Tile drainage causes flashy streamflow response in Ohio watersheds

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Abstract

Artificial subsurface (tile) drainage is used to increase trafficability and crop yield in much of the Midwest due to soils with naturally poor drainage. Tile drainage has been researched extensively at the field scale, but knowledge gaps remain on how tile drainage influences the streamflow response at the watershed scale. The purpose of this study is to analyse the effect of tile drainage on the streamflow response for 59 Ohio watersheds with varying percentages of tile drainage and explore patterns between the Western Lake Erie Bloom Severity Index to streamflow response in heavily tile-drained watersheds. Daily streamflow was downloaded from 2010 to 2019 and used to calculated mean annual peak daily runoff, mean annual runoff ratio, the percent of observations in which daily runoff exceeded mean annual runoff ($T_{Q_{mean}}$), baseflow versus stormflow percentages, and the streamflow recession constant. Heavily-drained watersheds (>40% of watershed area) consistently reported flashier streamflow behaviour compared to watersheds with low percentages of tile drainage (<15% of watershed area) as indicated by significantly lower baseflow percentages, $T_{Q_{mean}}$, and streamflow recession constants. The mean baseflow percent for watersheds with high percentages of tile drainage was 20.9% compared to 40.3% for watersheds with low percentages of tile drainage. These results are in contrast to similar research regionally indicating greater baseflow proportions and less flashy hydrographs (higher $T_{Q_{mean}}$) for heavily-drained watersheds. Stormflow runoff metrics in heavily-drained watersheds were significantly positively correlated to western Lake Erie algal bloom severity. Given the recent trend in more frequent large rain events and warmer temperatures in the Midwest, increased harmful algal bloom severity will continue to be an ecological and economic problem for the region if management efforts are not addressed at the source. Management practices that reduce the streamflow response time to storm events, such as buffer strips, wetland restoration, or drainage water management, are likely to improve the aquatic health conditions of downstream communities by limiting the transport of nutrients following storm events.

KEYWORDS

agriculture, baseflow, intensively managed landscapes, recession analysis, tile drainage
1 | INTRODUCTION

Artificial subsurface (tile) drainage is required for increased crop yield in much of the cropland in the Midwestern United States ('Midwest') due to soils with naturally poor drainage capabilities. Tile drains increase soil drainage by removing excess subsurface water that can inhibit plant growth, resulting in lower water tables that increase the trafficability of heavy machinery to operate in farm fields. Tile drains began to be installed in the Midwest during the late 19th century with the initial goal of strategically draining wet areas of farm fields that were susceptible to ponding, but installations are now common throughout the entire field to lower the water table (Blann et al., 2009). Drainage pipes are typically installed between 0.6 and 1.2 m below the surface approximately 10–30 m apart, depending on site-specific soils, crop type, and cost (Skaggs & van Schilfgaarde, 1999). Infiltrated water is captured underground by perforated drainage pipes and routed away from the field into adjacent ditches and streams.

According to the U.S. Department of Agriculture (USDA) National Agriculture Statistics Service (NASS) 2017 Census of Agriculture, 225 024 km² of cropland are estimated to have tile drainage with the vast majority occurring in the Midwest (USDA NASS, 2019). The amount of land with tile drainage in the United States increased by 28 484 km² (14.5%) between 2012 and 2017 (USDA NASS, 2014), with the largest increases occurring in the Midwest. Recent changes to precipitation patterns that generate more frequent large rain events in the Midwest (Williams & King, 2020) may partly explain the growing adoption of tile drainage. Further, as heavy rainfall events are projected to increase in frequency into the future due to climatic change, we can expect an expansion of land under tile drainage globally (Gordon et al., 2017). Understanding how tile drainage impacts the hydrologic response of downstream waterways, and subsequent transport of nutrients, is critical for the development of holistic management plans that improve downstream aquatic life and help communities assess flood risks.

However, the streamflow response, and subsequent export of nutrients, from farm fields under tile drainage is complicated to ascertain and predict due to compounding environmental, management, and site-specific soil conditions (Hannahan et al., 2020). For example, Boland-Brien et al. (2014) reviewed several field studies (<10 ha) and suggested that tile drainage can cause peak streamflow to decrease when water tables are close to the surface due to clayey soils with low permeability or during high rainfall events. In contrast, peak flows may increase on fields with deeper water tables with drier climates or more permeable soils (Boland-Brien et al., 2014). Such changes in peak flows across large scales could have impacts on timing and magnitudes of flood peaks for downstream communities. In addition, management practices that target particular flow pathways (e.g., reducing surface runoff or reducing tile outlet discharge) could have adverse effects on other nutrient transport mechanisms, and thus have unintended impacts to nutrient loads not initially targeted (Smith et al., 2015). Studies have consistently showed that water exiting tile drains contribute significant amounts of nutrients (e.g. nitrogen and phosphorus) to downstream waterbodies. In Illinois, riverine nitrate flux from tile-drained land was over twice the value compared to non-tile drained land despite higher net nitrogen inputs on non-tile drained land (McIsaac & Hu, 2004). Tile drainage exported 80% of stream nitrogen load, despite only contributing 15%-43% of the streamflow in a 122 km² watershed in northeast Iowa (Arenas Amado et al., 2017). In a headwater watershed in Ohio (4 km²), tile drainage accounted for 47% of total discharge, 48% of dissolved phosphorus, and 40% of total phosphorus (King et al., 2015).

Tile drains have been shown to reduce mean groundwater travel times, which is problematic for example when considering the transport of nitrogen which tends to have higher concentrations in groundwater compared to surface runoff (Schilling et al., 2012). A modelling study on a 74.3 km² watershed in north-central Iowa revealed that mean groundwater travel times are more than 150 times faster than those that existed prior to settlement, resulting in the majority of groundwater (>98%) bypassing perennial riparian buffers (Schilling et al., 2015), which drastically reduces the effectiveness of installing stream buffers to reduce nitrogen concentrations (Schilling et al., 2015). A study in western Indiana compared the residence time of baseflow in agricultural and adjacent undisturbed forested watersheds using multiple isotopic tracers (specifically CFC, SF6, 36Cl, and 3H) and suggested that baseflow in the agricultural watershed with tile drainage was controlled by a large contribution of tile drainage and/or soil water with short residence times (Frisbee et al., 2017). In contrast, Frisbee et al. (2017) concluded that baseflow in the adjacent, undisturbed forested catchments was supported by groundwater with much older residence times (at least 40 years old). Baseflow comprised of large contributions from tile drainage is problematic for the aquatic health of waterways due to the often high concentrations of nutrients measured in tile drainage.

