Lake Champlain
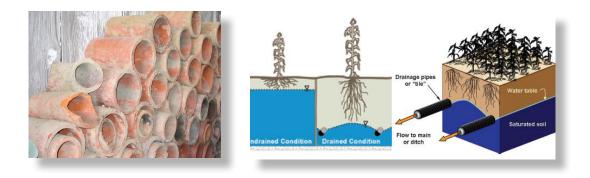Basin Program

Literature Review: Tile Drainage and Phosphorus Losses from Agricultural Land

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Final Report

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For:
The Lake Champlain Basin Program and
New England Interstate Water Pollution Control Commission

Literature Review: Tile Drainage and Phosphorus Losses from Agricultural Land

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Executive Summary

Tile drainage works by providing an open pathway for soil water to drain away, lowering the water table and allowing the upper soil layers to dry out. For farmers, tile drainage has multiple benefits: better growing conditions, improved soil structure, enhanced trafficability, more timely planting and harvest, and improved yields. Tile drainage pipes are typically installed at depths of 0.6 – 1.2 m and spaced 10–100 m apart, depending on soils, crop type, and cost. Historically, tile drainage was often installed strategically, targeting low spots and other frequently saturated areas. Today, drainage tends to be installed in a regular grid pattern, with pipes located 5 to 30 m apart under an entire crop field. Most drainage networks discharge directly to an open ditch or stream.

In agricultural watersheds, phosphorus (P) can enter surface waters through both surface runoff and subsurface flow. In agricultural fields with subsurface (tile) drainage, much of the subsurface flow is conveyed by tile drains directly to surface waters. Once dismissed as negligible, P levels in subsurface tile drainflow are now recognized as potentially significant, and tile drainflow has been clearly shown to influence both hydrology and phosphorus loading at the field and watershed scales in some areas of the United States.

Tile drainage is an essential water management practice on many agricultural fields in the Lake Champlain Basin (LCB). Reliable data on the location and extent of tile drainage in the LCB do not exist, but the Vermont Agency of Agriculture, Food, and Markets (VT AAFM) and the Vermont Agency of Natural Resources (VT ANR) have estimated that about 5% of Vermont's cropland (9,500 ha on 525 farms) has tile drainage, with cropland drainage in some agriculturally-intensive subwatersheds within the LCB as high as 70%. Of the reported tile drained acres in Vermont, 80% are associated with dairy production.

Effects of Subsurface Drainage on Hydrology

The use of tile drainage significantly alters the hydrology of the landscape. Compared to an undrained condition, the use of tile drainage:

- Increases total annual water output from a field, often by a factor of ∼2;
- Reduces surface runoff (including peak flows); subsurface drains lower the water table, eliminating saturated areas and providing more capacity for infiltration during rainfall events;
- Delivers the majority (50 to >90%) of field water loss as tile drainflow;

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

2

- Extends the duration of water flow from a field; and,
- Can sometimes contribute the majority of streamflow in small watersheds.

The volume of tile drainflow tends to follow strong seasonal patterns. Although tile drainflow can respond to large precipitation or snowmelt events at almost any time of year, the largest drainage volumes tend to occur from fall through spring, with tile drainflow becoming very small or entirely absent during the summer growing season.

Tile drainage often reduces sediment and nutrient export in surface runoff because of the significant reduction in overland flow from tile drained fields.

The hydrologic behavior of tile-drained fields is influenced by a variety of factors, not all of which are well-understood. Some major influences include:

- **Rainfall amount and intensity** – greater amounts and intensities of rainfall events tend to generate larger, more rapid tile drainflows;
- **Antecedent conditions, including soil moisture content** – drainflows may be larger and begin earlier when soils are wet;
- **Soil texture** – the reported influence of soil texture is variable; greater drainflows have been reported on coarse-textured soils and attributed to higher permeability, but have also been observed on fine-textured soils and attributed to preferential flow;
- **Cropping and tillage** – the reported influence is variable, as greater tile drainflows sometimes occur from grassland and no-till cropland due to the prevalence of preferential flow pathways;
- **Drainage system design** – most research has shown that shallow drains tend to respond more quickly to precipitation than deep drains, but drainage volume is significantly lower from shallow drains. For the same depth, drainage volume from narrow drain spacing (e.g., 9m) is greater than from more widely-spaced drains (e.g., 18m).

    It should be cautioned that these influences are often interactive. Research has documented major differences in tile drainflow among sites with identical drainage systems. Such spatial differences may be greater than differences observed between different rainfall events.

Phosphorus Concentrations in Tile Drainflow

Phosphorus concentrations measured in tile drainflow vary significantly, reportedly due to soil characteristics and P levels, agricultural management and cropping system, weather, and other factors. Significant concentrations of P have been found in tile drainflow across a variety of conditions. High P concentrations in tile drainflow have been observed in the Lake Champlain Basin.

Some research in the LCB has reported very low P concentrations in tile drainflow; a study in Franklin, VT reported all tile drainage samples contained less than 0.02 mg/L total P, the detection limit. More recently, monitoring of tile drainflow in Clinton and St. Lawrence Counties, NY found total P concentrations averaging 0.098 mg/L and dissolved P concentrations averaging 0.011 mg/L; these values were two orders of magnitude lower than those observed in surface runoff.

Other researchers have reported higher P concentrations in tile drainflow. Dissolved P concentrations as high as 1.17 mg/L have been reported in tile drainflow under fields receiving manure in New York. Numerous studies in the Missisquoi Bay watershed in Quebec have reported P concentrations in tile drainage exceeding provincial guidelines intended to prevent eutrophication.

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

3

P concentrations in tile drainflow vary with flow and season, although the reported patterns are somewhat inconsistent.

- Almost all research reports that P concentrations are higher in stormflow than in baseflow;
- Most research found that tile drainflow P concentrations tend to increase with increasing discharge rates;
- Some researchers reported that P concentrations in tile drainflow peak between February – July, declining to minimum levels August – September. However, other research has shown P levels to be lowest in winter, and increasing in the summer and fall.

While many forms of P have been measured in different proportions in tile drainflow, the general consensus of the literature is that dissolved P is an important component of the total P measured in tile drainflow under many circumstances, but that particulate P often makes up a large fraction of total P in tile drainflow, especially under high-flow conditions.
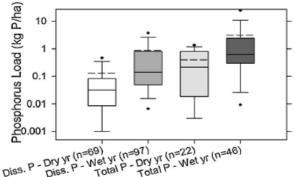
Phosphorus Loads in Tile Drainflow

Reported P loads attributed to tile drainflows are often of the same order of magnitude as those commonly reported for surface runoff from agricultural land.

Significant P export from agricultural fields in either dissolved or particulate forms occurs via tile drainflow under a variety of conditions, and this export can equal or exceed P losses via surface transport in areas dominated by subsurface drainage.

As with P concentration, reported P loads attributed to tile drainflows are highly variable. In New York, a total P load of 0.13 kg/ha/yr and a soluble reactive P load of 0.05 kg/ha/yr were observed in tile drainage from grass plots. In Quebec, however, significantly higher mean total P loads (from 0.69 to 1.23 kg/ha/yr) have been reported from corn fields in the Missisquoi Bay watershed, loads similar in magnitude to those delivered in surface runoff.

A 2015 compilation of 400 studies from across the U.S. reported ranges of dissolved and total P loads in drainage water from agricultural land (see figure at right). Mean dissolved P loads in tile drainage were in the ~0.1- 0.9 kg/ha/yr range under dry and wet conditions and mean total P loads were ~0.5 – 3.0 kg/ha/yr range during dry and wet years.

Researchers have documented variable – but generally high – proportions of total field P export being delivered in tile drainflow. For example, several researchers in Quebec have reported that 40 – 80% of annual P loss from crop fields was exported in tile drainflow.

Despite sizeable P loads observed in tile drainflow, researchers have generally reported that these loads represent a very small fraction (<4%) of P applied to agricultural land.

Reports on the seasonal distribution of P loads from tile drainflow have been somewhat conflicting. Most research indicates that P export is low during the growing season, with the majority of the annual P export occurring outside the growing season. Some researchers have identified the spring snowmelt period as the most critical. One Quebec study reported that spring and fall combined to account for 87 – 92% of annual total P export in tile drainflow.

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

4

Tile drainflow has been shown to be a significant source of P at the watershed-scale, although high-quality data quantifying contributions of tile drainflow loads as a fraction of the overall watershed load are scant. A watershed modeling study in the LCB estimated that 7.3% of the annual total P load to St. Albans Bay could be attributed to tile drainflow, representing 13% of the overall agricultural P load. However, other estimates derived from monitoring data suggest that tile drainage can contribute as much as 40 – 80% of annual soluble and total P load from agricultural watersheds.

Watershed management efforts must consider the potential contributions of tile drainflow in watershed P budgets. Researchers in the U.S. Great Lakes region and in Europe have identified significant basin-scale P loading and eutrophication impacts from tile drainflow.

Factors Controlling P Losses in Drainage Water

Numerous factors have been identified that may influence P concentrations and loads in tile drainflow, including soil characteristics, drainage system design, management practices, climate, and hydrology. The most important of these are discussed below.

- **Preferential flow:** Preferential flow through soil cracks or macropores connecting the soil surface with tile drains is probably the most important influence on P loads from tile drainflow. Preferential flow can lead to rapid transport of sediment and surface-applied materials to the tile system, bypassing the filtering and buffering capacity of the soil matrix. Where conditions promote significant preferential flow, mass losses of sediment, and of particulate and dissolved P, can be comparable to losses in surface runoff.
  - The presence of high levels of sediment and particulate P in tile drainage water, and the rapid appearance of surface applied nutrients in tile discharge, are both indicators of the delivery of particulates through preferential flow channels not filtered through the soil matrix.
  - Certain soil and crop management practices may favor or reduce crack and macropore formation. For example, clay soils are more prone to cracking than are coarse-textured soils. Tillage destroys cracks at the soil surface, while no-till or long-term perennial grass allows macropores to persist due to the lack of soil disturbance.
- **Drainage system design**: The design of the drainage system itself – primarily the depth and spacing of drain lines – influences water and nutrient losses:
  - At the same spacing, shallower drains will yield greater P concentrations than deeper drains with more soil cover. However, deeper drains generally export more water, so the total amount of P exported may be greater from deeper drains.
  - In general, the more closely spaced the drains, the greater the P loss. A Quebec study reported that for every 5m increase in drain spacing, total P loads in subsurface drainage decreased by 6 – 20%, depending on soil type.
- **Manure and fertilizer application**: The influence of land-applied P in manure and/or fertilizer is complex. Manure or fertilizer applications to soils prone to preferential flow, close in time to storm events, or at rates in excess of crop need can lead to significant P losses.
  - A few studies have reported little or no effect on tile drainage P losses from manure applications, especially under dry antecedent soil conditions, appropriate application rates, and significant elapsed time between application and rainfall.
  - In contrast, significant and rapid effects on P loss have been reported in tile drainage from manure applications, especially liquid manure. In New York, for example, soluble P concentrations in tile drainflow peaked at 1.17 mg/L immediately following manure application.

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

5

Further, P concentrations peaked before the tile drainflow peaked, indicating that the manure may have been delivered directly to the tile drains.

- High P losses in tile drainflow have been observed from fields that received long-term manure applications, particularly at excessive rates.
- Application of inorganic P fertilizers – particularly at high rates and at times outside the growing season or under wet conditions – has been reported to affect P transport in tile drainflow, especially dissolved P.

The overall consensus of the literature is that manure and fertilizer can be applied without major increases in P loss in tile drainage, but that soil conditions, timing, and application rate are important.

- **Cropping system**: The specific influence of crop and cropping system on losses of P in tile drainflow is difficult to assess because of differences in tillage, nutrient applications, and other factors among cropping systems. In very general terms, it seems that greater crop cover leads to lower P losses; for example, losses from corn tend to exceed losses from soybeans or small grains. Most of the differences in P loss in tile drainflow reported by crop or cropping system, however, are likely the result of differences in the level of P inputs and the tillage practices associated with those crops, rather than the influence of the crops themselves.
- **Tillage**: There is broad consensus in the literature that subsurface P transport is greater under reduced tillage and no-till systems compared with conventional tillage due to a greater probability of preferential flow, coupled with stratification of P in soils as a result of surface application of nutrients. Tillage may break up macropores or soil cracks, thereby disrupting preferential flow pathways. Reduced tillage has also been observed to increase the infiltrative and holding capacity of the soil, ultimately resulting in increased tile drainflows. Analysis of an extensive tile drainage load database confirmed that the practice of no-till significantly increased dissolved P loads (0.12 kg/ha/yr) in tile drainflow compared to conventional tillage (0.04 kg/ha/yr)
- **Soil test P:** Although research results are variable, it has been widely observed that elevated levels of soil test P or soil P saturation (e.g., from long-term over-application of manure and/or fertilizer) lead to greater concentrations of P in tile drainflow. A soil test P threshold (i.e., "change point") is believed to exist, above which a unit increase in soil P results in higher P concentrations and losses in drainflow. There is no widespread agreement, however, on the specific value for the threshold, which is likely to differ across soil types. Work in Quebec has shown that the highest P levels tile drainflow tend to be observed in soils with the highest clay content, the highest soil test P/water-extractable P, and the highest level of soil P saturation. However, other influences may become dominant in soils with low P saturation.

The factors listed above interact with each other. A 2015 review of U.S. tile drainage data suggested that in general, sites prone to preferential flow, sites with high organic matter soils, and sites with historically high P applications and/or soil P concentrations are primary concerns for subsurface P leaching.

Practices to Reduce P Loads in Tile Drainflows

Numerous management measures have been proposed to reduce P loads delivered by subsurface drainage, starting with fundamental nutrient management practices – apply manure and fertilizers at the right rate, in the right location, and at the right time (e.g., not when tile lines are flowing). Other practices have been proposed to specifically address tile drainage:

- **Drainage water management:** A variety of practices have been proposed that allow landowners to adjust the level to which the water table in a tile drained field is allowed to rise; this is variously called

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

6

drainage water management (DWM), controlled drainage (CTD), or conservation drainage. In practice, DWM/CTD uses a water control structure near the outlet of a drain to adjust the effective outlet elevation. By adjusting the outlet elevation, the farmer can change the functioning of the drainage system throughout the year, lowering the drain so that water can drain freely during field operations, raising the water table after planting to increase water available for use of crops during the growing season, and raising the water table again after harvest to limit drainage outflow during the non-growing season.

There is ample evidence that DWM/CTD can reduce the annual volume of tile drainflow (with consequent effects on constituent loads) and can significantly reduce concentrations of nitrate-nitrogen in drainage water. Research evidence for the effectiveness of DWM/CTD in controlling P losses is conflicting.

- DWM/CTD has been widely reported to reduce P loads in annual tile drainflow, primarily through significant reduction in the total outflow volume.
- Changes in redox conditions and P sorption in the soil due to altered hydrology and water table elevation from DWM/CTD may actually promote desorption and enhance mobility of dissolved P – especially in P-saturated soils – and lead to higher dissolved P concentrations in tile flow. These changes can reduce the effectiveness of DWM/CTD for P control.
- Increases in P concentration and load in tile drainflow under DWM/CTD have been documented in several instances. Researchers in Quebec reported increased P loads in tile drainflow from DWM/CTD plots, even though total outflow volumes were reduced by 27% compared to free draining plots. Total and dissolved P concentrations in tile drainflow from DWM/CTD plots increased, on average, by 131% and 178%, respectively, compared to free draining plots.

Given this uncertainty, drainage water management cannot be unequivocally recommended as a management practice to reduce P flux in tile drainage.

- **Drainage system modifications**: When installing new drainage or renovating existing systems, reduction in drainage intensity can reduce P losses via tile drainflow. Lowering drainage intensity through wider line spacing and shallower depth would tend to reduce nutrient loads and improve drainage water quality. Maintaining field drains below peak efficiency (i.e., postponing repairs or upgrades) may help to reduce subsurface P losses. Although surface inlets (tile risers) are not common in the LCB, elimination or plugging of surface inlets (which allow direct introduction of surface runoff into subsurface drainage systems) has been demonstrated to reduce subsurface P loads.
- **P sorption/treatment**: Where agronomic or drainage system management practices alone do not sufficiently reduce P transport via tile drainflow, remediation efforts may shift toward treatment of tile drainflow before it enters surface waters. A variety of technologies have been proposed and assessed to capture concentrated flows of P from surface and groundwater. Many of these proposals have focused on the use of industrial byproducts, such as slag or water treatment residuals, to adsorb P from tile drainflow. Several materials offer the promise of high P-sorption capacity.
- **Tillage**: Given the critical role of preferential flow in delivering water and P to tile drains, surface soil tillage has been recommended in several instances to break up macropores as a means to reduce P delivery. Reports of the effectiveness of tillage, however, have been mixed. In some cases, tillage was not effective in reducing P flux in tile drainflow, and tillage can increase the risk of erosion.

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

7

Literature Review: Tile Drainage and Phosphorus Losses from Agricultural Land

Contents

Stone Environmental

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

8

Table of Figures

Table of Tables

Acknowledgements

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

9

1. Introduction

In agricultural watersheds, phosphorus (P) can enter surface waters through surface runoff and subsurface flow. In agricultural fields with subsurface drainage, much of the subsurface flow is conveyed by tile drains directly to surface waters. Early work on P transport from agricultural fields focused on surface runoff and on applying improved management to reduce soil erosion (King et al. 2015). Phosphorus transport via subsurface flow pathways was generally considered "negligible", due to widely-held assumptions concerning low P concentrations and an affinity of subsoil to bind P (Benoit 1973, Baker et al. 1975). As late as 1980, the vertical movement of soluble P through the soil profile was largely dismissed as containing only trace quantities of P (Logan et al.1980). Perceptions of the importance of subsurface P transport, however, have evolved over the last several decades. Tile drainage has been clearly shown to have significant impacts on hydrology and nutrient loads at the watershed scale (Hansen et al. 2002, McIsaac and Hu 2004, King et al. 2014).

Subsurface drainage tends to substantially increase losses of nitrate N and other soluble nutrients that leach into water through the soil profile. Subsurface drainage also contributes to increased potential for total N loss because the cropping systems required to provide a return on drainage investment are often "leakier." In the U.S. Midwest, for example, subsurface drainage encourages the planting of high-value crops such as corn and soybeans, relative to crops such as small grains and alfalfa that are typically associated with lower nitrate losses (Blann et al. 2009). High nitrogen losses (especially NO_3-N) in tile drainage have been extensively documented (Lowrance 1992, Keeney et al. 1993, David et al. 1997, Tomer et al. 2003).

Recent research has revealed that subsurface drainage systems in agricultural fields can also export significant quantities of P under a wide range of soil characteristics and management practices (Kleinman et al. 2015a). Phosphorus in drainage water occurs in all forms (dissolved, particulate, organic, inorganic), and during storm flow the concentrations and forms of P in drainage water are often similar to those in surface runoff (Kleinman et al. 2015a). Subsurface drainage systems can be a significant pathway for P transfer from some soils to surface waters in southern Quebec (Beauchemin et al. 2003). In the mid-Atlantic region, it was found that P losses in subsurface runoff can be an important component of the total P export from some agricultural watersheds, and thus should be considered in management strategies to minimize nonpoint source pollution of surface waters (Sims et al. 1998). In an Illinois watershed, cropland tile drainage was a significant contributor to dissolved P export and in some years with low surface runoff, nearly all dissolved and total P inputs to the river were from tile drainage (Royer et al. 2006). In Pennsylvania, P transport by subsurface pathways was found to be an important mechanism of P transfer from land to water in heavily manured soils, especially those that are artificially drained or have preferential flow pathways connected to a receiving water (Kleinman et al. 2003).

1.1. Literature Review Methods

This literature review synthesizes the current state of knowledge concerning the effects of subsurface drainage on hydrology, reported P concentrations and loads in subsurface drainage water, and major factors influencing the loss of P through subsurface drainage, derived from published scientific research. The review also briefly identifies techniques of drainage management and treatment to reduce P losses.

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

10

This review was conducted according to an approved Quality Assurance Project Plan (QAPP) (SEI 2016). Resources included in the review were identified through extensive searches of online scientific databases, including the *Web of Science*, the National Agricultural Library (AGRICOLA), Elton B. Stephens Co. (*EBSCO*), and the web search engine *Google Scholar*. Additional resources were obtained through direct contact with researchers in the Lake Champlain Basin (LCB). References cited by each reviewed source were searched for additional resources. If a review article summarized data from other studies or reports, the original documents were obtained so that all information was taken from original sources.

This review emphasized peer-reviewed sources (published journal articles), but included other references such as approved graduate theses, conference presentations, and agency reports if those sources met the criteria established in the QAPP.

In all, 252 references were identified and obtained for the review. Of these, 86 were not used because they were not applicable (e.g., they did not report P data, or represented a setting not relevant to the LCB). Of the remaining 166 references, 95% were peer-reviewed journal articles. All of the non-peer-reviewed sources represented high-quality information presented by authors published elsewhere in their fields. Work conducted in the LCB was given highest priority; research conducted elsewhere in North America and Europe was also included. The review resulted in 699 individual records reporting P concentration in tile drainflow, and 727 records reporting P loads. Discussion in this literature review first addresses work conducted in or near the LCB, then expands to reports from the U.S. Midwest and eastern Canada, and lastly, to research studies conducted elsewhere in North America and Europe.

Full data on reports of P concentrations or loads are reported in a separate spreadsheet database that includes reported P concentrations/loads and other relevant data such as soils, cropping, fertilization, and monitoring approach. Examples of P concentrations and loads are discussed in the narrative and are summarized in Tables 3 and 4.

Phosphorus is analyzed and reported in a variety of forms. Total P (TP) is considered to represent all P in a sample after chemical digestion that converts all P in the sample to an analyzable form. Within the total, P is frequently reported as "particulate P" (PP, or the P adsorbed to solid matter that will not pass through a filter) or "dissolved P" (synonymous with "soluble P"), based on filtration of the sample to separate the particulate matter from the water. Some researchers analyze "orthophosphate" (any compound containing the PO_4^- ion) or "PO_4-P," which may be quantified for either filtered or unfiltered samples. Within the dissolved fraction, P is often reported as "reactive" (based on its response to certain analytical methods); less frequently, an "unreactive" form of P will also be reported. Dissolved reactive P (DRP) is sometimes referred to as "soluble reactive P" (SRP). Sometimes total soluble P (TSP) will be reported, based on chemical digestion of a filtered sample. Some researchers have reported "bioavailable P," usually based on a chemical extraction that is analogous to the P that algae or other plants can readily access; unfortunately, these forms are not always standardized across the field, especially in older work.

