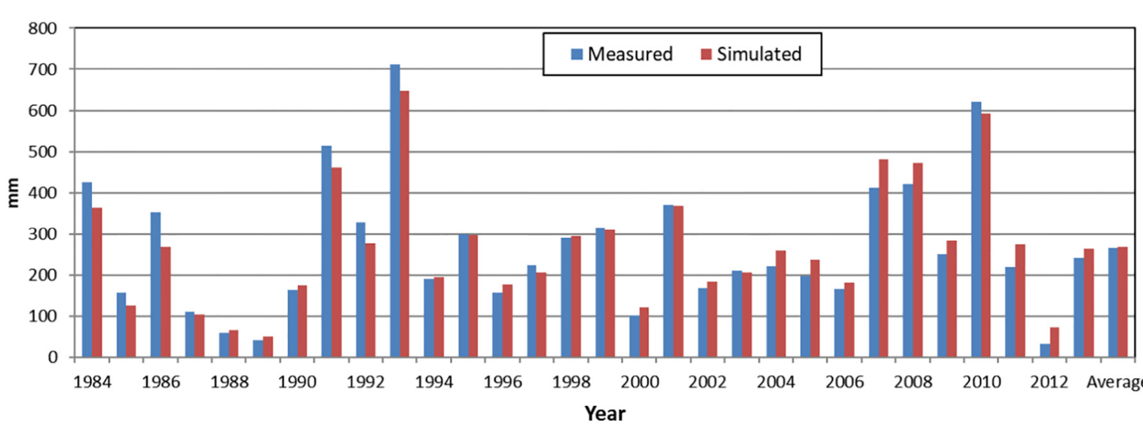

Fig. 5. Comparison of BRW SWAT-predicted and measured annual streamflows (mm) for the 1984 to 2013 simulation period.

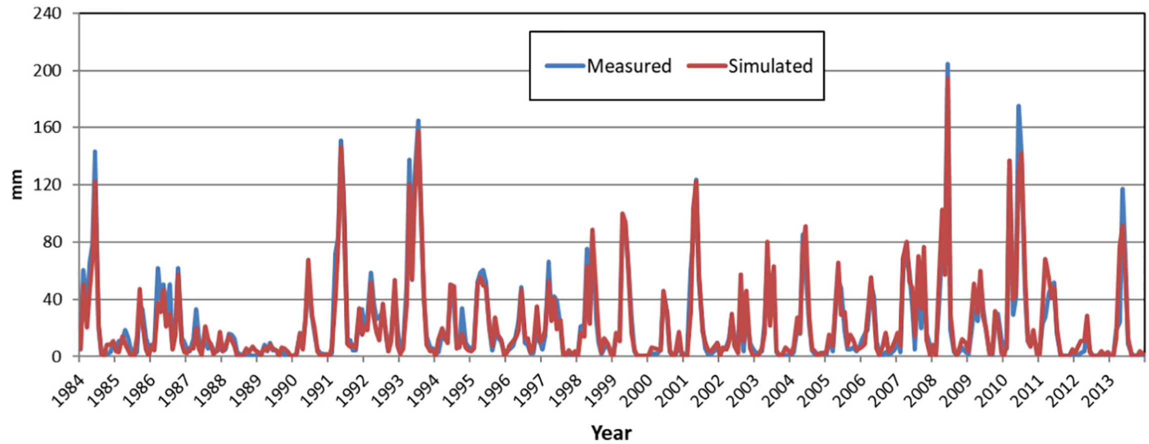

Fig. 6. Comparison of BRW SWAT-predicted and measured monthly streamflows (mm) for the 1984 to 2013 simulation period.

at a value of approximately 18% ($R^2 = 0.91$), suggesting that tile drainage may be contributing to streamflow across the entire UMRB. The change in best-fit regression lines from an exponential to power function is likely due to changing the analysis from a single landform region (DML) to one that includes several different agro-hydrologic regions (Schilling et al., 2014a).