Baseflow proportions can be used to assess hydrologic impacts of land use and conservation practices and have been found to be strongly correlated to legacy nutrient concentrations; thus, baseflow estimations provide a first approximation of stream vulnerability to legacy nutrients (Tesoriero et al., 2013). Tile drainage was demonstrated to increase the proportion of baseflow to receiving streams in Iowa (Schilling & Libra, 2003; Schilling and Helmers, 2008; Boland-Brien et al., 2014), but a gap remains understanding the relationship between tile drainage and baseflow in other regions, particularly in regions with different soil and precipitation characteristics, such as Ohio. Baseflow proportions are generally thought to increase in larger or flatter watersheds as groundwater tends to be the main contributor to streamflow. According to Boland-Brien et al. (2014), while watersheds in Iowa with large proportions of tile drainage tended to have larger baseflow proportions compared to non-tiled watersheds, the variability of baseflow percentage with watershed size was much lower for watersheds with large proportions of tile drainage compared to non-tiled watersheds which exhibited an increase in baseflow proportion with watershed size. Boland-Brien et al. (2014) found that tile drainage had a similar homogenizing effect on all flow regimes, where heavily tile-drained watersheds showed little to no variability in streamflow response across a range of drainage areas compared to watersheds with a smaller...
proportion of tile drainage that exhibited larger variability in streamflow response when considering various streamflow metrics across a range of watershed sizes, which is expected for natural systems.

In addition to baseflow assessments, hydrograph recession analysis has proven to be a helpful mathematical exercise that estimates the potential change in the storage-discharge relationship for a particular watershed. Recession analysis can be used to evaluate storm responses and thus infer storage properties and mean residence times (e.g., Troch et al., 2013). For example, Schilling and Helmers (2008) found the master recession curves for tile-drained watersheds in Iowa to be more linear compared to less-tiled watersheds that showed a non-linear recession, typical of natural systems where hydraulic conductivity decreases with depth. They suggested that downstream hydrograph recession may be controlled by longer recession times from tiled regions, but also found inconsistent recession coefficients between tiled and non-tiled regions and advocated for additional research in this field. Boland-Brien et al. (2014) also performed streamflow recession analysis on watersheds with varying percentages of tile drainage across Iowa and concluded that tiled regions were less flashy compared to non-tiled regions based on master recession curve analysis.

Clearly, tile drainage can have confounding impacts on hydrological response depending on scale and the combination of physical and climatic characteristics considered. Given an emphasis in the literature on tile drainage impacts to streamflow response in Iowa (e.g., Schilling and Helmers, 2008; Boland-Brien et al., 2014; Schilling et al., 2015; Arenas Amado et al., 2017), we wondered how tile drainage impacts hydrological response under other landscapes and climatic conditions? As such, the goal of this study is to assess the impact of tile drainage on the streamflow response of Ohio watersheds with varying percentages of tile drainage. The shallow, poorly-drained soils of Ohio provide an excellent contrast to those in Iowa, which tend to be deeper and coarser, thus have different drainage tendencies. We used an automated baseflow separation technique combined with hydrograph recession analysis to determine if the effects of tile drainage on the storage-discharge relationship are evident at the watershed scale and postulate the consequences for downstream nutrient transport. To this latter aspect, phosphorous loads from March to July have previously been identified as a major driver of the severity of HABs in the western Lake Erie basin (Baker et al., 2019; GLWQA, 2019; Stumpf et al., 2012), which is where the majority of tile drainage occurs in Ohio. Therefore, we focused on this critical time period in order to isolate the effects of tile drainage from heavily-drained watersheds in the western Lake Erie basin on hydrograph partitioning that could be exacerbating HAB severity by creating a quicker hydrologic connection between agricultural fields and adjacent streams.

2 | MATERIALS AND METHODS

2.1 | Data and study area

Daily mean streamflow for each study watershed was downloaded from 2010 to 2019 for 59 U.S. Geologic Survey (USGS) stream gaging stations in Ohio using the R package ‘dataRetrieval’ (De Cicco & Hirsch, 2018). The station ID for each stream gage is included as supplementary material. Streamflow was converted to area-weighted runoff (‘runoff’) using the total watershed area and daily time interval. The time period of data considered was selected to match with the responses from the recent county-level tile drainage census data used to generate AgTile-US (Valayamkunnath et al., 2020). Monthly PRISM precipitation data from the same period (i.e., 2010–2019) was aggregated to watershed boundaries to determine mean monthly and annual precipitation for each study watershed (PRISM Climate Group, 2019).

The 59 study watersheds were selected based on streamflow record and limited hydrological modifications using the following criteria: (1) had at least 8 years of complete data from 2010 to 2019, with each year having at least 90% daily streamflow records available, (2) had less than 6 major dams, (3) were located at least 5 miles downstream of dams, (4) had less than 25% developed land, (5) had at least 25% agricultural land, and (6) had area less than 2000 km² (Falcone, 2011). The watershed size limitation was suggested as a threshold in which the effects of tile drainage were likely to become less apparent due to channelization and in-stream attenuation (Boland-Brien et al., 2014). These 59 watersheds were split into three roughly equal groups with increasing proportions of tile drainage to evaluate the mean streamflow response for watersheds with low (<15% area), medium (15%–40% area), and high (>40% area) amounts of tile drainage.