To simplify the discussion, this review focuses on the most commonly reported P fractions: total P (TP), soluble reactive P (SRP or DRP), particulate P (PP), and – to a lesser extent – total soluble P (TSP). The designations SRP and DRP are used synonymously and references to "dissolved P" in the text refer to SRP or DRP unless otherwise noted. In a few cases, papers report "dissolved inorganic P," which this review assumes as equivalent to SRP or DRP because where both inorganic and organic dissolved P have been reported, inorganic P is by far the dominant fraction. A problem arises when a publication reports simply "ortho-P" or "PO_4-P." These fractions are often poorly defined with respect to dissolved, particulate, or total fraction. Where an examination of the analytical methods reported in a paper could verify that samples were filtered before analysis, reports of ortho-P was designated as soluble P. However, often filtration was not reported and

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

11

could not be inferred, so these values were reported as they were designated by the author. The P concentrations reported from analysis of unfiltered ortho-P are likely to be intermediate between SRP/DRP and TP. Any non-standard P fractions encountered are reported as used by the author(s).

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

12

2. Nature and Importance of Subsurface Drainage

Installations of subsurface drainage in the United States are reported as early as the mid-1700s; the first documented use in the US occurred in 1835 by a New York farmer who imported "horseshoe-type drain tile" patterns from Scotland (Christianson and Harmel 2015). The term "tile drainage" derives from the use of ceramic pieces (tiles) – later pipe sections – to capture and convey subsurface water (Figure 1). Today, subsurface drainage is most commonly done with perforated plastic pipeline, but the practice is still commonly referred to as tile drainage. Subsurface drainage has been described as "the most extensive soil and water management activity in agriculture" (Pavelis, 1987).

Figure 1. Old drainage tile sections on an Ohio farm.

Subsurface drainage works by providing an open pathway for soil water to drain away, lowering the water table and allowing the upper soil layers to more readily support plant growth (Figure 2). Drainage pipes are typically installed at a depth of 0.6-1.2 m and spaced 10-100 m apart, depending on site-specific soils, crop
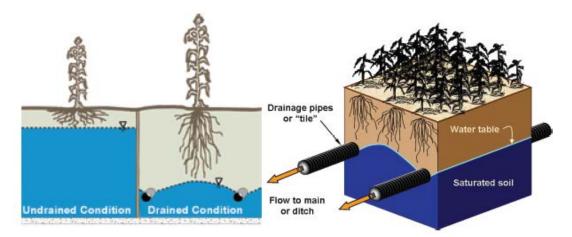

Figure 2. Subsurface drainage lowers the water table to improve crop root growth in soils with poor internal drainage (Blann et al. 2009).

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

13

type, and cost (Blann et al. 2009, Strock et al. 2010). Drainage intensity (depth and drain spacing) determines the length of time required for the drainage network to reduce the depth of a water table between the drain lines and the depth of the water table achieved after a rain event. Drainage intensity plays a critical role in nutrient losses, as nutrient loads are primarily influenced by the volume of water drained (Strock et al. 2010).

Historically, drainage was often installed strategically, based on the landowners' observation of frequently saturated areas. Today, drainage lines tend to be installed in a regular grid pattern under an entire crop field. Most subsurface drainage systems discharge directly to an open ditch or stream through open outlets. Unfortunately, although drainage outlets can be easily observed, in most cases in Vermont, the location and extent of underground drainage networks is not well documented.

Subsurface drainage is an essential water management practice on many agricultural fields in the LCB and throughout North America, Europe, and elsewhere, allowing increased crop production and timely equipment access in fields otherwise too wet to effectively farm. Improved drainage enhances crop growth and yield and improves farm operations by increasing the number of days available for on-farm activities (Christianson and Harmel 2015). Fraser and Fleming (2001) noted that for farmers, tile drainage is both agronomically and economically beneficial for reasons including: better growing conditions, improved soil structure, better trafficability, reduced energy consumption, more timely planting and harvest, and improved yields for a variety of crops. Economics is a key driver for subsurface drainage. Installation of subsurface drainage systems can cost $740-$1,480 per ha, but can increase crop yields by up to 25% (Blann et al. 2009, Christianson and Harmel 2015).

There are no good data concerning the exact extent of drainage on agricultural land in the U.S. Up to 1974, the U.S. Census of Agriculture collected farm drainage data directly from reporting farmers; at that time, it was estimated that 42.8 million acres of drained land existed in the U.S., although the accuracy of that figure has been questioned (Jaynes and James 2007). For several states, Jaynes and James (2007) estimated the percentage drained by assuming that poorly drained soils that are in crop production must be drained. Their estimates ranged from 2% (New York) to 28% (Indiana). Using similar assumptions, the World Resources Institute (2007) estimated 39.3 million tile-drained acres in eight U.S. corn-belt states (Iowa, Illinois, Ohio, Indiana, Minnesota, Michigan, Wisconsin, and Missouri); these states were estimated to have from 3% (Missouri) to 48% (Illinois) of their cropland acres underlain by subsurface drainage (Sugg 2007).

Few precise estimates of the extent of cropland drainage in the LCB exist. In the Vermont portion of the Missisquoi River Basin (MBB), Winchell et al. (2011) assumed that all poorly-drained cropland (hydrologic soil group C or D) with slopes less than 6% must be tile drained and thereby estimated that 40% of the MBB was tile drained. Subbasin estimates ranged from <20% for Mud Creek, Trout River, Tyler Branch, and Upper Missisquoi River to >75% for Rock River and Hungerford Brook.

More recently, VT AAFM and VT ANR (2016) reported estimates from the National Resources Inventory (NRI) via the U.S. Census of Agriculture that statewide, 4.8% of Vermont's cropland (23,500 ac on 525 farms) has subsurface drainage, with cropland drainage in some subwatersheds within the LCB as high as 70%. Of the reported drained acres, 80% are associated with dairy production.

More than 70% of the agricultural fields in the Jewett Brook watershed draining to St. Albans Bay of Lake Champlain are believed to be tile drained (VT AAFM 2015); however, the specific locations of tile systems and their outlets are largely unknown.

Stone Environmental

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

14

3. Effects of Subsurface Drainage on Hydrology

The extensive development of surface and subsurface drainage systems to facilitate agricultural production throughout North America has significantly altered the hydrology of landscapes compared to historical conditions (Blann et al. 2009). In a review, Fraser and Flemming (2001) identified specific influences of subsurface drainage on field hydrology:

- Rather than rely on evaporation and transpiration alone to remove excess water from the soil, tile drainage removes excess water within a matter of days rather than weeks. As a result, tile drained soil has increased water storage capacity.
- Soils with increased storage capacity, such as tile drained soils, have a higher infiltration capacity. Higher infiltration means:
    - the soil acts as a buffer to rainfall, decreasing stream peak flow volumes and extending watershed total runoff over a longer period of time; and
    - surface runoff volumes can be reduced.
- The degree to which peak flows are affected by tile drainage depends on the moisture conditions in the soil. When soil is dry prior to rainfall, peak flows can be reduced by tile drainage by as much as 87%. Soil type, slope and drainage spacing also affect infiltration and peak flows.
- Tile drainage increases annual total water output volumes compared to surface drainage only.

Gilliam and Skaggs (1986) observed that subsurface drainage removes excess water from the soil profile over a relatively long period of time compared to surface runoff. Subsurface drains lower the water table, providing more storage for infiltration from rainfall events, thereby reducing the proportion of outflow that is surface runoff. In North Carolina, adjacent watersheds with similar soils and slopes expressed approximately equal total outflow, but the peak flow rate from the subsurface drained watershed was half that from the non-tiled watershed (Figure 3). In addition, the flow period was extended in time from the drained watershed compared to the non-tiled watershed. Bilotta et al. (2008) reported similar results from England, where peak discharge from drained land tended to be lower than that from undrained land during the same rainfall events.

In another review, Evans et al. (1995) reported that subsurface drainage of agricultural land typically increases total annual outflow from the field. Specifically, subsurface drainage increased outflow rates by a factor of two compared with natural conditions. However, peak outflow rates from systems dominated by subsurface drainage tend to be about half as high as surface systems (e.g., ditches).

In recent research in the New York portion of the LCB, Klaiber (2015) reported a significant increase in total annual water yield from a tile-drained plot (560 mm), compared to an undrained plot (166 mm), representing 54% of total rainfall that fell on the tile-drained plot vs. just 16% of rainfall received by the undrained plot. Despite the increase in total water yield, overland flows only occurred during 6% of the study duration in the tile-drained site as compared to 14% of the time on the undrained site.

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

15

Figure 3. Runoff hydrographs from a 3.25 cm rainfall event for NC Watershed A (poor subsurface drainage) and Watershed B (good subsurface drainage (Gilliam and Skaggs 1986).

In the Quebec portion of the LCB, Eastman et al. (2010) reported that tile drained crop fields discharged 1.7 – 2.2 times more water (in combined surface and subsurface flow) than did undrained fields.

King et al. (2015) reviewed agricultural drainage literature and reported that tile drainage increases total water yield between 10 and 25% because it tends to increase the proportion of annual precipitation that reaches surface waters via subsurface flow relative to the amount that is stored, evaporated, or transpired. In several studies the authors reviewed, it was suggested that tile drainflow from can constitute the majority of stream flow in agricultural watersheds across the Midwestern U.S. and Canada. Bottcher et al. (1981) reported contradictory results from a tile system in Indiana, where water yield was much lower from a tile drained field than from a neighboring undrained field. This difference, however, was not tested or controlled statistically.

Subsurface drainage tends to reduce the amount of water lost as surface runoff. Consequently, subsurface drainage has sometimes been proposed as a strategy for reducing non-point source pollution in areas where sediment and phosphorus are the major concerns (Blann et al. 2009). In New York (within the LCB), although Klaiber (2015) found no significant differences in cumulative TP export between drainage treatments (231 g/ha from an undrained plot and 234 g/ha from a drained plot), 55% more SRP was exported from an undrained plot (131 g/ha) than from a drained plot (84 g/ha). In North Carolina, Gilliam and Skaggs (1986) reported that P loss in drainage (surface plus subsurface) water was decreased as the proportion of water lost through subsurface drainage increases. In Louisiana, Bengtson et al. (1995) reported that subsurface drainage was effective in reducing surface runoff by an average of 35%, and reduced soil and P loss by 31%. In Albania, Grazhdani et al. (1996) reported that although 30-40% more water left drained plots than undrained plots, subsurface drainage reduced surface runoff by 30-56%.

In Iowa, Schilling et al. (2015) used a model to evaluate how groundwater travel times change with increasing drainage intensity. Results indicated that mean groundwater travel times are reduced with increasing degrees of tile drainage. In the study watershed, mean groundwater travel times to the stream decreased from 5.6 to 1.1 years, with drainage densities ranging from 0.005 /m to 0.04/ m, respectively. Model simulations indicated that mean travel times with tile drainage are more than 150 times faster than those that existed before settlement. The authors noted that with intensive drainage, less than 2% of the groundwater in the basin appears to flow through a stream buffer, thereby reducing the effectiveness of this practice to control stream nitrate loads.

3.1. Field-Scale Tile Drainage

Considerable data on field-scale outflow from tile drainage systems have been reported from studies in the Quebec portion of the LCB. Jamieson et al. (2003) reported that subsurface drainage flow from an agricultural field in southeastern Quebec was 52% of the total runoff volume during a spring snowmelt event. From three years of monitoring of field sites in the Quebec LCB, Enright and Madramootoo (2004) reported that subsurface drainage was the dominant pathway by which water left the fields. On average, tile drainage accounted for 81% of the total annual water leaving the fields; that proportion was higher (84 – 93%) in years that lacked a major spring snowmelt event. In the same region of Quebec, Simard (2005) reported that two corn fields exported 35 – 49% of the precipitation they received through tile drain systems.

Eastman et al. (2010) measured subsurface flows from fields with different soil types in Quebec, reporting that total outflow from a tile-drained clay loam site was four times that from an undrained site with the same soils, whereas a tile-drained sandy loam site discharged 1.8 times more water than a similar undrained site. The authors concluded that construction of subsurface drainage in sandy loam soil would greatly reduce the likelihood of surface runoff occurrence, and thus minimize the likelihood of P losses to surface waters.

Morrison et al. (2013) used field data with the DRAINMOD model (Skaggs 1980) to evaluate the effect of tile drain spacing on surface runoff and subsurface drainage flows from the same Quebec fields studied by Enright and Madramootoo (2004). Under existing conditions, annual drainage volume averaged about 50% of annual precipitation. Simulation results indicated that when lateral tile drain spacing is increased, the volume of subsurface drain flow decreases and the volume of surface runoff increases at sites with sandy and clay loam soils. The effects of drain spacing on drainage properties were more pronounced for fine-textured soils than for the site with coarse-textured soils.

In a comprehensive review of 400 studies of tile drainage, Christianson and Harmel (2015) reported that across 1,279 site-years 1961-2012, a mean of 25% of annual precipitation input to agricultural fields was exported as tile drainage outflow, with wet years yielding significantly greater drainflow. Of course, the proportion of precipitation expressed as tile drainage flow varies by a variety of factors, including soil physical properties, land cover, evapotranspiration, and drainage intensity, as well as precipitation input. Consequently, a wide range has been reported in the literature (Table 1).

Table 1. Selected values reported for tile outflow as a percentage of annual precipitation.

Location	Land Use	Tile Outflow as % of Precipitation	Reference
IA	Corn-soybeans	13%	Logan et al. 1980
MN	Corn-grain	19%	Logan et al. 1980
OH	Corn-soybeans	22%	Logan et al. 1980
IN	Corn	6-27%	Kladivko et al. 1991
OH	Corn-soybeans	28%	King et al. 2014
WI	Corn	11-40%	Madison et al. 2014
WI	Pasture	17-22%	Madison et al. 2014
Quebec	Corn	35-49%	Simard 2005
Ontario	Corn-soybeans	16-22%	Lam et al. 2016
Lithuania	Small grains	Dry years: 16-20%	Buciene et al. 2007

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

17

Lithuania	Small grains	Wet years: 52-66%	Buciene et al. 2007
New Zealand	Pasture	16-51%	Tanner and Sukias 2011

In Illinois, Algoazany et al. (2007) reported that subsurface drainage and surface runoff across four study sites exported an average of 16% and 3% of rainfall, respectively.

When tile drainage is installed, the volume of surface runoff tends to be reduced. The actual percentage is site-specific and is influenced by precipitation, soil characteristics, drainage intensity, and other factors. The range of values reported in the literature is summarized in Table 2.

Table 2. Selected values reported for annual tile outflow as a percentage of total field water output.

Location	Land Use	Tile outflow as % of total field water output	Reference
NY	Grass	95%	Klaiber 2015
NY	Corn	40%	Hergert et al. 1981
OH	Corn-soybeans	47%	King et al. 2014
Quebec	Corn	81%	Enright and Madramootoo (2004)
Quebec	Corn-grains	98%	Goulet et al. 2006
Ontario	Corn-soybeans	97%	Tan and Zhang 2011
Ontario	Corn-soybeans-wheat	78-87%	Van Esbroeck 2015.
England	Pasture	50-66%	Bilotta et al. 2008
Finland	Barley-grass	Old system: 10-40%	Turtola and Paajanen 1995
Finland	Barley-grass	New system: 50-90%	Turtola and Paajanen 1995
Albania	Corn	47-69%	Grazhdani et al. 1996

3.2.   Tile Drainage Contributions to Streamflow

As a consequence of the changes in hydrologic behavior from tile drainage at the field scale, researchers have reported that in intensively drained agricultural watersheds, tile drainage flow is a major contributor to annual streamflow.

In the Netherlands, Rozemeijer et al. (2010) reported that tile drains contributed 80% of the volume carried in ditches draining crop fields.

In Ohio, King et al. (2014) reported that annual watershed discharge originating from tile flow ranged from 37-74%, with an 8-year average of 56%. Madison et al. (2014) measured tile drainage contributions to total basin discharge as high as 87% from a no-till watershed and 66-77% from chisel plowed watersheds. In Illinois, Xue et al. 1998 estimated that tile drainage flow from cropland in corn-soybean rotation contributed more than 86% of the river flow from a 48,000 ha watershed. In Ontario, Macrae et al. (2007) estimated that 42% of basin annual discharge from a first-order agricultural catchment originated from drainage tiles, the majority of which occurred during the winter and spring months.

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

18

Schilling and Helmers (2008b) applied hydrograph analysis techniques to model simulation output and field monitoring from Iowa tile-drained landscapes to explore how flow from drainage tiles affects stream baseflow and streamflow recession characteristics. Results indicated that flow from tile drainage primarily affects the baseflow portion of a hydrograph, increasing annual baseflow in streams. Tile drainage is expected to account for a substantial portion of baseflow in some extensively tiled watersheds and may have been a significant contributor to increasing baseflow in Iowa's streams over the 20th century.

3.3. Seasonality

Tile drainflow volumes tends to follow strong seasonal patterns, although the exact timing varies by regional climate patterns and agricultural management. Bryant et al. (1987) reported that approximately 50% of the annual volume of tile drainflow from Ontario cropland occurred in March and April. In Quebec, Simard (2005) measured the greatest tile drainage volumes in fall and spring, when up to 90% of precipitation was exported via tile drainage. In Ohio, King et al. (2014) reported that mean monthly and annual tile drainflow generally followed precipitation patterns, with greater flows observed during the winter, spring, and fall, compared with summer.

In general, tile drainflow is reported to be either very small or entirely absent in the summer months. In an Ontario study, Macrae et al. (2007) reported that drainage tiles typically flowed for 8-9 months of the year, and ceased flowing during the summer. Ball Coelho et al. (2012) also reported that drain flow volumes in Ontario were greater in the non-growing season than during the growing season. Also in Ontario, Lam et al. (2016) stated that tiles were generally hydrologically active through fall, winter and spring, with the greatest flows during snowmelt. The authors also observed that much of the annual tile flow occurred during discrete events and tiles did not flow at all during drier periods.

Hirt et al. (2011) reviewed data from 11 artificial drainage study sites in Europe and found that tile drainflow responded to 70% of all rainfall events during the year, and that the response rate differed significantly between 56% of events in summer and 84% of events in winter. A median of 23% of the yearly precipitation rate was discharged by artificial drainage systems, varying from 9% of the precipitation in summer to 54% of the precipitation in winter. The contribution of tiles to basin discharge on the 32 discrete sampling dates ranged from as low as 0% to as high as 90%. There was considerable variability in tile drainflow at both moderate (wet versus dry periods) and smaller (within event) temporal scales and the proportion of tile flow to basin discharge was not constant. When the stream was dry (23% of the year), tiles did not flow at all. When basin discharge was ranged from 0.1 to 40 L/s (46% of the year) tiles either did not flow or contributed very little to basin discharge. When basin discharge ranged from >40 to 60 L/s (13% of the year), tile contribution to basin discharge was most variable, ranging from 0 to 90%.

3.4. Factors Influencing Hydrologic Response

The hydrologic response of tile-drained fields is influenced by a variety of factors, not all of which are well-understood. Many of these factors are likely to be site-specific. In Ireland, Ibrahim et al. (2013) reported major differences in flow behavior among plots with identical drainage systems for several monitored events. The authors noted greater differences in both overland and subsurface drainage patterns between all plots than between different events for the same plot, and attributed this pattern to inherent soil and subsoil heterogeneity of the plots, which impacted the hydrologic connectivity between the surface and the subsurface drains.

Precipitation is a principal driver of tile drainflow. Ball Coelho et al. (2010) stated that the amount of precipitation required to trigger tile outflows depends on rainfall intensity, initial soil water content, presence of surface inlets, crop type, and soil texture. Faster flow response tended to occur with increased rainfall

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

19

intensity, increased soil water content and presence of surface inlets; and slower or less response with alfalfa and coarse soil texture. On wet soil in Ontario, tiles generally flowed within a few hours of rainfall with an intensity greater than 10mm/h.

Heppell et al. (2002) use a variety of multivariate statistical techniques to explore the antecedent and rainfall controls on drainage characteristics for an agricultural underdrained clay site in England. Principal component analysis revealed that rainfall characteristics were more important than antecedent conditions in generating high tile drain flows (largely via macropore flow). Of the rainfall characteristics studied, rainfall amount and intensity were the dominant controls on the amount of macropore flow, with duration as a secondary control.

Hirt et al. (2011) reported that European artificial drainage systems usually started to respond within the first hour of rainfall, although the response time was delayed at lower rainfall intensities (<1 mm/h). The peak outflow normally occurred within the first two days. Their review suggested that drainage systems have a short response time to rainfall events. This effect is independent of land use and soil texture. Overall, results clearly indicate that high rainfall intensities accelerate the water fluxes through preferential flow pathways in the soil.

Bryant et al. (1987) examined tile drainflow over a 14-year period in Ontario to determine the effects of crop cover on tile flow and reported that the crop grown and level of fertility have an important effect on tile drainflows from clay loam soils. Land in fertilized crops contributed a greater volume of drain flow than did land in unfertilized crops. Continuous corn and bluegrass contributed a larger drainage volume than rotational crops. The authors proposed that fertilizer appears to promote root proliferation and therefore more continuous biopores and cracking through the surface profile which results in a more direct channel to the drain thus increasing the volume of tile drainflow.

In Minnesota, Oquist et al. (2007) reported results indicating that alternative farming practices (no inorganic fertilizers, improved crop rotations) reduced outflow from subsurface drainage systems by 41% compared with conventional practices. Annual drainage losses were greater under conventional practices, with subsurface drainage representing a greater proportion of precipitation received under conventional farming practices in comparison with alternative practices, especially during wet years.

Several researchers have reported on the influence of drainage design on tile drain flow. In an Iowa watershed, Schilling et al. (2012) reported from a modeling study that varying tile drainage density while maintaining constant tile depth of 1.2 m resulted in the mean groundwater travel time to decrease exponentially from 40 years to 19 years and increased the tile contribution to baseflow from 0% to 37%. In contrast, varying tile depths from 0.3 to 2.7 m, while maintaining a constant tile drainage density, caused mean travel times to decrease linearly from 22 to 18 years and increased the tile contribution to baseflow from 30% to 54% in a near-linear manner. The decrease in the mean travel time was attributed to decrease in the saturated thickness of the aquifer with increasing drainage density and incision depth.

King et al. (2015) stated that shallow drains reported to respond more rapidly to precipitation than deep drains, but drainage volume was significantly less in shallow drains. At the same depth, drainage volume from narrow drain spacing (e.g., 9m) was significantly greater than from wider spaced drains (e.g., 18m). In Ohio, Hoover and Schwab (1969) reported that narrow (10m) drain spacing resulted in higher tile drainflow than wider (20m) spacing. Although the average drainflow from tile at 1m depth was slightly more than that from tile at 0.6m, the depth of tile did not significantly affect drainage volume. The 0.6m depth/10m spacing tile system yielded significantly higher flow than all other drainage treatments, nearly twice that from a 0.6m depth/20m spacing system. However, Hoffmann et al. (2004) reported that annual drain flows in Indiana were greatest for 20m tile spacing, 19 and 30% greater than for 10 and 30m tile spacing, respectively.

