Research Article

Characterizing Phosphorus Transport to Agricultural Tile Drains in Vermont

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Ryan Ruggiero 1\*, Don Ross 1 and Joshua Faulkner 1,2,3,4

1 Department of Plant and Soil Science, University of Vermont, Burlington, VT 05405

2 Department of Civil and Environmental Engineering, University of Vermont, Burlington, VT 05405

3  University of Vermont Extension, Burlington, VT 05405

4  Gund Institute for the Environment, University of Vermont, Burlington, VT 05045

**\*** Correspondence: joshua.faulkner@uvm.edu

**Abstract:** Tile drainage has been identified as a potential non-point source of phosphorus (P) pollution and subsequent water quality issues. Three tile drained fields in Vermont were monitored to characterize hydrology and P export. Fields were in corn silage and used minimal tillage and cover cropping practices. Preferential flow path (PFP) activity was explored by separating tile flow into flow pathway and source connectivity components using two hydrograph separation techniques, electrical conductivity end member unmixing and hydrograph recession analysis. Results show that the non-growing season has the potential to dominate annual P loading, and peak P concentrations in tile drains occurred during events following manure injection in the fall, as well as in the spring after the cover crop was terminated. Tile drainage was the dominant P export pathway because of higher total discharge. Drought conditions during this study limited surface runoff, and possibly resulted in maximum PFP activity in the active clay soils. Intra-event analysis of rainfall pulses showed that tile flow and P concentrations were higher as a result of higher intensity pulses. This study highlights the impacts of current manure management, as well as the potential for climate change to increase P transport to tile drains.

**Keywords:** Phosphorus, Tile Drainage, Preferential Flow, Hydrograph Separation, Manure Injection, Soil, Rainfall Intensity, Drought, Climate Change

1. Introduction

Reducing nutrient loss and subsequent water degradation is a challenge for agriculture as we explore the boundaries of crop and livestock yields [1]. Phosphorus (P), among other required nutrients, is applied to farmland to increase fertility; it is easily transported from the soil to runoff and eventually surface waters, resulting in non-point source P pollution [2]. Accumulated legacy P from long term application of P fertilizers and manure increases the difficulty of managing agricultural runoff [3], [4]. Despite this, dairy cropping systems continue to apply manure P since land application is the primary economically viable method for its disposal, and nitrogen contained in the manure is needed for crop production [5]. In addition, in the face of climate change, where rainfall has and is expected to continue to increase during the period leading up to planting, tile drain installation has increased as a solution to concerns around spring field accessibility and crop yields [6]–[8]. Tile drainage alters the hydrology and hydraulics that control P transport during storm events, and in some instances is regarded as a best management practice (BMP) for reducing P in agricultural runoff [9]–[12]. However, tile drains installed on poorly drained soils consisting of fine textured clays that are prone to desiccation cracking, usually embody preferential flow pathways (PFP) that permit rapid movement of water, reducing resorption of P to the soil matrix [13]–[15]. Thus, tile drainage in conjunction with current dairy cropping practices poses an increased risk to water quality [16].

Increasing temporal and spatial contact between P and the soil matrix can result in lower P concentrations in runoff [17]. This is achieved by tillage and fertilizer incorporation, which also have the effect of disrupting PFP, thus reducing P loss to tile drains [15], [18], [19]. However, mechanical action is known to reduce soil structure and aggregate stability that can increase sediment in runoff [20], which is easily transported to tile drains via PFP [21]. P export dynamics are a function of season and antecedent moisture, which allude to the biogeochemical process controlling P solubility and export [22], [23]. While P concentrations in agricultural runoff correspond to P levels in the soil [24], peak P loading occurs during rainfall and snowmelt events because hydrology is usually the controlling factor of P export in agricultural watersheds [23].

Previous studies have used two different hydrograph separation methods for estimating PFP contributions to tile drains, and until recently the two have yet to be combined to clarify matrix-PFP interactions and its impact on P transport [25]. The first method, hydrograph recession analysis (HRA), separates matrix and PFP contributions into slow flow (SF) and quick flow (QF), respectively, by examining the hydraulics of the system. Here, the soil profile is assumed to drain via multiple reservoirs, thus PFP are separated from matrix contributions based on groupings of pore sizes that drain at similar rates [26], [27]. The second method, a mass balance or end member mixing analysis (EMMA), separates matrix and PFP into old and new water, respectively, via a tracer that accumulates in infiltration as contact with soil media increases. This method estimates matrix and PFP contributions based on contact time with the bulk soil [19], [28]–[30]. By combining the two methods into a four-component hydrograph model, the mixing of infiltrating water between the matrix and PFP can be assessed, thus improving estimates of P export to tile drains [25].

