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Effect of subsurface drainage on streamflow in an agricultural headwater watershed

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SUMMARY

Artificial drainage, also known as subsurface or tile drainage is paramount to sustaining crop production agriculture in the poorly-drained, humid regions of the world. Hydrologic assessments of individual plots and fields with tile drainage are becoming common; however, a major void exists in our understanding of the contribution of systematic tile drainage to watershed hydrology. A headwater watershed (4 km^2) in central Ohio, USA and all functioning tile were monitored from 2005 to 2010 in order to characterize the magnitude and frequency of flows, quantify the role and seasonal contributions of tile drainage to watershed hydrology, and relate tile drainage to precipitation and antecedent conditions. Results indicated that tile drainage contributions to watershed hydrology were significant. Specifically, 21% of precipitation (206 mm) was recovered through tile drainage annually. Tile drainage also accounted for 47% of watershed discharge and was seasonally variable. Median monthly tile discharges in winter (23.4 mm), spring (10.2 mm), and fall (15.6 mm) were significantly greater ($P < 0.05$) than the median monthly summer discharge (0.9 mm). Results from this study will help enhance hydrology and water quality prediction technologies as well as the design and implementation of best management practices that address water quality concerns.

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1. Introduction

Subsurface drainage tiles are used extensively throughout the Midwestern U.S., Canada, and northern Europe to lower the water table and drain soils that are seasonally or perennially wet (Pavelis, 1987; Gilliam et al., 1999). In the humid Upper Midwestern portion of the U.S., in excess of 20.6 million ha (37%) of land has been artificially drained to produce highly productive cropland (Zucker and Brown, 1998). Tile drain systems allow for earlier planting (Kornecki and Fouss, 2001), increased soil aeration and root zone soil quality (Fausey, 2005), and improved field conditions for greater crop yields (Fausey, 2003; Du et al., 2005). Relative to undrained land, subsurface drainage also results in significant changes to the hydrology of a system (Blann et al., 2009). While hydrologic assessments of individual tile drains exist, the hydrologic effects of tile drainage at the watershed scale are not well documented (Eidem et al., 1999; Schilling and Helmers, 2008; Schilling et al., 2012). Nutrient losses from agricultural landscapes are often driven by hydrology (Williams et al., 2014); thus, characterizing the hydrology associated with tile drainage and tile drained watersheds is essential for understanding nonpoint pollution transport dynamics (Tomer et al., 2003), and identifying and implementing best management practices in these landscapes (King et al., 2008; Schilling and Helmers, 2008).

The installation of subsurface tile drainage has been shown to increase the water storage capacity within the upper layers of the soil profile (Skaggs and Broadhead, 1982; Fraser and Flemming, 2001), which often results in more water infiltration and less surface runoff (Natho-Jina et al., 1987; Skaggs et al., 1994; Robinson and Rycroft, 1999). Where land has already been converted to agricultural production, subsurface drainage may also reduce peak flows (Robinson, 1990; Konyha et al., 1992; Skaggs et al., 1994) and result in less flooding (Robinson and Beven, 1983; Schilling and Helmers, 2008; Henine et al., 2010). The effects of subsurface drainage on peak flows at the field scale however have been found to be variable depending on local soil properties as well as antecedent moisture conditions and precipitation characteristics. Poorly drained soils generally have less surface runoff and lower peak discharge rates with improved subsurface drainage compared to sites that depend primarily on surface drainage (Skaggs et al., 1994). On more permeable soils, where infiltration, water storage capacity, and lateral seepage are great enough to handle a given precipitation event, subsurface drainage may have the opposite effect and increase peak discharges by increasing

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the rate of subsurface discharges (Robinson, 1990; Wiskow and van der Ploeg, 2003).

Regardless of whether peak flows are increased or decreased, subsurface tile drainage tends to increase watershed baseflow (Moore and Larson, 1980; Schilling and Libra, 2003); therefore, subsurface tile drainage can affect both the total water yield from a system, and the timing and shape of the hydrograph (Blann et al., 2009). Surface inlets and other fast flow pathways (e.g., macropores) connected to tiles may also affect event flow (Schilling and Libra, 2003). Increases in baseflow have been found to be relatively minor (~10%), but occur because tile drainage increases the proportion of annual precipitation that is discharged to surface waters relative to the amount that is stored, evaporated, or transpired (Serrano et al., 1985; Magner et al., 2004; Tomer et al., 2005). Hence, Logan et al. (1980) observed a linear relationship between rainfall and tile discharge. The authors found that average annual rainfall recovered in tile drainage across multiple sites was 12.6% in Iowa, 18.9% in Minnesota, and 22.2% in Ohio. Similarly, Algoazany et al. (2007) reported that approximately 16% of precipitation was recovered in tile discharge from four field sites in Illinois. The contribution of tile discharge to watershed hydrology, however, is less well known. It has been suggested that tile discharge may contribute between 0% and 90% of watershed discharge seasonally with annual contributions around 40% (Macrae et al., 2007). For example, Macrae et al. (2007) and Eastman et al. (2010) both reported large seasonal differences in the contributions of tile discharge to streamflow. They concluded that tile drainage comprises a larger proportion of streamflow during the winter and spring compared to the summer and fall.

