SEASONAL TRENDS IN PHOSPHORUS EXPORT

SEASONAL TRENDS IN PHOSPHORUS EXPORT FROM THREE MAJOR CANADIAN LAKE ERIE TRIBUTARIES

By RACHELLE FORTIER, B.SC

A Thesis Submitted to the School of Graduate Studies in Partial Fulfilment of the Requirements

for the Degree Master's of Science

McMaster University

Master of Science (2022) Department of Biology

McMaster University Hamilton, Ontario, Canada

TITLE: Seasonal trends in phosphorus export from three major Canadian Lake Erie tributaries

AUTHOR: Rachelle Fortier, B.Sc. (Trent University)

SUPERVISOR: Dr. Patricia Chow-Fraser

NUMBER OF PAGES: xiii, 73

General Abstract

The re-appearance of algal blooms in Lake Erie in recent decades has been attributed to increased loading of bioavailable phosphorus (soluble reactive phosphorus; SRP) in US tributaries, a trend linked to agricultural practices, tile drainage, and climate change. Here, we explore P-loading trends for three major Canadian tributaries of the Canadian Lake Erie Basin (CLEB) and investigate if increased loading can be related to increased use of tile drainage. Our results confirm that SRP loading from the Canadian tributaries has been increasing over the past decade in the late winter early spring, and that tile drainage is a significant driver of SRP across all seasons. However, the effects of tile drainage are not consistent across all regions where climate conditions, soil characteristics and agricultural management practices vary. This study highlights the complexity of P transport via tile drains and underscores why no single solution should be applied to manage P across the CLEB.

Acknowledgments

First, I would like to say a huge thank you to Dr. Patricia Chow-Fraser for giving me the opportunity to do this work, and her guidance, patience, and support over the past 2 years (despite all the hurdles it entailed). I would also like to thank Dr. Jonathon Stone for his advice and flexibility over the past few years as a member of my committee.

Secondly, I would also like to thank all the member of the PCF lab, past and present, who have helped me get to this point. Thank you all for your thoughtful advice, moral support, and willingness to help whenever needed. A very special thank you to Alana Tedeschi for taking me under her wing, and her constant support in all aspects of my project as not only a lab mate, but a friend.

Most importantly, I would like to thank my family for their constant support and love through everything I take on, and my partner, Kelton Adderley-Heron for always being there and never letting me give up.

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ORGANIZATION OF THE THESIS

There are three chapters in this thesis. The first is the introductory chapter and the third is the concluding chapter, which are written by me alone. The second chapter is co-authored with another graduate student, Alana Tedeschi, who is a Ph.D candidate in the Chow-Fraser lab. Alana assembled the data for the Grand River, while I assembled data for the East Sydenham and Thames Rivers, but I performed all the statistical and graphical analyses and completed the writing.

GLOSSARY OF TERMS

AAFC	Agriculture and Agri-food Canada
ACI	Annual Crop Inventory
BPM	Best management practice
CLEB	Canadian Lake Erie Basin
CTD	Controlled tile drainage
DEM	Digital elevation model
DRP	Dissolved reactive Phosphorus
ECCC	Environment and Climate Change Canada
ESR	East Sydenham River
FALL	Fall
GLWQA	Great Lakes Water Quality Agreement
GR	Grand River
GRCA	Grand River Conservation Authority
GROW	Growing Season
LULC	Land use and land cover
LWES	Late winter-early spring
P	Phosphorus
PP	Particulate Phosphorus
PTNWQMP	Priority Tributary Nutrient and Water Quality Monitoring program
SRP	Soluble Reactive Phosphorus
TP	Total Phosphorus
TR	Thames River
USGS	United States Geological Survey
WINT	Winter
WLEB	Western Lake Erie Basin

WSC	Water Survey of Canada

Chapter 1: GENERAL INTRODUCTION

Water Quality Impairments in Canada

Canada contains 20% of the world's freshwater, with 2 million lakes and 8500 rivers (Monk and Baird 2014), making freshwater environments in Canada a unique and important component of the world's biodiversity (Desforges et al., 2022). Surface water ecosystems such as lakes, river and wetlands provide habitat for over 3000 taxa of freshwater species in Canada (Desforges et al., 2022) while also being the primary source of drinking water for approximately 28 million Canadians (Statistics Canada, 2021). Despite the importance of freshwater in Canada, water quality deterioration is a major concern. Anthropogenic activities have dramatically changed the natural landscapes of Canada over time, influencing the transport of pollutants through watersheds and contributing to increasing water-quality impairment. Both point sources (known localized source) and non-point sources (diffuse sources) of pollutants, like pharmaceuticals, pesticides, and nutrient have been related to deterioration in water quality and aquatic health. Agricultural intensification and increased agricultural runoff, rich in nutrients from non-point sources, has become a key driver of increased aquatic productivity and ultimately eutrophication in both marine and freshwater aquatic ecosystems (Moss, 2008; Conley et al., 2009; Withers et al. 2014).

Phosphorus (P) is the primary nutrient that drives algal blooms in freshwater environments such as the Great Lakes (Jarvie et al., 2017). Blue-green algae, also referred to as cyanobacteria, can produce cyanotoxins that may be toxic to human and animal health, and in severe cases can result in death (Conley et al., 2009). The presence of these harmful algal blooms has been significantly related to both point sources such as municipal wastewater and non-point sources from agricultural inputs (Jarvie et al., 2017; Van Meter et al., 2020).

History of Lake Erie Water Quality

Lake Erie (**Figure 1.1**) has a long history of eutrophication and poor water quality. For decades, Lake Erie has been experiencing large-scale annual harmful algal blooms (cyanobacteria) in the western basin (Bridgeman et al., 2012; Berry et al., 2017) and nuisance filamentous algal blooms (*Cladophora*) in the eastern basin (Millner, Sweeney, & Frederick, 1982; Watson et al., 2016). These water-quality impairments were the spark that led to the creation and implementation of the Great Lakes Water Quality Agreement (GLWQA) in 1972, targeting point source P from wastewater treatment effluent (Bruce and Higgins, 1978). The GLWQA was updated in both 1978 and 1983 to focus more on non-point sources of P, by promoting improved fertilizer management and conservation tillage to reduce soil erosion and particulate phosphorus (PP) in runoff (IJC, 1987; Richards et al., 2008). There were improvements in water quality and decreases in algal bloom during the 1980s and 1990s; however, Lake Erie has experienced a “re-eutrophication” and a resurgence in algal blooms beginning in the early 2000s (Watson et al., 2016; Kane et al., 2014).

The Western Lake Erie watershed, specifically the Maumee and Sandusky Rivers, supply majority of the P loading to Lake Erie, and has also been linked to increases in the most bioavailable fraction of P, soluble reactive phosphorus (SRP), also referred to as dissolved reactive P (DRP) (Jarvie et al., 2017, Kane et al., 2014; Daloğlu et al., 2012; Baker et al., 2014; Stow et al., 2015). Increases in the severity and frequency of algal blooms in the Western Lake Erie Basin (WLEB) have been related to an increase in bioavailable SRP (Daloğlu et al., 2012; Stow et al., 2015), which have been attributed to changes in climate and agricultural practices such as increases in intensive crop land and artificial drainage (Jarvie et al., 2017; Stow et al., 2015). These increases have been occurring during the non-growing season (typically defined as October-April; Stow et al., 2015), when most major snow melt and precipitation events occur, and thus lead to high P losses from barren agricultural lands (Lam et al., 2016; Macrae et al., 2007; Stow et al., 2015; Van Esbroeck et al., 2016). The combination of subsurface tile drainage along with other landcover characteristics (i.e. agricultural management, soil characteristic and climate variables) has also been suggested as a driver of these trends, as this can influence the form and rate of transport of P from agricultural landscapes (Macrae et al., 2007; Kokulan, 2019).

