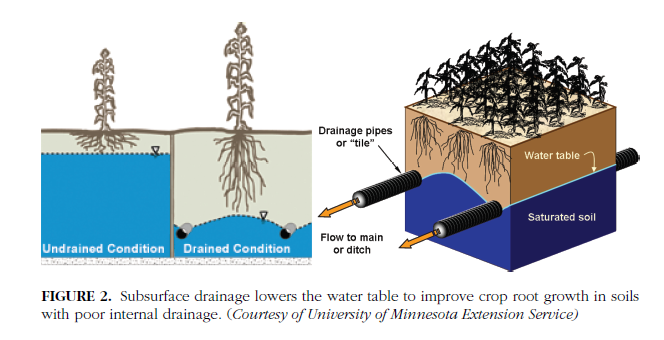
Executive Summary

* In agricultural watersheds, phosphorus (P) can enter surface waters through 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 significant and tile drainflow has been clearly shown to influence both hydrology and phosphorus loading at the field- and watershed-scales.
* 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, better 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 tend to be installed in a regular grid pattern with pipes 5 to 30 m apart under an entire crop field. Most drainage networks discharge directly to an open ditch or stream.



* 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 VT AAFM and 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 drained acres in Vermont, 80% are associated with dairy production.

## Effect of subsurface drainage on hydrology

* Use of tile drainage significantly alters the hydrology of the landscape. Compared to an undrained condition, use of 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;
* 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 drainflow can respond to large precipitation/snowmelt events at almost any time of year, the largest drainage volumes tend to occur from fall through spring, with tile drainflow very small or entirely absent during the summer growing season.
* Because of the significant reduction in overland flow from tile drained fields, tile drainage often reduces sediment and nutrient export in surface runoff.
* 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 amount/intensity 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 – reported influence 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 – reported influence is variable, 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).

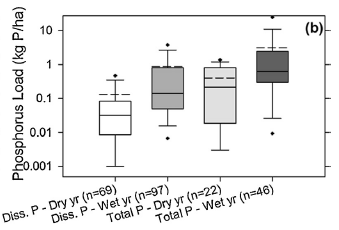
It should be cautioned that these influences are often interactive. Research has documented major differences in tile drainflow among sites with identical drainage systems. Such spatial differences may be greater than differences observed between different rainfall events.

## 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 to intended to prevent eutrophication.
* 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 has found that tile drainflow P concentrations tend to increase with increasing discharge rates;
  + Some researchers have 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, increasing in 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 surprisingly 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
* Just as with P concentration, reported P loads attributed to tile drainflows have been highly variable. In New York, total P load of 0.13 kg/ha/yr and 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; 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 delivered in tile drainflow. For example, several researchers in Quebec have reported 40 – 80% of annual P loss from crop fields 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 seasonal distribution of P loads 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.
* Tile drainflow has shown to be a significant source of P at the watershed-scale, although good 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 to 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, and climate/hydrology. The most important of these are discussed below.

* **Preferential flow:** Based on extensive research findings, 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 particulate and dissolved P can be comparable to losses in surface runoff.
  + Many researchers have concluded that 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 indicates 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. 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. Specifically:
  + 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, many researchers have observed significant and rapid effects on P loss in tile drainage from manure applications, especially liquid manure. In New York, for example, soluble P concentrations in tile water peaked at 1.17 mg/L immediately following manure application. Further, P concentrations peaked before the tile drainflow peaked, indicating that the manure may have been delivered directly to the tile drains.
  + Researchers have frequently reported high P losses in tile drainflow from fields that have 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 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 probably 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 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 concentration and loss in drainflow\; however there is no widespread agreement 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 of course 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 researchers have proposed management measures to reduce P loads delivered by subsurface drainage, starting with fundamental nutrient management – apply manure and fertilizers at the right rate, the right location, and 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 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 to various depths. 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 outflow during the non-growing season

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

* + Numerous research articles report that DWM/CTD can reduce P loads in annual tile drainflow, primarily through significant reduction in the total outflow volume.
  + Several researchers have expressed reservations about the effectiveness of DWM/CTD for P control, pointing out that 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.
  + Several research reports have documented increases in P concentration and load in tile drainflow under DWM/CTD. 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 drainflow from DWM/CTD plots increased, on average, by 131%, and 178%, respectively, compared to free draining plots.

Given this uncertainty, it does not seem that drainage water management can 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 improve drainage water quality. Some researchers have suggested that maintaining field drains below peak efficiency (i.e., postponing repairs or upgrades) could help to reduce subsurface P losses. Although surface inlets (tile risers) are not common in the LCB, elimination or plugging of surface inlets (which provide 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 in 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, several researchers have recommended surface soil tillage 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.