Tile drainage research in the U.S. Midwest provides a foundation for research in the Northeast, where intensive dairy cropping agroecosystems are also prevalent [31]. In the Lake Champlain Basin (LCB), 38% of P loading to the lake has been attributed to agriculture [32], and rainfall and climate trends suggest more extreme periods of wetness and drought [8]. Thus, this study aims to improve the understanding PFP and P transport to tile drains to help adapt nutrient management decisions to the impacts of climate change. Year-round monitoring of rainfall and tile discharge metrics were performed to 1) characterize P transport from tile drains in Vermont (VT) and 2) assess the role of PFP and rainfall dynamics on P transport. Effects of antecedent moisture condition (AMC), seasonality, P application timing, and transport/source limitation behavior were explored to characterize P transport dynamics [33]–[35]. A dataset of high temporal resolution measurements of tile flow, tile P concentrations, and rainfall from an archetypal VT dairy agroecosystem was used for this analysis. Also, the four-component hydrograph separation model proposed by Nazari et al. [25] was used to assess PFP activity, as well as matrix-PFP interactions. A unique intra-event rainfall pulse analysis was performed using temporal rainfall data, where it was hypothesized higher intensity rainfall pulses would result in higher P concentrations in tile drains because of PFP activity.

2. Materials and Methods

2.1 Site Description

Tile drainage was measured year-round from intensive dairy forage production fields, located within the western LCB (Addison County, VT). Three different tile networks draining two separate field sites were monitored for this study. The first site is drained by the tile network AHS and the second field site, DC, is drained by the two separate networks of DC south (DCS) and DC north (DCN). The tile network at AHS was installed in 2016 and both networks at DC were installed in 2018. Tile network drainage areas were determined from installation maps provided by the installer; AHS is 14.16 ha, DCS is 8.0 ha and DCN is 4.85 ha. At both sites, tiles were installed to a depth of 1 meter and are spaced 7.62 m (25 ft) apart. Tile laterals at AHS are 101.6 mm (4 in) in diameter and are connected to a 203.2 mm (8 in) tile main, and at DC the tile laterals are a diameter of 101.6 mm and are connected to 152.4 mm (6 in) tile mains. The sites are 3.2 km apart and the mean annual rainfall and temperature for the area is 94 cm and 7.8 degrees C, respectively. Site soils were not identical but are dominated by fine-textured soils that are prone to desiccation cracking. AHS is of the Vergennes clay soil series, while soils at DC are dominated by the Covington and Panton silty clay series with a small vein of the Swanton fine sandy loam series in the east/upper parts of the field [36].

Both sites were in corn silage production during the study period and since tile installation occurred, yet AHS was in hay production prior to tile installation. Before tiles were installed, the farmer had formed multiple broad swales extending across the entire field that were sloped to the edges to improve surface drainage. This grading occurred at DCS, and the southern portion of DCN, but not at AHS. These surface features remain, and the broad swales drain to surface inlets that have individual outlets and are not linked to the tile drainage network. During the study period and in the few years prior, both sites received light chisel tillage prior to planting and dairy manure was injected after the corn harvest (Table 1). In the fall of 2020, the farmer performed deep tillage along the field topographic contours to effectively create surface roughness features (i.e., ‘water bars’) throughout the field that were intended to intercept surface runoff and promote infiltration.

Table 1 Site management practices and timing. P.A.E. is P application equivalent. A standard application rate of 0.34 kg (0.75 lbs) of glyphosate (acid equivalent) per acre assumed. Nitrogen side dress was entirely urea ammonium nitrate (UAN), and the cover crop was Winter Rye (*Secale cereale*).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| AHS | | | DC | | |
| **Date** | **Action** | **P.A.E (g/ha)** | **Date** | **Action** | **P.A.E (g/ha)** |
| 10/6/18 | Manure injected | 152,435 | 9/29/19 | Cover crop planted |  |
| 5/19/19 | Pop-up | 22,949 | 10/12/19 | Manure injected | 152,435 |
|  | Corn planted |  | 4/27/20 | Cover crop terminated | 154 |
|  | Starter | 15,300 | 4/30/20 | Light chisel till |  |
|  | Cover crop terminated[[1]](#footnote-1) | 154\* |  | Pop-up | 22,949 |
| 7/2/19 | Nitrogen side dress |  |  | Corn planted |  |
| 9/25/19 | Corn harvested |  |  | Starter | 15,300 |
| 9/29/19 | Cover crop planted |  | 6/23/20 | Nitrogen side dress |  |
| 10/6/19 | Manure injected | 152,435 | 9/12/20 | Corn harvested |  |
| 5/5/20 | Light chisel till |  | 9/19/20 | Cover crop planted |  |
|  | Pop-up |  | 9/28/20 | Manure injected | 121,948 |
|  | Corn planted |  | 11/13/20 | Subsoiled |  |
|  | Starter | 15,300 | 4/15/21 | Cover crop terminated | 154 |
|  | Cover crop terminated | 154 | 5/21/21 | Light chisel till |  |
| 6/20/20 | Nitrogen side dress |  | 5/24/21 | Pop-up | 22,949 |
| 9/18/20 | Corn harvested |  |  | Corn planted |  |
| 9/22/20 | Cover crop planted |  |  | Starter | 15,300 |
| 10/6/20 | Manure injected | 121,948 | 6/20/21 | Nitrogen side dress |  |