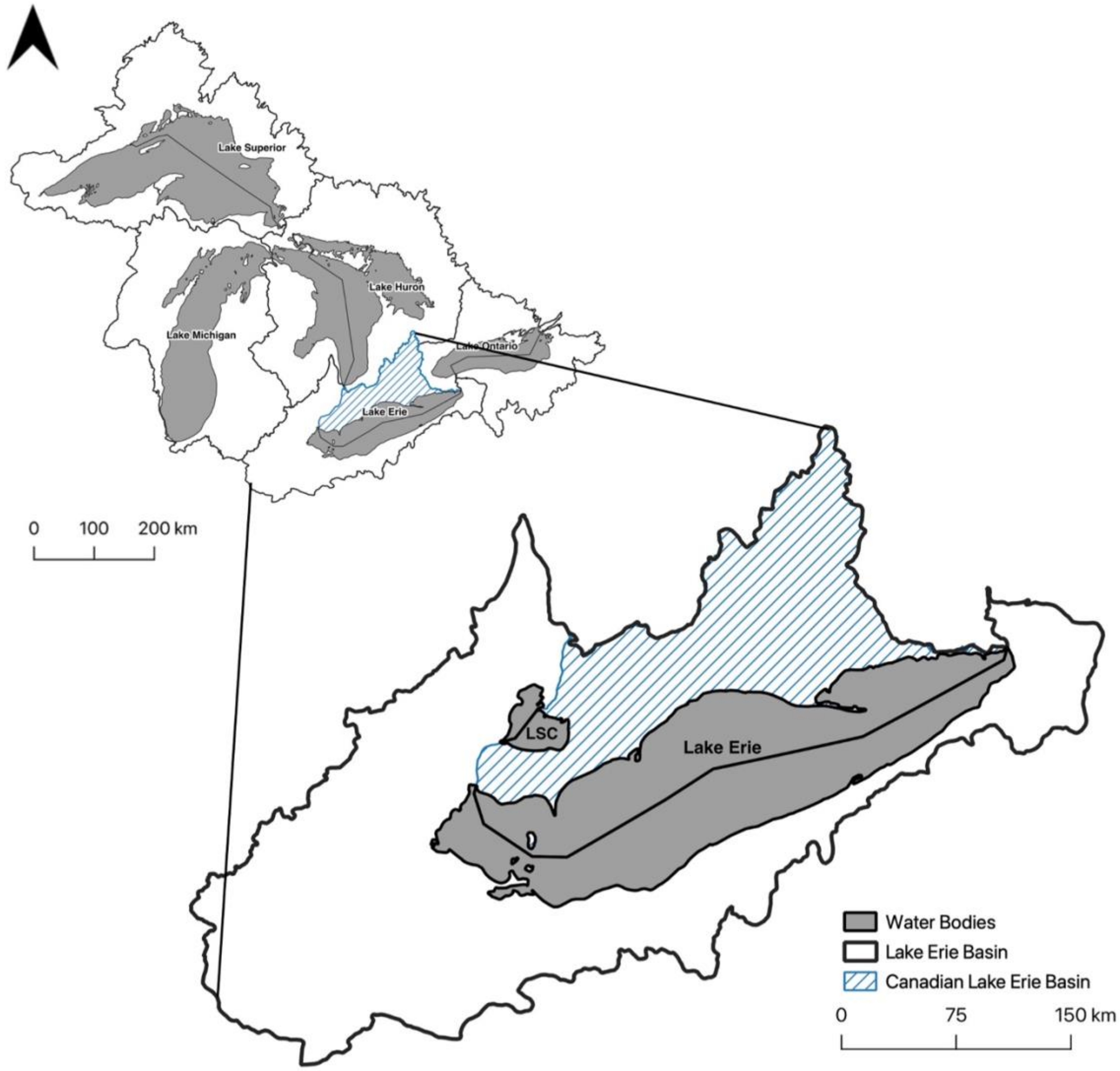

Figure 1.1. Map of the Great Lakes and their drainage basins, with Lake Erie and the Canadian Lake Erie Basin highlighted.

Tile Drainage

Drainage is a natural process and is a key component of water cycling; however, it is often less effective in preventing oversaturated farmland soils due to soil compaction, slope, and hydraulic conductivity (Kokulan, 2019). Implementation of artificial surface and subsurface drainage (see **Table 1.1**) can mitigate these issues by removing excess water from the upper soil profile and stabilizing the water table to create more ideal conditions for crop planting and root zones, thus increasing overall crop yield (Fausey, 2005; Ghane, 2018). In temperate regions where soils are often oversaturated and water tables are high, subsurface tile drainage (networks of subsurface conduits that lower the water table and remove excess soil moisture) is a common and often necessary agricultural management practice to improve crop yields in regions with a combination of high-water tables or soil moisture (Valayamkunnath et al., 2020).

In the United States, 84% of cropland is artificially drained with tile drainage, concentrated within six midwestern states surrounding Lake Erie (Valayamkunnath et al., 2020). In Canada, 45% of the total crop area is artificially drained, with 19% being subsurface tile drainage, and the artificially tile-drained land being mostly confined to the southern regions of Ontario and Quebec (Statistics Canada, 2019). As of 2011, an estimated 1.75 million hectares, or approximately 48% of cropland have tile drainage systems installed in Ontario (Smith, 2015). In southern Ontario specifically, there is currently over 16,700km^2 of tile drainage (Eimers, Liu & Bontje, 2020). Such artificial drainage and associated water management in agriculture has greatly altered watershed hydrology and nutrient transport, significantly impacting wetland, stream, river, and floodplain riparian ecosystems (Blann et al., 2009). For example, nutrient inputs from agricultural drainage systems are the key driver of water quality impairments in the Mississippi River Basin, which has resulted in eutrophication and hypoxia in the Gulf of Mexico (Blann et al., 2009).

Table 3.1. Description of dominant surface and subsurface flow pathways in agricultural landscapes. Published sources are; 1) Ghane (2018), 2) Van Stempvoort et al. (2021), 3) Michaud, Poirier, and Whalen (2019), 4) Zhang, Zhang, and Zheng, (2016).

Flow Pathway	Flow Direction	Flow Location	Definition
Surface runoff/overland flow	Lateral	Soil surface	- Movement of non-infiltrated water over the surface soil[1,2] - Occurs when precipitation/snow melt rate exceeds the soil infiltration capacity and results in water accumulation[1,2]
Surface drainage	Lateral	Soil Surface	- Purposeful movement of excess water from soil surface by artificially sloping ground toward surface drain inlets and ditches[1]
Subsurface tile drainage	Lateral	Subsurface	- Movement of excess water from saturated subsurface soils and management of water table level through networks of subsurface conduits (buried perforated piping)[1]
Vadose flow	Vertical and Lateral	Subsurface	- Flow of water through the unsaturated zone of the soil profile (between the soil surface and water table)[2]
Matrix flow	Vertical and Lateral	Subsurface	- Infiltration of water through the soil profile/matrix via micropores [2,3,4]
Preferential flow	Vertical and Lateral	Subsurface	- Rapid infiltration and movement of water through the soil profile, most often occurring through macropore (ie. cracks and fissures, worm holes, tile drains) pathways of soils[2,34]

Nutrients are transported in agricultural landscapes via both surface runoff and/or subsurface flow (see **Table 1.1**; King et al., 2015). Most watershed scale research has focused only on P export from surface runoff, which is known to strongly influence eutrophication in agriculturally dominated landscapes in Ontario (e.g. Rutledge & Chow-Fraser, 2019). Even though surface runoff is responsible for majority of annual total phosphorus (TP) losses (Van Esbroeck et al., 2016), subsurface tile drainage can contribute substantially to agricultural P export (Plach et al., 2018; Van Esbroeck et al., 2016). Since water and P transport through tile drainage are known to be more variable than that through surface runoff, it is more difficult to pin-point factors controlling P transport in tile drains (Eastman et al. 2010; Sharpley et al., 2011).

Tile drainage transports P via two hydrologic pathways, preferential and matrix flow (see **Table 1.1 & Figure 1.2** ; Michaud, Poirier, & Whalen, 2019; Zhang, Zhang, & Zheng, 2016). Matrix flow typically moves more dissolved P compounds through micropores (**Figure 1.3**) while preferential flow transports both dissolved and particulate P through macropores (**Figure 1.3**) to tile drains (Michaud, Poirier, & Whalen, 2019; Steenhuis et al., 1994). Tile drains and their influence on surface soil moisture often facilitate the formation of macropores, therefore increasing P transport through preferential flow pathways, which bypass the buffering potential of the soil matrix (Eastman et al., 2010, Macrae et al., 2021; King et al., 2015). Within the Great Lakes region, tile drains can account for 47–66% of annual dissolved P export, but under some conditions could account for up to 95% (Van Esbroeck et al., 2016; Williams et al., 2016). A multi-year study found that tile-drained sites across southern Ontario exported 40 to 77% of TP load and 19 to 67% of total SRP load (Van Esbroeck et al., 2016). The timing, magnitude, rate, and form of P in tiles drain effluent is suggested to depend on multiple factors including environmental conditions and land use management practices (Beauchemin, Simard, & Cluis, 1998; Kokulan et al., 2019; Macrae et al., 2007; Van Esbroeck et al., 2016).