Stone Environmental

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

20

4. Reported P Concentrations and Loads in Subsurface Drainage Water

4.1. Phosphorus concentrations in tile drainage

Phosphorus concentrations measured in tile drainflow as reported in the literature are summarized in Table 3. Data are included for a wide range of monitoring periods, from single events to annual means. The data in this table are reported with some basic information on location, land use, and soil texture, but are generally pooled across management, treatments (e.g., manure application, fertilizer rate, and tillage) and drainage design. All of the reports in Table 3, however, are from studies of conventional free subsurface drainage; data from application of drainage water management or controlled drainage are discussed elsewhere in this review.

Phosphorus concentrations measured in tile drainage from agricultural fields have been enormously variable. Much of that variability is reportedly due to soil characteristics, agricultural management (e.g., fertilization, tillage), weather, and other factors (see Section 5). Within this variability, the consensus of the literature is that significant concentrations of P are often found in tile drainflow. Quantities of P leached below the root zone in annually-cropped, conventionally-tilled soils are often reported to be above levels required to stimulate eutrophication (Carefoot and Whalen 2003), so it is not surprising that some of this P reaches subsurface drainage systems.

Some research has reported very low concentrations of P in subsurface drainage. In corn silage and hay plots on a Cabot silt loam in Franklin, VT, Benoit (1973) reported all tile drainage samples contained less than 0.02 mg/L TP, the detection limit. More recently, Young (2015) sampled 14 fields on five farms in Clinton and St. Lawrence Counties, NY and reported TP concentrations of 0.023 – 0.175 mg/L (mean 0.098 mg/L) and SRP concentrations of 0.009 – 0.041 mg/L (mean 0.011 mg/L). These values were two orders of magnitude lower than those observed in surface runoff. In the same area, Klaiber (2015) reported P concentrations in tile drainage from 7 events over a year. Mean TP concentration in tile drainage was 0.029 mg/L (compared to 0.324 mg/L in surface runoff from the same plot); mean SRP concentration in tile drainage was 0.012 mg/L (compared to 0.125 mg/L in surface runoff).

In four years of monitoring drainage water in Iowa, Baker et al. (1975) reported PO_4-P levels averaging 0.005 mg/L and characterized annual P losses as "negligible." Owens and Shipitalo (2006) reported average TSP concentrations < 0.05 mg/L in drainage from an Ohio beef pasture. Daigh et al. (2015) observed a mean total TP concentration of <0.04 mg/L in two years of subsurface drainage from fields in corn-soybean rotation in Iowa. Note that this data came from non-frozen periods only, so may represent an underestimate of P concentrations (see Section 4.1.2).

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

21

Table 3. Range of tile drainage P concentrations reported in the literature.

Location	Time Base	Land Use	Soil texture	[TP] mg/L	[TSP] mg/L	[SRP] mg/L	[PP] mg/L	Reference
VT	Seasonal	Alfalfa, corn	Silt loam			<0.02		Benoit 1973
NY	Annual		Muck			0.2-7.8		Duxbury and Peverly 1978
NY	Annual	Corn	Silty clay loam	0.11-9.8				Geohring et al. 2001
NY	Annual	Corn	Loam, silt loam			0.009-0.441		Hergert et al. 1981
NY	Multi-event	Corn silage	Silty clay	0.029		0.012		Klaiber 2015
NY	Multi event			0.098		0.024		Young 2015
Quebec	Seasonal	Corn-soybeans	Coarse	0.011-0.075				Beauchemin et al. 1998
Quebec	Seasonal	Corn-soybeans	Medium	0.017-0.037				Beauchemin et al. 1998
Quebec	Seasonal	Corn-soybeans	Clay	0.015-1.17				Beauchemin et al. 1998
Quebec	Annual	Corn-soybeans	Loam-sandy loam	0.01-0.13		0.01-0.03	0.02-0.11	Beauchemin et al. 2003
Quebec	Annual		Sandy loam	0.06-0.08				Enright and Madramootoo 2004
Quebec	Annual		Sandy clay loam	0.10-.37				Enright and Madramootoo 2004
Quebec	Seasonal		Sandy clay loam	0.11		0.04*		Jamieson et al. 2003
Quebec	Seasonal	Corn	Sandy loam, clay loam				0.03-0.27	Poirier et al. 2012
Quebec	Annual	Corn	Clay loam	0.2		0.04	0.1	Simard 2005
Quebec	Annual	Barley-soybeans	Clay loam	0.2		0.02	0.1	Simard 2005
Quebec	Annual	Corn	Sandy loam	0.011-0.053		0.001-0.012	0.01-0.012	Simard 2005
Quebec	Annual	Corn, grains, grass	Silty loam	0-2.726	0-0.916		0-2.688	Goulet et al. 2006
Ontario	Seasonal	Corn, soybean, alfalfa	Sandy loam, silty clay			0.03-0.24		Ball Coelho et al. 2010
Ontario	Annual	Corn				0.004-0.016	0.027-0.035	Ball Coelho et al. 2012
Ontario	Annual	Corn, oats, alfalfa	Clay		0.17-0.22			Bolton et al. 1970
Ontario	Annual	Corn, oats, alfalfa	Clay loam	0.08-1.17	0.04-1.10			Culley et al. 1983a
Ontario	Single event	Barley	Clay loam	0.48-9.75				Frey et al. 2013
Ontario	Annual	Corn	Clay loam			0.2-1.07		Gaynor and Findlay 1995
Ontario	Multi-event	Soybeans	Silt-clay loam	0.02-1.35		0.02-0.43*		Gottschall et al. 2009
Ontario	Annual	Corn, soybeans, wheat	Loam, slit loam	0.044-1.55		0.009-0.549		Macrae et al. 2007
Ontario	Multi-event	Corn-soybeans	Various	0.03-0.24		0.015-0.072		Miller 1979
Ontario	Annual	Corn-soybeans	Clay	0.417-0.530		0.02-0.05	0.31-0.44	Tan and Zhang 2011
Ontario	Annual	Wheat, corn, soybeans	Silt loam, clay loam	0.03-0.08		0.003-0.007		Van Esbroeck 2015
Ontario	Annual	Various	Clay loam	0.40-0.54		0.09-0.35		Zhang et al. 2015b

Location	Time Base	Land Use	Soil texture	[TP] mg/L	[TSP] mg/L	[SRP] mg/L	[PP] mg/L	Reference
MI	Annual	Corn-soybeans	Loam	0.10-0.15	0.04-0.07			Gold and Loudon 1989
MI	Multi-event	Corn silage	Loam	0.40-1.08		0.17-0.30		Haack and Duris 2008
WI	Annual	Corn silage	Fine loamy	0.54-1.76		0.23-0.95		Madison et al. 2014
WI	Annual	Corn-soybeans	Fine loamy	0.08-0.19		0.07-0.14		Madison et al. 2014
WI	Annual	Pasture	Fine loamy	0.84-1.78		0.63-1.41		Madison et al. 2014
WI	Annual	Continuous corn		0.5-0.7				Ruark et al. 2012
WI	Annual	Corn-soybean		0.22				Ruark et al. 2012
WI	Annual	Pasture		1.31				Ruark et al. 2012
MN	Annual	Corn-soybeans	Clay loam	0.024-0.038		0.006-0.036*		Logan et al. 1980
MN	Seasonal	Various	Various		0.03-0.09	0.02-0.14		Oquist et al. 2007
MN	Annual	Corn	Clay loam	<0.03-<0.035		<0.01-<0.019*		Randall et al. 2000
IL	Annual	Corn-soybean	Silty clay loam			0.083-0.194		Algoazany et al. 2007
IL	Annual	Row crop	Loess	0.16-0.406		0.027-0.314		Gentry et al. 2007
IL	Annual	Corn-soybean				0.08-0.18		Xue et al. 1998
IN	Multi-event	Corn-soybean	Sandy loam, silt loam			0.003-0.478		Ahiablame et al. 2011
IN	Multi-event	Soybeans	Loam, silt loam	0.05-0.17		0.005-0.024		Vidon and Cuadra 2011
IN/MN	Annual	Corn, wheat, soybeans	Silty clay	0.28-0.35		0.02-0.06	0.22-0.26	Bottcher et al. 1981
OH	Annual	Corn, soybeans	Silt loam, clay loam	0.11-0.30		0.08-0.27		King et al. 2016
OH	Multi-event	Corn	Silt loam	0.072-0.112				Logan and Schwab 1976
MO	Annual	Corn	Silt loam			0.09-0.15		Nash et al. 2015
IA	Single event	Corn	Loam			0.01		Allen et al. 2012
IA	Annual	Corn	Loam	0.01-0.037**				Daigh et al. 2015
IA	Annual	Prairie	Loam	0.006-0.023**				Daigh et al. 2015
IA	Annual	Corn	Silt loam	0.025-0.037		0.002-0.01*		Baker et al. 1975
IA	Annual	Corn, soybeans	Silty clay loam			0.005 – 0.013		Nayak et al. 2009
IA	Multi-event	Row crops, grass	Fine	1.3 – 1.7				Schilling and Helmers 2008a
IA	Seasonal	Corn	Loam			0.013 – 0.163*		Hruby 2015

Stone Environmental

Lake Champlain Basin Program / Literature Review: Tile Drainage and Phosphorus Losses from Ag. Land / November 23, 2016   23

Location	Time Base	Land Use	Soil texture	[TP] mg/L	[TSP] mg/L	[SRP] mg/L	[PP] mg/L	Reference
TX	Annual	Turf grass	Loamy sand			0.09-0.13		King et al. 2006
Nova Scotia	Annual	Various	Various	0.23		0.08		Kinley et al. 2007
Manitoba	Annual	Corn	Sandy loam			0.04-0.32*		Cordeiro et al. 2014
England	Annual	Grassland	Clay loam			0.3		Hawkins and Scholefield 1996
England	Annual	Grassland	Sandy loam, clay loam	0.033-0.073	0.023 – 0.031		0.01-0.042	Heathwaite and Dils 2000
England	Single event	Wheat	Silt loam, silty clay	<0.1-2.75		<0.0-1.8	0.01-1.3	Heckrath et al. 1995
England	Seasonal	Winter cereals	Clay	0.26-0.60		0.03-0.07*		Catt et al. 1998
Ireland	Multi-event	Grassland	Clay	0.042-0.172		0.002-0.006	0.004-0.13	Ibrahim et al. 2013
Netherlands	Annual	Grass	Sandy	0.094				Rozenmeijer et al. 2010a
Germany	Annual	Grass				0.03		Gelbrecht et al. 2005
Spain	Seasonal	Cotton, sugar beets	Clay	0.072-0.152		0.039-0.073		Delgado et al. 2006
Albania	Annual	Corn	Silty clay			0.086-0.105*		Grazhdani et al. 1996
Denmark	Annual	Wheat	Sandy loam	0.02-0.111	0.01 – 0.085		0.01-0.026	Grant et al. 199
Denmark	Annual	Various	Various	0.05-0.62				Kronvang et al. 2005
Finland	Seasonal	Plowed fallow	Silty clay	0.24		0.04		Turtola and Paajanen 1995
Finland	Multi-event	Barley-wheat	Clay	0.46-1.42		0.03-0.078		Uusitalo et al. 2001
Sweden	Annual	Wheat, small grains	Clay	0.72		0.19		Ulen et al. 2016
Sweden	Annual	Potato, small grains	Loamy sand	0.022		0.006		Wesstrom and Messing 2007
Sweden	Annual	Barley	Sandy loam	0.027-0.036		0.014-0.023		Wesstrom et al. 2014
NZ	Seasonal	Pasture	Silt loam	1.2		0.33	0.83	McDowell et al.2008
NZ	Annual	Pasture	Silt loam	0.074	0.029	0.023		Monaghan et al. 2002

*ortho-P reported

** Total Reactive P reported (undefined)

In contrast, other researchers have reported higher P concentrations in tile flow. On New York sites (one of which was in the LCB), Scott et al. (1998) reported TSP concentrations as high as 1.17 mg/L in tile drains under fields receiving manure. Beauchemin et al. (1998) found TP concentrations in drainage water in Quebec that exceeded the Provincial standard of 0.03 mg/L for surface waters in 14 out of 27 and 6 out of 25 samples in 1994 and 1995, respectively. Similarly, Simard (2005) reported that median TP concentration in tile drain outflow from an agricultural field in the Missisquoi Bay watershed exceeded Quebec guidelines to prevent eutrophication. In northern Quebec, Goulet et al. (2006) reported average TP in tile drainflow from plots of 0.119 mg/L, but TP concentrations as high as 2.726 mg/L were observed in individual samples. Mean TSP and PP concentrations were 0.029 mg/L and 0.090 mg/L, respectively. Algoazany et al. (2007) reported that TSP concentrations in tile drain outflow in Illinois were substantially greater than the critical values that promote eutrophication.

In an Ontario watershed, Macrae et al. (2007) reported that concentrations of SRP and TP in tile drainflow varied in response to storm/melt events, season, and management. Mean SRP and TP concentrations in seven tiles were 0.01–0.55 and 0.04–1.55 mg/L, respectively. Occasionally SRP and TP concentrations were very large (e.g. 2.73 and 8.28 mg/L, respectively). Ruark et al. (2012) reported annual mean TP concentrations in tile drainflow as high as 2.73 mg/L from a no-till crop field in Wisconsin. Also in Wisconsin, Madison et al. (2014) observed average annual surface TP and DRP concentrations ranging from 2.66 to 6.48 mg/L and 0.75 to 5.21 mg/L across sites, respectively; average annual tile TP and DRP concentrations ranged from 0.21 to 1.32 mg/L and 0.17 to 0.89 mg/L, respectively. In long-term drainage monitoring in Ohio, King et al. (2014) reported a peak TP concentration of 5.48 mg/L and DRP concentration of 4.64 mg/L, compared to a maximum TP concentration of 1.92 mg/L and DRP of 1.74 mg/L in surface water at the watershed outlet. Schelde et al. (2006) reported mean TP concentrations in drains from Danish plots of up to 2 mg/L, with peak concentrations up to 4.8 mg/L. In a study of Nova Scotia agricultural fields, Kinley et al. (2007) reported high variability of P concentrations in tile drainflow between fields and samples. Concentrations varied from week to week, and particularly in April, May, October, and November when the highest average TP, SRP, and flow rate were measured. Even though large numbers of samples had P concentrations below the detection limit (0.04 mg/L), mean TP concentrations exceeded the USEPA TP guideline of 0.10 mg/L (USEPA 1994) at 82% of the fields, and periodically concentrations more than 50 times higher than the guideline were found. Ninety percent of the fields had some sample TP concentrations exceeding 1.0 mg/L

Despite the significant P concentrations sometimes observed in tile drainage water, those P concentrations are usually much lower than concentrations in overland flow from the same site or in adjacent receiving surface waters. Sims et al. (1998) reported that the consensus of more than 21 studies reviewed was that losses of P are typically lower in subsurface drainage than surface runoff at the field scale. In Quebec, Jamieson et al. (2003) reported that average TP and ortho-P concentrations from tile drains were about 45% lower than the average TP concentrations for surface runoff. Also in Quebec, Enright and Madramootoo (2004) reported that, on average, P concentrations in surface runoff were 10.9 times higher than those found in subsurface drainage. Goulet et al. (2006) reported P concentrations in tile drainflow one to two orders of magnitude lower than those in surface runoff from the same plots. Researchers in Ontario have also reported that P concentrations in subsurface drainage were lower than those observed in surface runoff from agricultural land (Ball Coelho et al. 2010, Van Esbroeck 2015). Algoazany et al. (2007) observed soluble P concentrations in Illinois tile drainage water that were just 15 – 39% of the concentrations in surface runoff from the same sites.

In a small German agricultural catchment, Gelbrecht et al. (2005) reported that tile drain SRP concentrations were an order of magnitude lower than those in surface runoff, and comparable to levels found in ditches and groundwater (Figure 4).
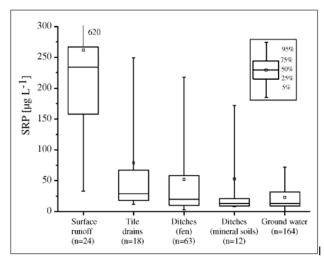
Figure 4. Distribution of SRP concentrations in different loss pathways in a German agricultural catchment (Gelbrecht et al. 2005).

4.1.1. Seasonality and Flow

Phosphorus concentrations in tile drainflow vary with flow and season, although the reported patterns are somewhat inconsistent.

Surprisingly little research has been published on seasonal variations in tile drainage P concentrations; rather, work has focused on seasonal P mass flux from drained fields (see Section 4.2). Bolton et al. (1970) reported that N, P, K, and Ca concentrations in drainage flow in Ontario tended to be lower in the spring than during fall and winter. In Illinois, Algoazany et al. (2007) reported that soluble P concentrations in tile drainflow peaked from February until July each year for all stations; soluble P concentrations were low from August to December. In Ohio tile drains, King et al. (2014) observed that winter and spring DRP concentrations in tile drainage were significantly lower than those observed in summer and fall. The winter tile drainage mean TP concentration (0.12 mg/L) was significantly lower than all other seasons. The highest monthly TP concentration in tile drainage (0.33 mg/L) was observed in August. King et al. (2016) expanded on these findings, reporting that mean weekly DRP concentration in the growing season under corn (0.27 mg/L) was approximately three times greater than non-growing season concentration (0.08 mg/L). For soybeans, the growing season concentration of DRP was two times greater compared to the non-growing season. Similarly, mean weekly TP concentration under corn was significantly greater in the growing season (0.30 mg/L) compared to mean weekly TP concentration in the non-growing season (0.11 mg/L). The growing season concentration of DRP for soybeans (0.21 mg/L) was approximately twice that measured during the non-growing season (0.11 mg/L).

Substantially more work has been published on variations in drainage water P concentrations associated with changing flow. In New York, Duxbury and Peverly (1978) observed that P concentrations in tile drainage water increased with increasing drainage flow. In Ontario, Van Esbroeck (2015) reported that tile P concentrations were higher during event flow than in baseflow conditions; King et al. (2014) also reported that DRP and TP concentrations increased with increasing tile drainflow. The highest P concentrations were observed when tile flow was >0.024 mm/h (75th percentile of flow). Also in Ontario, Lam et al. (2016) observed that during periods of low flow or baseflow, TP and DRP concentrations in all tile systems were generally <0.01 mg/L, with very little difference between TP and DRP concentrations. Elevated DRP and TP concentrations coincided with tile drainflow peaks. DRP concentrations ranged from 0.005-0.225 mg/L during

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

26

events, typically ranging between 0.05 and 0.15 mg/L during peak flow. Event-based instantaneous TP concentrations ranged from 0.007 to 1.316 mg/L, with peak TP concentrations generally ranging between 0.10 and 0.50 mg/L.

From England, Heathwaite and Dils (2000) reported that P concentrations in drainflow were over six times greater in stormflow compared to baseflow. The authors stated that under baseflow conditions, tile drains were largely fed by water percolating through the soil matrix and consequently TP concentrations were low and largely in the soluble phase. Under stormflow conditions, large quantities of P were rapidly transported in preferential flow pathways to the tile drain system, and as the water table elevated there were delayed contributions from groundwater sources.

Vidon and Cuadra (2011) researched P dynamics in tile drain flow during four spring storms in two tile drain systems in Indiana. Phosphorus concentrations tended to be higher and more variable in larger storms, possibly due to differences in the mix of macropore and matrix flow to tile lines. Depending on the storm, median concentrations varied between 0.006-0.025 mg/L for SRP and 0.057-0.176 mg/L for TP. For large storms (>6 cm bulk precipitation), for which macropore flow represented between 43 and 50% of total tile-drain flow, SRP transport to tile drainage systems was primarily regulated by macropore flow. For smaller tile-flow generating events (<3cm bulk precipitation), for which macropore flow was a minor component of tile flow, SRP transport was primarily regulated by matrix flow. Total P transport to tile-drains was primarily regulated by macropore flow regardless of the storm. Variations in P concentrations in tile flow due to variations in precipitation were more important than variations between the tile drain systems. Finally, the authors noted that because precipitation characteristics are strongly positively associated with spring SRP and TP losses, increases in the frequency and intensity of storm events due to climate change will likely lead to significant increases in P losses to tile drains in agro-ecosystems.

4.1.2. Forms of P in Tile Drainage

There are numerous forms of P that can be determined in water. Because there is no universal agreement on which form(s) to measure, research reports vary widely in which forms have been measured. The most common forms reported are total P (TP), dissolved P (DP, DRP, SRP), and particulate P (PP). Numerous studies have been published that document the prevalence of these P forms in tile drainage. The general consensus of the literature is that dissolved P can be an important form of P measured in tile drainage under some circumstances, but that PP sometimes makes up a surprisingly large fraction of TP in drainage water, especially under high-flow conditions.

In Quebec, Beauchemin et al. (2003) reported that DRP and PP were the main forms of P in tile drain outflow. Zhang et al. (2015a) reported that dissolved P was the major fraction of TP in drainage from fertilized cropland in Ontario, accounting for 72% of TP under corn-soybean rotation, but that PP was the major P fraction in drainage from fertilized continuous corn and from non-fertilized cropland, where PP accounted for up to 74% of TP.

Beauchemin et al. (1998) reported variable prevalence of dissolved and particulate P in Quebec tile water. In 1994, more than 50% of TP was in the particulate form, while dissolved P represented less than 30% of the total. In 1995, PP accounted for less than 50% of TP and dissolved P accounted for more than 40% of TP. Also in Quebec, Simard et al. (2000) stated that PP in tile drainage water is important in drainflow generated by storm events after periods of low rainfall. Carefoot and Whalen 2003 reported that PP was the dominant P form collected in subsurface drainage water at a Quebec study site. The forms of P collected in tile drainage were related to antecedent soil moisture and rainfall events, and PP concentrations were typically higher in tile drainage experiencing post-storm flow conditions (heavy rainfall following a dry period) than baseflow conditions. The authors found that PP was between 58 and 89% of the TP in subsurface water samples

collected in a post-storm period and in the spring following snowmelt. Simard (2005) reported that PP was 40-70% of TP in tile drainage from agricultural fields in the Quebec-portion of the Missisquoi Bay watershed.

Soil characteristics appear to be a strong influence on P forms in tile drainage. At Quebec Pike River sites, Eastman et al. (2010) reported that 80% of TP occurred as PP in drainage from clay loam sites, while only 20% occurred as PP at sandy loam sites. In contrast, Delgado et al. (2006) found that dissolved P accounted for about 50% of TP in drainflow from an organic soil amended with manure in Spain.