Watershed characteristics and boundaries were obtained from the GAGES-II dataset (Falcone, 2011). For each of the 59 watersheds in Ohio, a 30-m resolution tile drainage map (AgTile-US) was aggregated to calculate the percent of each watershed under tile drainage (Valayamkunnath et al., 2020). This dataset was generated using soil drainage information, topographic slope, and county-level tile drainage census data for the most-likely tile-drained area of the contiguous United States. Accuracy across the Midwest ranges from 82.7% to 93.6% (Valayamkunnath et al., 2020). The raster dataset is available in binary format, where 1 indicates tile-drained land and 0 indicates undrained land. For each watershed, the percent of tile drainage was calculated by summing the total amount of tile-drained area divided by the total watershed area.

Watersheds were also grouped by the dominant (highest percentage of area) U.S. Environmental Protection Agency Level III ecoregion, derived from Omernik (1987), to assess how mean runoff metrics and tile drainage prevalence vary across different ecoregions that have similar geology, physiography, vegetation, climate, soils, land use, wildlife, and hydrology (U.S. EPA, 2013). The most dominant level III ecoregions for all 59 study watersheds were Eastern Corn Belt Plains, Huron/Erie Lake Plain, Erie Drift Plain, and Western Allegheny Plateau. The difference in hydrology among these four ecoregions is substantially influenced by Wisconsin (14 000–24 000 years old) and Illinoian (130 000–300 000 years old) glaciations that resulted in glaciers, perhaps as much as one-mile thick, from central Canada flowing into areas of Ohio.

The Eastern Corn Belt Plains are primarily rolling plains with local end moraines and occupy most of western Ohio. The region contains widespread Wisconsin age glacial deposits and has loamier and
slightly better drained soils compared to the Huron/Erie Lake Plain (U.S. EPA, 2013). Distinct, narrow linear patterns of thick glacially derived sediments are present in deeply incised limestone and dolomite bedrock caused by the Teays Valley drainage system, which existed prior to recent glaciations in this ecoregion (Ohio Division of Geological Survey, 2004). Extensive corn, soybean, and livestock production has replaced most of the original beech forests and elm-ash swamps that were once more common.

The Huron/Erie Lake Plain is a broad, fertile, nearly flat plain with relic sand dunes, beach ridges, and end moraines (U.S. EPA, 2013). In Ohio, this ecoregion occupies the northwest corner of the state and drains to the western basin of Lake Erie. Originally, soil drainage was typically poorer compared to the Eastern Corn Belt Plains, and elm-ash swamp, beech forests, and oak savannas were common. Most of the area has been cleared and artificially drained and now contains highly productive corn, soybean, and livestock farms. This ecoregion once contained the 4000 km² Great Black Swamp (Mitsch, 2017) and is now considered one of the most intensively artificially drained regions of the United States (Smith et al., 2008). Bedrock topography is smooth in this portion of Ohio and generally has little impact on hydrology due to the thick deposits of glacial outwash and fine-grained clay- and silt-size glaciolacustrine sediments (Macrae et al., 2021; Ohio Division of Geological Survey, 2005).

The glaciated Erie Drift Plain is characterized by low rounded hills, scattered end moraines, kettles, and wetlands in contrast to the unglaciated Western Allegheny Plateau to the south which is hillier (U.S. EPA, 2013). Much of the original maple-beech-birch forests have been converted to farmland, including many dairy operations. However, the Eastern Corn Belt Plains to the west are flatter, have more fertile soils, and thus have more productive agricultural land. The Western Allegheny Plateau was not impacted by recent glaciation, thus does not contain the extensive deposits of glacial sediments in other areas of Ohio that have translated to productive agricultural areas (Ohio Division of Geological Survey, 2004). Historic mixed mesophytic forests and mixed oak forests have been partially replaced with dairy, livestock, and general farm operations. Sedimentary rock underlying the region has been mined for bituminous coal.

2.2 Runoff metrics

To evaluate the effects of tile drainage on streamflow response, we calculated several of the runoff metrics suggested by Boland-Brien et al. (2014) including runoff ratio, mean annual peak runoff, and the percent of time daily runoff exceeded mean annual runoff ($T_{\text{Qmean}}$). Runoff ratios were calculated by dividing annual runoff by annual precipitation from PRISM and multiplying the result by 100 to have ratios expressed as a percent. To evaluate the impact of tile drainage on peak runoff conditions, we calculated mean annual peak daily runoff for each watershed considered. The final metric considered the percent of time daily runoff exceeded mean annual runoff, $T_{\text{Qmean}}$, which measures the flashiness of the hydrograph (Konrad & Booth, 2002). As such, a low value corresponds to a flashier response and a high value suggests a more dampened hydrograph. Differences in runoff metrics were compared among the three drainage categories using the Tukey test and Pearson’s correlation coefficient. All significant results are considered when $p < 0.05$.

Daily baseflow was calculated from the total daily runoff hydrograph using the R package ‘Ifstat’ (Koffler et al., 2016) following methodology from Tallaksen and van Lanen (2004) and WMO (2008). This procedure was developed for rainfall regimes with a typical runoff response in hours or days and partitions the hydrograph into delayed and quick components by identifying turning points of runoff minima for each non-overlapping five-day period. Turning points are joined by straight lines to obtain the baseflow hydrograph. Daily stormflow was subsequently calculated by subtracting daily baseflow from daily total runoff. A baseflow index (BFI) was then calculated by dividing baseflow by total runoff, expressed as a percent.

All runoff metrics were calculated from daily records and summarized to mean annual and monthly values to assess potential seasonality effects. Further, a time period of particular interest for the study area is from March to July, for which runoff (and phosphorus loads) have been shown to be critical for determining HAB severity in the western Lake Erie basin (Baker et al., 2019; Stumpf et al., 2012). Phosphorus load targets for key Lake Erie tributaries were established in 2016 under Annex 4 of the 2012 Great Lakes Water Quality Agreement (GLWQA, 2019). For this reason, we calculated runoff metrics by averaging daily values for these months in watersheds with high (>40% area) amounts of tile drainage. In addition, we calculated the day of calendar year in which 50% of annual runoff occurs to evaluate the effect that annual streamflow timing had on bloom severity. Runoff metrics were compared to the Western Lake Erie Bloom Severity Index, calculated by the United States National Oceanic and Atmospheric Administration based on algal bloom biomass, to evaluate relationships between streamflow response and HAB severity.