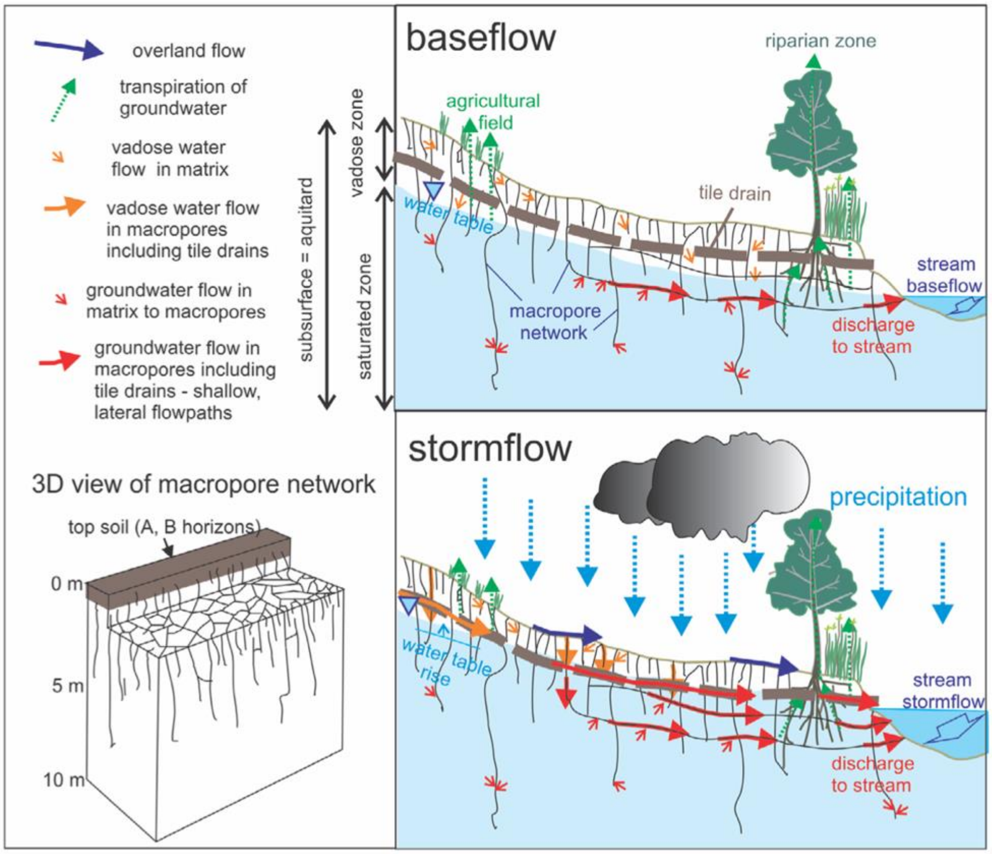

Figure 1.2. Conceptual model of different flow paths from Van Stempvoort et al. (2021) which illustrates concepts and flows described in **Table 1.1**. The larger the arrow, the more rapid the movement of water through those particular pathways. Therefore, the smaller, thinner arrows represent gradual infiltration of water through the soil profile (matrix flow), while the longer, thicker arrows indicate the more rapid movement of water through soil macropores (preferential flow). This figure helps to illustrate the episodic nature of tile drains, and how soil which are more susceptible to macropore formation can lead to greater flow through tile drains.

Factors Influencing P transport from tile drains

Hydrology, climate, soil characteristics, tillage practices and fertilizer management are all factors that can influence the P export from tile drains, and these will be discussed separately in more detail.

Hydrology and Climate

Phosphorus transport through tile drainage can vary temporally with changes in hydrologic conditions (baseflow and event flow; King et al., 2015). Variations in regional climate (i.e. precipitation, temperature, freeze-thaw cycles) can influence P export from agricultural lands. Phosphorus loss is understood to be episodic in tile drainage, driven by precipitation and snow melt events (King et al., 2015; Lam et al., 2016 Macrae et al., 2007; Van Esbroeck et al., 2017; Van Stempvoort et al. 2021) in cool, temperate climates such as the Canadian Lake Erie Basin (CLEB). Studies have suggested that 40-50% of watershed flow can originate from tile drains (King, Fausey, & Williams, 2014; King, Williams & Fausey, 2015, Macrae et al., 2007), which have been seen to export 16-41% of total annual precipitation (Lam et al., 2016). Both TP and dissolved P losses from tile drains have been correlated to major precipitation events in both the growing (typically May to September; Lam et al., 2016; Williams et al., 2016) and non-growing seasons (King, Fausey, & Williams, 2014; King, Williams & Fausey, 2015, Lam et al., 2016, Macrae et al., 2007; Van Esbroeck et al., 2017). Throughout the growing season, the influence of precipitation on dissolved P losses from tile drains can be quite variable, dependent on tillage and fertilization practices (Williams et al., 2016). In contrast, P export during the non-growing season seem to be more influenced by the snow melt and major precipitation events when there is a lack of vegetative cover and legacy P within the soils (Lam et al., 2016; King et al., 2015, Macrae et al., 2007).

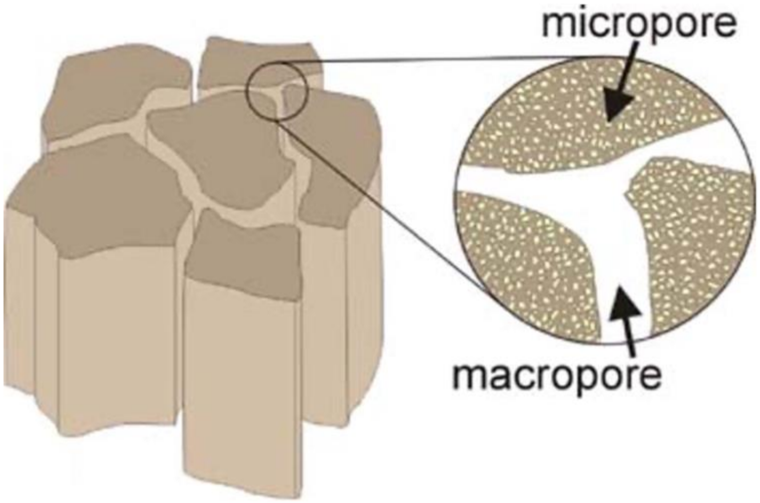

Figure 1.3. Diagram depicting the geometric characteristic of soil pore space from Dampier (2013; https://wiki.ubc.ca/File:16.1.1macro%26micropores.jpg). Macropores (diameter > 0.01 mm) are the larger spaces that occur between aggregates or individual soil grains which readily allow for the movement of air and water while also providing space for plant roots and soil organisms to inhabit the soil (Latshaw, Fitzgerald, & Sutton, 2009). Micropores (diameter < 0.01 mm) occur within aggregates, are often filled with water, allowing minimal movement of air (Latshaw, Fitzgerald, & Sutton, 2009).

Soil Characteristics

Soil texture is a major driver of dissolved P losses through subsurface drainage. Clay soils in temperate climates have a much smaller P storage capacity than comparable soils from warmer climates (Simard, Drury, & Lafond, 1996) and have shown to have greater TP losses than medium- and coarse-textured soils (Beauchemin, Simard, & Cluis, 1998). Presence of macropores (**Figure 1.3**) tends to increase from coarse- to fine-texture soils. For example, macropores that promote preferential flow are present in sandy loam soils, but they are often formed by biological activity (i.e. plant roots and earthworms) compared to cracking in shirking clay soils (Lam et al., 2016). Therefore, medium-to-moderately coarse-textured soils are less sensitive to the impacts of management (specifically tillage and fertilization) on P transport from tile drains (Lam et al., 2016). Beauchemin, Simard, & Cluis (1998) found that SRP made up the largest fraction of TP (78-86%) in tile effluent that drain clay soils, and suggested that clay-dominated soils can lead to large loading of SRP in tile drainage. However, this is contradicted by findings of Eastman et al. (2010), who found that clay soils were dominated by particulate P, accounting for 76-84% of TP whereas sandy loam soils were dominated by dissolved P, accounting for 68-83% of TP. These inconsistencies are likely because of confounding effects of precipitation and on-field cover, as clay soils with moderate-to-high P content can experience P losses in the particulate form under extreme precipitation events that favour rapid movement of water through macropores (Beauchemin, Simard, & Cluis, 1998, Van Esbroeck et al., 2017).

Tillage

Tillage practices can also influence P transport in both surface runoff and subsurface tile drains. This disturbance of surface soils that occurs under conventional tillage practices has been blamed for P export from fields through overland runoff, as they increase the risk of erosion and therefore allows for more particulate-bound P to be transported through runoff (Busari et al., 2015). Conservation tillage, which is any form of soil manipulation that leaves at least 30% of the soil surface covered with crop residue after planting (Busari et al., 2015), has been used as an agricultural best management practice (BMP) to combat nutrient losses and erosion. Despite this, conservation tillage methods such as no-till can facilitate dissolved P losses through tile drains under certain conditions (Christianson et al., 2016; Kleinman et al., 2009; Lam et al., 2016). This is because no-till often increases the presence of macropores (Sims et al., 1998), which then further facilitate agricultural P losses under extreme precipitation events through increased rapid preferential flow (Eastman et al. 2010; Williams et al., 2016; Van Stempvoort et al. 2021).