Poirier et al. (2012) studied bioavailability of P in fine sediments transported from agricultural fields in the Quebec LCB. Particulate P in drainage water varied among fields and temporally, with concentrations as high as 1.35 mg/L in tile drainage. About 30% of this PP was determined to be bioavailable (BAPP). The researchers determined that sediments with particle size <1 μm (e.g., submicron) contained more BAPP and their loss from agricultural fields could contribute to eutrophication downstream. Study results showed that the submicron-fraction was the dominant particle size class in the tile drains regardless of soil texture. At some sampling events, submicron fraction materials were more abundant in tile drainflow than surface runoff, indicating that colloids and clays tended to be transported through soil macropores while larger materials were probably filtered out as the water moved through the soil profile.

Water from the fields with clay soils had 68% PP associated with submicron particles, indicating the dominant contribution of this size fraction to the PP leaving the study fields. In drainage water from fields with sandy soils, the average values were 50% of PP in the submicron fraction particles.

In Ontario, Tan and Zhang (2011) reported that PP was the dominant component of TP in tile drainflow; mean concentrations over five years of monitoring were: TP 0.480 mg/L, PP 0.393 mg/L, and dissolved P 0.087 mg/L.

Vidon and Cuadra (2011) observed that soluble P accounted for a maximum of 22% of the TP flux in tile drainflow at their Indiana study site. In Ohio, Williams et al. (2016) observed that DP was the primary form of P measured in tile drainflow immediately following fertilizer application, but that for storms prior to fertilizer application, PP was the main P form observed. In England, Heathwaite and Dils (2000) reported that in baseflow conditions, dissolved P was the dominant (70%) fraction in tile drainflow but that during stormflow conditions P losses in drainflow were predominantly in the particulate fraction. Over seven years of monitoring three tile drained areas in Ohio, King et al. (2016) reported that DRP was the primary form of P in drainage water, comprising 75% of TP.

In the U.K., Heckrath et al. (1995) reported that dissolved P was the largest fraction in tile drainflow (66-86% of TP); PP accounted for 8-35% of TP.

In Sweden, Grant et al. (1996) reported high PP concentrations in tile drainflow during storm events as a result of particulate matter mobilization and transport from the soil to the drainage system. In Finland, Uusitalo et al. (2001) stated that the dominant P form in drainflow was PP, comprising 92% of TP. However, because ~47% of potentially bioavailable P consisted of desorbable PP, the PP in the drainflow could be an important contributor to potentially algal-available P in drainage.

Finally, in an extensive review of P in drainage water, Christianson et al. (2016) reported that 86% of the TP load could be identified as PP when those two values were reported in a given site-year, whereas 40% of the total load was due to dissolved forms when both dissolved and total P loads were reported. Only two studies reported all three forms (dissolved, particulate, and total), indicating a potential gap in understanding of P forms in drainage water.

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

28

STONE ENVIRONMENTAL

4.2. Phosphorus loads in Tile Drainage

Phosphorus loads exported from tile-drained fields reported in the literature are summarized in Table 4. Only data reporting annual loads, either from full year(s) monitoring or as extrapolated by the author(s), are included. Episodic load data from one or a few monitoring events are not included, although such data are included in the spreadsheet database. As in Table 3, the data in Table 4 are reported with some basic information on location, land use, and soil texture, but are pooled across management, treatments (e.g., manure application, fertilizer rate, and tillage) or drainage design. However, all of the reports in Table 4 are from studies of conventional free subsurface drainage; data from application of drainage water management or controlled drainage are discussed elsewhere in this review. To facilitate comparison, only areal P loads (kg/ha) are reported.

Before discussing reported P loads in tile drainage, it is important to note that there is much uncertainty in reported loads, although that uncertainty is rarely documented. Williams et al. (2015b) quantified uncertainty in annual nutrient load estimates from tile drained fields and small tile drained catchments in Ohio. The authors used Monte Carlo simulations drawn from long-term datasets with very high sampling frequencies. Results showed that uncertainty in annual DRP load estimates was influenced by both the sampling interval and the load estimation algorithm. Uncertainty in annual nutrient load estimates increased with increasing sampling interval for all of the load estimation algorithms tested. Continuous discharge measurements and linear interpolation of nutrient concentrations yielded the least amount of uncertainty, but still tended to underestimate the reference load. Compositing strategies generally improved the precision of load estimates compared to discrete grab samples; however, they often reduced the accuracy. Based on the results of this study, the authors recommended that nutrient concentration be measured every 13–26 h for DRP in tile-drained fields and small tile-drained headwater watersheds to accurately (±10%) estimate annual loads. Such intensive monitoring has rarely been conducted in studies examined in this review. To be fair, reported nutrient and sediment loads in surface runoff are equally subject to such uncertainty.

The consensus of the literature is that significant export of P in dissolved and/or particulate form can occur via subsurface drainage and that export can be of equal or greater importance compared to loads in surface runoff (Blann et al. 2009). However, just as with P concentration, the reported P loads attributed to tile drainflow have been highly variable. In New York (within the LCB), Klaiber (2015) reported TP load of 0.13 kg/ha/yr and SRP of 0.05 kg/ha/yr in tile drainage from grass plots. The author concluded that tile drainage may not have a negative impact on water quality relative to a naturally drained field. Miller (1979) reported TP losses of 0.28 kg/ha/yr and PO_4-P losses of 0.08 kg/ha/yr from Ontario crop fields, which the author characterized as low and not considered to be a threat to water quality. Schwab et al. (1980) measured average TP losses of 0.08 – 1.2 kg/ha/yr and asserted that except for sediment load, "rainwater would … cause about as much pollution as drainage water."

Most published research, however, has reported significant P losses in tile drainflow from agricultural fields (Gentry et al. 2007, Smith et al. 2015). Field research in the Quebec-portion of the LCB has confirmed this. Jamieson et al. (2003) reported an estimated TP load in subsurface drainage from a corn field during snowmelt of 0.1 kg/ha, representing 37% of the total snowmelt P load from the field. Simard (2005) measured mean P loads exported from corn fields in the Missisquoi Bay watershed averaging 0.61 kg/ha/yr (compared to 1.21 kg/ha/yr in surface runoff). Annual TP loads in tile drainage from one field varied from 0.69 to 1.23 kg/ha/yr. In northern Quebec, Goulet et al. (2006) reported average loads from plots of: TP 0.51 kg/ha/yr, TSP 0.08 kg/ha/yr, and PP 0.44 kg/ha/yr; annual TP loads from individual plots >1.0 kg/ha were observed. These TP loads in drainflow represented 95% of all TP export from the plots.

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

29

Table 4. Range of tile drainage annual P loads reported in the literature.

Location	Time Base	Land Use	Soil texture	TP kg/ha/yr	TSP kg/ha/yr	SRP kg/ha/yr	PP kg/ha/yr	Reference
NY	Annual		Muck			0.6-30.7		Duxbury and Peverly 1978
NY	Annual	Corn	Loam, silt loam			0.027-1.062		Hergert et al. 1981
NY	Multi-event	Corn silage	Silty clay	0.13		0.05		Klaiber 2015
Quebec	Annual	Soybeans	Clay loam	2.3				Eastman et al. 2010
Quebec	Annual	Alfalfa	Sandy loam	0.3-0.4				Eastman et al. 2010
Quebec	Annual		Sandy clay loam	0.10-1.23				Enright and Madramootoo 2004
Quebec	Seasonal		Sandy clay loam	0.0098		0.034*		Jamieson et al. 2003
Quebec	Annual	Corn, barley, soybeans	Clay loam	0.69-1.23				Simard 2005
Quebec	Annual	Corn	Sandy loam	0.23-0.27				Simard 2005
Quebec	Annual	Corn, grains, grass	Silty loam	0.36-1.13	0.04-0.10		0.32-1.03	Goulet et al. 2006
Ontario	Annual	Corn				0.005-0.041	0.05-0.13	Ball Coelho et al. 2012
Ontario	Annual	Corn, oats, alfalfa	Clay	0.13-0.24	0.01-0.29			Bolton et al. 1970
Ontario	Annual	Corn	Clay loam	0.39-1.23	0.10-1.02			Culley et al. 1983a
Ontario	Annual	Bluegrass	Clay loam	0.24-3.50	0.15-3.29			Culley et al. 1983a
Ontario	Annual	Oats	Clay loam	0.28-1.40	0.09-1.10			Culley et al. 1983a
Ontario	Annual	Alfalfa	Clay loam	0.28-1.44	0.10-1.08			Culley et al. 1983a
Ontario	Annual	Corn	Clay loam			0.286-1.338		Gaynor and Findlay 1995
Ontario	Annual	Soybeans	Sandy loam	0.09-0.84		0.018-0.19		Lam et al. 2016
Ontario	Annual	Wheat	Sandy loam	0.024-0.072		0.005-0.024		Lam et al. 2016
Ontario	Multi-event	Corn-soybeans	various	0.28		0.08		Miller 1979
Ontario	Annual	Corn-soybeans	Clay	0.21-2.13		0.012-0.12	0.19-1.82	Tan and Zhang 2011
Ontario	Annual	Wheat, corn, soybeans	Silt loam, clay loam	0.17-0.26		0.017-0.023		Van Esbroeck 2015
Ontario	Annual	Various	Clay loam	0.25-1.88		0.02-0.58		Zhang et al. 2015b
MI	Annual	Corn-soybeans	Loam	0.15-0.18	0.04-0.08			Gold and Loudon 1989
WI	Annual	Corn silage	Fine loamy	0.24-1.53		0.16-0.86		Madison et al. 2014
WI	Annual	Corn-soybeans	Fine loamy	0.49-2.73		0.36-2.10		Madison et al. 2014
WI	Annual	Pasture	Fine loamy	0.27-2.63		0.13-2.08		Madison et al. 2014
WI	Annual	Continuous corn		1.01				Ruark et al. 2012
WI	Annual	Corn-soybean		1.46				Ruark et al. 2012
WI	Annual	Pasture		1.57				Ruark et al. 2012

Location	Time Base	Land Use	Soil texture	TP kg/ha/yr	TSP kg/ha/yr	SRP kg/ha/yr	PP kg/ha/yr	Reference
MN	Annual	Corn-soybeans	Clay loam	0.1-0.2		0.04-0.09*		Logan et al. 1980
MN	Seasonal	Various	Various		0.01-0.19	<0.01-0.15		Oquist et al. 2007
IL	Annual	Corn-soybean	Silty clay loam			0.11-0.23		Algoazany et al. 2007
IL	Annual	Row crop	Loess	0.13-1.31		0.05-0.35		Gentry et al. 2007
IL	Annual	Corn-soybean				0.18-0.79		Xue et al. 1998
IN	Annual					0.03		Smith et al. 2015a
IN	Multi-event	Soybeans	Loam, silt loam	0.00-0.086		<0.001-0.018		Vidon and Cuadra 2011
IN	Annual	Corn, soybeans	Silty clay loam			0.02-0.23		Hernandez-Ramirez et al. 2011
IN	Annual	Corn	Silt loam		0.02-0.08			Kladivko et al. 1991
IN/MN	Annual	Corn, wheat, soybeans	Silty clay	0.03-0.43		0.002-0.073	0.02-0.32	Bottcher et al. 1981
OH	Annual	Corn, soybeans	Silt loam, clay loam	0.28-0.92		0.22-0.84		King et al. 2014
OH	Seasonal	Corn, soybeans	Silt loam, clay loam	0.52-1.20		0.26-0.99		King et al. 2016
OH	Multi-event	Corn	Silt loam	0.11-0.34				Logan and Schwab 1976
OH	Annual	Corn-oats	Silty clay	0.74-0.80		0.07-1.37*		Logan et al. 1980
OH	Annual	Soybeans	Clay, loam	0.04-0.82		0.01-0.26*		Logan et al. 1980
OH	Annual	Corn-soybeans-oats	Silty clay	0.30-2.40				Schwab et al. 1980
OH	Annual	Alfalfa-grass	Silty clay	0.80-1.50				Schwab et al. 1980
OH	Multi-event	Corn-wheat	Silt loam	0.001-0.384	0.001-0.210			Williams et al. 2016
Multiple	Annual	Multiple	Multiple	0.36-1.18		0.04-0.12	0.33-0.88	Christianson et al. 2016
IA	Annual	Corn	Silt loam	0-0.04		0-0.009		Baker et al. 1975
IA	Annual	Corn	Loam	0.001-0.14**				Daigh et al. 2015
IA	Annual	Prairie	Loam	0.04-0.07**				Daigh et al. 2015
IA	Annual	Corn, soybeans	Silty clay loam			0.002-0.009		Nayak et al. 2009
LA	Annual	Corn-soybean	Clay loam	0.50				Bengston et al. 1995
TX	Annual	Turf grass	Loamy sand			0.08-0.38		King et al. 2006
Manitoba	Annual	Corn	Sandy loam			0.3-0.6*		Cordeiro et al. 2014

Location	Time Base	Land Use	Soil texture	TP kg/ha/yr	TSP kg/ha/yr	SRP kg/ha/yr	PP kg/ha/yr	Reference
England	Annual	Winter wheat, oats	Clay	0.02-0.59		0.005-0.06		Addiscott et al. 2000
England	Seasonal	Winter cereals	Clay	0.37-0.91		0.05-0.24		Catt et al. 1998
England	Annual	Mixed cropland	Loam				1.57	Chapman et al. 2001
England	Annual	Permanent grassland	Clay loam			0.20		Hawkins and Scholefield 1996
England	Annual	Row crops	Clay	0.08-1.16	0.01-0.48	0.02-0.44		Hodgkinson et al. 2002
Netherlands	Annual	Grass	Sandy	0.31				Rozenmeijer et al. 2010
Netherlands	Annual	Grass	Sandy	0.14-0.15				Rozenmeijer et al. 2016
Spain	Seasonal	Cotton, sugar beets	Clay	0.02-0.28		0.01-0.16		Delgado et al. 2006
Albania	Annual	Corn	Silty clay			0.22-0.36*		Grazhdani et al. 1996
Lithuania	Annual	Small grains, potatoes	Sandy loam	0.055-0.298				Buciene et al. 2007
Denmark	Annual	Wheat	Sandy loam	0.07-0.33	0.03-0.44		0.04-0.18	Grant et al. 199
Denmark	Annual	Various	Various	0.14-1.3				Kronvang et al. 2005
Finland	Seasonal	Plowed fallow	Silty clay	0.14		0.03		Turtola and Paajanen 1995
Sweden	Annual	Small grains, beans		0.56-4.63		0.35-0.76		Stenberg et al. 2012
Sweden	Annual	Small grains	Clay	0.06-1.13		0.11-0.20	0.46-0.94	Svanback et al. 2014
Sweden	Multi-event	Small grains	Clay	0.02-0.09		0.003-0.042		Ullen 1995
Sweden	Multi-event	Fallow	Clay	0.03-0.06		0.02-0.03		Ullen 1995
Sweden	Seasonal	Wheat, barley	Silty clay	0.05-0.46		0.02-0.09		Ulen and Persson 1999
Sweden	Annual	Wheat, oats	Loam			0.04-0.54		Ulen et al. 2014
Sweden	Annual	Small grains, beans	Clay	2.26		0.60		Ulen et al. 2016
Sweden	Annual	Potato	Loamy sand	0.05-0.14				Wesstrom and Messing 2007
Sweden	Annual	Barley	Sandy loam	0.07-0.12		0.02-0.10		Wesstrom et al. 2014
NZ	Seasonal	Pasture	Silt loam	0.01-0.18		0.06-0.07	0.002-0.09	Sharpley and Syers 1979
NZ	Annual	Pasture	Clay loam/silt loam	0.12-1.93				Tanner and Sukias 2011
NZ	Annual	Pasture	Silt loam	0.06-0.59	0.01-0.35	0.002-0.14	0.05-0.24	McDowell et al. 2005
NZ	Seasonal	Pasture	Silt loam	1.92		0.45	0.92	McDowell and Sharpley 2008
NZ	Annual	Pasture	Silt loam	0.152	0.059	0.048		Monaghan et al. 2002

*ortho-P reported

** Total Reactive P reported (undefined)

Elsewhere, Gilliam et al. (1999) cited results from various researchers suggesting that subsurface drainage P export from different watersheds with mineral soils was in the range of 0.2 – 2.4 kg/ha/yr. In an Illinois watershed, Algoazany et al. (2007) reported that subsurface flow had substantially greater average annual soluble P loads than did surface runoff, due to greater flow volume. Soluble P export in tile drainflow averaged 0.11 – 0.23 kg/ha/yr (a maximum of 1 kg/ha/yr), which was 1.1 – 3.5 times loads measured in surface runoff. In England, Catt et al. (1998) reported losses of dissolved and total P in drainflow from field and small catchment sites in crop production of 1 kg/ha/yr for dissolved P and 3 kg/ha/yr for TP. Chapman et al. (2005) cited PP losses of 0.04 – 1.1 kg/ha/yr from English drainage systems.

Christianson and Harmel (2015) reviewed 400 studies and 91 journal articles for the MANAGE Drain Load database and reported ranges of dissolved and total P loads in drainage water from agricultural land, stratified by dry or wet precipitation conditions (Figure 5). Mean dissolved P loads in tile drainage were in the ~0.1-0.9 kg/ha/yr range under dry and wet conditions and mean TP loads were 0.5 – 3.0 kg/ha/yr range during dry and wet years.

Figure 5. Dissolved P load ranges in tile drainage from the MANAGE Drain Load database, shown by wet or dry year. Horizontal dashed lines represent means (Christianson and Harmel 2015).

Despite sizeable P loads observed in tile drainflow, researchers have generally reported that these loads represent a very small fraction of P applied to agricultural land. In Pennsylvania, Gaynor and Findlay (1995) reported that P loads in tile flow represented ~ 3% of applied fertilizer P. In Illinois, Algoazany et al. (2007) showed that soluble P losses represented approximately 0.3% of applied P. In Ontario, Frey et al. (2013) reported that tiles draining barley plots receiving liquid manure application exported 0.7% of the applied TP within 96 hours of manure application.

From the same MANAGE database, Christianson et al. (2016) reported that generally less than 2% of applied P was lost in drainage water flow in a given site-year (Figure 6).

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

33

Figure 6. Percent of P applied in manure/fertilizer lost in drainage from MANAGE Drain Load database (Christianson et al. 2016).

In an exception to this pattern, Culley et al. (1983a) reported that about 1, 3, and 11 % of applied P was leached out in tiles from Ontario plots in continuous corn, corn rotation, and sod covers, respectively.
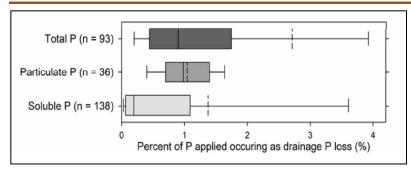
Finally, it is worthwhile to note that Xue et al. (1998) developed a simple one-parameter equation to predict dissolved P export in tile drainage from cropland in Illinois:

DP export = k' x (watershed surface water discharge) x (watershed area).

In this case the value of k' was 3.94×10^{-6} mg P/L/ ha. Of course, this value is highly site specific and cannot be directly applied to other regions.

4.2.1.   Subsurface P loads vs. Surface Runoff P Loads

Tile drainage can be considered as a major pathway for P to exit agricultural fields; those reported loads should be put in context with P loads more commonly measured in surface runoff. In a review that compiled data on annual nutrient loads from agricultural land in surface runoff from 40 publications and more than 1,100 watershed years of data, Harmel et al. (2006) reported median annual P loads from cropland in a variety of crops (Table 5).

Table 5. Median annual P load values in surface runoff from cropland (Harmel et al. 2006).

Land Use	Total P (kg/ha/yr)	Dissolved P (kg/ha/yr)	Particulate P (kg/ha/yr)
Corn	1.29	0.22	0.85
Soybeans	1.18	-	-
Oats/wheat	2.20	0.3	3.45
Fallow cultivated	1.08	0.48	0.45
Pasture/range	0.24	0.15	0.00
Various rotations	0.59	0.80	0.60

Based on the data shown in Table 5, P loads reported in tile drainage are in the same order of magnitude as those reported for surface runoff.

Researchers have reported variable – but generally high – proportions of total field P export delivered in tile drainflow. In the Quebec LCB, five years of monitoring crop fields showed that subsurface drainage accounted for 40% of annual dissolved P loss (Enright and Madramootoo 2004). Eastman et al. (2010) later reported that TP loss from the same fields were 38% of the total 0.8 kg/ha/yr P loss. Also in Quebec, Simard

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

34

(2005) reported that about 50 – 80% of total annual P loads were exported in tile drainflow over two years of field monitoring. In another Quebec study, Van Esbroeck (2015) determined that tile drainage was an equal or dominant contributor to annual TP export from crop fields, whereas overland flow was the dominant transport pathway for dissolved P at most sites.

Other reports of the proportion of total field P export as tile drainage are summarized in Table 6.

Table 6. Selected reports of the fraction of total site P export occurring in tile drainage.

Location	Total P (%)	Dissolved P (%)	Reference
Quebec	95%	91%	Goulet et al. 2006
Ontario	95 – 97%	--	Tan and Zhang 2011
Ontario	24%	31%	Ball Coelho et al. 2012
Ontario	--	55 – 68%	Gaynor and Findlay 1995
Ontario	40 – 77%	19 – 67%	Van Esbroeck et al. 2016
Wisconsin	17 – 53%	--	Ruark et al. 2012
Wisconsin	21 – 52%	21 – 68%	Madison et al. 2014
Indiana	25 – 80%	49%	Smith et al. 2015a
Louisiana	7%	--	Bengston et al. 1995.
England	29 – 41%	--	Bilotta et al. 2008

4.2.2. Seasonality and Flow in P Loads

Phosphorus loads in tile drainflow vary through the year, in response to variations in flow and seasonal influences. Phosphorus loads attributed to tile drainage systems obviously vary with flow, because flow is an element of the calculation of load. King et al. (2016) attributed most seasonal variation in P export to variations in flow.

Grant et al. (1996) reported that losses of PP from Danish catchments (0.04 – 0.18 kg/ha/yr) were episodic, mainly occurring in storm events; TP loss (0.07 – 0.63 kg/ha/yr) varied through the year, with much of the annual loss occurring during high flow storm events; the variation tended to follow variations in annual runoff. Ulen (1995) reported similar findings from Sweden, where 45% of annual TP loss from a field in tile drainflow took place in just two flow events.