A comprehensive understanding of the hydrology of tile drained landscapes is a major knowledge gap (Sims et al., 1998; King et al., in press) that limits informed decisions on watershed management, addressing water quality concerns, and selection and implementation of best management practices. The objective of this study was to characterize and quantify the contribution of subsurface tile drainage to watershed hydrology from a systematically tile drained headwater watershed in central Ohio, USA. Stream discharge from subwatershed *B* of the Upper Big Walnut Creek and all tile drain discharge within the subwatershed were monitored continuously over a 6-year period. Specific objectives of the study were to: (1) characterize the magnitude and frequency of flow from tile drains within the watershed; (2) quantify the contribution of tile drainage to stream discharge at the watershed outlet; and (3) investigate the seasonal impacts of tile drainage on watershed hydrology.

2. Materials and methods

2.1. Site description

Upper Big Walnut Creek (UBWC) is a 492 km^2 USGS 10-digit (HUC 05060001-13) watershed located 20 km northeast of Columbus, OH (Fig. 1). Formed during the Late Wisconsinan Glaciation, the UBWC watershed is characterized by 686 km (426 mi) of perennial and intermittent streams that drain to the Hoover Reservoir. The UBWC watershed is located in the humid continental-hot summer climatic region of the U.S. The climate provides for approximately 160 growing days per year, generally lasting from late-April to mid-October (NCDC, 2014). Average daily temperatures range from a minimum of −9.6 °C in January to a maximum of 33.9 °C in July (NCDC, 2014). The 30-year average rainfall at the Westerville, Ohio, gauge at the southwest portion of the watershed is 985 mm (NCDC, 2014). Thunderstorms during the spring and summer produce short duration intense rainfalls. Moisture in the form of frozen precipitation or snow averages 500 mm annually and occurs primarily from December to March (NCDC, 2014). During the winter and spring, precipitation often exceeds potential evapotranspiration (PET) (Fig. 2). This excess rainfall is further compounded by the wet natured, slowly permeable soils requiring the use of artificial subsurface drainage for assured agricultural production.

The experimental site is a 389 ha subwatershed of the UBWC identified as watershed *B* (Fig. 1). Crop production agriculture (86%) comprises the largest land use classification within the watershed, with the remainder of the watershed consisting of woodland (6%) and residential/farmstead (8%) land uses. The cropland is primarily in a corn-soybean rotation using rotational tillage (e.g., no-till soybeans into corn stubble and disk chisel of soybean stubble prior to corn planting). The soils within watershed *B* are a somewhat poorly drained Bennington silt loam (52.9%) and a very poorly drained Pewamo clay loam (46.2%). An estimated 80% of watershed *B* is systematically tile drained with laterals generally on 15 m spacing and placed approximately at a depth of 1 m. The estimated average age of the tile drainage is greater than 50 years.

2.2. Watershed and tile monitoring

From 2005 through 2010, stream discharge at the watershed outlet was monitored with a 2.4 m Parshall flume (Fig. 3a). The Parshall flume was equipped with an Isco (Teledyne Isco; Lincoln, NE) 4230 Bubbler Flow Meter, which was programmed to record flow depth every 10 min. The stream in watershed *B* had a low gradient and backwater or submergence was common. An Isco 2150 Area Velocity Sensor was therefore installed at the throat of the flume to aid in the development of a rating curve during submerged conditions. An annual stage-discharge relationship was developed for the watershed outlet and was used to calculate stream discharge.

In addition to monitoring discharge at the watershed outlet, all tile outlets (6 total) in the watershed, with the exception of one tile that drained approximately 7 ha, were instrumented with weirs and flumes (Table 1). This one tile was not functional for the first 4 years of the study and resource limitations prevented instrumentation once the functionality of the tile was restored. For each edge-of-field tile main, compound weir inserts (Thel-Mar, LLC; Brevard, NC) were installed at the tile outlet. The 20 cm edge-of-field tiles were cut and fitted with a 30 cm diameter pipe that could accommodate the compound weir (Fig. 3b). For the larger 38 and 61 cm drainage mains, an H-flume was fitted to the end of the tile and served as a control volume (Fig. 3c). Similar to the watershed outlet, each of the tile drains was equipped with an Isco 4230 Bubbler Flow Meter and an Isco 2150 Area Velocity Sensor. Discharge for each tile was determined using either the standard rating curve for either the compound weir or H-flume or data from the area velocity sensor.