Fertilization Practices

The source, timing, rate and method of P application to agricultural fields all influence their fate and transport through subsurface tile drainage. Phosphorus is applied to fields in two main forms: organic (i.e. manure) and inorganic (i.e. phosphate based fertilizers). Some studies have reported large P concentrations from tile drains during the non-growing season where manure had been applied the previous growing season (Kleinman et al., 2009; Macrae et al., 2007). In addition, there were higher SRP and TP concentrations in tile effluent from fields that received a mixture of inorganic fertilizers and organic manure, compared with fields that only received inorganic fertilizers (Christianson et al., 2016). Van Esbroeck et al. (2016) suggested that variations in P export from tile drains where fertilizers have been applied may depend upon the site history of P management and legacy P retained by the soils. Accordingly, application methods may also play a role, as broadcasting of fertilizer and manure can result in higher P export through tile drains mainly though preferential flow, whereas subsurface placement (ie. injection) can reduce P export (Kokulan, 2019). While no or reduced-till has been a recommended best management practice to reduce surface P runoff, plowing-in or significantly incorporating solid manures has been recommended to reduce SRP and TP losses from agricultural land via drainage systems because these methods disrupt the hydraulic conductivity of soil macropores (Van Esbroeck et al., 2016).

The Canadian Lake Erie Basin

The Canadian Lake Erie Basin (CLEB), which encompasses most of southwestern Ontario and the northern Lake Erie drainage basin, has not been immune to the extreme water-quality impairments documented in the U.S. portion of Lake Erie Basin over the last few decades. Located in the Carolinian zone, the CLEB contains areas of extremely high biodiversity, including some of the most endangered and rare species in Canada (Reid, 2002). The major tributaries of the CLEB, the Sydenham, Thames and Grand Rivers are home to many rare mussel, fish, reptile plant and invertebrate species, and are also some of the most important recreational waterways in Ontario (Kanter, 2005). Unfortunately, despite their importance for biodiversity, drinking water and recreation, water quality impairments associated with urbanization and agricultural practices have severely impacted the health of freshwater systems in this region, similar to those in the WLEB. For example, the proportion of large-scale cropping has also increased in Ontario, despite the total number of farms decreasing in some regions like Southern Ontario (Smith, 2015). With this increase comes the increased presence of P amendments to increase yield and plant health, irrigation, and artificial drainage which ultimately leads to increases in P entering surrounding waterways. Smith et al. (2019) suggested that if left unchecked, the harmful and nuisance algae in the CLEB (who tributaries discharge directly into both the Western and Eastern Lake Erie basin) will cost Canadians approximately $272 million (of 2015 prices) over a 30-year period due to declines in tourism and recreation.

Despite the large contribution of phosphorus to Lake Erie from the tributaries of the CLEB, they remain understudied compared to those of the WLEB, leaving a large knowledge gap that hinders development of effective management and restoration initiatives. My thesis addresses this information deficit by using data collected in the recent decade from three main tributaries in the CLEB (Thames, East Sydenham and Grand Rivers) to examine how tile drainage may be influencing seasonal trends in P export across the CLEB and to determine if there are increases in SRP loading in these tributaries similar to those in the WLEB.

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Chapter 2: Effects of tile drainage on seasonal phosphorus loading across three major Canadian Lake Erie tributaries

Rachelle Fortier

Alana Tedeschi

&

Patricia Chow-Fraser

McMaster University
Department of Biology,
1280 Main St. West
Hamilton, ON. L8S 4K1

Keywords: Phosphorus, Soluble Reactive Phosphorus, Tile Drainage, Seasons, Loading, Eutrophication

Abstract

The re-appearance of harmful algal blooms in the western basin of Lake Erie in recent decades has been attributed to increased loading of soluble reactive phosphorus (SRP) in US tributaries, which has been broadly linked to agricultural practices, artificial (tile) drainage, and climate change. In this study, we investigate if similar temporal trends in SRP loading exists for three major Canadian tributaries and if increased loading can be related to increased proportion of tile-drained area in watersheds. Though the proportion of tile-drained area in watersheds vary among the tributaries (58%, 49% and 24% in the East Sydenham River (ESR), Thames River (TR) and Grand River (GR), respectively), the proportion of tiled drainage in watersheds of all three tributaries has increased from 2004 to 2021. When sorted by crop season, standardized SRP and TP load (kg/d/km^2) increased significantly through time for all tributaries during the late winter-early spring (LWES), which appeared to be related to both increased discharge and concentrations of P. The ESR was the only tributary to experience significant increases in SRP and TP loading through time in the growing season and fall. We found no significant temporal trends in concentrations/loads of either P forms during winter except for increased TP concentration in the TR. Whereas increased P load during the growing reason in the ESR (watershed with the highest proportion of tile drainage) appears to be driven by increased discharge, the increased P load during the fall appeared to be driven by increased P-concentration. Although mean monthly and seasonal P concentrations/loads varied across tributaries, the dissolved portion of TP was consistently highest in January. Our results confirm that SRP loading from the Canadian tributaries has been increasing over the past decade during LWES, and that tile drainage is a significant driver of SRP across all seasons; however, tile drainage is likely not playing the same role in P transport across all seasons in each tributary.

Introduction

The presence of harmful and nuisance algal blooms has been an issue within the Lake Erie Basin for many years, and has been significantly related to both point source (i.e. municipal wastewater) and non-point sources (i.e. agricultural runoff) phosphorus (P) inputs (Jarvie et al., 2017; Van Meter et al., 2020). With implementation of the Great Lakes Water Quality Agreement in 1972 targeting point source P, total P (TP) loadings were reduced by more than half by the mid-1980s, and this eliminated problems associated with eutrophication during the late 1980s and 1990s (International Joint Commission, 2014). TP loadings have remained relatively unchanged since 2000, although 71% of TP loads in recent years have been dominated by non-point sources (Joosse & Baker, 2011; Maccoux et al., 2016). Despite consistent declines in TP loading, there has been a resurgence in algal blooms in the Western Lake Erie Basin (WLEB) during the early 2000s that was attributed to SRP loading from agricultural runoff from U.S. tributaries (Jarvie et al., 2017; Daloğlu et al., 2012, Kane et al., 2014). A similar increase in soluble reactive P (SRP) loading from tributaries of the Canadian Lake Erie Basin (CLEB) has not been investigated, even though the proportion of large-scale cropping has also increased in southern Ontario (Smith, 2015).

Trends in soluble reactive phosphorus in Lake Erie

In general, the non-growing season (typically October-April) in temperate regions has been identified as a critical time for P export (particularly SRP), since P is readily transported in runoff when crops have been removed from agricultural fields (Lam et al., 2016; Macrae et al., 2007; Stow et al., 2015; Van Esbroeck et al., 2016). For example, Van Esbroeck et al. (2016) found that 83 to 97% of annual combined surface and subsurface runoff (84 to 100% of SRP export, 67 to 98% of TP export) occurred between October to April at three edge-of-field plots across southern Ontario. The combination of subsurface tile drainage along with other landcover characteristics (agricultural management, soil characteristic climate variables) has been suggested to be a major driver for these trends, as it can facilitate the form and rate of transport of P from agricultural landscapes (Kokulan, 2019).

Increased SRP loading from agriculturally dominated watersheds within the U.S. tributaries of the Lake Erie Basin has been well documented (Jarvie et al., 2017; Daloğlu et al., 2012, Kane et al., 2014, Stow et al., 2015). Using long term data sets and predictive modeling, Daloglu et al. (2012) first demonstrated that agricultural practices since the mid 1990s (i.e. increases in fertilization, conservation tillage) combined with severity of storm events can all be linked to increases in SRP from the Sandusky River into western Lake Erie. Kane et al. (2014) then related increases in cyanobacterial biomass to both SRP concentration and load in the WLEB. Jarvie et al. (2017) hypothesized that agricultural land-use practices (conservation no-till tillage practices and tile drainage) increased SRP delivery from the Maumee, Sandusky and Raisin River watersheds. Stow et al. (2015) evaluated the seasonal P trends in the Maumee River watershed and found that TP concentrations have been relatively unchanged since the 1990s, but SRP concentrations have increased, especially during March, when there were also increased discharge from storm events.

East Sydenham, Thames and Grand Rivers

Compared to the tributaries of the WLEB, there is much less known about trends in TP and SRP in the CLEB and its tributaries. The East Sydenham River (ESR; located in the southwestern portion of the CLEB), the Grand River (GR; located at the northeastern portion of the CLEB) and the Thames River (TR; located between the East Sydenham and Grand Rivers) are all under immense pressure from agricultural and urban expansion. These tributaries are located in Southern Ontario, which is the most populated and most agriculturally dominated regions in Canada (DeBues et al., 2019). Southern Ontario is also the location of a large proportion of Canada’s prime agricultural land. Southern Ontario specifically is responsible for most of the province's considerable agricultural output, amounting to approximately 15% of Canada’s net farm income in 2017 (DeBues et al., 2019).

Even with their close regional proximity, there is high variation in climate, topography, soil texture and land use and land cover (LULC) among tributaries. There is a southwest to northeast gradient of climate conditions, soil type, topography and land uses as one moves from the ESR Watershed to the GR watersheds, with lower mean annual temperatures and annual precipitation, increase in duration of snow cover, increase in particle size (clay to loams), mean slopes and urbanization (Macrae et al., 2021). Therefore, the ESR watershed represents the warmest, most agriculturally dominated, clay dominated, and flattest tributary in the CLEB, whereas the GR watershed has the most diverse land uses, is steepest and contains the most coarse-textured soils. The TR watershed has intermediate characteristics and is transitional between the other two watersheds. Tile drainage is also a dominating agricultural feature in the CLEB. Tile drainage is most prevalent in the more poorly drained clay soils of the ESR watershed and decreases in prevalence in the TR and GR watersheds (Macrae et al., 2021).