Considerably more work has been reported documenting seasonality of P loads from tile drain systems. Reported seasonal distribution of P loads have been somewhat conflicting. Duxbury and Peverly (1978) noted that the greatest nutrient output in tile drainflow from organic soils in New York occurred during the late winter and spring high-flow events. In Quebec, Simard (2005) reported that the largest P loads in tile drainage occurred in spring and fall, the smallest loads in winter and summer. Fall contributed 16 – 24% of annual TP load; spring TP loads made up 63 – 76% of annual TP load in tile drainage. Thus, spring and fall combined to account for 87 – 92% of annual TP export in tile drainflow. Also in Quebec, Goulet et al. (2006) reported that losses of TP in tile drainflow occurred mainly during spring snowmelt and in the fall when rainfall is heavy and the crops harvested.

Van Esbroeck (2015) and Van Esbroeck et al. (2016) reported on seasonal distribution of P loads from tile drained field sites in Ontario. The non-growing season (NGS, October – April) was a critical period for P

export at all sites, with >90% of the annual tile-related TP export (0.27 – 0.42 kg/ha/yr) occurring in the NGS (Van Esbroeck 2015). In subsequent work on the same sites, Van Esbroeck et al. (2016) confirmed that the NGS was a critical period, with 83 to 97% of annual combined [surface+tile] runoff, 84 to 100% of DRP loss, and 67 to 98% of TP loss occurring in this time. The authors noted, however, that surface runoff, which primarily occurred during winter thaws, exported disproportionately more P relative to its contribution to total flow.

In Ontario, Ball Coelho et al. 2012 also reported that loads of P and sediment in both overland runoff and tile drainflows were greater in NGSs than growing seasons (GSs). Dissolve reactive P load averaged 0.02-0.08 kg/ha during the NGSs in tile drainflow and 0.003-0.01 kg/ha in GSs from two study fields. Also in Ontario. Lam et al. (2016) stated that the winter period and the NGS in general are crucial periods for nutrient export in subsurface drainage. Phosphorus losses through drainage tiles were primarily observed between October and May, with most losses occurring in March during snowmelt. The winter and snowmelt period (January through March) accounted for 52–78% of annual losses for DRP and 23–66% of TP losses. The winter and fall (October through December) periods combined accounted for 84–87% of annual runoff, 95–~100% of the annual DRP losses, and 86–99% of annual TP losses. Thus, only a small fraction of the annual P loss occurred throughout the growing season.

In Wisconsin, Ruark et al. (2012) reported the greatest losses through tile drainflow in the period January through June, with the maximum occurring in March. Schwab et al. (1980) reported 50 – 57% of annual P losses in Ohio tile drain systems in the NGS. In contrast, Algoazany et al. (2007) reported from Illinois that most of the annual subsurface flow soluble P losses occurred during the growing months. Negligible amounts of soluble P were lost during the NGS relative to the GS as a result of low flow for all of the sites during the study period.

In Ohio, King et al. (2014 and 2016) also found P loads in tile drainage to be greatest in the NGS.

Tile drainage DRP load was significantly less in the summer (0.03 kg/ha) compared with winter, spring, and fall loads. TP loads were also greater during the NGS compared to loads during the GS; mean weekly TP load in the GS was significantly less (0.008 kg/ha) than TP load in the NGS (0.013 kg/ha). The authors attributed the greater P loads in the NGS to differences in tile drainflow across seasons.

In Denmark, Grant et al. (1996) also reported that 35 – 40% of annual P loss in tile drainage occurred during the NGS, primarily December through March.

4.2.3. Forms of P in Tile Drainflow

Most research on forms of P in tile drainflow has focused on concentrations (see Section 4.1.3). Of course, P forms in loads would be expected to follow the same patterns noted for concentration, although seasonal variations coupled with flow variations might alter the pattern somewhat.

In Ontario, Tan and Zhang (2011) reported that of an annual average TP export from plots of 1.08 kg/ha/yr, 82% (0.89 kg/ha/yr) was PP and 18% was dissolved P.

From Denmark, Grant et al. (1996) reported that the major part of subsurface TP loss from tile-drained catchments was DP in the case of the catchment with the highest loss (71%), but PP at the other three catchments studied (55-71%). Tile drains from New Zealand dairy pasture sites exported 0.12 to 2.90 kg/ha/yr of TP, of which 15 to 93% was DRP (Tanner and Sukias (2011)). Ulen and Persson (1999) found that the majority (63%) of P measured over six years in a Swedish drainage system was in the particulate form.

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

36

Clearly, the distribution of different P forms in P loads from tile drainage is highly variable and likely depends on soil characteristics, management, and weather (see Section 5).

4.3. Contributions of Tile Drainflow to Watershed P Loads

Tile drainflow was shown to be a significant source of water and P at the watershed scale, although good data on contributions of tile drainflow loads to watershed loads are scant.

In a modeling study of the St. Albans Bay watershed in the LCB, Gaddis and Voinov (2010) estimated that 0.77 t/yr or 7.3% of the annual total P load to St. Albans Bay comes from tile drainage, representing 13% of the total agricultural P load. The highest tile drain loads were estimated to come from the clay soils in Stevens Brook and Jewett Brook drainages because of the high P concentration in tile drainflow from clay soils compared to other soil types.

In a 52 km^2 Ontario watershed, Culley et al. (1983b) estimated that at least 25% of the annual TP and 50% of the annual dissolved P loads derived from tile drainflow. Also in Ontario, Macrae et al. (2007) reported that at the basin scale, both dissolved P and TP export from drainage tiles exceeded basin export on most of the 32 discrete sampling dates, suggesting that there was retention of both forms of P in the stream during these periods (tile drainflow SRP export averaged 118% of basin soluble P export, ranging from 4 to 344%; tile drainflow TP export averaged 43% of basin TP export, ranging from 0 to 200%). The authors concluded that drainage tiles are an important source of P in the study basin. In contrast, another Ontario study (Ball Coelho et al. 2010) found that tile drainflows were a less important source of suspended solids than overland flow, and that P loads from tiles were small relative to those from a wastewater treatment plant.

In Illinois, Algoazany et al. (2007) reported that tile drainflow from cropland represented 50 – 78% of total watershed soluble P load. King et al. (2014) collected discharge and P concentration data for eight years from six tile drain outlets and at the outlet of a headwater watershed within the Upper Big Walnut Creek watershed in central Ohio. Results showed that tile drainage accounted for 47% of the discharge, 48% of the dissolved P, and 40% of the TP exported from the watershed. Annual TP loading at the watershed outlet ranged from 0.52 to 1.85 kg/ha (mean, 0.98 kg/ha), whereas annual tile drainage TP loading ranged from 0.28 to 0.77 kg/ha (mean, 0.48 kg/ha). Annual DRP loads at the watershed outlet ranged from 0.33 kg/ha in 2009 to 1.26 kg/ha in 2011 (mean, 0.66 kg/ha). In comparison, annual soluble P loading from tile drainage ranged from 0.22 to 0.69 kg/ha (mean, 0.39 kg/ha). In an English watershed, Chapman et al. (2005) reported that PP loads from monitored tile drains comprised 40% of watershed yield.

The importance of P loading from tile drainflow should not be discounted in watershed management efforts. Lemke et al. (2011) reported from a watershed land treatment program in the Mackinaw River watershed (Illinois) that no significant changes in N, P, sediment, or hydrology were observed over seven years of monitoring after implementation of best management practices (BMPs). The authors stated that their results suggest that BMPs established during this study were not adequate to override nutrient export from subsurface drainage tiles. Conservation planning in tile-drained agricultural watersheds will require a combination of surface-water BMPs and conservation practices that intercept and retain subsurface agricultural runoff.

In a recent review article, Smith et al. (2015b) attributed increased soluble P loads and harmful algae blooms in Lake Erie to the expansion of tile drainage and the proliferation of no-till, with its role in promoting preferential flow through soil macropores.

Kronvang et al. (2005) cited estimates of P contributions via different pathways to agricultural P losses in Denmark. From 1993-2001, tile drainflow was estimated to contribute 84 – 426 Mg P/yr to Danish surface

Stone Environmental

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

37

waters, compared to just 7 – 35 Mg P/yr from soil erosion and surface runoff. However, in a later basin-scale nutrient loading overview of European river basins, Kronvang et al. (2007) estimated that an average of just 3% (0-14%) of TP load was contributed by tile drainflow, compared to 53% from soil erosion and surface runoff.

Stone Environmental

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

38

5. Factors Controlling P Losses in Drainage Water

In an extensive review, King et al. (2015) identified the major factors that influence P transport in tile drain systems:

- **Soil characteristics**
  - Preferential flow: preferential flow paths (cracks/fissures, macropores) provide a direct connection between the soil surface and tile drains.
  - P sorption capacity: research results are mixed, may be less important when macropores are extensive.
  - Redox conditions: reducing conditions under high water tables influences P mobility.
- **Drainage depth and spacing:** the depth and spacing of drain lines influence P concentration, drainage volume, and P mass losses.
- **Surface inlets:** P losses tend to be equivalent to those representative of surface runoff, higher than typical of tile drainage.
- **Management practices**
  - **Tillage:** Subsurface P transport is greater under ridge tillage and no-till compared with conventional tillage due to preferential flow coupled with stratification of P in soils due to greater surface application of fertilizers.
  - **Cropping system:** overall results of research mixed; most consistent influence is the level of P input associated with the cropping system
  - **Soil test P:** elevated levels of soil test P lead to greater concentrations of dissolved P in subsurface drainage.
  - **P source – organic vs. inorganic:** Research suggests that that losses from organic sources are greater than those from inorganic sources.
  - **P placement – broadcast vs. incorporated:** losses tend to be greater with broadcast applications as incorporation promotes soil adsorption; but differences diminish after several rainfall events
  - **P application rate:** potential for P loss increases with an increase in P application rate, especially if rates are greater than the crop removal rate.
  - **P application timing:** when applied relative to planting and how soon after application before a precipitation event are most important.
- **Hydrology and Climate**
  - **Hydrology: baseflow and event flow**: Majority of P loss through tile drainage generally observed during periods of elevated flow. Some studies report positive association between tile flow rate and P concentrations, but others report no relationship.
  - **Season:** non-growing season tends to represent a significant portion of annual discharge and P loss.
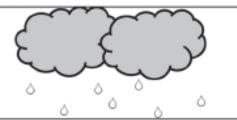
These factors are illustrated in Figure 7.

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

39

Hydrology & climate
Higher P losses in tile drains are typically observed during periods of elevated flow.

Greater P transport is often found during the cooler, wetter months of the non-growing season.

Cropping system
Cropping systems that receive greater P inputs or have minimal soil disturbance (e.g., perennial crops, no-till) pose a greater risk of P loss to tile drains.

Effect of tillage on reducing annual P loss to tile drains is minimal.

P source, rate, placement, & timing
Organic P sources tend to pose a greater risk of leaching to tile drains compared to inorganic P.

The potential for P transport to tile drains significantly increases with an increase in P application rate.

P losses in tile drains are generally greater when P is broadcast on the soil surface compared to P that is incorporated into the soil.

A greater risk of P transport to tile drains is found when P is applied in the fall and winter compared to the spring and summer.

Precipitation soon after P application (regardless of season) also increases the risk of P transport to tile drains.

Soil test P
P transport to tile drains is generally found in soils with greater soil test P concentration. The effect of soil test P however is likely dependent on soil type.

Preferential flow paths & surface inlets
High P concentrations and loads are often found in tile drains where soils are prone to preferential flow and/or in drainage systems with surface inlets.

P sorption capacity & redox conditions
Fine textured soils have a high capacity to sorb P compared to coarse soils, but P loss to tile drains is often greater in fine textured soils due to preferential flow.

P concentrations in drainage water can increase under reduced conditions (e.g., high water table)

Drainage depth & spacing
Deeper tile drains tend to decrease P concentration and increase P load compared to shallow tiles.

Tile spacing has little impact on P transport.

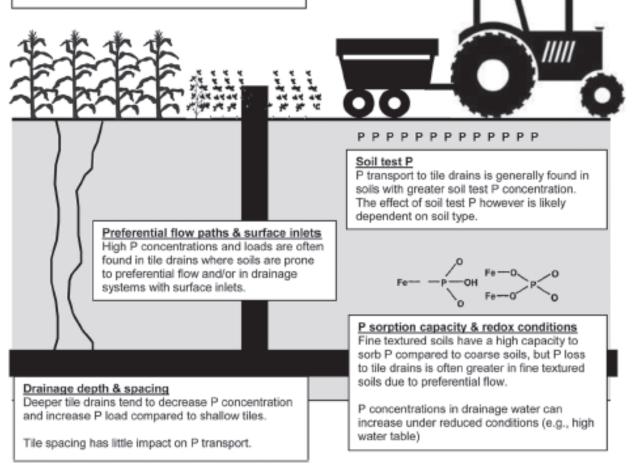*Figure 7. Conceptual diagram of major factors that influence P movement to subsurface tile drainage (King et al. 2015).*

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

40

From their extensive database on nutrient losses in tile drainage, Christianson et al. (2016) concluded that sites prone to preferential flow, sites with high organic matter soils, and sites with historically high P applications and/or soil P concentrations are primary concerns for subsurface P leaching.

The following sections will summarize reported research concerning the most important factors influencing P loss through tile drainflow, on which significant research results have been reported.

5.1. Preferential Flow

Based on extensive research findings, preferential flow connecting the soil surface with subsurface tile drains is probably the most important influence on P loading in tile drainflow. Preferential flow through soil cracks and macropores can lead to rapid transport of surface-applied nutrients to the subsurface drainage system, bypassing the P buffering capacity of the soil matrix (Sims et al. 1998, Heathwaite and Dils 2000, Shipitalo and Gibbs, 2005, Akay and Fox 2007, Blann et al. 2009, Reid et al. 2012, Kleinman et al. 2015a, Smith et al. 2015a, Zhang et al. 2015a, Christianson et al. 2016).

Preferential flow is a term that describes water movement through large (i.e., > 75 μm) cavities that can transmit water, solutes, colloids, and particulates rapidly through the soil. Preferential flow occurs through soil cracks (shrinkage and cracking typical of clay soils under dry conditions) or macropores (sometimes called biopores), voids left by burrowing animals or plant roots. Allaire et al. (2011) noted that preferential flow occurs in the presence of specific features (e.g., high clay content) that tend to favor the development of larger cracks or a higher spatial density of cracks. Certain soil and crop management practices may favor or reduce crack formation. For example, tillage destroys cracks and macropores at the soil surface, while no-till favors their formation by reducing soil disturbance. Corn roots create larger and deeper biopores, while legumes create only fine shallow passages. However, all of these factors favor crack development only if soil desiccation occurs during sufficiently long periods of time, and if runoff occurs once the cracks are formed. King and Fausey (2013) stated that the potential for preferential flow and P loss increases with increasing soil clay content. King et al. (2015) reported that studies have shown that medium and coarse textured soils generally have a lower P loss compared with soils with higher fractions of clay where macropores are common.

Where conditions promote significant preferential flow, mass losses of sediment, PP, and solutes can be comparable to losses in surface runoff (Blann et al. 2009). Many researchers have concluded that the widely-reported presence of high levels of sediment and PP in tile drainflow water indicates the rapid delivery of particulates through preferential flow channels not filtered through the soil matrix (Grant et al. 1996, Addiscott et al. 2000, Monaghan et al. 2002, Chapman et al. 2005, Schelde et al. 2006, Gentry et al. 2007, Eastman et al. 2010, Vidon and Cuadra 2011, King et al. 2015). Flow through cracks and macropores is most significant during storms or other high flow periods, particularly those that occur after extended periods of dryness (Heppell et al., 2002, Heathwaite and Dills 2000, Simard et al. 2000, Shipitalo and Gibbs 2005, Macrae et al. 2007, Hirt et al. 2011).

In Norway, Oygarden et al. (1997) examined agricultural clay soil structures with macropores and cracks to evaluate water and particle transport via preferential flow pathways. The soil down to 50 cm was cracked both vertically and horizontally and some cracks were leading into the tile path. Cracks of up to 10 mm width were found, indicating that transport of particles through them was possible. The measured field hydraulic conductivities varied over three orders of magnitude, indicative of a preferential flow network. Infiltration with dye tracer visually demonstrated rapid flow of water through cracks leading directly to the drainage system; with a hydraulic conductivity of 9.9×10^{-4} m/s in the soil. These results indicate that particles can be eroded from the plow layer and transported both laterally and vertically, through macropores and cracks into the backfill, and then directly to drain pipes.

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

41

Sediment delivered to tile drains via macropores was a significant component of watershed sediment load in an English watershed (Chapman et al. 2005). In one catchment, tile drains contributed over 50% of the annual watershed sediment budget. More than 70% of sediment exported in the tile drainflow was derived from topsoil, confirming the importance of macropore flow. The authors concluded that the majority of sediment and PP removed from topsoil through vertical translocation to field drains will contribute directly to excess nutrient loads in downstream watercourses.

In New York field studies, Scott et al. (1998) reported that P concentration peaks in tile drainflow occurred before the tile outflow peaks, indicating that nutrients were delivered to the tile drains on the order of 60 min after application/irrigation. This rate of nutrient delivery could not be explained assuming uniform matrix flow, indicating that preferential flow to the tile lines delivered the nutrients much more rapidly.

In Denmark, Villholth et al. (1998) used tracers to document macropore flow through the soil profile under an agricultural field. Rapid breakthrough of chloride and dye tracers confirmed the dominant contribution of macropores to infiltration and transport processes. Initial transport through macropores delivered a small immediate load to the drainage system (~1% of the applied tracer), followed by a steady leaching over a longer time period, governed by subsequent release of solute retained in the soil matrix. The significance of macropore flow in the investigated soil was found to extend to relatively low and commonly occurring rainfall rates. Also in Denmark, Laubel et al. (1999) conducted rainfall simulations on plots with loam soils. Chloride tracer concentration in drainage water peaked within 1 hr of the onset of irrigation, indicating rapid macropore flow to the drains. Particulate matter, PP, and dissolved P were highest in initial drainage flow (0.177 – 0.876 mg PP/L, 0.042 – 0.103 mg DP/L, and later declined. Isotope analysis revealed that particulates in tile drainflow were derived from the topsoil.

In Ontario, Frey et al. (2013) reported that Rhodamine WT dye applied to a crop field with liquid manure appeared in tile drain effluent within 5 minutes to 3 hours of the manure application.

In laboratory studies, Akay and Fox (2007) demonstrated direct connectivity between surface-applied contaminants and tile drains via macropores. Transmission of water downward was rapid with macropores that opened to the soil surface; flow response time decreased and the percentage of total drain flow from macropores increased (35-40%) when even closed (buried) macropores were closer to the soil surface. The authors' data supported a "contributing area" concept, indicating that macropores located within 20 to 25 cm of the drain act as though directly connected. For preferential flow paths not directly connected to tile drains, Allen et al. (2012) reported that the subsoil can serve as a filtering mechanism to reduce P transport to tile drains in lateral flow.

Field studies of earthworm burrows in Ohio (Shipitalo and Gibbs 2000, and 2005) documented similar behavior. Average infiltration rate of burrows connected to tile drains was 138 ml/min, twice that of burrows not connected to tile lines; dye added to connected burrows rapidly appeared in tiles (Shipitalo and Gibbs 2000). The rate at which water entered the burrows declined with the log of their distance from the tile line. Beyond ~0.5 m, the tile had no apparent effect on the infiltration rate in the burrows and water added to these burrows did not enter the drain. In later studies, Shipitalo and Gibbs (2005) reported that the amount of rainfall transmitted by earthworm burrows increased with storm intensity and could amount to as much as 10% of total rainfall. Laboratory studies indicated that if a heavy, intense storm occurs shortly after surface application of agrochemicals, the water transmitted to the subsoil by earthworm burrows may contain significant amounts of applied chemical, up to a few percent, regardless of the affinity of the chemical for the soil.

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

42

In England, Heppell et al. (2002) identified two types of macropore flow: intensity-driven and duration-driven. Intensity-driven events are characterized by rainfall of high intensity and short duration. During such events the amount of macropore flow is proportional to the rainfall intensity and the interaction between macropore and matrix flow is kinetically limited. The second style of macropore flow is characterized by long-duration events. For these events the amount of macropore flow approaches a maximum value whatever the rainfall duration. This suggests that these events are characterized by an equilibrium interaction between macropores and matrix flow. In Ontario, Macrae et al. (2007) observed that P export in tile drainflow during storms and snowmelt was characterized by a pulse of P early in the storm, likely due to preferential transport of surface water through macropores to tiles. The authors attributed increased tile P export during storm periods to increased hydraulic connectivity between P-rich surface soil horizons and drainage tiles provided by macropores.

Numerous researchers have reported that preferential flow was a significant influence on the P concentrations and loads they observed in tile drainflow. Beauchemin et al. (1998) noted that P loss in the particulate form from flat, clay soils in Quebec may be high when weather conditions favor rapid flow through cracks or macropores. Simard et al. (2000) observed that particulate P in tile drainage water is important in drain flow generated by storm events after periods of low rainfall in Quebec.

Because of the absence of tillage, permanent grasslands with preferential flow pathways will be vulnerable to transfer large amounts of P through subsurface pathways. P transfer through preferential flow pathways may be particularly important after storm events that follow periods of drought and/or surface P inputs as inorganic fertilizer or manure. Fortin et al. (2002) compared leaching behavior of bromide and pesticides to tile drains under different tillage practices in corn plots in Quebec; rapid chemical movement to tile drains suggested that preferential flow was important in both conventional and reduced tillage and that tillage practices had little influence on this phenomenon. In the Quebec LCB, Enright and Madramootoo (2004) reported that high P losses from their clay soil site resulted from preferential flow through soil cracks. Also in Quebec, Eastman et al. (2010) reported that preferential flow in clay loam soils facilitated higher P transport than in sandy loam soils; the high percentage of PP that the authors observed was attributed to preferential flow conditions that facilitated the migration of particulate material through porous soil media.

From lab and field studies in the New York LCB, Goehring et al. (2001) reported that high P concentrations observed in the tile drain effluent soon after manure application could be attributed to macropore transport processes. Even small continuous macropores were potential pathways. Column studies utilizing packed soil and artificial macropores showed that in the absence of macropores, no measurable P was transported through the soil columns.

In Ontario field studies, Ball Coelho et al. (2007) reported that liquid swine manure application rate was a critical driver of preferential flow to tile as detected by turbidity, concentrations of NH_4–N, soluble P, and the presence of *E coli* bacteria.

Data from Vidon and Cuadra (2011) suggest that in tile–drained watersheds, large quantities of PP can be exported to streams via preferential transfer of surface water to tile drains through soil macropores Overall, data indicate that TP transport to tile drains is primarily regulated by macropore flow, whereas a combination of matrix flow and macropore flow regulates SRP losses to tile drains The dominant role of macropore flow in SRP transport to tile drains occurs in large storms (>6cm bulk precipitation) but not for smaller tile drainflow generating events (<3cm bulk precipitation).