2.3. Statistics and data analysis

Discharge rates were calculated for each site using the 10-min measured stage in conjunction with the standard rating curve for each specific control volume or the area velocity data collected from the site. Watershed and tile discharge rates were aggregated to daily, monthly, and annual volumes. Tile discharge from individual tile lines was summed to provide total tile discharge. A combination of baseflow and event flow was used to calculate daily watershed and tile discharge. Baseflow was estimated daily using the local minimum method (Pettyjohn and Henning, 1979) within the Hydrograph Separation program (HYSEP) (Sloto and Crouse, 1996). Storm events were defined as any event with precipitation amount in excess or equal to 6.35 mm (0.25 in) separated by at least six hours with no precipitation. Event flow and the duration

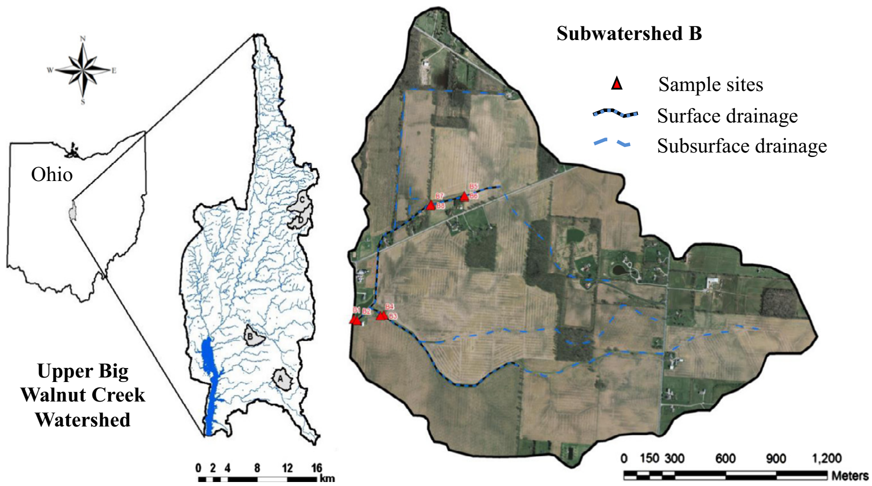

Fig. 1. Location of Upper Big Walnut Creek watershed and study watershed B.

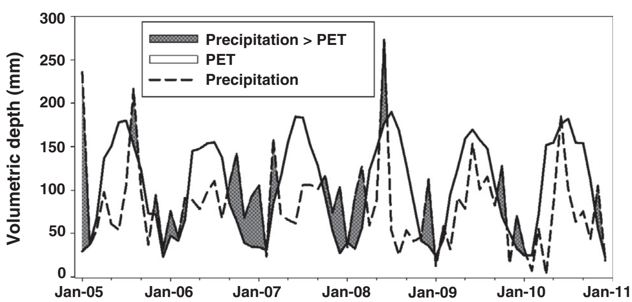

Fig. 2. Mean monthly precipitation and potential evapotranspiration (PET) illustrating the period when precipitation exceeds PET, requiring subsurface drainage.

of the event discharge was determined by examining the peak discharge rate of the event and summing the series of discharges until the discharge rate returned to 10% of the peak discharge rate or until three days had passed from the time of peak discharge. Descriptive statistics (mean, median, maximum, minimum, 10th, 25th, 75th, and 90th percentile) for watershed and tile discharges were determined from daily discharges for the continuous 6-year record. Frequency of full pipe flow in tile drains was also calculated for each tile drainage outlet.

Reference evapotranspiration (ET) was estimated using the American Society of Civil Engineers (ASCE) standardized Penman–Monteith method (Allen et al., 2005) using climatic data from the UBWC watershed and a reference crop of alfalfa. Crop coefficients were determined by the FAO 56 method for corn and soybean (Allen et al., 1998). Crop coefficients were multiplied by daily reference ET to calculate potential ET (PET) by crop. Crop areas were determined from management records and 'windshield' surveys throughout the study period and aerially weighted to estimate the watershed PET. Potential crop ET was not adjusted for water stress conditions.