To assess how water is stored and released following storm events, we performed hydrograph recession analyses for each of the watersheds considered in this study. The calculation of the recession constant required selecting an analytical expression to fit to the recession curve, determining the typical recession period, and optimizing the recession parameters (WMO, 2008). We used the R package ‘Ifstat’ to determine recession rates (Koffler et al., 2016). The recession curve was modelled using an exponential equation assuming a single linear reservoir where storage is proportional to outflow:

\[ Q_t = Q_o e^{-\frac{t}{C}} \]  

where $Q_t$ is total runoff at time $t$; $Q_o$ is total runoff at the beginning of the recession period ($t = 0$), and $C$ is the recession constant [time], which is the number of days needed for runoff to decrease one log cycle. The recession curve plots as a straight line with slope $-1/C$ on a semi-logarithmic plot of $t$ versus $\ln Q_t$. Both master recession curve (MRC) and individual recession segments (IRS) methods require criteria for selecting recession segments and the period of discharge to disregard following peak runoff to avoid selecting times of rapid response following a rainfall event that were not caused by groundwater.
discharge. For both analyses, a minimum segment length of 5 days was chosen and recession segments began at least 2 days after peak flood discharge and after runoff was below a Q25 threshold (i.e., the highest 25% of runoff following peak flood discharge was omitted). Several minimum segment lengths were tested, but the five-day fixed value produced the most consistent results among all of the watersheds, was similar to the length chosen by Boland-Brien et al. (2014), and was recommended by the WMO (2008). The MRC method constructs a single mean recession curve, while in the IRS method a recession model is fit to each segment and the recession constant C is determined as the mean value of individual recession segments.

3 | RESULTS

3.1 | Watershed characteristics

According to the AgTile-U.S. dataset (Valayamkunnath et al., 2020), mean areal coverage of tile drainage for the watersheds analysed in this study was 27.8% and ranged from 0.5% to 61.0%. Watersheds were split into three roughly equal groups to compare the mean streamflow response: low (<15% tile drained, n = 18), medium (15%–40% tile drained, n = 24), and high (>40% tile drained, n = 17) (Figure 1). Watersheds in the medium and high drainage categories were located primarily in northwestern Ohio, while watersheds in the low drainage category were spread out throughout the state. Mean watershed size was similar for all three drainage categories (Table 1). There was a significant positive relationship with agricultural land and tile drainage (Pearson’s r = 0.86, p < 0.001, Figure 2a, Table 1) and a significant negative relationship with mean watershed slope and tile drainage (Pearson’s r = −0.77, Figure 2b, Table 1). Tile drainage was significantly positively correlated to clay content (Pearson’s r = 0.54, Figure 2c, Table 1) and significantly negatively correlated to the depth of the seasonally high water table provided in the GAGES-II dataset (Pearson’s r = −0.71, Figure 2d, Table 1; Falcone, 2011).

3.2 | Precipitation

Mean annual precipitation (PRISM Climate Group, 2019) for the 59 watersheds over the 10-year period (2010–2019) was 1109 mm and ranged from 945 mm in 2010 to 1465 mm in 2011. Mean annual precipitation was significantly greater for the low drainage category (1160 mm) compared to the medium (1099) or high drainage (1067 mm) categories (Table 2). On average across all 59 watersheds, spring and summer months (April–September) were wetter than fall and winter months (October–March). The five-month period from March to July contributed 50% of annual precipitation in high drainage watersheds.

3.3 | Runoff metrics

Mean annual runoff for the 59 watersheds from 2010 to 2019 was 435 mm and ranged from 298 mm in 2012 to 717 mm in 2011. Mean annual runoff was significantly greater for the low drainage category (469 mm) compared to the medium (429 mm) and high drainage (407 mm) categories (Table 2). On average, across all 59 watersheds, winter and spring months (January–June) produced more runoff compared to summer or fall months (July–December). The 5-month period from March to July contributed 57% of annual runoff in high drainage watersheds.

For high drainage watersheds March had the most runoff (59 mm), followed by April (56 mm) and June (44 mm), while August had the least runoff (6 mm), followed by September (7 mm) and October (12 mm). In medium drainage watersheds March had the most runoff (64 mm) followed by April (59 mm) and February (49 mm), while September had the least runoff (8 mm), followed by August (9 mm) and October (13 mm). For low drainage watersheds March had the most runoff (71 mm), followed by April (65 mm) and February (57 mm), while August and September had the least runoff (13 mm), followed by October (16 mm).

Mean annual runoff ratio for the 59 study watersheds from 2010 to 2019 was 39.1% and ranged from 33.6% in 2010 to 47.8% in 2018. There was a significant positive relationship between mean annual runoff ratio and mean annual precipitation among all 59 watersheds (Pearson’s r = 0.48). Despite significantly greater mean annual
Precipitation and runoff for the low drainage category, mean annual runoff ratio was the same among all drainage categories (Table 2). Mean annual runoff ratio was not significantly correlated to tile drainage (Figure 3a) or watershed area (Figure 4a) for any of the drainage categories considered. Peak daily runoff was similar among all drainage categories and not significantly correlated to tile drainage (Figure 3b; Table 2). Peak daily runoff was significantly negatively correlated to watershed area for the medium (Pearson’s $r = -0.67$) and
high (Pearson’s $r = -0.76$) drainage categories, but not for the low drainage category (Figure 4b).

The percent of time in which mean daily streamflow was greater than mean annual streamflow ($T_{Qmean}$) was significantly negatively correlated to tile drainage (Pearson’s $r = -0.57$, Figure 3c, Table 2). A lower $T_{Qmean}$ value implies a flashier hydrograph response for the high drainage category watersheds. There was a significant positive relationship between watershed area and $T_{Qmean}$ for the medium (Pearson’s $r = 0.47$) and high (Pearson’s $r = 0.51$) drainage categories, but not for the low drainage category (Figure 4c). The mean annual BFI for the high drainage category was 20.9% compared to 40.3% for the low drainage category. Conversely, watersheds with a high percentage of tile drainage had significantly higher stormflow proportions compared to watersheds with low to medium percentages of tile drainage. There was no significant relationship between watershed area and BFI for any of the drainage categories (Figure 4d). Other watershed properties strongly significantly correlated to $T_{Qmean}$ and BFI that likely explain the remaining variability with these runoff metrics and tile drainage were (1) average clay content in soils (Pearson’s $r = -0.68, -0.71$, respectively) and (2) average soil permeability (Pearson’s $r = 0.71, 0.84$, respectively).