2.2 Field Measurments

Tile flow and nutrient data were collected at AHS for the entirety of the 2019 and 2020 water years (WY) and for three events in the 2021 WY. At DC, data were collected for the entirety of the 2020 and 2021 WY and throughout October of the 2022 WY. Rainfall was measured using both a tipping bucket rain gauge (Onset Computer Corp.) and a manual rain gauge at DC. Rainfall was estimated for the 2019 water year at AHS using NOAA NOWData for the Burlington, VT area [37]. Tile flow was monitored at the edge of field (EoF) where tile mains discharged. Flow from the tile outlet at AHS was directed into an H-flume (1.5ft) and was measured using the flume along with a compound weir (Thel-Mar, LLC) inserted into the pipe. Stage in the weir at the tile outlet was measured using a bubbler flow module (Teledyne ISCO 730 Bubbler Flow Module) and converted to flow rate using rating curves. Below the full capacity of the weir of 10.7 L/s, the weir rating curve was used to determine flow. At or above this flow rate, a relationship between the water pressure at the tile outlet and stage in the flume was used to determine flow. Tile flow at both DCS and DCN was measured using in-line electromagnetic flow meters (ModMag M1000, Badger Meter, Inc). The flow meters were set back several meters from the tile main outlet and installed below ground. Manholes were dug to access the tile main and the main was then cut and the flow meter placed at the end of the new outlet. The end of the flow meter was allowed to drain freely into the manhole, where a standpipe was installed on the inlet of the old tile outlet to control the water level in the manhole. The electromagnetic flow meters required pipe-full conditions during measurements, thus the outlet elevation using the standpipe was set just above the top of the flow meter outlet.

Automatic water samplers (Teledyne ISCO-6712) were used to record stage or flow at five-minute intervals at each tile outlet, as well as sample the discharging tile water. At AHS samples were taken using an anchored intake just before the outlet and at DC the sample tubing was anchored at the outlet of the flow meter. Samplers contained 24 1-liter bottles and a two-part program was typically used; the first set of bottles were reserved for composite baseflow sampling (part A) and the second set were reserved for discrete event flow sampling (part B). Baseflow sampling was time-based and was disabled during events. Event sampling was triggered based on rise in flow rate, and rather than 1 hour composite samples throughout the hydrograph [21], [30], event sampling was discrete and both time and flow proportional sampling was used in an effort to maximize resolution during peak flows. Flow-based pacing was determined based on prior observations of the network response and flow characteristics, while time-based sampling in baseflow occurred every six hours. Minor modifications to the automatic sampler programming occurred throughout the study period to account for storm size, baseflow, etc. yet the general approach remained consistent.

Surface runoff was measured from distinct surface watersheds above the DCS and DCN tile networks as part of a paired watershed study in the calibration phase occurring at the DC site. Surface runoff was measured using automatic water samplers with methods like those at the tiles except for the flow measurement device. At DCS surface runoff was collected by a surface inlet set back several meters from the EoF and directed underground through a 0.3 m (12 in) pipe to the EoF, where flow was measured using a bubbler module to determine stage in a compound weir inserted into the pipe. At DCN surface runoff was directed using wooden wing-walls into a 0.47 m (1.5 ft) H-flume located at the EoF where a bubbler module was used to determine stage in the flume. At DCS water samples were collected using an intake anchored in the outlet pipe and at DCN the intake was placed in a plastic box anchored at the flume outlet.

2.3 Water Quality Analysis

Events were anticipated from the weather forecast, however a wireless modem was used to communicate with the automatic samplers to remotely determine if event sampling had occurred. Event samples were retrieved from sites and transported to the lab within 24 hours, and grab samples were returned to the lab the same day. Samples were analyzed at the University of Vermont Agriculture and Environmental Testing Laboratory (UVM AETL) located in Burlington VT by standard methods for TP (SM 4500-P F: alkaline persulfate digestion and flow injection analysis) and SRP. Sample splits for SRP were filtered using a 0.45 um membrane filter and frozen until the analysis. Most event samples in this study were turbid and thus centrifuged until they were non-turbid and then decanted to ease with filtering. The P fraction of TP-SRP is equal to particulate P (PP) plus dissolved unreactive P (DUP) where DUP is organic and PP smaller than the filter pore [38]. However for simplicity, herein it is assumed that TP-SRP is PP [21], [34], [39]. Runoff sample and rainwater (collected from the manual rain gauge) EC was measured using a benchtop EC meter (Amber Science, Inc.).

2.4 Analytical Methodology

Runoff event initiation points corresponded with the initial rise in tile flow, usually from low- or no-flow conditions. Events during the dry season usually ended when tile flow returned to zero, while events during the wet season usually had long recession limbs. For these events the last visible inflection point on the recession limb was used to determine the end of the event hydrograph [40]. Event volumes were calculated as the area under the hydrograph, time to peak was calculated as the time between the start of the event and the maximum flow rate for the event, runoff ratio (RR) was calculated as the ratio of total event runoff depth to the total rainfall depth, and hydrograph response time was calculated as the time difference between the start of rainfall and the initial hydrograph rise [30]. Event total rainfall was determined as the rainfall in the 24 hours leading up to the event start time plus rainfall during the event.