Linear regression was used to quantify the contribution of tile drainage to watershed discharge. Monthly watershed discharge was regressed against summed monthly tile discharge. The slope of the regression line represents the contribution of the tile drainage at the watershed outlet. Monthly data were also divided into four seasons: winter (Jan, Feb, Mar); spring (Apr, May, Jun); summer (Jul, Aug, Sept); and fall (Oct, Nov, Dec). Watershed baseflow, watershed event flow, total watershed discharge, and summed tile discharge were analyzed on a seasonal basis using a one-way analysis of variance (ANOVA). Data were not normally

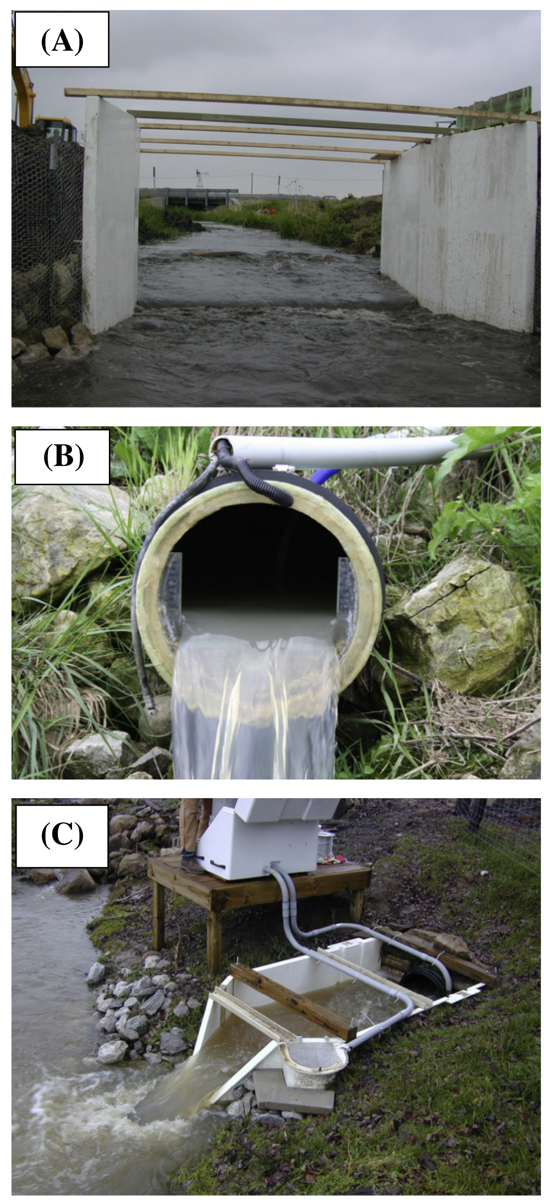

Fig. 3. Examples of Parshall flume (A), compound weir tile insert (B), and H-flume (C) control volumes used in the study.

Table 1
Sampling site characteristics for all monitoring locations within study watershed.

Site	Description	Control volume	Estimated contributing area	Soil types	Average land slope (m/m)
B1	Watershed outlet	8′ Parshall flume	389	Bennington – 52.9% Centerburg – 0.9% Pewamo – 46.2%	0.00868
B2	8″ Field tile	12″ Compound weir	13.8	Bennington – 71.9% Pewamo – 28.1%	0.00860
B3	24″ County main	3′ H-flume	211.6	Bennington – 37.3% Pewamo – 62.8%	0.00686
B4	8″ Field tile	12″ Compound weir	14.9	Bennington – 52.2% Pewamo – 47.8%	0.00761
B5	15″ Main	2′ H-flume	21.6	Bennington – 40.8% Pewamo – 59.2%	0.00827
B6	15″ Main	2′ H-fume	48.6	Bennington – 43.6% Centerburg – 3.2% Pewamo – 53.2%	0.00972
B8	8″ Field tile	12″ Compound weir	7.7	Bennington – 86.3% Pewamo – 13.7%	0.00931

distributed; therefore, an ANOVA on ranks was performed using the Kruskal–Wallis test. When significant, all pairwise comparisons of medians were assessed using the Tukey post hoc test. All statistical analyses were completed using SigmaStat 3.5 statistical software (Systat Software, 2006) with a significance level of $P < 0.05$.