Both MRC and IRS techniques for hydrograph recession analysis revealed a significant negative correlation between recession constants and tile drainage (Pearson’s $r = -0.45$, Figure 5a; Pearson’s $r = -0.46$, Figure 5c, Table 2). In addition, MRC and IRS recession constants were significantly correlated to average soil permeability (Pearson’s $r = 0.79$, both) and likely explain some of the remaining variability between tile drainage and recession constants. There was no significant relationship with watershed area and recession constant using either MRC or IRS methods for any of the drainage categories (Figures 5b,d). Both MRC and IRS recession constants were significantly positively correlated to annual BFI (Pearson’s $r = 0.89$), $T_{Qmean}$ (Pearson’s $r = 0.70$), and average soil permeability (Pearson’s $r = 0.79$) (Falcone, 2011). These relationships suggest a flashier hydrograph response from watersheds with higher percentages of tile drainage and poorer drainage capabilities.

It should be noted that the March–July BFI was similar to the annual BFI and was significantly lower for the high drainage category watersheds (Table 2). In addition, the amount of March–July stormflow as a percentage of total annual runoff was significantly positively correlated to tile drainage (Pearson’s $r = 0.58$, Figure 6a). The amount of annual runoff from March to July stormflow approached 50% for watersheds with high percentages of tile drainage, while the percent of total annual runoff from March to July stormflow in watersheds with low percentages of tile drainage was around 30%.
We compared runoff metrics from the high drainage category watersheds, which predominantly drain into western Lake Erie, to the Western Lake Erie Bloom Severity Index and found mean March–July total stormflow (mm) to be the best predictor of bloom severity for all of the runoff metrics (Pearson’s $r = 0.90$, Figure 6b). The March–July stormflow runoff ratio (i.e., the ratio of total stormflow to total precipitation during March–July) was also highly positively correlated to bloom severity (Pearson’s $r = 0.87$, Figure 6c), unlike the March–July baseflow runoff ratio that did not show any correlation (Figure 6c). Another runoff metric that was highly correlated to the bloom severity index was the mean day of year in which 50% of annual runoff occurred (Pearson’s $r = 0.89$, Figure 6d). Recent years with the highest bloom severity index (>10) observed 50% of annual streamflow in June, while years with less severe blooms saw 50% of annual streamflow occurring much earlier in the year.

Mean runoff metrics for the dominant ecoregions are shown in Table 3. The majority of watersheds were primarily located in the Eastern Corn Belt Plains (36), with fewer sites located in the Erie Drift Plain (11), Western Allegheny Plateau (8), and Huron/Erie Lake Plain (4). On average, tile drainage percentage was significantly greater for watersheds located in the Eastern Corn Belt Plains (37.1%) and Huron/Erie Lake Plain (42.7%) compared to the Erie Drift Plain (11.2%) or the Western Allegheny Plateau (1.5%). The mean annual precipitation, runoff, and runoff ratio was significantly greater in the Erie Drift Plain compared to the other ecoregions. Mean $T_{Q\text{mean}}$ was significantly greater for the Erie Drift Plain compared to the Eastern Corn Belt Plains or Huron/Erie Lake Plain, implying a less-flashy streamflow behaviour; however, mean annual peak runoff, BFI, and recession constants were not significantly different among all four ecoregions.

Pearson’s correlation coefficients calculated between watershed tile drainage percentage and runoff metrics in sites located in the Eastern Corn Belt Plains and Erie Drift Plain follow similar patterns as described in the paragraphs above. Tile drainage was not related to mean annual peak daily runoff (Pearson’s $r = 0.08$) or mean annual runoff ratio (Pearson’s $r = -0.27$), but was found to be significantly correlated to $T_{Q\text{mean}}$ (Pearson’s $r = -0.47$), mean annual BFI (Pearson’s $r = -0.63$) and both MRC and IRS recession constants (Pearson’s $r = -0.63$ and $-0.64$, respectively). The lack of correlation between mean annual runoff ratio and mean annual peak daily runoff with tile drainage emphasizes the role that various local soil drainage characteristics, management practices, and annual climate variability have on the responsiveness of tile drainage to rainfall events across these individual watersheds. The strength of correlation between tile
drainage and runoff metrics for Eastern Corn Belt Plains and Erie/Huron Lake Plain watersheds are similar to the values described above when considering all 59 watersheds and suggest a flashier streamflow response for watersheds with large percentages of tile drainage with similar soil properties and land uses dominated by agriculture.