Chemographs were constructed by linearly interpolating between sample bottle concentrations to achieve a concentration dataset for each event at the resolution of the flow data (i.e. 5 minutes). Starting and ending concentrations were assumed to be entirely SRP and set to the average concentrations in baseflow samples at each site during the study period. Loadographs were constructed by multiplying the continuous flow (i.e. hydrograph) and nutrient concentration (i.e. chemograph) datasets. Event loads of TP, SRP, and PP (TP-SRP) were determined by integrating the loadographs, and event flow weighted mean concentrations (FWMC) were back-calculated by dividing the mass exports by the total event volume. At AHS, for six relatively small to moderately sized events, insufficient samples were obtained to calculate P export as described above. For these, an average P concentration for the event was assumed based on the samples available and on concentrations in other events temporally nearby. Also at AHS, for three large events, equipment failure resulted in both incomplete hydrographs and incomplete TP samples. For these, export was estimated from either another nearby monitored tile or from previous storms of similar rainfall intensity. At DC, loadographs were constructed for events that fell between 5/12/2020 and 7/21/2021, while compositing sampling was used outside of this period [16]. At the DC site, P export during missed events was estimated using regression relationships with nearby tiles. For all tiles, to simplify and because baseflow sampling was intermittent, P loading from baseflow was set to a constant site-specific value, and it was assumed this loading rate occurred every day there was tile flow but no event hydrograph.

2.4.1 Four Component Hydrograph Separation

Analysis of both flow pathway and source contribution is a novel approach to tile drain data; this study closely follows the methods used in Nazari et al. [25] to combine the two hydrograph separations into one model. The methods are presented in detail in that study, and modifications to them are described here. First, their approach uses 30-minute data while here we used 5-minute data, which maximized the resolution of the flow data due to significantly shorter recessions observed in this study. Our results suggested that daily aggregated data of flow and P concentrations would result in under-estimating P loading due to flashy tile hydrographs [37]. We also found that there was high multicollinearity between flow components in the four-component hydrograph separation model. Thus, we chose not to pursue the multiple linear regression analysis. We performed the master recession curve (MRC) analysis in RC 4.0 using the matching strip method [41]. Results from the MRC analysis showed that QF:SF recession constant ratios were greater than 3, thus suggesting that reservoir distinctions were valid (Supp. Table 3) [21], [25]. Concerning the individual event hydrograph separations, intermediate reservoirs [42], [43] of tile hydrograph recessions in log-normal space were frequently observed, making it difficult to isolate a single inflection point to represent the peak of SF [25]. Thus, to separate QF and SF for each event, the recession constant of the shallowest of the observed linear reservoirs was used as the slope of the linear increase in slow flow from the start of the event. The intersection of this straight line with the recession of the actual hydrograph represented the end of QF and the subsequent hydrograph was set to SF.

An additional modification from the Nazari et al. [25] methods was that continuous EC data were not available in this study because EC was measured in discrete samples (i.e., individual event and baseflow bottles) [44]. Thus, only the events where baseflow EC was available prior to the event were used in the source contribution analysis and subsequently the four-component hydrograph separation. This was determined since rapid dilution of EC was observed between baseflow samples and the event’s first discrete sample, even if event sampling occurred prior to tile flow reaching 1.0 L/s. To perform the EMMA with the discrete EC values, EC was linearly interpolated between sample values, and the value for baseflow EC prior to the event was used as starting and ending values for the tile signature (i.e. new water = 0 at the start and end of event). In addition, rainwater EC was consistently several orders of magnitude less than surface runoff and surface runoff was not available for most events. Thus, the minimum value of surface runoff EC was used across all events as the signature for new water. This assumption represents the minimum amount of mixing of surface runoff with the layer of interaction [45], and is the most accurate signature of the new water end member available in this study.

2.4.2 Rainfall Pulse Analysis

Tile drains readily and rapidly responded to rainfall, thus, rainfall pulses were analyzed to better understand how pulse intensity affects tile discharge metrics associated with the timing of a rainfall pulse. Pulse data were determined from the temporal rainfall data from the tipping bucket rain gauge. The tipping bucket rain gauge records the duration of time between rainfall increments of 0.254 mm (0.01 in). The tipping bucket rain gauge data was aggregated on an hourly basis by clock hour to obtain rainfall pulses. Consecutive 30-minute pulses greater than zero were lumped together into a single pulse, and pulse metrics of total volume, maximum intensity, and duration were calculated. The maximum pulse intensity of the pulse group was set equal to the highest 30-minute intensity contained within the group. The maximum intensity was compared to the quartiles of the period of record of the 30-minute pulse data to assign levels to pulse group (herein ‘pulse’) intensities. Pulses that fell below Q4 were assigned to 'Low' and pulses above Q4 were set to ‘High’. The response variable window for a rainfall pulse was the hour following the start of a pulse group hour following the end of a pulse. The mean of the three P species loadographs, along with the maximum of the hydrograph, in the response variable window were calculated as the response variables associated with the pulse.