All tributaries are known to contribute substantial P to Lake Erie (Staton et al., 2003; Shaker, 2014; Van Rossum & Norouzi, 2021); however, less is known about how they compare to each another and what factors may be influencing trends in P loading and concentrations through time. The diversity in landscape characteristics and tile drainage composition make these tributaries ideal for examining factors that influence seasonal P loading in the CLEB.

In this study, we examine the effect of tile drainage on seasonal trends in P loading across the three Canadian Lake Erie tributaries. Our main objective is to determine if similar seasonal increases in SRP loading to the WLEB from the U.S. tributaries are occurring in tributaries of the CLEB. Based on what we know from the WLEB about the influence of tile drainage on SRP at the smaller watershed and edge-of-field scales, we test the predictions that: 1) the highest P loading will be observed in the non-growing seasons, specifically during the late winter-early spring (LWES), 2) SRP loading has been increasing through the past decade across all tributaries during LWES, and 3) P loading will be higher in tributaries with higher density of tile drains, specifically during the non-growing seasons (including winter and fall). Results of this thesis should provide a better understanding of the effects of tile drainage and shed light on factors that are influencing the re-eutrophication of Lake Erie.

Methods

Study areas

In this study, we included all sub-watersheds in the CLEB that fit the following three criteria: 1) watersheds should include a gradient of land uses from agriculturally dominated to more mixed-land use 2) watersheds should include areas with tile drainage and 3) there are long-term monthly data for SRP and TP concentrations and corresponding discharge rates to calculate annual P loads. The three drainage basins that fit these criteria were the sub-watersheds of the East Sydenham River (ESR), the Thames River (TR) and the Grand River (GR), and which together accounted for 61% of the CLEB (**Figure 2.1**).

Delineation of land use/land cover (LULC) classes

We downloaded the relevant shapefiles for the three river basins from the United States Geological Survey (USGS) ScienceBase Catalog (Great Lakes and Watersheds Shapefiles; https://www.sciencebase.gov/catalog/item/530f8a0ee4b0e7e46bd300dd). To determine yearly land use/land cover (LULC) changes within each watershed, we used information from the Agriculture and Agri-food Canada's (AAFC) Annual Crop Inventory (ACI; 2012-2019). All data layers were imported into ArcGIS Pro 2.8.2 (ESRI 2021) where data were clipped to each watershed. Agricultural practice employed each year between 2012 and 2019 were classified into "row crop" (corn + soybean + cereal grains + wheat), "pasture/forage" or "other agriculture" (fruits + vegetables + other specialty crops + other agriculture), in addition to "natural" (forest, wetlands and grasslands) and urban land cover. The proportion of sub-watershed area corresponding to each LULC class was then calculated for each year in the ESR, TR and GR watersheds.

We determined the cumulative annual area of tile drainage in each of the three river basins between 2004 and 2021 using annual data obtained from the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA, 2022). Cumulative tile area per year was calculated by summing the tile area installed each year and adding it to the total tiled area from the previous year. Maps in this study were produced with QGIS v.3.22.

Calculation of slope

To determine mean slope for each watershed, we used the provincial digital elevation model (DEM; Ontario Open Government, 2021). In ArcGIS Pro 2.8.2, we first used the Fill tool to eliminate sinks in the DEM. We then use the Slope tool to determine the change in slope (precent rise, %) across each watershed, which created a new slope raster layer. We then use the Zonal Statistics (as Table) tool to calculate the mean slope per watershed ± the standard error.

Long-term nutrient, discharge data and load calculations

We downloaded SRP and TP concentrations (µg/L) for the ESR, TR and GR collected from 2012 to 2019 from the Environment and Climate Change Canada (ECCC) Priority Tributary Nutrient and Water Quality Monitoring program (PTNWQMP portal: https://datastream.org/dataset/082d57d8-44dc-460d-bca2-67ebf83a64cc; DataStream ,2022). This was the only publicly available long-term dataset that included both SRP and TP concentrations collected monthly throughout the calendar year in the past decade. The names of the monitoring stations were: *ESR at Florence*, *TR at Thamesville* and *GR at York* (see **Figure 2.1**). ECCC collected water samples from the rivers using automated samplers on a minimum bi-weekly basis; additional samples were also taken during weather-induced flow events (DataStream, 2022). In some cases, multiple samples were taken per day. Given the unevenness of sample sizes for each month and the fact we had no objective way to eliminate data for months with larger amount of data, we decided to calculate means for each month/year on a site-by-site basis, so as not to bias our temporal trend analyses. Due to large data gaps in 2016 (more than 3 months with no data through the year), we had to exclude all PTNWQMP data from this study.

We obtained daily discharge (m^3/day) data from ECCC through the Water Survey of Canada (WSC) monitoring program (https://wateroffice.ec.gc.ca/search/historical_e.html) for hydrometric gauging stations located closest to nutrient sampling stations located on the ESR at Florence and TR at Thamesville (ECCC, 2022). Since the WSC monitoring station on the GR at York has been inactive since 1923, we obtained daily discharge data from the Grand River Conservation Authority (GRCA; https://data.grandriver.ca/downloads-monitoring.html) at the York monitoring station for this study (GRCA, 2022). We calculated monthly SRP and TP loads from 2012 to 2019 using mean monthly concentrations and mean monthly discharges, and then standardized the data as kg/d/km^2 for cross-site comparisons.

Selection of Seasons

For this study, seasons were selected based on agricultural activities and prevailing weather conditions. Months were grouped into four seasons; 1) Winter (WINT – January and December), 2) Late winter/early spring (LWES – February, March and April), 3) Growing season (GROW – May to September), and 4) Fall (FALL – October and November). These distinctive seasons were first described and used by Tedeschi and Chow-Fraser (unpublished manuscript). WINT is characterized by typically frozen soils, snow cover, increased water availability and typically bare agricultural soils (unless cover cropped; Nutrient Management

Act, 2022; OMAFRA, 2010b; Li et al., 2016; OMAFRA, 2016). LWES is characterized by frequent storm and thaw events, prominent snowmelt, saturated and bare soils (unless cover cropped; Li et al., 2016; Wuebbles et al. 2018; OMAFRA, 2016), and also represent the main crop planting period toward the end of the season (Li et al., 2016). GROW is characterized by low precipitation (and therefore runoff), covered soils, and active water/nutrient uptake by growing crops (Li et al., 2016; Wuebbles et al. 2018). Finally, FALL is most characterized by decreased precipitation and increased air temperature relative to WINT and LWES, while also being the primary time for crop harvest with large machinery, post-harvest tillage (with the exception of conservation tillage systems) and has bare soils (Wuebbles et al. 2018; OMAFRA, 2016).

Statistical methods

Statistical analyses were performed with SAS JMP software version 16.2.0 for MacIntosh (SAS Institute Inc.). For regression analyses proportions were arcsine-transformed. The Mann-Kendall test was used to evaluate long-term seasonal trends and changes. The Kruskal-Wallis rank sum test was used to test for inter-watershed variations. All means reported are arithmetic.

Results

Comparison of tributary characteristics

The ESR watershed is the smallest (1,537 km^2) and is 23% smaller than the GR, which is 6,786 km^2; by comparison, the TR watershed has an intermediate size (5,680 km^2) and is 84% of the GR watershed (see **Figure 2.1**). The mean slope of the ESR watershed was calculated to be 1.31 ± 1.97, and it is almost half the mean slope of 2.78 ± 3.10 calculated for GR; TR has an intermediate mean slope of 1.82 ± 2.62. Overall, moving from northeast From the ESR to the GR, there is a gradient from row crop dominated to more mixed-use (more natural and urban land cover; **Figure 2.2**), from more heavily tile drained to least heavily tile drained (**Figure 2.5**), and from fine- to medium-textured soil particles (Macrae et al., 2021).

Annual and seasonal P load and concentration

To investigate the seasonal variation in P loading across the tributaries. we first inspected month to month changes in concentrations of SRP and TP in the three watersheds. In all cases, TP concentrations were initially high during spring months, fell to low levels during summer months, and then rose again during the fall (**Figure 2.4**). Specifically, highest TP concentrations occurred in April in both ESR and the GR, whereas they occurred in November in the TR. By contrast, SRP concentrations were initially high during January and then remained low after March and stayed low during the summer months until they peaked in November (**Figure 2.4**). For both the ESR and the TR, the second highest concentrations were measured during January, whereas in the GR, they occurred in March. There were more similarities among tributaries when examined on a seasonal basis; mean SRP concentrations were highest in the FALL for both ESR and TR, but highest in the LWES for the GR (**Table 2.1**). Mean TP concentrations were highest during LWES for ESR and GR, but highest in the FALL for the TR (**Table 2.1**). Finally, when we calculated monthly mean TP and SRP concentrations across all years from 2012 to 2019, P concentrations were highest in the TR and lowest in the GR (**Table 2.2**).