4 | DISCUSSION

4.1 | Comparison with other studies across the Midwestern United States

Our results on the streamflow response of watersheds with varying percentages of tile drainage in Ohio are markedly different from previous studies conducted in Iowa watersheds. We showed a significant negative relationship between tile drainage percent and mean annual baseflow index (BFI) (Figure 3d) and a significant positive relationship between tile drainage percentage and Mar-Jul total stormflow (Figure 6a) for 59 watersheds in Ohio. These results are in contrast to extensive research performed with Iowa watersheds that showed an increase in baseflow proportions with tile drainage percentage (Schilling & Libra, 2003; Schilling and Helmers, 2008; Boland-Brien et al., 2014). The contrast between the states however should not come as a surprise since previous work showed a linear relationship between rainfall and tile drainage in which 12.6% of rainfall was recovered in tile drainage in Iowa, compared to 22.2% in Ohio (Logan et al., 1980). Of course, Schilling and Zhang (2004) reported an average runoff ratio (ratio of total stream discharge to precipitation) of 25.6% from 1972 to 2000 in the Raccoon River watershed in Iowa. Similarly, Boland-Brien et al. (2014) reported a mean runoff ratio of 28% from 1996 to 2005 in 24 Iowa rivers and Jones et al. (2018) calculated an average runoff ratio of 28% from 1987 to 2001 and 30% from 2002 to 2016 for nine Iowa rivers. Looking at Ohio, King et al. (2015) found that tile drainage water accounted for as much as 47% of total discharge in a headwater stream. As such, assuming runoff consists of a mix of tile drainage water and other flow pathways, we would still expect a difference in the responsiveness of tile drainage water to rainfall between Iowa and Ohio landscapes. Further, according to 30-year climate normal the watersheds used our study have significantly greater mean annual precipitation (979 mm) compared to Iowa watersheds (869 mm) analysed by Boland-Brien et al. (2014) (Falcone, 2011). It stands to reason that in the Midwest, Ohio and Iowa roughly represent two end-members in terms of the meteorological and physical characteristics of watersheds with high percentages of tile drainage; thus, it is fair to assume that tile drainage could result in greater baseflow or stormflow proportions, depending on site-specific meteorological and physical conditions.

When our results are compared to the work from Boland-Brien et al. (2014)—who calculated similar runoff metrics—it is clear that large percentages of tile drainage can cause a notably different
hydrologic response at the watershed scale in terms of baseflow and stormflow proportions and the general flashiness behaviour. Boland-Brien et al. (2014) reported a mean BFI of 67% for the Iowa watersheds considered with a high degree of tile drainage (>50%), compared to 22% reported for the high drainage category (>40%) in our Ohio study. The mean annual runoff ratio was notably higher for watersheds analysed in our study (39%) compared to those by Boland-Brien et al. (2014) (28%). In addition, our results suggest $T_{Q_{\text{mean}}}$ and the recession constants indicate flashier streamflow behaviour in watersheds with high amounts of tile drainage compared to the Iowa watersheds that showed the opposite trend. Given low drainage category watersheds had significantly greater mean annual precipitation and runoff (Table 2), we would usually expect to observe a significantly greater mean annual runoff ratio and peak daily runoff for the low drainage category. However, there were no significant
difference between mean annual runoff ratio or peak daily runoff for any of the drainage categories, suggesting medium and high drainage category watersheds had greater mean annual runoff ratios and peak daily runoff than expected. All of these results suggest an increasing percentage of tile drainage leads to flashier watersheds in Ohio.

Of course, the watersheds analysed by Boland-Brien et al. (2014) were substantially larger (average area of 1666 km$^2$) compared to the ones presented in this study (average area of 605 km$^2$), which likely partially explains the larger observed BFI in Iowa watersheds. This difference, however, does not explain the opposite trend observed between the relationship of percent tile drainage and runoff metrics. Despite similar mean watershed slope, soil thickness, and soil textures (i.e., sand, silt, clay percentages) between our watersheds and the ones presented in Boland-Brien et al. (2014), the Ohio watersheds showed significantly greater soil bulk density (1.54 g/cm$^3$) compared to the Iowa watersheds.

### TABLE 3

| Level III ecoregion          | Number | Drainage (%) | RR (%) | Peak Q (mm/day) | $T_{Q_{\text{mean}}}$ (%) | BFI (%) | MRC (days) |
|------------------------------|--------|--------------|--------|----------------|--------------------------|---------|------------|
| Eastern Corn Belt Plains     | 36     | 37.1 a       | 38.7 b | 19.7 a         | 24.2 b                   | 30.0 a  | 6.5 a      |
| Huron/Erie Lake Plain       | 4      | 42.7 a       | 38.3 b | 15.8 a         | 22.6 b                   | 24.9 a  | 4.9 a      |
| Erie Drift Plain             | 11     | 11.2 b       | 42.0 a | 15.5 a         | 28.2 a                   | 40.0 a  | 6.7 a      |
| Western Allegheny Plateau   | 8      | 1.5 b        | 37.7 b | 18.6 a         | 28.1 ab                  | 39.7 a  | 7.6 a      |

Note: Unique letters represent significant differences ($p < 0.05$) using the Tukey test.
(1.44 g/cm³) (Falcone, 2011). The lower bulk density values observed in Iowa favor faster infiltration rates compared to Ohio, which likely results in greater groundwater recharge and smaller proportions of stormflow in Iowa. In fact, the Ohio watersheds analysed in this study had a significantly greater proportion of soils in hydrologic group C (62%) characterized by moderately fine or fine texture, slow soil infiltration rates with layers impeding the downward movement of water (Falcone, 2011). In contrast the Iowa watersheds had a significantly lower percent of soils in hydrologic group C (16%) and were dominated by soils in hydrologic group B, characterized by moderately deep, coarse, well-drained soils with moderate infiltration rates.

Another substantial difference between the two areas is the depth to seasonally high water table, which was significantly smaller for the Ohio watersheds (which averaged 0.80 m) compared to the Iowa watersheds (which averaged 1.23 m) (Falcone, 2011). As a consequence of shallower depth to groundwater and finer textured soils in Ohio watersheds, tile drains are likely installed closer to the surface compared to fields in Iowa. In addition, there is evidence that additional drainage is being installed to reduce the spacing between tile drains to facilitate additional drainage following rain events (Macrae et al., 2021). As a result, tile drains installed at shallow depths in Ohio fields with slow soil infiltration rates and shallow water tables create a more direct response to rainfall events observed in tile drainage outlets compared to deeper installations in fields with moderate infiltration rates and deeper water tables.

Another major difference in hydrologic response of Ohio and Iowa watersheds to varying percentages of tile drainage was the homogenization of all runoff metrics with high percentages of tile drainage reported by Boland-Brien et al. (2014). While our study watersheds with high percentages of tile drainage did not show a relationship with drainage area for mean annual runoff ratio or mean annual BFI, we found significant correlations between drainage area and Tmean (Figure 4c) and peak daily runoff (Figure 4b) for the medium and high tile drainage category watersheds, but not for the low drainage category watersheds. In contrast, drainage area was not correlated to any of the runoff metrics for the low drainage category (Figure 4). As mentioned before, larger watersheds typically show higher percentages of baseflow and a more attenuated streamflow response as groundwater contributions increase (Price, 2011). However, the influence of geological conditions on streamflow response will be most apparent during dry conditions when baseflow contributions are high (Cross, 1949). Since the low drainage category watersheds are more dispersedly located throughout Ohio (Figure 1), it is possible the geological conditions are more variable for these watersheds compared to the medium or high drainage categories, which are predominantly located in northwest Ohio and likely have more similar geological conditions.