A two-sample t-test was used to compare means from the two groups of pulse intensities. This analysis was essentially an experiment where rainfall pulses are treatments, and the response variables are tile mean P loading rates and maximum flow rate in the time window post rainfall pulse. For the assumption of independence to be met between replicates, we must assume that the P pool is inexhaustible, thus there is an equal chance for the effect of pulse intensity to generate a given tile P concentration regardless of how much was exported previously. This was not the case for events close to manure application since data suggested old water contained high soluble P prior to events, suggesting source limitation post manure application. Osterholz et al. [34] suggested removing observations six months post P application to isolate the effects of legacy P on tile drain concentrations. However,, because of the drought and frequent P applications, very few events and rainfall pulses met this assumption in this study. As a result, we removed pulses that occurred within 100 days of manure application to minimize the effect of source limitation P transport.

2.4.3 Statistical Analysis

The Kendall’s rank correlation coefficient was used to determine the relationship between event rainfall and tile discharge metrics and time series, namely day of hydrologic year, number of days since manure injection, and number of days since P application, which included manure injection, cover crop termination, and fertilizer application during planting (Table 1) [33], [34]. Pearson correlations were used to correlate tile discharge and rainfall metrics. Event rainfall metrics included total rainfall, which was determined as the rainfall in the 24 hours leading up to the event plus the rainfall during the hydrograph, max hourly rainfall intensity, and 24-hour and 7-day and 30-day rainfall totals. Event tile discharge metrics included P species loads and FWMC, total water discharge, peak flow rate, response time, time to peak, and RR. The Kruskal-Wallis (KW) nonparametric test was used to evaluate significant differences when data was not normally distributed. Factor groups with significant KW p-values were compared using the Dunn test post-hoc analysis to determine significant differences between individual levels [46]. Analysis was performed using R software [47].

3. Results

3.1 General Hydrology and P Transport

Rainfall was 108, 63, and 70 cm during the 2019, 2020. and 2021 WY, respectively. Event rainfall metrics, namely total rainfall, maximum hourly rainfall intensity (MHRI), and 24 hour and 7- and 30-day antecedent rainfall, were positively correlated to the day of hydrologic year (Supp. Figure 1). For MHRI this is the expected result because of high intensity summer thunderstorms, however, correlations were highly influenced by a very wet July in the 2021 WY (Supp. Figure 1). An abnormally dry to moderate drought period occurred from June 2020 to August 2021, and during this period, tile drains regularly responded to rainfall without surface runoff occurring [48]. A lack of surface runoff was also attributed to high surface roughness from subsoiling in the fall of 2020. Tile drainage was the dominate P export pathway and results coincide with the notion that hydrology dictates P transport in tile drained landscapes [23]. In fall 2020 there was no baseflow prior to and after event hydrographs because of the drought, suggesting the entirety of the event flows and P was transported to the tile via PFP. Also, runoff ratios for these events were among the lowest and hydrograph response times were relatively high (above the interquartile range; Supp. Table 1), suggesting that a soil moisture deficit needed to be overcome to allow PFP activity [49], [50].

TP and SRP FWMC in this study and elsewhere in the LCB [13] were higher in surface runoff than in tile drainage, however event peak TP concentrations in tile flow were found to exceed surface runoff TP FWMC on some occasions. Findings in other cold climate regions have found that the majority of surface P export occurs during the non-growing season because the majority of annual flow may stem from snowmelt [51], [52]. Results in this study showed that snowmelt did not result in higher surface runoff volumes relative to summer thunderstorms. Also, P concentrations in surface runoff and tile drainage were higher in the summer than during the snowmelt event, thus the non-growing season was not a significant P export period via surface runoff. Most of the annual TP export through the tiles was during events flows, where larger events generally exported more P (Supp. Table 1). In the 2019 and 2020 WY most of the annual TP loading through the tiles was during the non-growing season, while in the 2021 WY TP loading was similar between the growing and nongrowing seasons (Table 2). This stems from the drought that limited the number of events during the growing season in WY 2020 and during the non-growing season in WY 2021. Despite this, average event volumes and RR were still highest during the non-growing season across all sites and WY (Table 2).

Graphical user interface, text, application, email

Description automatically generatedTable 2: Annual estimates of TP export for each water year (WY). Volume is mean event volume, RR is mean event runoff ratio, G is growing season, and NG is non-growing season.

3.2 Tile Discharge and P Export Dynamics

3.2.1 Seasonal Differences

Event TP and SRP FWMC in tiles were not significantly different between the four seasons, however SRP loads were significantly higher in the winter (Figure 1). King et al. [53] found that while tile SRP FWMC were lowest in the winter, SRP loads were significantly higher than summer and fall values. The winter represents a period when legacy P acts as homogeneous P source during events, i.e., more transport limited [34]. SRP FWMC may be lower in winter because it’s the longest time since P application, and thus legacy P is the main contributing P-source to concentrations in tile drains [34]. However, since legacy P-mineral soil binding energies decrease due to wetter soils in winter, SRP loading is higher [23]. In the summer, event maximum rainfall intensity was the highest, and time to peak flow rate and runoff ratios were significantly lower than the other seasons (Figure 1).