The scaling of tile drainage flows to basin-scale water yield reported herein for the DML and UMRB regions greatly expands the downstream effects of drainage tile influence beyond what has been previously reported. Tile drainage contributions to streamflow have been correlated to upstream drainage areas in small (<10 km^2) watersheds (King et al., 2014; van der Velde et al., 2010; Macrae et al., 2007). Thomas et al. (2016) investigated the scaling of tile drainage to watershed discharge within the 45 km^2 Beaver Creek watershed in northeast Iowa using HGS model simulations. They reported that within-watershed scaling varied depending on whether the period corresponded to an event or non-event timeframe. The effects of tile drainage on peak discharge events and flooding in watersheds was the focus of Sloan et al. (2016) who reported that the effects of tiles to reduce peak events were most apparent at intermediate scale (100 to 1000 km^2) but decreased at the largest scales (>10,000 km^2). To our knowledge, the contribution of tile drainage flows to basin-scale annual water yields has not been explicitly reported for watersheds the size of the Boone and Des Moines rivers. The scaling relation of drainage flows suggests that the consequences of drainage should scale as well. Indeed, Schilling et al. (2012) reported that nitrate concentrations in the Des Moines River watershed from the Lyons Creek drainage tiles to the City of Des Moines systematically decreased with log drainage area (see Section 3).

4.3. Implications

In intensely tiled agricultural regions, the environmental consequences of subsurface tiling are profound and well-documented. Subsurface drainage increases the amount of nitrate lost from agricultural landscapes (Carluer and De Marsily, 2004; Jaynes et al., 2001; Kladivko et al., 2004; Rozemeijer et al., 2010; Sands et al., 2008; Skaggs et al., 1994; Stamm et al., 2002; Van den Eertwegh et al., 2006; van der Velde et al., 2010), causes a decrease in groundwater travel times (Schilling et al., 2015; David et al., 2010; Gentry et al., 2009; McIsaac and Hu, 2004), bypasses riparian buffers (Schilling et al.,

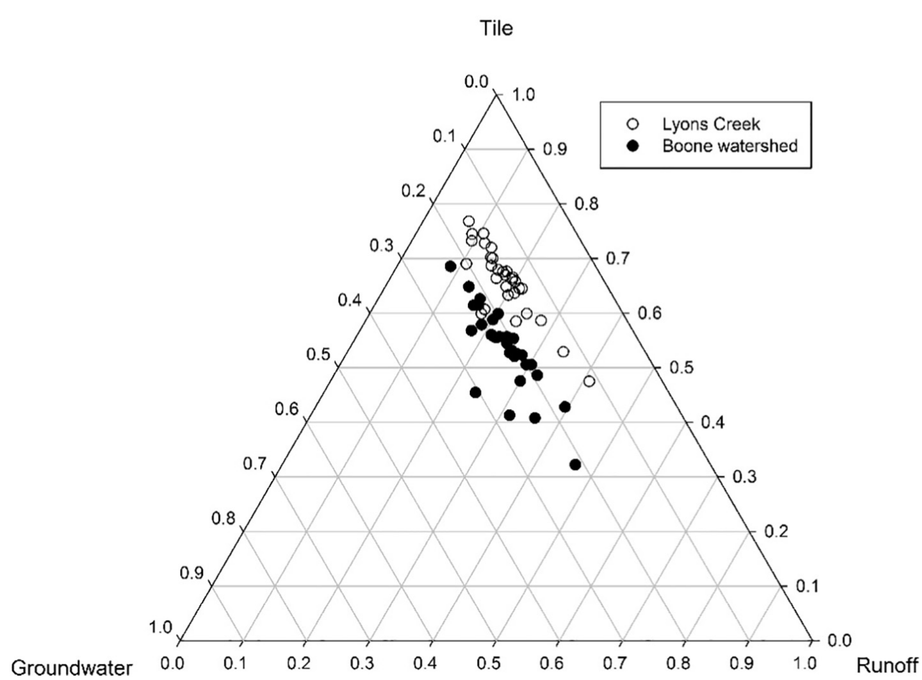

Fig. 7. Ternary diagram of the relative contribution of surface runoff, tile drainage and groundwater (GW) for the Boone River and Lyons Creek based on SWAT model output.