The proportion of TP that was in the dissolved form (i.e. SRP) changed throughout the calendar year in all three tributaries but were more consistent among the rivers, with the least amount of monthly variations occurring in the GR (**Figure 2.5**). Mean proportion of SRP was highest in all tributaries in January (48.8% in the ESR; 59.3% in TR and 37.3% in the GR). In the ESR and TR, the second highest proportion of SRP was reported in December (47.7% and 42.6% respectively), whereas in the GR, the second highest proportion occurred in February (34.5%). Across all tributaries, the mean proportion of SRP decreased between January and April and then increased steadily from September to December (**Figure 2.5**). When grouped by season, WINT had the highest mean proportion of SRP across all tributaries, followed by the FALL in the ESR and TR but LWES in the GR (**Table 2.1**). The lowest proportion of SRP for all tributaries occurred during the Growing Season **(Table 2.1).** Over the study period as a whole, the mean proportion of SRP was highest for ESR, with a SRP:TP ratio of 0.34, whereas those for TR (0.30) and GR (0.24) were lower (**Table 2.2**).

We also compared mean daily P loads across the three rivers on a monthly basis. Because of the high monthly variations, there were no significant differences in mean SRP or TP loads among the three tributaries (Kruskal-Wallis test; P=0.4485 and 0.3188, respectively). Nevertheless, the highest calculated loads were recorded for TR, due largely to the relatively high P concentrations. Despite the relatively low TP concentration in the GR however, TP loads were almost the same as that for the ESR, as the Grand River mean discharge (0.0168) was 72% higher than ESR (0.0121; **Table 2.2**).

When we examined P loads on a seasonal basis for each tributary, we found very different patterns. The highest SRP loads occurred during WINT in ESR, during the FALL in the TR, and during LWES in the GR (**Table 2.1**). In all cases, SRP loads were lowest during the Growing Season, by more than 75% in all cases. By comparison, TP loads were highest during LWES and lowest during the Growing Season for all tributaries (**Table 2.1**). The summer loads were lower than LWES loads by 66 to 75% across the three tributaries.

Seasonal P load, P concentration and discharge changes through time

Given the significant seasonal trends in P concentrations and loads for each tributary, it would have been inappropriate for us to examine temporal changes without accounting for the different seasons. In the ESR, SRP concentrations increased significantly during LWES and the FALL, while in the GR, they increased significantly only during LWES (**Figure 2.6a**). In the TR, SRP concentration did not change significantly in any season (**Figure 2.6a**). SRP loads increased significantly for all three tributaries during LWES (**Figure 2.7b**). In addition, we found significant positive temporal trends during the Growing Season and the FALL for ESR. The pattern of significant temporal increases in TP concentrations were repeated for ESR and GR (**Figure 2.7a**). For TR, we also found that TP concentrations increased significantly through the years during both WINT and LWES. The same pattern of significant increases was repeated for TP load, with significant increases through time during LWES for all three tributaries and additional significant increase during GROW and FALL for ESR (**Figure 2.7b**). Change in discharge through time was also variable across tributary watersheds, with significant increases only observed for the ESR during LWES and the Growing Season as well as a significant increase for the GR during LWES (**Figure 2.8**). There was no significant change in discharge during any season for the TR.

Land use and land cover trends and tributary characteristics

Lastly, we conducted LULC analysis to better understand what LULC changes have occurred in each tributary watershed from 2012 to 2019, and how these changes may have influenced trends in P loading. We found that the proportion of LULC categories only changed slightly over this period in the ESR (**Table 2.3**). The % Natural land cover in the ESR has dropped significantly from 1.14% to 1.06% (Mann Kendall τ = -0.71, p = 0.013), while %Pasture/Forage has significantly increased from 7.6% to 9.5% (Mann Kendall τ = 0.57, p = 0.048; **Table 2.3**). The %Row Crop has decreased in the ESR from 75.1% to 73.2%; however, it was not a significant change. Although there were no significant changes over time in any LULC classes for TR, %Row Crop has increased marginally from 66.7% to 68.1%, while % Pasture/Forage decreased marginally from 12.4% to 11.1%. Again, there were no significant temporal changes in any LULC in the GR watershed; however, %Row crop has increased and %Pasture/Forage has decreased. Although the %Urban land in all three watersheds have increased at a few points between 2012 and 2019, there was no significant change in %Urban land cover in any tributary.

The total amount of tile drainage areas in the three watersheds has increased from 2004 to 2021, and when expressed as proportion of total watershed area, the proportion was highest for ESR and lowest for GR (**Figure 2.9**). The rates of change have been similar across the three watersheds, but the ESR experienced the greatest increase (84%) between 2004 and 2012, while over the same time period, the TR and GR increased by 82% and 73% respectively.

Finally, we found significant positive linear relationships between SRP concentration and proportion of tile drainage in all seasons and all tributaries (**Figure 2.10**). TP concentrations and proportion of tile drainage were significantly related across all seasons except for FALL (**Figure 2.10**). The strongest relationship between P concentrations and proportion of tile drainage were associated with the Growing Season (**Figure 2.10.** $p < 0.0001$ for SRP and $p=0.0084$ for TP). Although the largest rate of change (slope) was associated with the relationship between SRP and proportion of tile drainage during FALL, the associated relationship between TP and proportion of tile drainage was highest during LWES (**Figure 2.10**).

Discussion

Influence of LULC in subwatersheds

P concentrations and loads were higher in the more heavily agriculturally dominated and tile-drained ESR and TR tributaries (ESR = 83% agriculture with 58% tile-drained; TR = 80% agriculture with 49% tile-drained) than in the more mixed-use GR watershed (68% agriculture with only 24% tile-drained, and the remaining 9% urban and 18% natural). It is important to note that the mean SRP concentrations were almost 1.8 to 1.9 times higher in the ESR and TR than in the GR, but the TP concentrations were only 1.4 to 1.6 times higher, indicating that the proportion of soluble P in the GR was substantially lower. Since the mean total discharge (adjusted for differences in watershed size) was highest in the GR and lowest in the ESR, the calculated SRP load for the ESR was only 1.3 times higher than that for the GR.

Variations in P across tributaries

Our results support the hypothesis that the non-growing seasons (winter, LWES and fall) are the most critical times for P export from agricultural land across the CLEB. In this study, the non-growing seasons contributed to 83-85% of SRP and 76-79% of TP concentrations, as well as 90-94% of SRP and 74-89% of TP loading. As expected, the LWES was a critical time for both TP and SRP loading across all watersheds, with the highest TP loading in all tributaries currently occurring during LWES. This is presumably because high export of P from surface runoff occurs during and after extreme precipitation and snowmelt events in March and April (Macrae et al., 2007, Van Esbroeck et al., 2016). We also noted the tendency for TP and SRP concentrations and loads to increase in the ESR and TR during fall (November, specifically), which we attribute to fertilizer application in these subwatersheds with higher agricultural land use and tile drains.

During late fall, the soil moisture is high, soils are unfrozen, and fields lack the vegetative cover to retain the SRP; therefore, tile drainage could be continuously contributing SRP via sub-surface flow (Baker & Laflen, 1983, Kleinman et al., 2009, Macrae et al., 2007, Van Esbroeck et al., 2016).

We found high variation in proportion of dissolved P among seasons and among tributaries. The most highly tile-drained watershed, the ESR, had the highest mean SRP:TP ratios of all the tributaries (0.34) over the study period, followed by the TR (0.30) and then the GR (0.24). Seasonally, the highest SRP:TP ratios for each tributary occurred during the winter (ESR: 0.48, TR: 0.47, GR: 0.35). We found the highest proportion of dissolved P in January across all tributaries, possibly because the onset of extreme flow events associated with winter thaw and snowmelt periods increases the tile discharge (Macrae et al., 2007; Van Esbroeck et al., 2017; Lam et al., 2016; Van Stempvoort et al., 2021). Even though our study was conducted at the basin scale, our results are in-line with the edge-of-field studies conducted in this region. Similar to our findings, Van Esbroeck et al. (2017) found that most P export in both surface runoff and tile drains occurred during peak-flow events within the non-growing season, specifically January. These peak events accounted for 65-75% of combined annual runoff (surface and tile flow) and 90-96% of SRP export; however, surface runoff exclusively accounted for 44-83% of the SRP export which were highest in January (Van Esbroeck et al., 2017).