A picture containing box and whisker chart

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Figure 1: Boxplots of tile discharge and rainfall metrics for four hydrologic seasons (Fall: Oct-Dec, Winter: Jan-Mar, Spring: Apr-June, Summer: July-Sep). Letters denote significant differences between seasons.

The mean event tile drain RR was 44%; AHS and DCN had mean RR of 55% and 54%, while DCS had a mean of 26% (Supp. Table 2). There were 5 events where RR were greater than one, all of which corresponded to fall rain-on-snow events. Mean RR at DCN during the NG season of the 2020 WY was 94% (Table 2) suggesting that shallow ground water was significantly augmenting event flows at this site during this period. At the field scale with extremely fine textured clay soils, relatively short response times to rainfall and flashy hydrographs are usually attributed to PFP [21], [30]. Because during the NG season soils are wetter and closer to field capacity, clay soils would be expected to swell and thus the PFP network would decrease [54]. However, results here suggest that PFP were highly active regardless of antecedent soil moisture [25], [29]. High PFP transport to tiles in this study could be a function of the recent tile installations (2016 at AHS and 2018 at DC). Tiles backfilled incorrectly or backfilled during a drought period when soils are dry and blocky may result in large PFP that exist directly over tile laterals, which may not diminish until years of freeze-thaw cycles help settle the backfill material [63].

3.2.2 P Export Relative to P Application Periods

Days since P application was the better predictor of event TP and SRP loads, peak sample concentrations, and FWMC, as opposed to days since manure application (Supp. Figure 2). However, P concentrations in event samples and event FWMC were highest post manure injection. There were four manure injection periods observed during this study, namely the autumns of each year. There was moderate and severe drought pre-manure injection in the falls of the 2019 and 2021 WY, respectively, while conditions pre-injection in the 2020 and 2022 WY were abnormally dry and normal, respectively. In the falls of the drier years, event TP export through tiles was relatively low because of small FWMC (< 1000 ugP/L) and small event discharges in 2019 and 2021 WY, respectively. In the falls of the wetter years, event FWMC remained elevated throughout the fall (>1000 ug P/L), where in the 2020 WY the result was that fall events contributed to most of the annual P export. P concentrations in tiles were also elevated following the P application periods later in the WY, namely post cover crop termination and during planting. In the 2019, 2020, and 2021 WY P concentrations in event samples post cover crop termination were elevated relative to events prior. As the glyphosate-P application rates were relatively small (Table 1), this suggests that the cover crop could have been the contributing P-source during this period, which can occur during the spring thaw if their cells lyse over winter [55]. The 2019 WY was the only year that had events post planting and subsequent fertilizer application and showed P concentrations spiking slightly higher than post cover crop termination.

3.2.3 P Concentrations in Tiles During Events

Chart

Description automatically generatedThere were 840 tile event samples analyzed for TP, and 467 were also analyzed for SRP. Overall, while linear trends were significant for TP, flow rate explained little of the variation in P concentrations during events (*R*2 = 0.05). This agrees with others who have concluded that flow rate poorly predicts P concentrations in tile drains due to high variability at low flow rates [25], [44]. In this study, high TP and SRP concentrations at low flows corresponded to the initial samples during the hydrograph during events post P application. When removing samples that occurred within the first hour of the event, the relationship between SRP concentrations and flow rate was significant, and when removing samples in the first 10 hours, linear trends drastically improved (Figure 2).

Figure 2: Event TP and SRP concentrations as a function of tile flow rate. Regressions were performed after removing the points in green, i.e., samples taken within the first 10 hours of events.

Post manure injection, the highest event P concentrations in tiles corresponded to the initial hydrograph response, while in the spring and summer, the highest event sample concentrations corresponded to the highest flow rates (Supp. Figure 3). While this suggests P transport was source limited post manure injection, and transport limitation post fertilizer application, events during the fall also showed transport limitation behavior apart from the samples corresponding to the initial hydrograph rise. These samples, which likely represent manure transport to the tile line because of PFP, corresponded to periods when soils were wetter. For example, the event on 12/25/2020 at DCN, where there was snow on the field prior, resulted in a RR > 1 and soils were likely saturated prior to the hydrograph response. Under this condition, peak event TP and SRP concentrations were 3-4 times higher than the peak concentrations on 12/01/2020, when soils were still dry (no baseflow). The dry conditions likely prohibited full saturation of the soils throughout the event because most of the flow was transported to the tile via PFP, bypassing the matrix, thus P export was transport limited. This can be seen in Supp. Figure 3, where the chemograph for the 12/01/2020 event at DCN resembles that of the spring and summer events. The more saturated soil matrix on 12/25/2020 would have permitted matrix-PFP interactions, where P-laden pre-event water was quickly transported to the tile, as seen by the event P peak concentration coinciding with the initial tile response (Supp. Figure 3).