3. Results

3.1. Magnitude and frequency of tile flow

Daily tile discharge from individual tile drains was used to characterize the low, central, and high flow magnitudes (Table 2). Low flow magnitudes are defined as the minimum flow and the 10th and 25th percentiles of flow, while central flow magnitudes are defined as the mean and median flows (Olden and Poff, 2003; King et al., 2009). High flow magnitudes are defined as the 75th and 90th percentiles of flow as well as the maximum flow (Olden and Poff, 2003; King et al., 2009). Mean daily discharge for the three edge-of-field tiles (B2, B4, and B8) was 0.85 mm/day (1.0 L/s) (Table 2). In comparison, mean daily discharge for the intermediate tile mains (B5 and B6) was approximately 1.2 mm/day (4 L/s), while mean daily discharge for the large county main (B3) was 0.6 mm/day (14 L/s). Low flow magnitudes (minimum, 10th, and 25th percentile) for all tile drains were 0 mm/day with the exception of the county main (Table 2). High flow magnitudes varied across all tile sties and increased with increasing contributing area (Table 2). The 90th percentile of flow for the edge-of-field tiles was 1.5 mm/day (2 L/s) compared to 2.4 mm/day (8 L/s) for the intermediate tile mains, and 1.4 mm/day (32 L/s) for the county main. On average, the edge-of-field tiles in subwatershed *B* were flowing full for approximately 2 days per year with a maximum of 3–7 days. For the intermediate mains, full pipe flow was rare, while for the county main, full pipe flow was measured approximately 1.5 days per year.

3.2. Tile contributions to watershed hydrology

Over the 6 year study, an average of 42 precipitation events were measured annually (Table 3). Precipitation amounts during individual events ranged from 6.4 to 90.1 mm and averaged 19.9 mm. Annual precipitation amounts averaged 999 mm. Total watershed discharge over the study period averaged 498 mm, which was equivalent to 49% of measured annual precipitation (Table 3). Depending on the year, however, the discharge to precipitation ratio (Q/P) varied between 44% and 61%. Watershed storm event discharge comprised, on average, 59% of total watershed discharge (30% of measured annual precipitation), while watershed baseflow

Table 2
Daily volumetric discharge (mm), rate (L/s), and frequency characteristics of measured tile drains from 2005–2010.

	Edge-of-field Tile			Intermediate Main		County Main
	B2	B4	B8	B5	B6	B3
Magnitude (mm (L/s))						
Average flows						
Mean daily discharge	0.63 (1.01)	0.68 (1.18)	1.23 (1.10)	1.67 (4.18)	0.67 (3.77)	0.60 (13.97)
50th percentile	0.00 (0.00)	0.05 (0.083)	0.22 (0.20)	0.20 (0.51)	0.03 (0.16)	0.11 (2.52)
Low flows						
Min daily	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
10th Percentile	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.03)
25th Percentile	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.03 (0.59)
High flows						
75th Percentile	0.23 (0.37)	0.40 (0.70)	0.82 (0.73)	0.74 (1.86)	0.30 (1.66)	0.35 (8.08)
90th Percentile	1.18 (1.89)	1.30 (2.25)	2.24 (2.01)	3.28 (8.19)	1.49 (8.38)	1.40 (32.6)
Maximum	23.4 (37.4)	20.1 (34.6)	34.3 (30.7)	64.3 (160.8)	21.2 (119.3)	13.5 (314.7)
Frequency (days/yr)						
Time ⩾ full pipe flow						
Minimum	3.10	1.49	1.73	0.00	0.00	0.00
Median	4.28	1.94	2.13	0.00	0.00	1.08
Average	4.71	2.18	2.86	0.05	0.01	1.57
Maximum	6.83	3.55	4.85	0.15	0.06	4.99

Table 3
Annual precipitation, number of precipitation events, and volumetric depth of watershed discharge resulting from baseflow, storm event discharge, and tile drainage. Values in parentheses correspond to the volumetric depth expressed as a fraction of precipitation.

Year	Precipitation (mm)	Number of precipitation events	Watershed base flow discharge (mm)	Watershed storm event discharge (mm)	Watershed total discharge (mm)	Summed tile flow discharge (mm)
2005	1121	40	281.3 (0.25)	328.0 (0.29)	609.3 (0.54)	185.7 (0.17)
2006	1064	42	207.0 (0.19)	259.8 (0.24)	466.9 (0.44)	153.3 (0.14)
2007	1095	47	213.9 (0.20)	305.3 (0.28)	519.3 (0.47)	178.3 (0.16)
2008	1006	42	205.9 (0.20)	405.1 (0.40)	611.1 (0.61)	311.2 (0.31)
2009	938	42	165.3 (0.18)	275.6 (0.29)	440.9 (0.47)	198.3 (0.21)
2010	773	37	138.2 (0.18)	202.0 (0.26)	340.2 (0.44)	207.0 (0.27)
Average	999	42	202.0 (0.20)	296.0 (0.30)	497.9 (0.49)	205.6 (0.21)

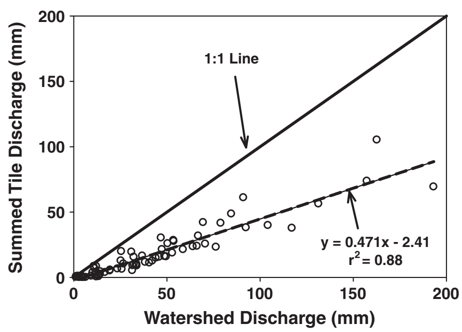

Fig. 4. Relationship between monthly watershed discharge and summation of tile discharge for 389 ha tile drained subwatershed of the UBWC watershed.