High winter SRP concentrations and loads have been partly explained by frozen surface soil conditions, which can increase the export of P during runoff and freeze-thaw events when crop residue and decaying plant matter are present on fields (Elliot, 2013; Van Esbroeck et al., 2017; Weyers et al., 2021). The presence of crop residue and decaying plant material (sometimes due to unsuccessful cover crops like winter wheat) are common in no or reduced-till conservation tillage systems which are becoming increasingly prevalent in Ontario (Liu & Brouwer, 2022; OMAFRA, 2018). Currently, approximately 38% of Ontario farmers use some kind on conservation tillage on their farm (Liu and Brouwer, 2022), and the percentage of crop land undergoing conservation tillage in Ontario has increased from 21.8% to 61.9% between 1991 and 2016 (OMAFRA, 2018). SRP export can also increase in the winter with the presence of tile drainage, since winter infiltration is prevalent in temperate climate of the southwestern Lake Erie basin and the ESR (Macrae et al., 2021). This is because freezing does not appear to impede subsurface flow in tile drains since there is flow year-round (Plach et al., 2019); however, in colder climates, where ground frost is more prominent, sub-surface flows may be impeded during winter (Kokulan et al., 2019). Additionally, tile drains in no-till or reduce-till systems (especially with clay soils) are more susceptible to macropore formation, and therefore preferential flow is more common (King et al., 2015). This can allow for the rapid movement of SRP and PP runoff through the soil matrix during snow melt and storm events, increasing concentrations in winter and LWES tile effluent (King et al., 2015).

Influence of tile drainage on P trends

While there only a few significant LULC changes have occurred in each subwatershed since 2012, tile drainage has increased steadily in each watershed since 2004. This is no doubt because of the active promotion by the Province of Ontario, which is prompted by the agronomic benefits of tile drainage, that includes increased crop production due to improved crop health and root structure, and earlier access to fields when there is reduced surface soil moisture (Eimers, Liu & Bontje, 2020). Since 2007, OMAFRA has run the Tile Loan Program (under the Tile Drainage Act) that gives property owners and farmers the opportunity to apply for loans to install tile drainage on their property (Eimers, Liu and Bontje, 2020). The rate of tile drainage expansion in southern Ontario, specifically in the furthest southwest region and the CLEB, is increasing at a more rapid rate that urban expansion over the past 20 years (Eimers, Liu & Bontje, 2020). These increases have also been attributed to higher grains and oilseed prices, which have influenced not only the installation of new tile drainage systems but also the repair/replacement of old systems (Smith, 2015). However, it is important to note that the current total area of tile drainage in Ontario is likely an underestimation. This is due to the advanced age of many tile systems where records may not align with modern record keeping, and that privately installed tile systems are not required to be reported (Eimers, Liu & Bontje, 2020). Additionally, the efficacy of tile drains can change over time, as drains could become damaged and move less water due to factors such as clogging from roots and sediments, cracking from freeze-thaw events and rodent chewing (OMAFRA, 2010a). Therefore, there is a possibility that not all tile systems currently present in the CLEB are contributing to P and water transport equally, solely based on the age and quality of the tile drains. However, it is assumed that if the properly maintained, tile systems can last a "lifetime" (OMAFRA, 2010a)

This increased presence of tile drainage across the CLEB cannot be ignored when trying to understand what factors are influence P loading within the Lake Erie Basin. Most notably, we found that tile drainage is playing a significant role in seasonal loads of SRP and TP, which are inextricably linked to discharge. We found a significant positive relationship between SRP and TP concentrations and the annual proportion of tile drainage across all watersheds and seasons, except for TP concentration in the fall. We suggest that tile drainage may play a significant role in P loading during the growing season because the most highly tile-drained watershed (ESR) was the only one where we observed increased SRP and TP loading during the growing season.

Recent studies have shown that tile drains can transport large proportions of both particulate P (PP) and SRP, especially when present in finer textured soils (Smith, 2015; Williams et al., 2016; Macrae et al., 2007). In all cases, we found a significant increasing trend in TP and SRP concentrations and loads during LWES, except in TR, where SRP concentration did not show an increasing trend. These increases in load and concentrations are not unexpected, as many studies have seen highest P export in agricultural landscape during extreme flows after significant snowmelt and precipitation events between January and April (Macrae et al., 2007; Van Esbroeck et al., 2017; Lam et al., 2016; King, Fausey, & Williams, 2014). Jarvie et al. (2017) found significant increases in cumulative yearly SRP load across three WLEB watersheds since 1974 and attributed the change to the increased prevalence of both conservation tillage and tile drainage. At the seasonal scale, Stow et al. (2015) also found that TP, SRP, and discharge have significantly increased in March since the 1990s in the Maumee River watershed in the WLEB. Because March generally precedes peak precipitation in the Maumee River watershed, these increases were linked to runoff from snowmelt and high soil moisture and agricultural activities like fertilizer application post-harvest (Stow et al., 2015).

While few watershed-scale studies have evaluated long-term trends in seasonality, many studies based on edge-of-field and headwater streams have noted the significant role tile drainage plays in seasonal P export and loading (Beauchemin et al., 1998; Plach et al., 2018a; Van Esbroeck et al., 2016; Osterholz, Hanrahan & King, 2020; Macrae et al., 2007; Macrae et al., 2021). We found the most heavily tile-drained watershed, the ESR, experienced significant increases in both SRP and TP loads over the past decade in LWES, growing season and the fall, but SRP and TP concentrations did not increase during the growing season. This could be explained by both the presence of crops and by the effects of tile drainage on watershed hydrology. During the growing season, the presence of crops and other growing vegetation actively up-take nutrients, making P less readily lost through surface runoff and tile flow (Kladivko et al., 2004). In spring or fall, fertilizers are often applied, and uptake is low, therefore increasing P availability and the potential for P exports from agricultural fields through runoff and tile flow (Kladivko et al., 2004).

While the presence of crops can explain why P concentrations are not increasing in the growing season but continue to increase in LWES and fall, it does not explain why SRP and TP loads are increasing. The increases in SRP and TP loads in the growing season (without increase in concentration) could be explained by the effect of tile drainage on watershed hydrology and discharge. There is limited evidence that tile drains increase total water export from a watershed or increase peak flows (Macrae et al., 2021); however, some studies have found that the contribution of tile drainage to overall discharge varies seasonally (King, Fausey, & Williams, 2014; Schilling and Helmers, 2008). King, Fausey, & Williams (2014) found that tile drainage can account for 47% of watershed discharge, with highest flows between November and March. By contrast, Schilling and Helmers (2008) found that tile drainage increased total streamflow and baseflow in the Walnut Creek watershed, and can contribute most to increases in annual baseflow in streams, primarily in late spring and early summer (April, May, and June). Schilling and Helmers (2008) noted that stormflows were clearly detectible in the tile drain hydrograph and that tile drainage accounts for a substantial portion of baseflows in highly drained watersheds.

Contribution to base flow were explained by higher water tables in late spring and early summer, with tile drains increasing the movement of groundwater to surface water (Schilling and Helmers, 2008). Groundwater would alternatively only be introduced through seepage if subsurface drainage were not present (Schilling and Helmers, 2008). The result from Schilling and Helmers (2008) could support why the heavily tile-drained ESR was the only watershed to experience a significant increase in discharge and P loading in the growing season, since P load is likely driven by increased discharge in the growing seasons and by P availability during spring and fall. Additionally, P export from tile drains is known to be episodic (especially in the clay soils of the ESR), and the increased presence of extreme rainstorm events due to climate change over the growing season is also likely contributing to increasing discharge, tile flow and P loading (Kladivko et al., 2004; Van Esbroeck et al., 2017). Summer storm intensity and frequency have also been estimated to increase by <10% in southwestern Ontario specifically (Rudra et al., 2015), which would likely mean that tile drains will continue to contribute more to watershed flow and loading in the future.

Our results show large variation in P export across CLEB tributaries, demonstrating that each plays a unique role in P loading to Lake Erie. There is a gradient of LULC, agricultural management, topography, soil, and climate characteristics across our study sites, all of which may influence the degree to which tile drainage affects P export from agricultural fields. The ESR, TR and GR are situated where they provide a gradient of change, from finer textured clay soils, row crop and tile drain dominated agricultural landscape in the ESR, to coarser textured loamy soils, more diverse crop, and urban mixed-use landscape in the GR. The TR almost perfectly represents a transitional zone between the ESR and GR, still dominated by agriculture and row crops, but also having a more diverse soil textures and topography, as well as a growing urban presence. While this study did not explicitly examine climate trends in relation to P export (due to a lack of consistent data available across our desired locations in the CLEB region), it is well known that mean annual precipitation, snow cover duration, and mean annual temperature also vary across the CLEB (Macrae et al., 2021).

These variations could help partially explain why the GR had the lowest P concentrations and loads compared to the ESR and TR, in addition to why P loading and concentrations were significantly increasing in the LWES exclusively. As we move toward the north and east of the CLEB where the GR is located, climate becomes colder, annual snowfall increase, there are fewer winter thaws or freeze–thaw cycles and therefore duration of snowpack is longer during winter (Macrae et al., 2021; Scott and Huff, 1996). Accordingly, higher snowpack produces more significant runoff in the spring, which also increase surface soil erosion and TP export (Macrae et al., 2021; Van Esbroeck et al., 2017). Additionally, due to cooler climates in the GR, one or a few peak melt events will occur in the spring, leading to more prolonged flooding (Macrae et al., 2007, Van Esbroeck et al., 2017, Macrae et al., 2021); by comparison, the warmer southwestern regions of the CLEB (the ESR and TR) experience multiple shorter events occur throughout the winter and early spring, rather than a main snowmelt event (Macrae et al., 2021; Plach et al., 2019).