3.3. Flow Pathways and Source Connectivity

3.3.1 QF, SF, New and Old Water Metrics

Differences in the timing of the two hydrographs separations suggests that flow pathways were not equivalent to source contribution [25]. On average, the peak of old water occurred over 20 hours prior to SF (Table 4). Also, the timing of peak QF contributions occurred over one hour prior to peak contributions from new water, however there were five events at DCS and ten events at DCN where QF and new water timing was equivalent (Supp. Table 4). QF and new water, as well as SF and old water had different cumulative volumes, further supporting the notion that flow pathways are not equivalent to source contribution in tile drained landscapes [25]. Mean flow contributions of QF and new water were 78% and 48% of total event tile flow, respectively (Table 3). Peak flow contributions of QF and new water were 96% and 80%, respectively. While Nazari et al. [25] reported lower peak flow contributions for QF (and similarly for new water) than in this study, mean new water (and QF) contributions were similar to the Nazari et al. [25] study and others also using EC-EMMA hydrograph separations [30], [56]. Also, we observed similar but slightly lower mean RR across all sites as compared to Nazari et al. [25], who’s study site was twice the size of DCS. Here, total, QF, and new water RR were consistently higher at DCN, the smaller of the two DC fields, suggesting field size and thus tile drainage area may have less of an impact on event volumes and pathway/source contributions. Differences between RR may be explained by the fact that DCN has a greater topographic relief than DCS. Surface ponding at the DCN site will have a higher chance of finding the soil cracks because it is sloped, and in addition, the deep tillage may have resulted in substantially more PFP, which led to more QF and new water at DCN.

Table

Description automatically generatedTable 3: Summary stats for tile flow metrics, fraction of total flow (FTF), and time to peak (TTP) for total tile event flow and hydrograph separation components of flow pathway (QF, SF), source connectivity (new, old), and the four-component model.

3.3.2 Four Component Hydrograph Separation

Correlation analysis suggests that QF, new water, and QFnew were the superior predictors of event P loads (Supp Table 5). On average, QFnew represented a high proportion of total flow (46%), and peak contributions were as follows: 73% for QFnew, 68% for QFold, 49% for SFold, and 18% for SFnew (Table 4). Nazari et al. [25] found lower peak contributions from QFnew (66%), yet higher peak contributions from SFnew (33%) and from SFold (98%). This could be because of the differences in data collection and analysis methods, as well as differences in soils, tillage, and slope. For example, conservation tillage was employed in the Nazari et al. [25] study while here deep tillage (i.e. subsoiling) was performed to promote infiltration. While QFnew had higher mean volumes, QFold volumes were equal to or exceeded that of QFnew for eight of the smaller 28 site-events in the analysis (Supp. Table 4). We observed similar correlations between QFold and QFnew volumes (r = 0.49) as in the Nazari et al. [25] study (r = 0.40), who also found that only the smaller events had QFold volumes exceeding QFnew (3 of 27 events). An example of QFold dominating the entirety of event flow here was during back-to-back events of July 2 and July 3 of 2021. For the duration of a multi-peak event on 07/02/2021 QFnew remained higher than QFold. The event the following day, which occurred on saturated soils, QFold remained higher than QFnew. This suggests that in back-to-back events AMC can have an impact on matrix-PFP mixing, however 7-day or even 24-hour rainfall was not found to have any significant positive effect on or trend with total tile flow, QFnew, and QFold volumes throughout the entirety of the study (Supp. Table 5). While higher AMC corresponds to wetter macropore walls and the potential for increased transport of water from the matrix into PFP [19], [57], results here suggest that soils needed to be near field capacity for this to take effect at these sites.

We found negative correlations between 7-day rainfall and QFnew and SFnew, and between maximum rainfall intensity and QFnew, SFold, and SFnew (Supp. Table 5). Also, we observed positive correlations between time to peak and the volumes for each of the four components except for QFold. Since QFold time to peak was correlated to the overall hydrograph time to peak, it is expected QFold volumes would be as well. Here and in Nazari et al. [25] the finding is that AMC and event rainfall are not good predictors of QFold and the other three hydrograph components volumes. While QFold was the only component not correlated to above mentioned rainfall metrics, and had the lowest coefficient of variation, this suggests that this pathway is controlled by different mechanisms relative to the other three components.

The peak of SFnew occurred at an average time of 27.4 hours into the event, which is slightly quicker that in Nazari et al. [25]. Nazari et al. [25] found a negative relationship between the timing of SFnew and 10 day rainfall, while here we found a semi-strong negative relationship between SFnew with 24 hour rainfall, and very strong negative relationship with maximum rainfall intensity (Supp. Table 5). Saturated flow through the matrix of clay soils is calculated to reach tile drains (at a depth of 1 m) on the order of a week, suggesting that a portion of event water is transported into the matrix at deeper horizons through PFP; this is what the SFnew pathway represents [25], [30]. PFP supply event water to deep portions of the soil matrix, i.e., PFP feed the SFnew hydrograph component, thus PFP may have an important role in ground water recharge [25]. Frequent recharge of ground water via PFP suggests P from the surface could be transported and accumulate as legacy P in much deeper soil horizons [58].