discharge comprised the remaining 41% of total watershed discharge (20% of measured annual precipitation). Summed tile drainage from all 6 monitoring sites ranged between 153 and 311 mm (14–31% of the annual precipitation) annually and averaged 206 mm (21% of the annual precipitation) (Table 3). Tile drainage in subwatershed *B* accounted for 41% of the total annual watershed discharge (Table 3) with a range from 30% to 61%. Summed tile drainage discharge was essentially equivalent to the watershed baseflow (Table 3). On a monthly basis, 47% of the total watershed discharge in subwatershed *B* was from tile drainage (Fig. 4).

3.3. Seasonal variations in tile discharge

Individual monthly contributions of tile drainage to watershed discharge ranged from near 0% to 100% and varied seasonally. Additionally, tile flow was observed throughout the year in response to precipitation, but was cyclic with greater discharges measured in the non-growing season periods (Fig. 5). Monthly tile discharge was separated into four seasons in order to quantify the temporal variability in tile flow (Table 4). Mean monthly tile discharge in subwatershed *B* was greatest during the winter period (Jan-Mar) and least during the summer period (Jul–Sept) (Fig. 6). Median monthly tile discharge in the summer (0.9 mm) was significantly less ($P < 0.05$) than median monthly discharges in the winter (23.4 mm), spring (10.2 mm), and fall (15.6 mm) (Table 4). During the winter, the combination of summed tile discharge and surface discharge in subwatershed *B* accounted for a significant portion of the measured precipitation (Fig. 6). In all other seasons, the contribution of tile drainage to total watershed discharge was approximately 50%.

4. Discussion

4.1. Magnitude and frequency of tile flow

As the drainage area increased, the magnitude of the mean daily flow also increased (Table 2). Results also indicated that large events with high flow rates influenced mean daily discharge since median discharges were found to be considerably less than mean daily discharges (Table 2). Additionally, the minimum flow and 10th and 25th percentiles of flow were all 0 mm/day (0 L/s), indicating that for greater than 25% of the study period, tile drains were not discharging. A comparison between monthly precipitation and PET also suggests that tile drainage was not required in subwatershed *B* for much of the year (Fig. 2). Similar findings regarding the temporal variability of tile discharge have been reported in Canada (Macrae et al., 2007; Eastman et al., 2010), and the US (Kladivko et al., 1991).

Maximum discharge rates for each tile suggest that the tiles were flowing full and in some instances may have been under pressure since the maximum measured flow exceeded typical design rates of 0.95–1.25 cm/day (0.38–0.50 in/day) (Wright and Sands 2001). Multiple factors might lead to pressure flow or pipe full flow. These include: increasing the drainage intensity or connecting additional laterals onto an existing main that was not designed for the extra discharge; adding surface water to the tile through a breather, surface inlet, or 'blowout'; and/or positioning the tile outlet in the landscape where submergence is likely (Henine et al., 2010).

Mean frequency of observed full pipe flow for edge-of-field tile B4 and B8 (0.7%) was consistent with expected frequencies (Table 2). The two fold increase in number of days with full pipe flow in B2 compared to B4 and B8 was likely the result of the tile location within the drainage network (Fig. 1). B2 is situated on the downstream end of the surface drainage ditch and thus is more prone to submergence than either B4 or B8 which are located on the upstream portion of the ditch. The county main (B3) is also prone to submergence as a result of its location (Fig. 1). B3 is adjacent to a grassed waterway that conveys surface drainage water from 75% of subwatershed *B* and during large rainfall/runoff events the grassed waterway often flowed at maximum capacity, submerging the outlet of B3. The pipe full annual average of 2 days and maximum of 5 days at B3 was therefore representative of a combination of actual full pipe flow and submergence.