4.2 | Implications for nutrient transport

The agricultural economic benefits of tile drainage are accompanied with environmental and economic costs associated with impaired water quality. Water exiting tile drain outlets transport agricultural pollutants (e.g., nitrogen, phosphorous, and pesticides) downstream which can accumulate leading to hypoxic zones and harmful algal blooms (HABs), with detrimental effects to human and aquatic systems (Diaz, 2001). Harmful algal blooms are not unique to Ohio and have become a global problem in recent decades (Ho et al., 2019). The environmental consequences of HABs are difficult to remediate and can negatively impact tourism, recreation, property values, wildlife, and commercial fishing. In August of 2014, elevated microcystin toxin levels associated with a HAB resulted in 400 000 residents left without drinking water. In Lake Erie, the world’s largest walleye fishery, summer-long HABs can result in $5.6 million in lost fishing expenditures alone (Wolf et al., 2017).

Tile drainage is thought to reduce surface runoff, therefore improve soil stability and limit the amount of erosion and particulate nutrient concentrations exporting via surface runoff. While nutrient concentrations measured in tile drainage are often low during low discharge periods, elevated nutrient concentrations have been measured during high discharge periods, proving that tile drains can act as effective conduits for nutrient export from agricultural fields (Dils & Heathwaite, 1999). Numerous studies have showed a strong surface connection to tile drainage through macro pores and other preferential flow paths (Macrae et al., 2019; Smith et al., 2015; Stamm et al., 1998; Williams et al., 2016), and thus potential to transport nutrients applied to the soil surface. In addition, recent research suggests storm events can accelerate the subsurface transport of particulate and dissolved nutrient species (Jiang et al., 2021).

The results reported in this study suggest that Ohio watersheds with large percentages of tile drainage could be exacerbating the problem with downstream nutrient transport due to increases in total stormflow amounts and proportions (Figure 3d; Figure 6a). In fact, recent HAB severity observed in the western Lake Erie basin was significantly correlated to March–July stormflow amounts (Figure 6b). It should be noted that one of the strongest correlations of watershed attributes from the GAGES-II dataset with tile drainage percentage were estimates of applied nitrogen (Pearson’s r = 0.79) and phosphorus (Pearson’s r = 0.70) from agricultural censuses (Falcone, 2011). This should not be surprising given the strong correlation between agriculture and tile drainage (Figure 2a) but emphasizes the role that watersheds with high percentages of tile drainage, and higher percentages of stormflow, play in the downstream transport of nutrients.

Direct HAB remediation is costly and involves either physical, chemical, or biological control measures, but will not help mitigate future severe HABs. If left uncontrolled, HABs in Lake Erie are estimated to cost Canada alone $5.3 billion over the next 30 years (Smith et al., 2019), thus targeting conservation efforts at the source could prove to be cost-effective. A combination of both nutrient and water management practices are probably needed to improve downstream aquatic conditions (Hanrahan et al., 2019). In Ohio, soil test phosphorus concentrations were found to be linearly related to dissolved concentration loads in tile-drained fields, thus soil test phosphorus can be a good screening method to identify fields at risk for greater phosphorus loss (Duncan et al., 2017). Limiting fertilizer application prior to
spring storm events or incorporating fertilizer into the soil structure could help to reduce the downstream transport of phosphorus from tile-drained fields (Williams et al., 2016). The strong positive correlation between the timing of 50% of annual streamflow and HAB severity (Figure 6d) supports an earlier application of fertilizer to avoid excess nutrient transport during large late-spring storms which could be contributing to more severe HABs when water temperatures are greater. Soil phosphorus stratification caused by repeated surface application without incorporation can cause elevated phosphorus losses to surface runoff (Daverede et al., 2004). In addition, soil phosphorus stratification combined with the clay soils common in the western Lake Erie basin has created conditions prone to substantial phosphorus losses in tile drainage due to preferential flow (Grant et al., 2019). A combination of subsurface phosphorus placement and periodic conservation tillage that breaks up macro pores has been suggested to mitigate both surface and subsurface phosphorus losses (Macrae et al., 2021).

Conservation practices that decrease the hydrologic response time to storm events in Ohio watersheds could benefit the aquatic health of downstream communities (e.g., erosion control using vegetation, wetland restoration). Restoring 5%–10% of the 4000 km² Great Black Swamp in the Maumee River basin could reduce phosphorus loading by 18%–37% (Mitsch, 2017). Another technique that could decrease the hydrologic response time and thus greatly reduce the export of nutrient loads from agricultural fields is drainage water management, which has been shown to significantly reduce annual tile drainage discharge (Gunn et al., 2015) and subsequent nutrient loads (Williams et al., 2015). Through drainage water management, tile drainage outlets can be manipulated at the edge of field to reduce discharge during winter fallow periods and times in which field accessibility is not imperative. For example, during a 5-year study period in southern Ontario, drainage water management resulted in reduced losses of particulate phosphorus by 15% and total phosphorus by 12%, but had similar dissolved reactive phosphorus losses compared to a field under traditional free drainage (Tan & Zhang, 2011). There is a concern that elevated groundwater levels caused by drainage water management could increase the hydraulic gradient from agricultural fields to adjacent streams, facilitating increased groundwater discharge via lateral seepage to streams (Williams et al., 2015). In addition, modelling studies suggest reduced tile drainage discharge caused by drainage water management may cause increased surface runoff (Gilliam & Skaggs, 1986). In fact, Tan and Zhang (2011) calculated that 29% to 35% of the total soil phosphorus loss in a field under drainage water management was transported via surface runoff, while only 3%–5% was accounted for in surface runoff for a field under traditional free drainage.