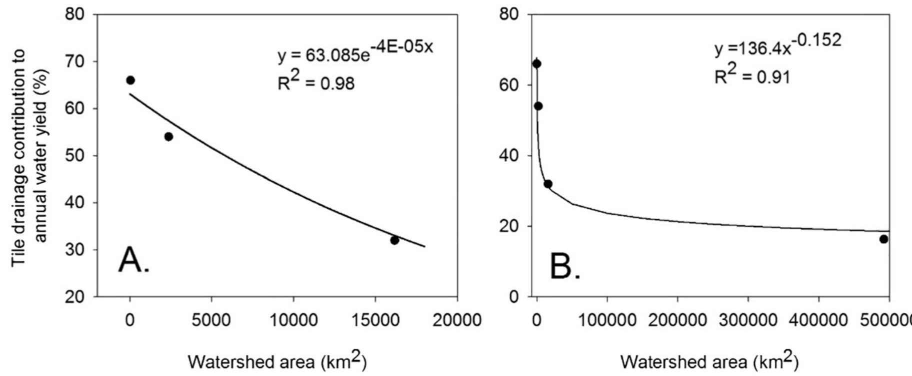

Fig. 8. Estimated contribution of tile drainage flows to annual discharge within (a) the DML region of Iowa; and (b) within the UMRB. Note that drainage areas (x-axis) are different for both plots and best fits line is an exponential curve in (a) and power curve in (b).

2015; Dinnes et al., 2002), and reduces the extent of denitrification in upland regions (Skaggs et al., 1994) of agricultural watersheds. Tile drainage has also been implicated in excessive loss of dissolved phosphorus (Schilling et al., 2018; King et al., 2015; Smith et al., 2015).

In the case of the Boone-Des Moines River system, the Des Moines Water Works (DMWW) uses surface water from the Des Moines River as part of its drinking water supply for >400,000 people in central Iowa. Recent assessment has indicated that the Des Moines River is impaired for use as a drinking water supply due to levels of nitrate that exceed the U.S. Environmental Protection Agency's Maximum Contaminant Level (MCL) (IDNR 2004). Previous SWAT modeling for the TMDL assessment suggested that drastic reduction in fertilizer applications in the Boone River watershed alone (from 170 to 50 kg/ha) could achieve a 5.5% reduction in nitrate loads at the water supply intake (Schilling and Wolter, 2009). However, such a reduction in fertilizer applications is hardly palatable to agricultural producers (McLellan et al., 2015). Alternatively, reducing the export of tile drainage discharge and nitrate loads at the drainage district scale may have cascading downstream benefits. Schilling et al. (2012) observed scaling in nitrate concentrations and MCL exceedances from drainage district tiles through the Des Moines River watershed with drainage area and concluded that simply reducing drainage district nitrate export by 25% would ensure MCL compliance at the drinking water intake. This present study further highlights the interconnectedness of upstream tile drainage to downstream discharge. We found that discharge contributions from drainage tiles are not simply manifested at a local scale but are observable through >16,000 km^2 of the watershed.

So what can be done? In watersheds dominated by artificial drainage, conservation practices are needed that retain water in the soil profile (controlled drainage; Thorp et al., 2008) or pass the nitrogen-laden water though subsurface carbon filters (bioreactors; Jaynes et al., 2008), or resaturated buffers (Jaynes and Isenhart, 2014). Use of restored or constructed wetlands to intercept and treat subsurface drainage water is often very effective for nitrogen reductions in these poorly drained areas (Crumpton et al., 2008; Drake et al., 2018). Drainage ditches can be enhanced for nitrogen removal by creation of artificial benches (2-stage ditches; Roley et al., 2012) or weirs (Kröger et al., 2011), or by improving vegetation establishment (Strock et al., 2010). Overall, strategies for intensively drained regions should be focused primarily on reducing nitrogen export from widespread artificial drainage (Schilling et al., 2014a).

4.4. Study limitations

Although the methods used to estimate tile drainage contributions produced similar results, both methods relied on some key assumptions that warrant future research. The EMMA method assumed a range of end member nitrate concentrations from groundwater, surface runoff and tile drainage components but the true concentrations of these water sources are unknown. In our study, the estimated concentrations were obtained from local and regional knowledge, including tile concentration data provided by a commodity group (Iowa Soybean Association), but the EMMA method is sensitive to the selection of end member concentrations (Arenas-Amado et al., 2017). We evaluated tile drainage concentrations ranging from 10 to 30 mg/L in the EMMA, and the model identified end member tile concentrations that corresponded to the maximum contribution of tile drainage to water yield (24 mg/L) and minimum contribution (30 mg/L). It is important to recall that using a higher tile concentration means less tile water is needed to satisfy the linear equations and thus identifies a minimum tile contribution to water yield. However, end member tile concentrations were consistent with measured concentrations at field sites (Ikenberry et al., 2014; Lawlor et al., 2008; Tomer et al., 2003). Estimated end member concentrations for surface runoff were within well-understood ranges, but the estimated concentrations for groundwater were unknown. Nitrate concentrations in shallow aquifers (<10 m) within the DML region are often <10 mg/L, but concentrations measured at the water table beneath cropped fields can be very high. For example, Schilling et al. (2018) reported nitrate concentrations of 20–40 mg/L (max of 102 mg/L) in the water table below farmed wetlands in the DML. Tile concentrations are typically much higher than in-field groundwater because groundwater discharges to streams through perennial buffers (e.g., Simpkins et al., 2002; Hill, 1996) whereas tile drainage bypasses buffer biogeochemical processing (Schilling et al., 2015).