4.2. Tile contributions to watershed hydrology

During the study period, mean annual precipitation (999 mm) was slightly greater than the long-term average (985 mm). Results for *Q*/*P* ratios from subwatershed *B* were greater than *Q*/*P* ratios reported by Schilling and Zhang (2004). In a 28 year study of the tile drained Raccoon River watershed in west central Iowa, USA, Schilling and Zhang (2004) reported watershed *Q*/*P* ratios ranging from less than 10% to greater than 40%, with an annual average of 26%. The differences in the *Q*/*P* ratios from the current study compared to the Schilling and Zhang (2004) study may be explained by and examination of precipitation and study scale. In the immediate study, precipitation was only reported for that in liquid form and does not reflect frozen precipitation or snowfall. Annual snowfall for the Columbus, OH area is approximately

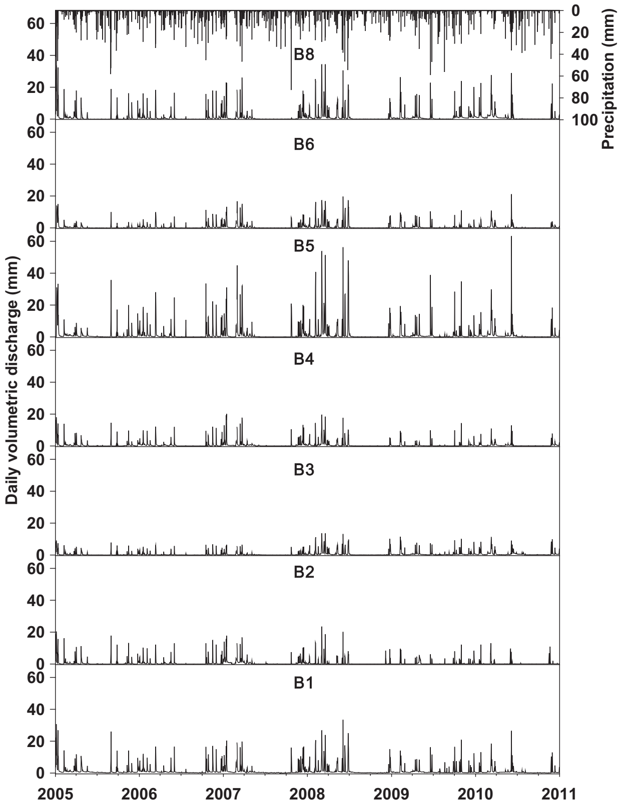

Fig. 5. Time series of all tile and watershed discharge and precipitation for period of record (2005–2010).

Table 4
Seasonal median monthly discharges (2005–2010).

	Watershed baseflow discharge (mm)	Watershed storm event discharge (mm)	Watershed total discharge (mm)	Summed tile flow discharge (mm)
Winter	29.7a	34.5a	55.9a	23.4a
Spring	16.4ab	13.1ab	31.9a	10.2a
Summer	4.8c	2.4b	9.0b	0.9b
Fall	11.3bc	27.3a	36.2a	15.6a

Values in columns followed by different letters indicates statistically ($P < 0.05$) significant differences in median discharge.

500 mm. Additionally, the annual amount of precipitation between the two studies is significantly different; 870 mm in Iowa compared to 999 mm in the immediate study. The discrepancy in watershed *Q*/*P* ratios between studies may also be due to differences in scale, as subwatershed *B* (4 km^2) is much smaller than the Raccoon River watershed (9400 km^2). Generally, as scale increases, watershed response is often dampened. For example, Tomer et al. (2003) found a dampening effect during a 9 year study examining the hydrology of two subbasins within the Walnut Creek watershed in central Iowa, USA. The authors observed that discharge was substantially larger from each of the two subbasins within the larger watershed compared to the watershed outlet.

Summed tile drainage from all 6 tile monitoring sites ranged from 14% to 31% of the annual precipitation with an average of 21% (Table 3). Similar results for tile drainage have been reported in several studies (Algoazany et al., 2007; Kladivko et al., 1991; Logan et al., 1980). In a 7 year study in the Little Vermillion Watershed in Illinois, USA, Algoazany et al. (2007) observed that 13–18.5% of precipitation was recovered in tile drainage from four individual fields ranging in size from 3.0 to 7.5 ha. Similarly,

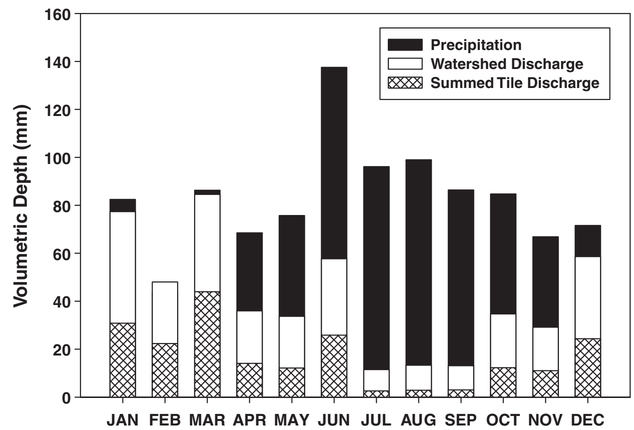

Fig. 6. Stacked bar graph of mean monthly distribution of precipitation, watershed discharge, and subsurface discharge expressed as volumetric depth over 389 ha watershed during the period 2005–2010. Breaks in each bar represent the volumetric depth contributed.