In England, Heathwaite and Dils (2000) reported that preferential flow pathways, particularly soil macropores, are important contributors to the overall P load; most P is transported in the particulate fraction

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

43

STONE ENVIRONMENTAL

and associated with organic or colloidal P forms. High P concentrations (mean TP: 1.2 mg/L) were recorded in macropore flow in the upper 0-15 cm of a grassland soil, and generally declined with increasing soil depth. On average, P concentrations in drainflow were over six times greater in stormflow compared to baseflow. Stormflow P losses in drainflow were predominantly in the particulate fraction; significant correlation was recorded with suspended sediment concentrations in drainflow. P concentrations in macropore flow averaged 0.58 – 1.18 mg/L TP, 0.45 – 0.79 mg/L PP, and 0.13 – 0.39 mg/L dissolved P. Preferential flow was an important pathway of PP transport. About 68% of TP transported in macropore flow was in particulate fraction (which was dominated by organic/colloidal form, 77%). The authors summarized that under baseflow conditions, tile drains were largely fed by water percolating through the soil matrix and consequently TP concentrations were low and largely in the soluble phase. Under stormflow conditions, large quantities of P (including particulate matter) were rapidly transported in preferential flow pathways to the drain system.

The overall significance of P transport to tile drains by preferential flow has been illustrated by several researchers. In an analysis of incidents where agricultural wastes in drainage waters had contaminated streams in Ohio, Hoorman and Shipitalo (2006) reported that such incidents occurred most frequently with land application of liquid manure. Regardless of whether mismanagement occurred, preferential flow of the liquid wastes to subsurface drains via soil macropores was a major contributing factor to offsite movement of nutrients associated with liquid waste application. The reports indicated that soil cracks and earthworm burrows were cited as contributing factors in 21 percent of the incidents.

In Switzerland, Gachter et al. (1998) concluded that P loads delivered through vertical macropores in combination with fast lateral water movement (mainly along drainage systems) contribute significantly to lake eutrophication. In Sweden, Svanback et al. (2014) documented large P contributions to the Baltic Sea from tile drainage with macropore flow and concluded that mitigation efforts should focus on dealing with soil cracking and soil structure rather than on promotion of no-till and P fertilizer management.

In a contrary result from Iowa soils enriched by long-term poultry litter applications, Hruby (2015) reported that even though no-till plots had significantly greater macropore densities above tile lines than did chisel plowed plots, peak P concentrations in tile flow associated with macropore transport were short-lived and did not contribute significantly to overall P loading. In her study, elevated P concentrations in tile drainage resulted primarily from delivery of water to tile lines via matrix flow through soils with decreased P sorption capacity due to reduced tillage and long-term poultry litter application.

5.2. Drainage System

The design of the drainage system itself – primarily depth and spacing of drain lines – influences water and nutrient losses from agricultural land (Strock et al. 2010). In Ohio field studies, Hoover and Schwab (1969) reported that narrow (10m) drain spacing resulted in higher tile drainflow than wider (20 m) spacing. Although the average drainflow from tile at 1m depth was slightly more than that from tile at 0.6 m, the depth of tile did not significantly affect drainflow. The 0.6m depth/10m spacing tile system yielded significantly higher flow than all other drainage treatments, nearly double that from a 0.6m depth/20m spacing system. Fausey et al. (1995) reported evidence that the intensity of drainage influences subsurface drainage water quality. With less intense drainage (i.e., wider spacing and shallower depth), tile drainflow is of better quality.

King and Fausey (2013) reported that at the same spacing, shallower drains will yield greater P concentrations. In general, the closer the drains, the greater the P loss. King et al. (2015) stated that shallow drains are reported to respond more rapidly to precipitation than deep drains, but drainage volume is significantly less in shallow drains. At the same depth, drainage volume from narrow drain spacing (e.g., 9m) significantly greater than from wider spaced drains (e.g., 18m). Several studies have found that P

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

44

concentrations are higher from shallow drains compared to deeper drains. General consensus of the literature is that drains placed shallower will result in greater P concentrations, whereas deeper drains will have greater mass losses. Culley et al. (1983a), for example, reported data from plot studies in Ontario showing that in all cases, P concentration in tile drainage decreased when the depth of the tile increased.

In tile-drained crop fields in the Quebec portion of the LCB, Morrison et al. (2013) used field data and the DRAINMOD model to evaluate the effect of tile drain spacing on surface runoff, subsurface drainage flows, and field P loss. The results from this study clearly demonstrate that drain spacing has a significant effect on P losses through tile drainage and surface runoff.

Simulation results indicated that when lateral tile drain spacing is increased, the volume of subsurface drain flow decreases, and the volume of surface runoff increases, at sites with sandy and clay loam soils. For every 5m increase in drain spacing, TP loads in subsurface drainage decreased by 6% at a site with sandy loam soil, and decreased by 20% at a site with clay loam soil. TP loads in surface runoff increased as a result of increased drain spacing.

In Indiana, Kladivko et al. (1991) tested nutrient losses from tile drains at three different spacings. Total mass of pesticides, nutrients, sediment, and water removed by tile drainflow on a per-acre basis was greatest for the 5m spacing and least for the 20m spacing.

In contrast to other reported work, Addiscott et al. (2000) observed that increasing the spacing between mole drain channels in England from 2 m to 4 m increased losses of particulate P (but not dissolved P), probably because water moved farther horizontally to reach the 4 m drains and picked up more particulate P.

5.3. Manure and Fertilizers

According to King et al. (2015), research suggests that P losses in drainage water from applications of organic sources (e.g., manure, biosolids) tend to be greater than similar applications from inorganic sources (e.g., commercial fertilizer), possibly because organic P is less strongly adsorbed in soils than inorganic P and therefore more prone to leaching. The potential for P loss generally increases with increasing P application rates; when P source and application method are similar, increasing the P application rate is likely to increase the amount of P transported in subsurface pathways. P application rates greater than crop removal rate also increase subsurface P losses. Phosphorus losses tend to be greater with broadcast applications than with incorporation (soil incorporation increases soil adsorption and may disrupt macropores), but differences diminish after several rainfall events. When manure or fertilizer are applied relative to planting and how soon after application before a precipitation event are important factors. In addition, P losses are greater when P applied outside growing season as compared to at the time of planting. Precipitation soon after P application also significantly increases risks of P movement. King and Fausey (2013) asserted that swine (or any liquid) manure more of a problem than other P sources.

The specific influence of manure or fertilizer application on P losses in tile drainage is complex and research reports have been contradictory. Consideration of this influence must distinguish between the immediate effects of manure/fertilizer application on tile drainage and the influence of long-term manure application. In general, researchers have reported that P losses in tile drainage tend to be higher from land that has received annual or long-term nutrient applications. However, reports of immediate losses have been mixed; some researchers have found no apparent effect on P loads in tile drainage associated with a manure application event, whereas others have reported significant P losses.

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

45

5.3.1. Findings of Little or No Effect

A few studies have reported little or no effect on tile drainage P losses from manure applications. New York field studies conducted by Geohring et al. (2001) showed that dry antecedent soil moisture conditions and long periods between manure application and rain resulted in relatively low P loading in tile drainflow. Incorporating the manure into the soil also greatly reduced the TP concentration, especially if conventional moldboard plowing was used. Also in New York, Hergert et al. (1981) evaluated dissolved P concentrations and losses in tile drainflow before and after dairy manure application at two rates for three years. Although dissolved P concentrations were higher from plots receiving 200 t/ha of manure than from plots receiving 35 t/ha, 53% of the tile drainage samples contained <0.03 mg/L dissolved P. At the lower manure rate, 92% of samples were <0.03 mg/L. The authors concluded that manure applications to meet crop needs should not produce excessive P concentrations in tile drainflow.

In Wisconsin, Ruark et al. (2012) reported that manure applications were not found to consistently affect P loss via tile drainflow. In a two-year study of tile drainage from crop fields in Ontario, Ball Coelho et al. (2012) reported that liquid swine manure moved by preferential flow to tile drains only with manure injection and only on one of two fields. Along with being infrequent, the "incidental" dissolved P load through tile drains comprised only 2% of the annual P load from the catchment. It is worth noting that the tile lines in this study were new and it is possible that macropores had not yet developed to contribute to preferential flow. In Ohio, Haack and Duris (2008) reported that nutrient concentrations in tile drainage did not indicate any effect from liquid dairy manure applied at either 4,000 or 8,000 gal/ac rates under a variety of tillage treatments. These conclusions are difficult to confirm, however, as the study did not include any replication or statistical analysis of differences among treatments.

5.3.2. Findings of Immediate Effect

In contrast, many researchers have observed rapid and significant effects on P loss in tile drainflow following manure applications. In the New York LCB, Scott et al. (1998) reported that soluble P concentrations peaked at 1.17 mg/L following manure application and as much as 37% of the field soluble P loss was exported from the field site via subsurface drains. Phosphorus concentration peaks occurred before the tile outflow peaks, indicating that phosphorus was delivered to the tile drains on the order of 60 min after application/irrigation.

Dean and Foran (1992) reported that liquid manure application can rapidly penetrate the soil and be observed in tile drainflow. Eight of twelve manure spreading events at Ontario field sites resulted in water quality degradation within 20 minutes to 6 hours of manure application. Hoorman and Shipitalo (2006) related that reported incidents of agricultural waste contamination of Ohio surface waters were most frequently associated with liquid dairy or swine waste application. Preferential flow of the liquid wastes to subsurface drains via soil macropores was a major contributing factor to offsite movement of nutrients associated with liquid waste application. In Ontario, Frey et al. (2013) reported that tiles draining barley plots receiving liquid manure application exported 0.7% of the applied TP within 96 hours of manure application.

In Iowa, Cook and Baker (2001) conducted a lysimeter study to observe the transport of nutrients and bacteria to subsurface drainage as a function of liquid swine manure application rate. Liquid manure was surface applied to no-till soils at rates of 0 L/ha, 280,000 L/ha (low rate), and 830,000 L/ha (high rate). Although there were no consistent statistically significant differences between the control and the lower–rate treatments nor between individual lower–rate treatments, there were statistically significant differences between the high– and low–rate treatments, which suggest that over–application of liquid swine manure poses a direct threat to water quality. The authors also found that the time immediately following manure application may pose the greatest threat to subsurface drainage quality, particularly when application rates are higher than recommended.

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

46

In Ontario, Ball Coelho et al. (2007) evaluated the quality of tile drainflow from corn fields fertilized with liquid swine manure, either top-dressed or injected annually. For all years, application induced flow of liquid swine manure was observable as a change in tile water turbidity that occurred immediately following injection of the higher rates (74.8 or 93.5 m³/ha), while flow was clear from all other tiles. Generally concentrations of dissolved P in tile drainflow were low to undetectable before application, increased with increasing manure application rates, and returned to pre-application values within one week. Application method had only a minor impact on the movement of P to tiles. Concentrations of dissolved P increased immediately following injection, whereas increases were usually not observed until several days after topdressing, and were related to rain events. The rate of application had a consistently significant impact on liquid manure movement to tile each year. With high (74.8 or 93.5 m³/ha) sidedress rates, dissolved P concentrations increased, particularly in the 24 hours immediately following application. At lower application rates, which encompassed volumes sufficient to supply crop nutrient requirements, concentrations were dramatically reduced.

Also in Ontario, Zhang et al. (2015b) determined P loss in tile drainage was affected by composted swine manure application to a corn-soybean rotation. Swine manure compost applied at 75 Mg/ha dry matter resulted in high concentrations and losses of dissolved, particulate, and total P. The authors concluded that application of composted swine manure is not recommended from a water quality perspective, despite the soil quality benefits of compost.

In Indiana, Hernandez-Ramirez et al. (2011) reported that fall manuring increased nutrient losses from cropland with subsurface drainage. Compared with all other treatments tested, the continuous corn/fall manure treatment increased soluble P loads in tile drainage water from 0.02 to 0.44 kg P/ha/yr.

In England, Hodgkinson et al. (2002) studied the effects of annual application of different manures on P concentrations and losses in tile drainflow over four winter drainage seasons (tile drains apparently do not flow in summer in England). Application of swine slurry in November (before the onset of winter drainage) resulted in concentrations of dissolved P up to 10 mg/L and TP up to 75 mg/L in drain flow. Total P losses in the first drainage season after application were 1.16 kg/ha, four times the load from the control field that received no P. The majority of the increased loss occurred in the first drainage event due to rapid transport of the slurry through macropores. Of all treatments (broiler litter, cattle manure, biosolids), only swine slurry significantly increased P losses compared with untreated control. Although also in liquid form, biosolids did not increase P losses because of much lower solubility of P in biosolids compared to swine waste.

Schelde et al. (2006) reported rapid changes in tile drainflow following manure application in Denmark, with high turbidity peaking before the flow peak, indicating macropore flow. Before slurry application, PP dominated in the effluent. Just after slurry application, dissolved P fractions were high, ranging from 55-78% of TP. On the other hand, when slurry had not been applied recently, PP gradually increased relative to dissolved P in the effluent. The maximum was reached at the two final experiments when more than 80% of leached P was particle-bound.

In New Zealand, Sharpley and Syers (1979) reported that cattle grazing resulted in a dramatic increase in P, yielding 15- and 40-fold increases in soluble and particulate P, respectively, in tile drainflow. A greater increase in the loss of PP (46.9 g/ha/4 weeks), compared to that of soluble P (23.1 g/ha/4 weeks), was attributed to a 50% increase in the amount of sediment carried in tile water. Despite a reduction in the volume of tile drainflow due to reduced infiltration from livestock trampling of the pasture soil, a 50 and 100% increase in the amounts of soluble and particulate P, respectively, transported in tile drainage was measured in the four weeks after grazing.

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

47

Also in New Zealand, McDowell et al. (2005) compared P losses in tile drainflow from a plot receiving liquid dairy manure to losses from a plot that received the same P rate in inorganic fertilizer. Data collected over three years indicated that much more P was lost from the manured plot (mean TP load: 0.41 kg/ha/yr) compared to the plot receiving inorganic fertilizer (mean TP load: 0.20 kg/ha/yr), especially via incidental transfers (events coinciding with manure application or within a week of cattle grazing). Losses of dissolved organic P were, on average, 3.7 times greater from the manured compared to the fertilized plot; the authors noted that dissolved organic P is poorly sorbed by soils compared to dissolved orthophosphate. Preferential flow of P during incidental losses accounted for much of the larger losses from the manured plot.

In Spain, Delgado et al. (2006) found that manure application influenced P loading from tile-drained soils due to increased water flow under sprinkler irrigation and to increased loss of dissolved P in the first event after manure application. The authors noted, however, that the differences in P loss in tile drainflow due to different cropping systems and irrigation practices were much greater than those attributed to manure application.

5.3.3. Effects of Long-term Manure Applications

A number of researchers have reported on tile drain losses of P from cropland receiving manure over the long-term, not just following a single application. In Wisconsin, Madison et al. (2014) reported that individual manure applications to sites under a range of crop management practices did not consistently increase P concentrations in tile drainflow, but annual P concentrations were greater in years with manure application compared to years without manure application.

Macrae et al. (2007) reported high concentrations of soluble and total P in tile drainflow from fields receiving manure compared to fields receiving inorganic fertilizers. Fields in Ontario showed significantly higher contributions of both dissolved and total P from two tiles in a basin where cattle manure was applied exclusively, in contrast to lower tile TP concentrations measured in fields that received either inorganic fertilizers only or a mixture of manure and inorganic fertilizers Tiles draining fields with manure application exhibited the strongest temporal variability, having dissolved and total P concentrations ranging from very low (<10 mg/L) to very high (2,726 and 8,275 mg/L, respectively). The authors concluded that the importance of tiles draining fields where manure is applied to basin-scale P export cannot be overstated. These tiles exported large quantities of P long after the manure had been applied. The large P concentrations in tile drainflow from fields where manure had been applied were observed during winter thaws and the snowmelt period, long after manure had been applied to these fields. Thus, large melt or storm events occurring long after manure application are still generate substantial quantities of P in tile drainflow. And although P export in tile drainage was usually greatest immediately following manure application, tiles draining manure-treated fields are the largest contributors of P to the basin during large events long after the manure has been applied.

In Nova Scotia, Kinley et al. (2007) reported that fields with poultry and swine manure histories produced constantly high TP concentrations in tile drainage that were rarely lower than suggested environmental guidelines. Manure application history appeared to have a greater influence on P losses than soil texture.

Hoover et al. (2015) reported the highest concentrations of soluble P in tile drain water in Iowa associated with an exceptionally high rate of poultry litter application and a high manure P content, and high rainfall. This combination of increased PO_4-P applications from poultry manure, increased rainfall amounts, and stage of crop growth likely had a strong impact on PO_4-P transport in tile drainflow. The authors concluded that long-term impacts of poultry manure application on P concentrations in the tile drainflow were visible, but the average P concentrations remained well below the EPA-recommended criteria of 0.076 mg/L concentration for streams in Iowa.

Also in Iowa, Hruby (2015) evaluated ortho-P losses in tile drainflow from different levels of poultry litter application and different tillage practices on cornland. Median and mean PO_4-P concentrations were ≤ 0.04 mg/L in drainage water from all treatments that received no poultry litter and poultry litter at the recommended N rate for corn. Median and mean PO_4-P values for drainage from no-till plots receiving twice the recommended rate of poultry litter (0.122 and 0.163 mg/L PO_4-P, respectively) were above the US EPA's suggested criterion for total P of 0.118 mg/L P for rivers and streams in the Western Corn Belt States ecoregion 47. Median and mean values for all other combinations of tillage and treatment were at or below 0.04 mg/L PO_4-P. The mean concentration of PO_4-P in tile drainflow from these plots during this study period was higher than concentrations of PO_4-P in nearby surface waters that drain predominantly agricultural areas. Orthophosphate losses to tiles from no-till, high poultry litter plots were estimated at 0.26 kg/ha PO_4-P the growing season in a wet year.

Ulen et al. (2014) reported that in two years with application rates of broiler manure corresponding to 99 and 79 kg P/ ha/year to a tile-drained field in Sweden, mean dissolved P concentrations were significantly higher in peak tile drainflows than in 19 previous years without manure application of any kind. The authors noted that N leaching losses during peak and base flow conditions can persist for longer than a 5-year crop rotation and were shown to recede at a slower rate than P.

5.3.4. Effects of Fertilizer

In Ontario, Bolton et al. (1970) reported that P, N, and K losses in tile drainflow from corn and bluegrass plots were increased by fertilizer application, with P showing a small but consistent increase. Unfortunately, the authors did not report the magnitude of that increase. At the same sites, Bryant et al. (1987) reported that fertilized crops (corn, oats, alfalfa, and bluegrass) contributed a greater volume of drainflow than did unfertilized crops. Fertilizer appears to promote root proliferation and therefore more continuous biopores and cracking through the surface profile which results in a more direct channel to tile drains, thus increasing the volume of water discharged

Zhang et al. (2015a) reported that dissolved P was the major fraction of TP in drainage from fertilized cropland in Ontario, accounting for 72% of TP under corn-soybean rotation, but that PP was the major P fraction in drainage from fertilized continuous corn and from non-fertilized cropland, where PP accounted for up to 74% of TP. In Ohio, Williams et al. (2016) observed that soluble P was the primary form of P measured in tile drainflow immediately following fertilizer application, but that for storms prior to fertilizer application, PP was the main P form observed

In Pennsylvania, Gaynor and Findlay (1995) reported that P loads in tile flow represented ∼ 3% of applied fertilizer P. In Illinois, Algoazany et al. (2007) showed that soluble P losses represented approximately 0.3% of applied P.

In Illinois, Algoazany et al. (2007) reported that rate, timing, and method of P fertilizer application seemed to affect soluble P transport in subsurface flow. Greater application rates coupled with application timing (pre-plant fall application) tended to increase soluble P concentrations in subsurface flow. One site where P fertilizer was applied after soybeans were harvested and which had the second highest average application rate relative to the other sites, had the greatest average annual flow-weighted soluble P concentration and mass load in tile drainflow among all study sites. The authors noted that although P concentrations did not respond consistently to P applications (higher soluble P concentrations were sometimes observed in years with no P fertilizer application), P concentrations nevertheless tended to increase with high precipitation coupled with high application rates.

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

49

In England, Addiscott et al. (2000) reported that P losses from tile drains under cultivated land did not vary significantly by fertilizer rate during hydrologically normal years. However, losses were much greater in one year when P fertilizer was applied to wet soil after plowing, up to 1.71 kg/ha/yr vs. 0.41 kg/ha/yr in a normal year. Reducing P fertilizer application rates reduced loss of TP, but not soluble P. The authors attributed the lack of effect of reducing P fertilizer rate to the overwhelming influence of soil test P.

In contrast, Carefoot and Whalen (2003) observed no difference in the nutrient concentration of tile drainflow from corn-soybean rotations in Quebec that could be attributed to the types of fertilizer applied. Svanback et al. (2014) reported from Sweden that various P fertilization strategies and application methods had no clear effect on P leaching to tile drains over a 6-year study. Broadcasting or placement of fertilizer P had no clear effect on P leaching and a P fertilization at a level close to P removed by harvested crop did not result in higher P losses than when P fertilization was completely omitted.

5.3.5. Comparisons of Manure vs. Fertilizer

A few publications have examined differences in the influence of manure vs. fertilizer applications on P in tile drainflow. In Minnesota, Randall et al. (2000) reported that soluble P and TP concentrations in tile drainage did not differ between dairy manure and urea fertilizer applied to corn plots at equivalent N rates. In contrast, Nayak et al. (2009) compared P losses to tile drainflow from applications of swine manure vs. inorganic fertilizer (UAN) applied at the same N rate to corn-soybean plots in Iowa. The swine manure application significantly increased soluble P concentration in tile drainflow in comparison to UAN application.

Note that these comparisons are not entirely appropriate because the inorganic fertilizer did not add any P to the soils, while the manure did.

From their extensive database, Christianson et al. (2016) concluded that across P application site-years, organic versus inorganic applications did not result in significantly different dissolved or total P losses in tile drainflow.

5.4.   Cropping Systems

The specific influence of crop and cropping system on losses of P in tile drainflow is difficult to assess because of inherent differences in tillage, nutrient applications, and other factors among cropping systems. King and Fausey (2013) stated, in very general terms, that greater crop cover leads to lower P losses; for example, losses from corn tend to exceed losses from soybeans or small grains. King et al. (2015) concluded from their extensive review of the literature that the overall results of research on cropping systems and tile drainage P loss is mixed; the most consistent influence is the level of P input associated with the cropping system. From their analysis of the MANAGE drainage load database, Christianson and Harmel (2015) reported that no significant difference was observed in tile drainflow or N loads between continuous corn and corn-soybean cropping systems, although corn in rotation showed significantly greater yields.