3.3 Rainfall Pulse Analysis

Tile discharge metrics associated with rainfall pulses were compared using non-parametric comparison of means, and there was an uneven, yet similar, number of pulses identified (Supp. Table 6). P loading rates in the tiles during periods associated with high intensity rainfall were significantly greater than during periods associated with low intensity rainfall (Figure 3). Also, high intensity rainfall pulses resulted in significantly higher flow rates as compared to the lower intense rainfall pulses. Others have found relationships between rainfall metrics and P concentrations and loading in tile drains at the inter-event scale, however this is the first known study to examine these relationships at the intra-event scale. Vidon and Cuadra [45] found that P concentrations were more variable during larger rainfall events as compared to smaller, where we found similar results with higher variation associated with higher pulse intensities.

Diagram, schematic

Description automatically generated

Figure 3: Boxplots showing difference between pulse and tile flow and P metrics for high and low intensity pulses.

Most of TP was exported as PP through tiles throughout the year, suggesting PFP were the dominate P export pathway to tile drains. Further, because the clay soils in this region (Covington and Panton soil series) are dispersive (i.e. easily dislodged by rainfall and suspended in surface runoff) and thus highly erodible, legacy PP (i.e., P sorbed to eroded sediment) is easily exported through PFP to the tiles. The rainfall pulse analysis shows this was case, however because of the drought during this study period, as well as the recent tile installations, the PFP network at these fields possibly represented a maximum condition. As time proceeds, the PFP network may diminish, resulting in less rapid infiltration and possibly different rainfall-driven P transport dynamics. This may also shift the P export dynamic between the surface and subsurface, where the surface may have higher runoff volumes and thus P export since less water is being channeled to the tiles via PFP. Nevertheless, climate change is expected to continue to increase the intensity of both drought and rainfall events in the LCB [8], and results here suggest this has implications for tile drain P transport. In the LCB, P in the lake bottom sediment is easily mobilized to the overlying water column, thus P exported at any time throughout the year may contribute to cyanobacteria blooms [59]. Legacy P will continue to be a challenge for this region, which persists in the water course, acting as a source of P even after BMP reduce P export from agricultural fields [4].

4. Conclusions

P concentrations in tile drains and surface runoff were well above the threshold for eutrophication throughout the year. Tile drains were the dominate P export pathway, and results agree with the notion that annual P export from tile drainage has the potential to be the greatest during the non-growing season, since it is the time of year with the highest tile discharge [23]. Spikes in tile P concentrations during events coincided with periods of P influxes, namely manure injection, herbicide application/cover crop termination, and planting/fertilizer application. Near the end of the growing season, soil P levels were in the low-optimal range (6 mg/kg Modified Morgans). Despite this being relatively low for agricultural fields that are considered hot-spots for legacy-P export [24], [34], [60], here, annual tile drain P loading was still relatively high for the LCB [10], [61].

We performed the four component hydrograph proposed by Nazari et al. [25], which is a simple and more accurate representation of PFP activity because it includes a hydrograph component for matrix-PFP interactions. EC-EMMA was performed using discrete sample bottles, and dilution patterns showed QFold exceeding QFnew during periods of very high AMC. QFold, which represents the matrix-PFP mixing pathway, contributed to tile drains year-round and under a range of AMC. This pathway may coincide with higher SRP in tile drains; however, we were not able to confirm that here. Nazari et al. [25] found that including the four component hydrograph separation improved the prediction of SRP concentrations, suggesting matrix-PFP mixing is an important indicator of SRP in tile drains. Thus, the four-component hydrograph separation in this study could be valuable for validating field scale-P export models like the VT P-Index [62].

Manure injection has the potential for very high P concentrations in tile drains, however AMC and timing of injection could reduce P export. Future work should include more event data to be able to quantify the differences between events following manure injection on wet and dry soils, as well as if manure injection is an improvement over surface application for subsurface P export [17], [63]. Also, while subsoiling likely reduced surface runoff, it is still unknow the effect it had on tile P export. The intra-event rainfall analysis showed P concentrations were higher in tile drains following higher intensity rainfall pulses, yet more data is needed to confirm this as climate change is expected to have an impact on both AMC and rainfall characteristics.

**Supplementary Materials:** The following are available online at www.mdpi.com/xxx/s1, Figure S1: title, Table S1: title, Video S1: title.

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**Data Availability Statement:** Data available in a publicly accessible repository that does not issue DOIs

Publicly available datasets were analyzed in this study. This data can be found here: https://github.com/raruggie/MDPI-Agriculture-Ryan-Ruggiero

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1. A standard application rate of 0.34 kg (0.75 lbs) of glyphosate (acid equivalent) per acre assumed [↑](#footnote-ref-1)