Kladivko et al. (1991) reported annual precipitation recoveries of 6–27% from drainage plots in south central Indiana, USA. Variations in the Kladivko et al. (1991) study were found to be a function of both year and drainage spacing. Logan et al. (1980) also monitored tile drains in multiple fields in Iowa, Minnesota, and Ohio, USA. The authors showed that annual mean discharge expressed as a fraction of rainfall was 12.6% in Iowa, 16.7% in Minnesota, and 25.5% in Ohio. The mean across all sites was 20.9%; however, the annual range of precipitation recovery from individual fields ranged from 0% to 65.9%.

Tile drainage in subwatershed *B* accounted for 41% of the annual total watershed discharge (Table 3) with a range from 30% to 61%. Results from subwatershed *B* were similar to results from the Strawberry Creek watershed in Ontario, Canada where an estimated 42% of annual watershed discharge originated from tile flow (Macrae et al., 2007). Strawberry Creek is comparable to subwatershed *B* in terms of size, land use, and extent of tile drainage. Thus, results from subwatershed *B* are consistent with the study by Macrae et al. (2007), which suggested that at any time tile flow can contribute between 0% and 90% of watershed discharge with the greatest contributions occurring during the winter. Additionally, the mean annual tile discharge volume (206 mm) was similar to the watershed baseflow volume (202 mm) suggesting that tile drainage was responsible for a considerable amount of the watershed baseflow in subwatershed *B*. Similar findings on the substantial amount of baseflow contributed by subsurface tile flow have been reported in heavily tile drained watersheds in Iowa, USA (Schilling and Helmers, 2008).

4.3. Seasonal variations in tile discharge

Seasonal results from the present study are consistent with the findings reported by Kladivko et al. (2004) for tile drains in Indiana, USA. These authors found that the majority of tile discharge occurred during the fallow season between November and March. Other research has shown that tile drains in more northern latitudes tend to freeze during the winter, with the bulk of tile flow occurring during and shortly after snow melt (Randall and Goss 2001; Macrae et al., 2007). For instance, Eastman et al. (2010) reported that the greatest proportion of annual tile discharge was during the spring while the least amount of drainage was during the summer in the Pike River watershed in Quebec, Canada. Due to variations in temporal distribution of tile drainage, annual downstream discharge in a larger tile drained watershed may be comprised of a significant portion of tile drainage.

In spring, summer and fall, the contribution of tile drainage to total watershed discharge was roughly 40%, but tile drainage represented a much smaller proportion of the precipitation over each of these seasons (Fig. 6) compared to the winter season. The differences among seasons were likely due to the amount of ET (Fig. 2). During the winter, estimated PET in subwatershed *B* was very low, which would have resulted in more precipitation available for transport through tile drainage. Estimated PET during the summer was greater because of warm air temperatures and crop transpiration and uptake, which would result in a greater potential for precipitation to be stored, evaporated, or transpired rather than to be discharged via tile drainage. Furthermore, the summation of tile drainage represented a substantial amount of the monthly watershed baseflow for each season and even surpassed the watershed baseflow in the fall (Table 4). This suggests that there was considerable water storage within the surface ditch network.

5. Summary and conclusions

Discharge from all active tile drains within a headwater watershed in Ohio, USA was monitored from 2005 through 2010 in order to characterize the magnitude and frequency of flows and quantify the role and seasonal contributions of tile drainage to watershed hydrology to help inform watershed decisions related to management and water quality concerns. Tile discharge was strongly correlated with the size of contributing area, such that the larger the contributing area the greater the magnitude of tile flow. In general, tile drains did not flow for 25% of the year. At the other extreme, full pipe flow was measured at the edge-of-field sites an average of 2–4 days per year. The frequency of full pipe flow in the larger tile drains was considerably less and was a function of landscape position. Twenty-one percent of the annual precipitation (range of 14–31%) was recovered in the tile drainage. Likewise, tile drainage accounted for 41% of the annual total watershed discharge with a range of 30–61%. On a monthly basis, 47% of the total watershed discharge volume was recovered through the tile drainage, ranging from near 0% to 100%. Contributions of tile drainage to total watershed discharge were dependent upon season, management, rainfall characteristics, and antecedent conditions. Results showed that median monthly summer discharge was significantly less than median monthly discharges in the winter, spring and fall.

The findings from this study indicate that tile drainage can be a significant hydrologic pathway and an important consideration in developing and enhancing hydrology and water quality computer models, understanding nutrient transport dynamics, and identifying and developing best management practices for tile drained landscapes.

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