Benoit (1973) conducted a plot study in Vermont (within the LCB) on a Cabot silt loam to evaluate N and P losses from three cropping systems: hay-pasture, alfalfa hay, and corn silage. Results indicated that more P was lost from fertilized corn plots than from alfalfa or hay-pasture areas.

In Ontario, Bolton et al. (1970) evaluated nutrient losses in tile drainflow from three cropping systems over a seven year period: continuous corn, corn in rotation, and bluegrass sod. The highest P losses occurred with corn and the lowest with grass sod. The largest and most consistent P losses were from continuous corn, although corn in rotation also produced high losses. For all cropping systems, P losses increased with fertilizer application. The authors concluded that cropping systems had less effect on P concentration than did fertilizer application.

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

50

Also in Ontario, Culley et al. (1983a) reported on P contents of tile drainflow from continuous corn, rotational corn, bluegrass sod, oats, and alfalfa, combined with two fertilizer rates. Subsurface sediment associated P loads were highest from continuous corn; TP loads in tile drainage averaged 0.88 kg/ha/yr. More than 50% of the TP loads from plots were lost via tile drainflow. Overall 34% of the TP load in tile drainflow was sediment-associated. Crop cover, P fertilizer rate, and tile depth significantly affected dissolved P export. Dissolved P concentrations in tile drainflow from bluegrass sod exceeded those from continuous corn and rotational plots. Sediment associated P concentrations increased with P fertilization rate at one of the experimental locations.

Zhang et al. (2015a) evaluated the effects of long term (>40 years) cropping systems in Ontario: continuous corn, corn-oats-alfalfa rotation, and continuous grass, along with fertilization vs. no fertilization on P loss in tile drainflow. Compared with no fertilizer, long-term fertilization increased concentrations and losses of dissolved P and TP in tile drainflow, with the increments following the order: continuous grass > corn rotation > continuous corn. The long-term fertilized continuous grass treatment had TP concentrations up to 1.65 mg/L and TP loads of 1.51 kg/ha/yr in tile drainflow. Dissolved P was the dominant P form in tile drainflow, accounting for 72% of TP loss under fertilized grass, whereas particulate P was the major form of TP loss under fertilized continuous corn (72%), fertilized corn rotation (62%), and non-fertilized treatments (66 – 74%). Stepwise regression analysis showed that the concentration of P in tile drainflow, rather than event flow volume, was the most important factor contributing to P loss in tile drainflow, although event flow volume was more important in PP loss than in dissolved P loss. Continuous grass significantly increased P loss by increasing P concentration and flow volume of tile drainage water, especially under the fertilization treatment. The improved soil structure, reduced bulk density, and increased wet aggregate stability under long-term continuous grass might have enhanced the hydraulic conductivity and promoted water infiltration. The authors concluded that long-term grasslands, receiving frequent P additions without removal, may become a significant P source in tile-drained systems.

Findings reported from England by Bilotta et al. (2008) are consistent with the reported high P losses from continuous grassland. Results of grassland lysimeter studies showed that 1 ha grassland fields can yield up to 50 g of P in response to individual rainfall events; concentrations of TP in lysimeter drainage reached highs >0.8 mg/L.

In contrast, Logan and Schwab (1976) reported from Ohio that P losses in tile drainflow were 0.34 kg/ha/yr from corn sites and 0.11 kg/ha/yr from a continuous alfalfa site. Ulen (1995) reported from Sweden that a grass cover reduced P losses in tile drainflow compared with row crop or fallow soil. However, a rotational grass cover may perform very differently from a long-term alfalfa or grass stand.

In Iowa, Daigh et al. (2015) reported that mean annual P concentrations and yields from continuous corn with residue removal and with a cover crop and a prairie grassland system were generally low (>0.04 mg/L, <0.14 kg/ha/yr) and were not significantly affected by any cropping system or their rotational phases. In Ohio, King et al. (2016) monitored three end-of-tile locations in corn-soybean rotation. Dissolved and total P concentrations and loads did not differ between corn and soybean years, with loads averaging 0.46 kg/ha/yr and 0.57 kg/ha/yr, respectively. Seasonal differences in P concentrations and loads were more important than crop differences. In the growing season, larger P concentrations in tile drainflow were generally detected following fertilizer application. Significantly greater volumes of drainflow as well as P loads were measured during the NGS compared to the growing season. Greater loads in the NGS season were attributed to differences in the volume of tile drainflow between seasons. The authors suggested that high soil test P concentration may have negated any differences in P concentrations and loads in tile drainflow that would potentially be observed between crop types or rotations.

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

51

In Lithuania, Buciene, et al. (2007) studied two high-input and two low-input crop management systems, one reference treatment with field crop rotation, and one long-term, moderately treated pasture with respect to N and P flow and balance. Phosphorus losses during the first rotation in general were low and decreased in the following order: long term pasture > high-input > low input > control (zero input). Leaching losses of P were very minor component of all P losses; most P was lost in crop uptake. Total P leaching was positively correlated to the available P_2O_5-Al in the topsoil.

Two reports of atypical cropping systems were included in this review. Oquist et al. (2007) examined the effects of conventional (corn-soybean rotation) vs. alternative farming practices (no inorganic fertilizers, improved crop rotations) on tile drainflow losses of P in Minnesota. Alternative farming practices compared with conventional farming practices reduced mean daily losses and annual losses of nitrogen and phosphorus in tile drainflow, especially during years when precipitation was average or above average

King et al. (2006) reported on dissolved P concentrations from two French drains located on a Texas golf course. While this system is obviously quite different from agricultural tile drainage, results from long-term continuous turf receiving high fertilizer inputs may be of interest. Median soluble P concentration was 0.11 mg/L while soluble P loading was 0.46 kg/ha, values not dissimilar to those reported for subsurface drainage from corn. The timing of soluble P transport through the tile drains was highly correlated with P fertilizer applications, which occurred from March – August, with a lag of 6 months, indicating that P movement occurred primarily after the growing season. The magnitude of P concentrations in drainflow was dependent on the frequency and amount of fertility management practices. At the more intensively managed site, consistently higher P concentrations were detected in the drainflow than were measured from the less intensively managed site.

5.5.   Tillage

There is broad consensus in the literature that subsurface P transport is greater under reduced tillage and no-till systems compared with conventional tillage due to greater probability of preferential flow, coupled with stratification of P in soils due to surface application of nutrients (King and Fausey 2013, King et al. 2015). Reduced tillage may also decrease surface runoff through increased soil water infiltration and holding capacity, increasing subsurface flows (Blann et al. 2009). From their extensive tile load database, Christianson et al. (2016) confirmed that no-till systems significantly increased drainage dissolved P loads compared to conventional tillage, with mean P loads of 0.12 kg/ha/yr for no-till, vs. 0.04 kg/ha/yr for conventional tillage.

Patni et al. (1996) reported that the volume of tile drainflow over three years was significantly higher under no-till compared to conventional tillage in Ontario. In Michigan, Gold and Loudon (1989) monitored surface runoff and tile drainflow from fields in conventional and conservation tillage. Both TP and soluble P concentrations and loads were consistently higher in tile flow from the conservation tillage treatment, compared to conventional tillage. For conventional tillage, tile drainflow exported 20% of the TP and 15% of the soluble P load from the field, while for conservation tillage, tile drainflow exported 43% of the TP and 37% of the soluble P loads. In Ontario, Gaynor and Findlay (1995) also reported that ortho-P concentrations were higher in tile drainflow from no-till than from other tillage treatments. In Iowa, Hruby (2015) reported that despite similarity between corn plots soil test P levels, orthophosphate concentrations in tile- drainflow were significantly higher for no-till plots (>0.1 mg/L PO4-P) than chisel plow plots (≤0.04 mg/L PO4-P). However, the authors attributed this difference not principally to preferential flow but to reductions in P-sorption capacity in no-till soils.

In contrast, Lam et al. (2016) questioned whether reduced tillage actually increases P losses in tile drainage when good nutrient management strategies are used and fertilizers are applied by injection. The authors

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

52

suggested that tillage effects may not be exerted year-round, especially during snowmelt when episodic P export in both tile drainflow and surface runoff are high. Their results indicated that neither reduced tillage nor conventional tillage increased P losses in tile drainflow from corn-soybean-wheat rotation.

In Denmark, Schelde et al. (2006) cautioned that conventional tillage promotes soil particle mobilization and exposes new soil aggregates to the soil solution, increasing the risk of particulate and soluble P leaching in storms occurring shortly after tillage. The authors observed a nearly four-fold increase in TP leaching per volume of leachate when comparing irrigation experiments immediately before and after tillage.

5.6. Soil Test P

Although research results are inconsistent, it has been widely observed that elevated levels of soil test P - typically resulting from the long-term over-application of manure and/or fertilizer - lead to greater concentrations of P in subsurface drainage (King et al. 2015). A threshold (i.e., "change point") is believed to exist, above which a unit increase in soil test P results in higher P concentration and loss in tile drainflow; however there is no widespread agreement on the specific value for the threshold, which is likely to differ among different soil types.

Beauchemin et al. (1998) measured P concentrations in tile drainflow from nine different soil series in Quebec. The Quebec surface water quality standard for TP (0.03 mg/L) was exceeded on 14 of 27 sites; 10 of these sites were in clay soils. The highest TP concentrations were recorded in soils with the largest clay content and the highest soil test P/water-extractable P in the A horizon. The study suggested that tile drainflow from flat, clayey soils of medium- to high-P status may be at particular risk of exceeding surface water quality standards. In subsequent work on the same sites, Beauchemin et al. (2003) reported that TP concentrations in tile drainflow were significantly related to soil P status in surface soils. Soils with lower P-sorbing properties had, on average, twice the P concentrations and relative P loads in their tile drainflow as compared to soils with higher P-sorbing properties. Their A horizons had an elevated P saturation degree associated with tile-drainage water P concentrations consistently greater than the surface water quality standard of 0.03 mg TP/L. Conversely, low P concentrations in tile-drainage water (< 0.03 mg/L) and moderate P saturation degrees were observed in the higher P sorbing soil group. Temporal variability of P concentrations in tile drainflow was higher for soils with lower P-sorbing properties than for soils with higher P sorption capacity. The authors suggested that soil groupings based on their P-sorbing and P saturation properties could reasonably predict areas vulnerable to high P loading from tile drainflow, although accurate quantitative predictions were difficult to make.

Also in Quebec, Carefoot and Whalen (2003) reported that dissolved P concentrations in tile drainflow under a silt-loam Gleysol in corn-soybean rotation were highly correlated with soil test P (Mehlich-3), whereas TP and PP levels in tile drainflow were positively correlated with soil P saturation (Mehlich-3/Al ratio). Phosphorus levels in tile drainflow were unaffected by crop rotation or type of fertilizer applied. In contrast, Goulet et al. (2006) reported from a Quebec plot study that P saturation was low in all plots (<4%), whereas high P concentrations were observed in drainflow from some plots. The authors concluded that soil P saturation by itself cannot explain high P concentrations occurring in subsurface drainflow.

McDowell and Sharpley (2001) investigated P release from Pennsylvania soils via tile drainflow and surface runoff in lysimeters. The authors found a direct relationship between drainflow dissolved P concentration and soil test P (Olsen). The concentration of dissolved P in drainage waters was significantly related to and of similar magnitude to extractable P in lysimeter topsoils. The authors documented a change point at 193 mg P/kg (Mehlich-3), above which dissolved P loss increased rapidly with increasing soil test P.

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

53

Kinley et al. (2007) reported from Nova Scotia that TP concentrations were highest in tile drainflow from fields with a soil test P exceeding 60-70 mg P/kg (Bray) or 80-100 mg P/kg (Mehlich-3), although the authors did not propose these values as specific thresholds. In Ontario, Ball Coelho et al. (2012) reported that soluble P loads in tile drainflow were not correlated with soil test P (Bray) in a monitored field, but stated that this was likely due to the fact that P-saturation was low and soil test P levels were below a proposed threshold of 60 mg P/kg, above which P is believed to move into drainflow. Also in Ontario, Zhang et al. (2015a) reported that P concentrations in tile drainflow under various cropping systems were closely related to the P status in surface soils. High concentrations of dissolved P in tile drainflow from a corn-soybean rotation, for example, were attributed to high soil test P, in combination with no-till and macropore flow.

In Illinois, Gentry et al. (2007) observed continued elevated dissolved P concentrations in tile drainflow after the early tile flow events (in contrast to the more episodic pulses of nitrate and herbicides) and attributed the pattern to a pool of available soil P that readily desorbed during movement of water through the soil and into tile drains. From an Iowa field study, Nayak et al. (2009) reported that long-term continuous application of swine manure to corn-soybean rotations had increased soil test P levels 2 – 6 times over the agronomic optimum range. Dissolved P concentrations in tile drainflow increased with the increases in soil test P. In California, Hartz and Johnstone (2006) reported that leachate of soluble P from fields in vegetable rotations was significantly correlated with several measures of extractable P in soils.

Heckrath et al. (1995) investigated P levels in drainage water from English soils with varying soil P levels. Phosphorus concentrations in tile drainflow remained low (<0.15 mg/L) from plots containing <60 mg P/kg (Olsen). There was a rapid increase in dissolved P concentrations in tile drainflow up to the maximum soil P level of ∼100 mg P/kg. The authors identified 60 mg P/kg (Olsen) as the change point. Below this threshold, P was retained strongly in the plow layer; above this, P losses in tile drainflow were closely related to soil test P.

In Sweden, Stenberg et al. (2012) reported that dissolved P concentrations in tile drainflow from clay soils in small grain production were significantly correlated with the degree of P saturation. In Lithuania, Buceine et al. (2007) reported that TP concentrations in tile drainflow was positively correlated with available P_2O_5-Al in the topsoil.

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

54

6. Practices to Reduce P Loads in Tile Drainflow

Phosphorus loads from cropland tile drainflow can be a significant source of P to surface waters. Even if subsurface drainage outlets do not discharge directly to surface waters, P loads can be readily transmitted through agricultural ditches to receiving waters. In Indiana, Ahiablame et al. (2010, 2011) reported that sediments in agricultural drainage ditches often have high P content due to long-term P loadings from surrounding fields, and consequently have low ability to adsorb P in aquatic sediments. Therefore, nutrients inputs to ditches from tile drainflow could be transported downstream without significant attenuation.

Numerous researchers have proposed general management practices to reduce P loads delivered by tile drainflow. Management of nutrient applications at the field level has been recommended. Fraser and Flemming (2001) stated that nutrient management, water table management, and constructed wetlands can be used to improve the quality of tile drainflow. Ruark et al. (2012) recommended that the best management option is to apply manure at appropriate times, and not when tile lines are flowing. Kleinman et al. (2015a) reported that at field and plot scales, the effects of BMPs on drainage P losses (e.g., wetland treatment, chemical adsorption, and incorporation of liquid manure) could be substantial.

In an extensive review of P loads in tile drainage, King et al. (2015) identified several management approaches to control P losses via tile drainflow:

- Disconnect flow pathways between surface soils and subsurface drainage (e.g., periodically disrupting macropores through tillage, removal of surface inlets);
- Drainage water management (DWM), as significant reductions in flow volume drive reductions in P loss; and,
- In-stream and end-of-tile treatments (e.g., flow-through filter cells or structures installed in-line on the drainage outlet or in surface ditches to remove P from drainage waters).

Research findings for some of the major management practices proposed to control P losses in tile drain flow are discussed in the following sections. This discussion is not intended to be an exhaustive review of all available BMPs or management measures available to reduce P loading from tile systems, but only to give a general indication of management measures that could be considered to reduce P loading.

6.1. Drainage Water Management/Controlled Drainage

A variety of practices have been proposed that allow landowners to adjust the level to which the water table in a subsurface-drained field is allowed to rise; this is variously called drainage water management (DWM), controlled drainage (CTD), or conservation drainage. In practice, DWM/CTD uses a water control structure near the outlet of a drain to adjust the effective outlet to various depths (Figure 8). By adjusting the outlet elevation, the farmer can change the functioning of the drainage system throughout the year, lowering the drain so that water can drain freely during field operations, raising the water table after planting to increase water available for use of crops during the growing season, and raising again after harvest to limit drainage

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

55

outflow during the NGS. With proper use, DWM/CTD has been shown to improve crop yields and reduce water flow and nitrate N loads in tile drainflow significantly.

While there is ample evidence that DWM/CTD can reduce the annual volume of tile drainflow (with consequent effects on constituent loads) and concentrations of nitrate N in drainage water (Skaggs et al. 2012, Wesstrom and Messing 2007), research evidence for the effectiveness of DWM/CTD in controlling P losses is conflicting. At one level, reductions in the volume of tile drainflow achieved through DWM/CTD will likely serve to reduce nutrient loads. However, because N and P behave differently (there is no P loss pathway comparable to N loss through denitrification, for example), effects of DWM/CTD on P
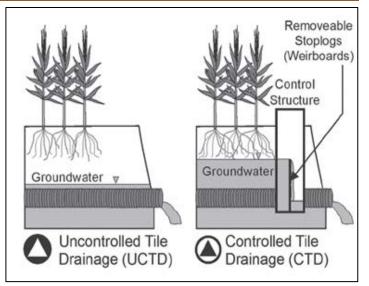

Figure 8. Schematic of uncontrolled and controlled drainage. When water levels are below the elevation of the top stoplog, no tile flow occurs (Sunohara et al. 2015).

loads cannot simply be extrapolated from data on the effects of DWM/CTD on N loss.

Numerous research articles report that DWM/CTD can reduce annual P loads associated with tile drainflow, primarily through significant reduction in outflow volume. In a review, Evans et al. (1995) cited N and P reductions of 30% to 50% resulting from controlled drainage reported in several studies, primarily because of the reduction in outflow volume. In another review, Strock et al. (2010) cited widespread work documenting that controlled drainage was capable of reducing drainage volume and nitrate-N loss by 40% to 50% compared to conventional free drainage. Phosphorus losses were decreased by 25% to 35%. In Ohio, Gunn et al. (2015) measured 40 – 100% reductions in daily tile drainflow volume under DWM/CTD and concluded that there is a general expectation that overall reductions in drainflow volumes from widespread implementation of DWM/CTD would translate into a reduction in nutrient loads exported from farm fields.

In Ontario, Tan and Zhang (2011) used large field plots to determine the effectiveness of conventional free drainage vs. DWM/CTD with sub-irrigation for mitigating P losses in surface runoff and tile drainflow. The DWM/CTD system produced greater surface runoff, but much less tile drainflow relative to the conventional system over a 5-yr period. Tile drainflow accounted for 80 and 97% of total flow volume for the DWM/CTD and conventional systems, respectively. The DWM/CTD system increased P concentrations in surface runoff and reduced some P concentration in tile drainflow. The DWM/CTD system produced greater cumulative P losses in surface runoff but a large reduction in cumulative P losses in tile drainflow relative to the conventional system. Of the total P loss, from 3 to 5% was accounted for in surface runoff water, while from 95 to 97% was accounted for in tile drainflow, for conventional drainage. For DWM/CTD, from 29 to 35% of the total P loss was in surface runoff water, while 65 to 71% was in tile drainflow. Overall, considering the combined total surface runoff and tile drainflow losses, the DWM/CTD system reduced PP and TP losses by 15 and 12%, respectively, relative to the conventional system. The authors concluded that DWM/CTD can be considered a beneficial management practice to reduce P loss under the similar climate and relatively flat field conditions in Southern Ontario.

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

56

Also in Ontario, Sunohara et al. (2015) used a paired-watershed approach to compare water and nutrient fluxes at the watershed scale with and without DWM/CTD implementation over multiple growing seasons. Their findings indicated that DWM/CTD widely implemented in a watershed during the growing season can significantly reduce growing season fluxes of stream water, dissolved P, and TP at the watershed scale. Effects of DWM/CTD on P concentrations in tile drainflow were mixed and inconclusive; the effect on P loads was due primarily to the effects of DWM/CTD on the total volume of tile drainflow. It should be noted that the authors conducted this research during the growing season only; as noted earlier in this review, P export in tile drainflow during the NGS can be significant.

In Manitoba, Cordeiro et al. (2014) reported that controlled drainage (coupled with sub-irrigation) was effective in decreasing tile drainflow from corn fields. Outflow from the DWM/CTD site was 39% lower than that from a site with conventional free drainage and overhead irrigation; the authors do not state how much of the change in drainflow was due to changes in irrigation management. In 2010, the export of PO_4-P from the site with conventional drainage during the growing season was 0.6 kg/ha, significantly greater than export (0.08 kg/ha) from the DWM/CTD site. In 2011, export of PO_4-P from the site with conventional drainage was 0.27 kg/ha, compared to 0.08 kg/ha from DWM/CTD. DWM/CTD showed significant (69%) reductions in PO_4-P load compared to free drainage. Again, however, note that these results do not include P loads from the NGS.

Williams et al. (2015a) conducted a before-after control impact study in Ohio to assess the impact of DWM/CTD on tile drainflow from crop fields. Results showed that DWM/CTD significantly decreased annual volume of tile drainflow by 8 to 34%. DWM/CTD significantly decreased annual dissolved P loads by 0.04 to 0.51 kg/ha (40 to 68%). Nutrient concentrations were not significantly affected by DWM/CTD, indicating that decreases in nutrient loads were primarily due to reductions in the volume of tile drainflow rather than changes in concentration.

In Missouri, Nash et al. (2015) quantified concentrations and losses of P in tile drainflow from a claypan soil to determine whether managed subsurface drainage could reduce ortho-P loss in tile drainflow compared with conventional free drainage. Flow-weighted ortho-P concentration in the tile drainflow was significantly lower with DWM/CTD (0.09 mg/L) compared with that of free drainage (0.15 mg/L). Ortho-P loss in the tile drainflow was reduced with DWM/CTD (36 g/ha) by 80% compared with free drainage (180 g/ha). Contrary to other research, the reduced P loss was not solely due to the reduced amount of water drained annually (63%) with DWM/CTD compared with free drainage. During the spring period, when flow was similar between the two treatments the ortho-P concentration in the tile drainflow was generally lower on sites with DWM/CTD compared with free drainage, which resulted in significantly less ortho-P loss with DWM/CTD. The authors speculated that DWM/CTD's ability to conserve water during the dry summer months increased crop uptake of water and P, which reduced the amount of P available for leaching loss in the spring period.