4.3 Limitations and future research needs

One of the main limitations to our analyses was accurately selecting appropriate watersheds to compare the hydrologic response. The medium and high drainage category watersheds analysed in this study are primarily located in northwest Ohio, while the low drainage category watersheds are scattered more throughout the state. Thus, the low drainage category watersheds have more variable soil properties, land cover, and precipitation patterns compared to the medium and high drainage category watersheds. In addition, some of the low drainage category watersheds have much greater mean slope (>4%) and forest cover, thus the processes leading to the observed streamflow response in these low drainage category watersheds are likely quite different compared to the medium or high drainage category watersheds or the remaining low drainage category watersheds with lower mean watershed slope (<4%). We performed the same analyses after removing the steepest watersheds (>4% mean watershed slope, n = 13), which tended to be located in eastern and southern Ohio and none of the results changed, suggesting that our results and interpretations presented are robust across a range of tile drainage percentage for Ohio watersheds.

Another limitation for this study was relying on the modelled tile drainage dataset (Valayamkunnath et al., 2020) for accurate identification of land drained by subsurface tiles. While recent advancements using thermal infrared sensors deployed with drones have provided adequate representation of tile delineation at agricultural fields (Allred et al., 2018), it is currently unrealistic to obtain this information at the scale of the watersheds analysed in this study. In Ohio, the total land area in the AgTile-U.S. dataset is within 0.22% of the total tile drained area reported in the USDA Census of Agriculture. However, neither of these datasets are able to provide information on whether drainage water management is implemented. For this reason, we assumed that drainage water management did not contribute substantially to the tile drained land or that drainage water management is uniformly practiced throughout the study watersheds, thus would not impact any particular watershed or drainage category.

Despite the high accuracy of AgTile-U.S. with the USDA Census of Agriculture for estimates of tile drainage in Ohio, the dataset does not provide information on the location and extent of surface inlets to tile drainage used to drain closed depressions. The impacts of surface inlets are thought to be underreported in drainage studies, possibly due to the lack of available databases at regional, state, or county levels that provide the location of these structures (Flores et al., 2021). The number of surface inlets in the western Lake Erie basin for example has been estimated to be as high as 75 000 (Feyereisen et al., 2015). These inlets can cause ponded surface water to completely bypass the soil matrix and provide a direct pathway for water, sediment, nutrients, and agrochemicals to enter waterways. Using 1500 site-years of drainage and nutrient data, Flores et al. (2021) calculated that annual phosphorus loads were twice as great in sites containing surface inlets (0.40 kg ha⁻¹) compared to sites without (0.21 kg ha⁻¹), but an opposite pattern for dissolved nitrogen was identified where sites with surface inlets had smaller annual losses (3.3 kg ha⁻¹) compared to sites without surface inlets (23.0 kg ha⁻¹). The inlets create a direct connection between field surfaces and tile outlets and could contribute to a flashier downstream hydrologic response. However, Flores et al. (2021) found no statistical difference in annual drainage volume between sites with and without...
surface inlets. Using the relationships between annual dissolved nitrogen and phosphorus loads, Flores et al. (2021) developed a logistic regression model that can be used to predict the presence of surface inlets.

Baseflow is a fairly ambiguous term but is generally thought to be representative of the water that sustains streamflow in between storms. In contrast, stormflow (i.e., quickflow, Hewlett & Hibbert, 1967) is a term used to represent the remaining streamflow not accounted for in baseflow. While mathematical baseflow separation techniques have been used since the early 20th century, more recently, chemical and isotopic mass-balance methods have become a popular alternative to mathematical approaches and are generally considered to be more physically-based due to incorporating chemical and/or isotopic information (Schilling and Helmers, 2008; Tesoriero et al., 2013; Frisbee et al., 2017; Schilling et al., 2019). However, mathematical approaches continue to be used widespread due to fewer data requirements, with only stream discharge being needed to perform baseflow separation (Schilling and Helmers, 2008; Boland-Brien et al., 2014; Schilling & Jones, 2019). Since the calculations for baseflow and stormflow used in this study are strictly based on the shape of the hydrograph, mathematical derivations of these terms cannot differentiate the geographic sources or ages and residences times of these two hydrograph sources. For example, under dry conditions tile drainage is likely composed of primarily baseflow derived from relatively older groundwater, whereas during wet storm conditions tile drainage could be comprised from a mixture of older groundwater and younger rainfall event water. Thus, the water discharging from tile drainage cannot be assumed to be entirely baseflow or stormflow. Additional research utilizing unique tracer signatures would be valuable for assessing the relative age of stream water and discharge from tile drainage outlets and downstream rivers and lakes.

5 | CONCLUSION

This study analysed the effect of tile drainage on various runoff metrics for 59 Ohio watersheds. We used a recently developed 30-m resolution tile drainage dataset to calculate the percentage of tile drainage in each watershed. Our results indicate that high percentages of tile drainage (>40% of watershed area) result in significantly greater percentages of stormflow and a flashier hydrograph response in general, which contrasts with similar studies conducted in Iowa that showed increases in baseflow percentages and less flashy hydrographs for heavily tiled watersheds. Using baseflow and recession analysis, watersheds with high percentages of tile drainage consistently reported flashier behaviour compared to watersheds with low percentages of tile drainage. The total amount of March–July stormflow and the stormflow proportion during this time was significantly positively correlated to western Lake Erie harmful algal bloom severity during the study period (2010–2019).

Increases in stormflow proportions, or the fast-varying portion of the hydrograph, are problematic for the downstream transport of nutrients and could be linked to exacerbated harmful algal bloom severity in Lake Erie observed in recent years. Given the recent trend in more frequent large rain events and warmer temperatures in the Midwest, increased harmful algal bloom severity will continue to be an ecological and economic problem for the region if management efforts are not addressed at the source. Management practices that reduce the hydrologic response time to storm events, such as buffer strips, wetland restoration, or drainage water management, are likely to improve downstream aquatic health conditions by limiting the transport of nutrients after storm events.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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