The EMMA method further relied on measured stream discharge data and high frequency measurements of nitrate using the Nitratax sensor at the watershed outlet. Since the N sensor could not be deployed during winter months, EMMA could not be conducted during the November to March period. However, the effects of the missing monitoring period on annual average tile drainage contributions were likely negligible because the missing months included both high tile drainage contributions (November and March) and low winter periods (December to February) (Table 3). Future work will explore the addition of other less sensitive parameters such as specific conductance to the EMMA to better account for seasonal deployment patterns and operational variations (Jones et al., 2018a).

There are further limitations to consider regarding the SWAT simulation results that were reported for this study. First, it is difficult to quantify the exact distribution of subsurface tile drainage that exists in the BRW and the Lyons Creek subwatershed. The assumption that all of the cropland <2.0% slope was managed with tile drainage resulted in 83% of the cropland being simulated as tile drained, which was higher than the 70% level indicated in 2012 census data (Gassman et al., 2017a, 2017b). Second, there is a need to test the new tile drainage algorithms (Moriasi et al., 2012, 2013) that have been incorporated in recent SWAT codes, which provide a more physically-based representation of tile drain functions and can directly account for pattern tile configurations. Third, further investigation is warranted regarding the choice of CNCOEF value, which greatly influences the amount of overall flow that is discharged via baseflow pathways. Fourth, representation of depressional features should be introduced to better present the effects of potholes and hydric soils on BRW water dynamics. In addition, there are numerous other input parameters that can affect the results of a given SWAT simulation that should be continually tested in future applications, within resource constraints, to further ascertain if improved representation of the BRW hydrologic system can be obtained.

Finally, we note that our study involved estimating tile drainage contributions from an inferred, but unknown extent of subsurface drainage. Improving the ability to locate field tile systems in agricultural watersheds remains an ongoing research focus (Naz et al., 2009; Schilling et al., 2015). Many watershed studies use hydric soils or other soil-based criteria to estimate the distribution of subsurface tile systems beneath row crop land cover (Schilling and Wolter, 2009). In the Boone River nearly 60% of soils have been mapped as "poorly drained" and over 75% of soils are characterized as "hydric" or "partially hydric". These poorly drained and hydric soils must be tile drained if they are cropped at all for row crop production. Considering that ~90% of the BRW is under corn and soybean cultivation, nearly all the row crop ground in the watershed is believed to be tiled. Although the true extent of drainage in the watershed is unknown and can only inferred through indirect means, we nonetheless observe the hydrologic impacts to downstream waterbodies.

5. Conclusions

The purpose of this study was to quantify the contribution of subsurface tile drainage to basin-scale water yields in the intensively-drained Boone River watershed located in north-central Iowa. Using EMMA analyses and the numerical model SWAT, we report the following main conclusions from this study:

1. EMMA and SWAT methods are very different yet both indicated that tile drainage provided approximately 46 ($EMMA_{max}$) to 54% (SWAT) of the discharge in the Boone River. During the March to June period, both methods confirmed that tile drainage accounted for a majority of flow in the Boone River. In the BRW subbasin of Lyons Creek, SWAT results further indicated that nearly 66% of the annual flow was sourced from tile drainage. Results from the BRW are consistent with other heavily tiled watersheds in the Midwest where tile drainage often accounts for one-half of the annual watershed discharge, but the percentage has not been explicitly reported for watersheds as large as the Boone River.
2. Within the same DML landform region, tile drainage appears to be contributing to basin-scale water yields at scales ranging from 40 to 16,000 km^2, with downstream effects diminishing with increasing watershed size. The scaling of tile drainage flows to basin-scale water yield reported herein for the DML region greatly expands the downstream effects of drainage tile influence beyond what has been previously reported.

Overall, given study limitations (Section 4.4), our study highlights the importance and interconnectedness of upstream tile drainage on downstream discharge. Considering the environmental impacts of tile drainage on water quality degradation, developing a better understanding of water sources contributing to river discharge is needed if mitigation and control strategies are going to be successfully targeted to reduce downstream nutrient export.

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