In Sweden, Wesstrom and Messing (2007) reported that DWM/CTD significantly lowered N and P loading in tile drainflow and altered N dynamics in the soil compared to conventional free drainage. The relative decrease in N and P loading in drainflow from DWM/CTD plots, compared with conventional drainage was of the same magnitude as the reduction in the overall drainflow (60–95%). In later related work, Wesstrom et al. (2014) reported that, compared to conventional drainage, DWM/CTD had lower tile drainflow all years of measurement. N and P concentrations in tile drainflow revealed no significant differences between DWM/CTD and conventional drainage. N and P losses, in contrast, tended to be lower in DWM/CTD than in conventional drainage, possibly due to lower volumes of tile drainflow in DWM/CTD systems. The yearly losses of NO_3-N, total N, PO_4-P, and TP through tile drainflow were, on average, 40% lower in plots with DWM/CTD systems compared to plots with conventional drainage.

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

57

Despite the reports of the effectiveness of DWM/CTD in reducing P loads, several researchers have expressed reservations, pointing out that changes in redox conditions and P sorption due to altered hydrology and water table elevation from DWM/CTD may actually promote desorption and enhance mobility of dissolved P – especially in P-saturated soils – and lead to higher dissolved P concentrations in tile drainflow (King et al. 2015, Kleinman et al. 2015a). Several research reports have documented increases in P concentration and load in tile drainflow at sites under DWM/CTD.

In North Carolina, Gilliam and Skaggs (1986) reported that DWM/CTD reduced N flux (e.g., from 44.4 kg N/ha under conventional drainage to 31.2 kg N/ha with DWM/CTD), but that DWM/CTD increased P flux (e.g., from 0.05 kg P/ha to 0.15 kg P/ha). Also in North Carolina, Deal et al. (1986) used model simulations to evaluate long-term N and P flux in tile drainflow from poorly drained soils. Under the conditions simulated in the study, controlled drainage reduced the nitrate flux by as much as 34%, but resulted in a small increase in P flux.

In Quebec, Sanchez Valero et al. (2007) reported increased P, consistently exceeding Quebec's surface water quality TP standard of 0.03 mg/L, which resulted in increased P loads in tile drainflow from DWM/CTD plots. This occurred even though the total outflow volume from the DWM/CTD plots were reduced by 27% compared to free draining plots. Total and dissolved P concentrations in drainage water from DWM/CTD plots were on average increased by 131% and 178%, respectively, compared to free draining plots. As a consequence, overall P loads from tile drainflow increased in DWM/CTD plots. Most of the P losses occurred in October due to increased P concentrations and heavy rainfall, whereas in the summer, P losses were reduced in DWM/CTD plots due to reduced outflows.

In Ontario, Frey et al. (2013) investigated the potential for DWM/CTD to reduce nutrient and bacteria loading from fall-season liquid manure loading on macroporous clay loam plots. In the short term, following manure application, nutrients and bacteria moved rapidly via tiles to surface waters from the free draining plots, whereas on the DWM/CTD plots, tile drainflow did not occur until the first post-manure application rainfall, so immediate loading to surface water was avoided. By 96 h after application, losses via tile drainflow at the free draining plots accounted for 0.72% of the applied P, while losses via tile drainflow at the DWM/CTD plots accounted for 1.45% of the applied P. Over the entire 36 day monitoring period, during times when all tiles were flowing, TP concentrations were four times higher in tile drainflow from the DWM/CTD plots than from the free draining plots. However, because tile flow at the DWN/CTD plots was less than at the free draining plots, there was no significant difference in nutrient losses from any of the plots.

In a modeling study, Ford et al. (2015) found that decreasing P loads in tile drainflow through DWM/CTD may increase P loads in surface runoff due to decreases in soil permeability and increases in evapotranspiration. These findings could explain why some studies have found increases in surface runoff P concentrations when DWM/CTD is used.

6.2. Drainage system modifications

As noted in Section 5.2, the design of the subsurface drainage system influences P export in tile drainflow. While it is unlikely that existing tile systems will be extensively altered or remodeled (except to install DWM/CTD), installation of new systems might consider some aspects of basic drainage system design to reduce P losses.

With regard to drain line spacing, in general, the closer the drains, the greater the water and P loss. At the same depth, drainage volume from narrow drain spacing (e.g., 9 m) is significantly greater than from wider spaced drains. Shallow drains are reported to respond more rapidly to precipitation than deep drains, but

Stone Environmental

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

58

drainage volume will be significantly less in shallow vs. deep drains. Several studies have found that P concentrations are higher from shallow drains compared to deeper drains. The general consensus of the literature is that drains placed shallower will result in greater P concentrations, whereas deeper drains will have greater mass losses.

Fausey et al. (1995) recommended that lowering drainage intensity (wider spacing and shallower depth) would reduce nutrient loads improve drainage water quality. In England, Catt et al. (1998) suggested that consideration be given to maintaining field drains below peak efficiency to reduce subsurface P losses.

In Finland, Turtola and Paajanen (1995) evaluated the effects of improvements to subsurface drainage on P losses in a heavy clay soil with a 29 year old tile system. The field was fitted with new drains and either topsoil or wood chips were used as backfill in the drain trenches. Where topsoil was used as backfill, the estimated soil erosion and particulate and dissolved P losses from plowed soil during winter were lower after improvement than before (1168 vs. 1408 kg/ha, 0.58 vs. 0.69 kg/ha, 0.09 vs. 0.12 kg/ha, respectively). Where wood chips were used as backfill, soil erosion and particulate P losses were not reduced.

One feature of subsurface drainage system design that could be addressed by retrofit is the surface inlet. Although not as common in the LCB, surface inlets (tile risers) are frequently part of subsurface drainage systems in the Midwest and elsewhere. Tile risers are open inlets that connect subsurface tile lines with depressions or internally drained features of agricultural fields (e.g., terraces). These surface inlets provide a direct conduit for surface runoff potentially carrying sediment and solutes into the subsurface systems, and often bypass any field practices such as filter strips or buffers intended to treat surface runoff (Kleinman et al. 2015a).

Although some researchers have reported that the presence of surface inlets did not have much effect on P and sediment loads in tile drainflow (Ball Coelho et al. 2012), some differences in P loss have been reported. Schilling and Helmers (2008a) reported that during storm events in tiled landscapes, the higher velocity of runoff carries sediment and other particulates through surface inlets into the tile network and mobilizes any sediment that had settled at the bottom of the tile network, as well as introducing sediment and solutes picked up from the ground surface. Ball Coelho et al. (2010) reported that growing season dissolved P loads from closed drainage systems (no surface inlets) in Ontario averaged 0.005 kg/ha, whereas mean dissolved P load from open drainage systems (with surface inlets) averaged 0.03 kg/ha. King and Fausey (2013) and King et al. (2015) stated that P losses through surface inlets tend to be equivalent to those characteristic of surface runoff, higher than typical of tile drainage; the authors recommended removal of surface inlets to improve the quality of subsurface drainage.

Significant improvements in tile drainage quality can be derived from elimination of surface inlets. Feyereisen et al. (2015) reported that in tile-drained agricultural landscapes, replacing open inlets with blind or sand/gravel-packed inlets will substantially reduce TSS and P losses to surface waters through tile drainflow. In an Indiana study, total and soluble P loads were 66 and 50% less for the blind inlets, respectively, compared to open inlets. In Minnesota, median soluble P concentrations in tile drainflow were reduced from 0.099 mg/L with open inlets to 0.064 mg/L for gravel-filled inlets.

6.3. P Sorption/Treatment

Where agronomic or drainage system management practices alone do not sufficiently reduce P transport from tile-drained watersheds, remediation efforts may shift toward treatment of tile drainflow before it enters surface waters. A variety of technologies have been proposed and assessed to capture concentrated flows of P in surface and groundwater before it reaches a surface water. Buda et al. (2012) reviewed emerging

Stone Environmental

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

59

technologies for removing P from surface and ground water, including the use of P-sorbing materials like iron oxides as an envelope around tile drains to adsorb dissolved P. Bryant et al. (2012) reported removal of 65 – 73% of total dissolved P from ditch flow draining high-P cropland soils in Delaware using flue gas desulfurization gypsum; the authors recommended adapting their system to intercept and treat groundwater before it entered the ditch. Penn et al. (2012) reported that a P removal structure using steel slag as the P sorption material trapped 25% of dissolved P in urban stormwater in Oklahoma. Penn et al. (2014) presented a design process for treatment of runoff from an Oklahoma poultry operation using a similar approach.

Several researchers have assessed specific materials of potential use in P sorption/treatment. In laboratory studies, King et al. (2010) observed over 50% average DRP load reductions in simulated tile drainflow filtered through activated carbon, zeolite, and activated alumina filters. Oliver et al. (2011) reported that water treatment residuals have the capacity to fix large amounts of P under both aerobic and anaerobic conditions and could be used in the field for P management with low risk of release of sorbed P even under anaerobic conditions. In New Zealand, McDowell et al. (2008) recommended using steel slag as a backfill in drains on a dairy farm. The authors reported reductions of about 70% in P load with subsurface drainage flow through slag fill. Based on the P sorption capacity of the slag, the authors calculated that it would take about 72 years for the slag to become saturated with P.

Vohla et al. (2011) reviewed existing information on different filter media used for P removal from wastewater in constructed wetlands. A great variety (more than 30 main categories of both natural and man-made materials plus industrial by-products) have been applied as filter media for phosphorus retention in constructed wetlands. The authors noted that important considerations for use of such filter media include local availability, risk of harmful side-effects such as heavy metal contamination, and the ability to recycle used media and P back to the land.

Finally, while constructed wetlands and similar "bioreactors" have been used to capture nutrients in surface and subsurface flows at the edge-of-field scale, their use for P removal is not well-proven. In New Zealand, for example, Tanner and Sukias (2011) evaluated N and P removal by constructed wetlands treating tile drainage from dairy pastures and reported that while TN removal was significant (7 – 63%, depending on season and hydraulic loading), none of the wetlands were effective at P removal. The constructed wetlands tested exported 12 – 115% more total P annually than they received.

6.4. Other Practices

Given the critical role of preferential flow in delivering water and P to tile drain systems, several researchers have recommended surface tillage to break up macropores as a means to reduce P delivery to tile lines. However, reports of the effectiveness of tillage have been mixed. In Iowa bench-scale studies, Cook and Baker (2001) reported that measures to disrupt or block soil macropores (by tillage and air-pressurization) appeared to have some beneficial effect in minimizing initial flow and therefore phosphorus losses in tile drainflow when comparing loss with a no-till treatment, but the differences were not significant. In Ohio, Williams et al. (2016) reported that disk tillage following fertilizer application decreased P concentrations and loads in tile drainflow compared to a no-till field. Event water transport through macropore flow pathways still occurred in the tilled field and was important for delivering TP to the tile drain system, but by incorporating the fertilizer into the soil, reducing the maximum relative contributions of event water, and decreasing tile drainflow volume, tillage decreased dissolved P losses. The authors noted, however, that the effect of tillage on the delivery of event water via macropore flow paths and tile drainflow was temporary, lasting less than three weeks.

Stone Environmental

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

60

Christianson et al. (2016) stated that plowing or significantly incorporating solid manures is a recommended practice to reduce P loss in drainage, as these methods disrupt the hydraulic conductivity of soil macropores. King et al. (2015) reported that significant TP reductions have been documented after tillage disrupted macropores. However, Christianson and Harmel (2015) reported that data from a comprehensive literature review provided no clear evidence that tillage was an effective management practice to reduce tile drainflow volume or N loads. In Sweden, Ulen and Persson (1999) observed that cultivation did not reduce particulate or dissolved P in tile drainflow.

Management of manure/fertilizer rates and application timing have also been proposed as effective management measures (Macrae et al. 2007). Cook and Baker (2001) tested three rates of liquid swine manure application with soil lysimeters and found significant differences in P and bacteria loading to subsurface drainage between the highest and lowest rates. The higher rate of application initiated flow and increased levels of nutrient and bacterial contamination within one hour after application as well as throughout the 15-day study period. Very high concentrations of P immediately after liquid manure application, followed by a precipitous decline led to the conclusion that some of the manure liquid had immediately moved from the soil surface into macropores. The authors concluded that the time immediately following application of lagoon water may pose the greatest threat to the quality of tile drainflow, particularly when application rates might be higher than those recommended. These high volumes might initiate or significantly increase tile drainflow.

In England, Catt et al. (1998) recommended that applications of inorganic fertilizer should be restricted to periods in the fall and summer when the soil is dry so that rain in the next few weeks will not result in drainflow. In sensitive areas, the authors recommended that managers consider maintaining drainage systems below peak efficiency, including postponing renovations or increasing the spacing between drains. Macrae et al. (2007) suggested that tile plugs should be explored as a method to minimize nutrient export from tile lines.

Stone Environmental

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

61

7. Future Work

7.1. Assessment of Tile Drainage Systems in the Lake Champlain Basin

With the exception of a few specific cases of data collected for localized studies, precise estimates of the extent of cropland tile drainage in the LCB do not exist. Even on fields known to be drained, the characteristics of the drainage system are largely unknown, especially for older systems. Where P loads in tile drainflow are found to be a significant management issue, knowledge of the extent and design of drainage systems will be essential, at both the watershed and the field scales, before mitigation efforts are undertaken.

7.1.1. Watershed Scale Assessment

Few options exist for assessment of the extent of tile drainage at the watershed scale. Some researchers have estimated the likely extent of drainage based on Geographic Information System (GIS) analysis of soil characteristics and cropping patterns. The underlying assumption of this approach is that relatively flat, poorly drained soils that are in active crop production must be drained for crop production to be carried out. Using this approach, Jaynes and James (2007) published state-level estimates of drained cropland ranging from 2% (New York) to 28% (Indiana). Using similar assumptions, the World Resources Institute (2007) estimated 39.3 million tile-drained acres in eight U.S. corn-belt states (Iowa, Illinois, Ohio, Indiana, Minnesota, Michigan, Wisconsin, and Missouri); these states were estimated to have from 3% (Missouri) to 48% (Illinois) of their cropland acres underlain by subsurface drainage (Sugg 2007). In the Missisquoi River Basin (MBB) within the LCB, Winchell et al. (2011) assumed that all poorly-drained cropland (hydrologic soil group C or D) with slopes less than 6% must be tile drained and thereby estimated that 40% of the MBB was tile drained. Subbasin estimates ranged from <20% for Mud Creek, Trout River, Tyler Branch, and Upper Missisquoi River to >75% for Rock River and Hungerford Brook. Application of this approach to the entire LCB would be a relatively straightforward GIS exercise and could be accomplished at a moderate cost.

In addition, several remote sensing techniques – including aerial imagery analysis and ground penetrating radar – and have been tested in other geographic areas for watershed and field scale detection of tile drain systems. Stone Environmental will be conducting a detailed literature review of the use of remote sensing techniques that may be applicable to identifying tile drain systems within the Lake Champlain Basin under separate contract with the Vermont Department of Environmental Conservation (VT DEC). This work will start soon and is scheduled to be complete by the end of calendar year 2016.

On a less technically demanding level, the long-used technique of smoke testing for inappropriate connections into urban storm drainage systems (e.g., Pitt 1993) has been adapted to detect the location of tile lines on agricultural fields. In Canada, Fleming and Bradshaw (1992) used smoke bombs and a blower to force smoke into tile outlets. Smoke emerged from the ground via soil macropores in a band over the tiles, ranging from 0.5 – 2 m in width and supported demonstration of the location of tile lines. More recently, Nielsen et al. (2015) reported from Sweden that smoke testing can not only locate tile lines but can also provide information on the magnitude of soil macropores and thereby predict the risk of contamination of tile drainflow by surface applied agrichemicals. In their experiments, size and hydraulic conductivity of soil macropores were highly correlated with the strength of smoke emission. Finally, in their work with tile drains in the New York LCB, Young et al. (2016) used smoke testing to document tile line location.

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

62

It should be noted that smoke testing is likely to be effective in locating buried drains only where soil macropores exist. However, as research has shown that water, sediment, and P transmission to tile drains is largely controlled by preferential flow, positive smoke testing results could not only locate tile lines but also identify priority sites for load reduction efforts.

7.2. Research Needs

A great deal is known about P transmission in tile drainwater, certainly enough to conclude that tile drainage is a potentially significant source of P at field and watershed scales in the LCB. However, additional research is needed to answer some important outstanding questions. This research is needed for three principal reasons. First, given the potential P contributions in tile drainwater, greater knowledge on the location and extent of tile drainage in the LCB is needed in order to fully understand the magnitude of the issue at the basin scale. Second, even though important data have been reported from Quebec and other regions near the LCB, most of the current knowledge of P transmission in tile drainage has come from work in the U.S. Midwest, Europe, and elsewhere and the quantitative transferability of these results to the LCB is uncertain. There is a need to confirm some of this knowledge under the climate, soil, and management conditions of the LCB. Third, uncertainties and contradictions reported in the global literature need to be explored and resolved.

The research needs identified below fall into three general categories: assessment of tile drainage extent in the LCB, quantification of P concentrations and loads in drainflow, understanding of factors controlling P transmission in tile drainage, and evaluating the effectiveness of management practices to reduce P losses in tile drainwater. While some of this work may be currently underway (e.g., at the Miner Institute in New York and in the Jewett Brook watershed in Vermont), all the recommended elements are listed below.

7.2.1. Quantify P Concentrations and Loads
- At the field scale:
  - Collect data on P concentrations and loads in tile drainwater. Such monitoring should meet several criteria:
    - Monitoring must be conducted over full annual cycle(s), not restricted to growing season or a few high-flow events. Short-term data collected under limited conditions may explain contradictory reports of very low or very high P outputs in tile drainwater.
    - Flow should be measured continuously and sampling conducted either flow-proportionally or at a high frequency (i.e., weekly or better) to ensure representative concentration data and to permit an accurate load estimate.
    - Where possible, surface runoff should be monitored at comparable intensity so that information on the proportion of total field P export in surface and subsurface flows can be determined.
  - Collect data on P speciation in tile drainwater, at minimum total P, soluble reactive P, and particulate P. In specific cases, data on other P fractions such as total soluble P or bioavailable P may be of interest.
  - Use monitoring data to evaluate seasonality of P concentration and load. Reports on the seasonal distribution of P loads from tile drainflow have been somewhat conflicting. Most research indicates that P export is low during the growing season, with the majority of the annual P export occurring outside the growing season. Some researchers have identified the spring snowmelt period as the most critical. These issues need to be explored under LCB-specific climate and management conditions.

Stone Environmental

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

63

- At the watershed scale:
  - Estimate the P contribution from tile drainflow to the total watershed P export. Tile drainflow has been shown to be a significant source of P at the watershed-scale in several studies, although high-quality data quantifying contributions of tile drainflow loads as a fraction of the overall watershed load are scant and essentially non-existent in the LCB.

Note that for all the efforts to quantify P concentrations and loads at the field or catchment scale, the research should not only monitor tile drainwater but also collect simultaneous site data (e.g., slope, soil texture, soil test P) and agricultural management data (e.g., cropping, tillage, manure/fertilizer application rates, timing, and method). These are likely to be important covariates useful in explaining observed P output and in understanding critical factors driving P loads in tile drainwater.

7.2.2. Investigate Factors Controlling P Transmission in Tile Drainwater

The following research items could be conducted at plot or field scale. Results from plot studies would need to be confirmed by field-scale studies because plot data may not be directly transferrable to larger systems. Note that some of these questions could be addressed by the same studies proposed above, if sufficient site and agronomic data are collected during monitoring.

- **Manure/fertilizer applications:** Document P loses in tile drainwater under different manure/fertilizer application scenarios. Published results on the influence of P application on tile drainwater have been conflicting; better data are needed on the influence of land-applied P on P losses in tile drainwater. Manure or fertilizer applications to soils prone to preferential flow, close in time to storm events, or at rates in excess of crop need can lead to significant P losses. However, P applications do not always generate high losses in tile drainwater. Studies of this issue should focus on rate, timing, and method of application and weather. Manure applications by surface broadcast, incorporation, and injection, as well as minimum tillage should be considered. The influence of preferential flow should also be evaluated.
- **Soil texture:** Evaluate correlations between soil texture and P losses in tile drainwater. The reported influence of soil texture is variable; greater drainflows have been reported on coarse-textured soils and attributed to higher permeability, but high drainflows have also been observed on fine-textured soils attributed to preferential flow.
- **Cropping and tillage:** Document P losses in tile drainwater under different crops and tillage practices common to the LCB. The reported influence of crop and tillage on P in tile drainflow is variable. High P loss in tile drainflow sometimes occurs from grassland and no-till cropland due to the prevalence of preferential flow pathways. The influence of crop type is also unclear, as results may be confounded by differences in nutrient application and tillage inherent for specific crops. In the LCB, evaluation of P loss in tile drainwater should focus on land in continuous corn, corn-hay rotations, soybeans, and permanent grass.
- **Soil test P:** Determine the influence of soil test P on P losses in tile drainwater. Although research results are variable, it has been widely observed that elevated levels of soil test P or soil P saturation (e.g., from long-term over-application of manure and/or fertilizer) lead to greater concentrations of P in tile drainflow. Research has suggested that a soil test P threshold or "change point" exists, above which a unit increase in soil P results in elevated P concentrations and losses in drainflow. This threshold is soil-specific and data for LCB agricultural soils do not currently exist. Studies to identify thresholds – as well as the influence of other soil factors such as clay content, soil P saturation, and water-extractable P – should be conducted on common LCB agricultural soils.

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

64

7.2.3. Evaluate Effectiveness of Management Measures

The effectiveness of management measures to reduce P losses in tile drainwater is not fully understood at the global scale and is essentially unknown within the LCB. The effectiveness of various Best Management Practices (BMPs) should be tested at either the plot or field scale.

- **Drainage water management/controlled drainage (DWM/CTD):** Evaluations of the effectiveness of DWM/CTD on P loads in tile drainwater have yielded mixed results. Reductions in P loads have sometimes been observed, in spite of increases in P concentration, due to significant reductions in flow. However, DWM/CTD is uncommon in the LCB and its potential to reduce tile drainage P loads needs to be tested under local conditions.
- **P sorption/treatment:** Research should be conducted on the practicality and effectiveness of P sorption treatments (e.g., slag, water treatment residuals) to reduce P loads in tile drainwater.
- **Tillage to close soil macropores:** Research results on the effectiveness of shallow or periodic tillage to close soil macropores and reduce potential transmission of water, sediment, and P to tile drains have been conflicting. The effectiveness of this approach should be tested in the LCB.

STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

65

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STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

66

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STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

67

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STONE ENVIRONMENTAL

Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

68

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Lake Champlain Basin Program
Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

STONE ENVIRONMENTAL   70

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Agricultural Land / November 23, 2016

71

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Agricultural Land / November 23, 2016

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Agricultural Land / November 23, 2016

73

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Agricultural Land / November 23, 2016

75

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Agricultural Land / November 23, 2016

76

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Literature Review: Tile Drainage and Phosphorus Losses from
Agricultural Land / November 23, 2016

77