Moving from southwest to northeast in the CLEB, the changes in slope and soil texture combined with tile drainage are likely to influence seasonal P export. Surface runoff and erosion are suggested to drive agricultural P export in the steeper, loamy soils such as those in the TR and GR watersheds, while tile drains play a more significant role in less steep and more clayey soils (Macrae et al, 2021; Plach et al., 2018b; Plach et al., 2019). Clay soils are very sensitive to P loss both hydrologically and biochemically, with tile drainage in these watersheds likely exacerbating the risk (Macrae et al., 2021). Since clay soils are more susceptible to macropore formation, especially in non-till environments that are tiled, preferential flow is more common and allows for rapid movement of SRP and PP runoff through the soil matrix during snow melt and storm events (King et al., 2015). Additionally, P in clay soils is often loosely bound and adsorbed to iron (Fe) oxides which are prone to desorption (Plach et al., 2018b), and therefore more vulnerable to mobilization in over saturated soils (Macrae et al., 2021). In contrast, while infiltration is still high in loamy soils during extreme snowmelt and precipitation events, P exports through tile drains are often less than in surface runoff that occurs at the same time (Macare et al., 2021; Van Esbroeck et al., 2016; Plach et al., 2019). This is because despite tile drains having maximum flow when discharge and runoff is high (e.g. LWES), loamy soils have stronger buffering potential and experience lower preferential flow and therefore proportionately lose less P compared to overland runoff (Macrae et al., 2007; Macrae et al, 2021). The trend towards higher TP concentrations in winter in TR may be due to increased frequency and earlier occurrence of extreme snowmelt, freeze-thaw and rain-on-snow events associated with a changing climate, as well as increased susceptibility of surface runoff.

Even though the GR subwatershed has comparatively steeper slopes and more loamy soils that together make it more prone to lose P through surface runoff, it consistently had the lowest TP and SRP concentrations across all seasons compared to the ESR and TR. This could be attributed to the mixed land-use with more natural landcover (forests, wetlands and grasslands) and less agricultural land. There is also a higher proportion of land with vegetative cover year-round (natural land and pasture; **Table 2.3**). Nevertheless, the GR subwatershed has the highest proportion of urban land, and the effects of urban land have not been considered in this study.

Mitigation of SRP losses

Given the benefits of tile drains to crop yield, there is great incentive to find ways to mitigate the SRP losses from agricultural land associated with tile drainage through best management practices (BMP). Controlled tile drainage (CTD) involves the installation of a control structure to control height of the water table to reduce sub-surface flow (Hanke, 2018), and this was shown to reduce P loads compared to conventional tile drainage; however, this BMP significantly increases dissolved nutrients like SRP (Hanke, 2018; King et al., 2015). Cover crops, which are planted on crop fields in the late fall to maintain root structures throughout the winter, have become more commonly used as BMPs in recent years. Maintaining vegetative cover on fields through cover crops (e.g. winter wheat) have helped reduce nutrient losses and erosion from surface runoff (Dabney et al., 2001). Planting cover crops can also increase biological water demand and evapotranspiration in the non-growing season, at a time when it is otherwise absent (Dabney et al., 2001). Maintaining cover crops through the growing season can create soil aggregations and reduce preferential flow, therefore enhancing water and nutrient retention in soils, thus reducing the potential for P export through tile drains (Trentman et al., 2020).

The most significant effect of cover crops is mitigating agricultural SRP losses from tile drains in the non-growing and early growing season (January-June; Hanrahan et al., 2021a; Trentman et al., 2020). Over a four-year study, Trentman et al. (2020) observed reduced tile drainage flow and SRP loads; however, lower SRP loads were only found at one of two sites. This difference was attributed to variations in soil biogeochemistry, and the prevalence of clay soils and increased macropores at one site that likely overwhelmed any effect of cover crops (Trentman et al., 2020). Hanrahan et al. (2021a) also found reduced tile drain flow from fields with cover crops, and lower SRP loads from tile drainage compared to those associated with no cover crop. This relationship occurred during spring and only where there was low flow through the tiles (Hanrahan et al., 2021a). This relationship has only been shown at the field scale, as no statistically significant effect has been observed at the watershed scale, despite there being reduced SRP loads (Hanrahan et al., 2021a). Hanrahan et al. (2021b) found no significant difference in average monthly discharge, or SRP and TP loads between fields with cover crop and those without even though there was a significant effect on nitrogen loads. Overall, more research is needed on the influence of cover crops on P export from tile drains, as it is apparent that their effectiveness is dependent on many factors.

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Table 4.1. Mean seasonal SRP and TP concentration (µg/L), standardized* load (kg/d/km2) and proportion of TP that is SRP (PROP) for the East Sydenham River (ESR), the Thames River (TR) and the Grand River (GR) between 2012 and 2019. WINT=Winter; LWES=Late winter/early spring; GROW=Growing season; FALL=Fall. The highest seasonal value for each tributary is bolded.

Tributary	**Season**	**SRP** (µg/L)	**SRP Load** (kg/d/km^2)	**TP** (µg/L)	**TP Load** (kg/d/km^2)	**PROP**
ESR	WINT	51.01	0.079	114.02	0.184	**0.48**
	LWES	38.97	**0.092**	**138.15**	**0.332**	0.31
	GROW	29.80	0.021	103.74	0.081	0.28
	FALL	**53.41**	0.077	128.31	0.174	0.39
TR	WINT	56.57	**0.114**	119.06	0.233	**0.47**
	LWES	45.57	0.105	148.94	**0.359**	0.31
	GROW	30.28	0.022	134.81	0.105	0.22
	FALL	**56.70**	0.090	**155.68**	0.229	0.36
GR	WINT	26.23	0.056	77.04	0.161	**0.35**
	LWES	**27.59**	**0.069**	**104.44**	**0.281**	0.28
	GROW	13.56	0.016	77.12	0.091	0.16
	FALL	27.12	0.057	94.44	0.177	0.27

* P loads were standardized by watershed size

Table 2.2. Mean SRP and TP concentration (µg/L), standardized* loads (kg/d/km^2), standardized* discharge (m^3/s/km^2) and SRP:TP ratios for the East Sydenham River (ESR), the Thames River (TR) and the Grand River (GR) between 2012 and 2019. Data for each tributary were first averaged by month for each year, and then data were combined to generate monthly means.

Tributary	**SRP** (µg/L)	**SRP Load** (kg/d/km^2)	**TP** (µg/L)	**TP Load** (kg/d/km^2)	**Discharge** (m^3/s/km^2)	**SRP:TP**
ESR	39.26	0.056	117.69	0.171	0.0121	0.34
TR	42.31	0.066	139.57	0.203	0.0132	0.30
GR	21.30	0.044	86.94	0.167	0.0168	0.24

* P loads and discharges were standardized by watershed size

Table 2.3 Change in proportion (Prop) land use-land cover (LULC) classes in the East Sydenham River (ESR), Thames River (TR), and Grand River (GR) watersheds from 2012 to 2019

Watershed	Year	Prop Natural	Prop Row Crop	Prop Pasture/ Forage	Prop Other Agriculture	Prop Urban
ESR	2012	0.1139	0.7509	0.0755	0.0126	0.0250
	2013	0.1121	0.7517	0.0782	0.0084	0.0258
	2014	0.1106	0.7096	0.0883	0.0090	0.0497
	2015	0.1107	0.7444	0.0660	0.0082	0.0471
	2016	0.1113	0.7452	0.0882	0.0029	0.0467
	2017	0.1084	0.7496	0.0818	0.0070	0.0455
	2018	0.1103	0.7318	0.0894	0.0119	0.0450
	2019	0.1058	0.7316	0.0950	0.0079	0.0457
TR	2012	0.1024	0.6667	0.1244	0.0181	0.0667
	2013	0.1045	0.6866	0.1000	0.0082	0.0700
	2014	0.1003	0.6598	0.1088	0.0102	0.0887
	2015	0.0987	0.6743	0.1069	0.0051	0.0866
	2016	0.1108	0.6742	0.1085	0.0036	0.0882
	2017	0.1126	0.6765	0.0999	0.0042	0.0849
	2018	0.1086	0.6559	0.1109	0.0211	0.0837
	2019	0.1005	0.6809	0.1110	0.0079	0.0806
GR	2012	0.1960	0.4108	0.2690	0.0106	0.0744
	2013	0.2047	0.4479	0.2245	0.0092	0.0755
	2014	0.1750	0.4406	0.2269	0.0069	0.0927
	2015	0.1758	0.4499	0.2208	0.0050	0.0944
	2016	0.2036	0.4396	0.2352	0.0042	0.0945
	2017	0.1717	0.4469	0.2192	0.0051	0.0932
	2018	0.1758	0.4418	0.2251	0.0098	0.0946
	2019	0.1651	0.4438	0.2367	0.0065	0.0918

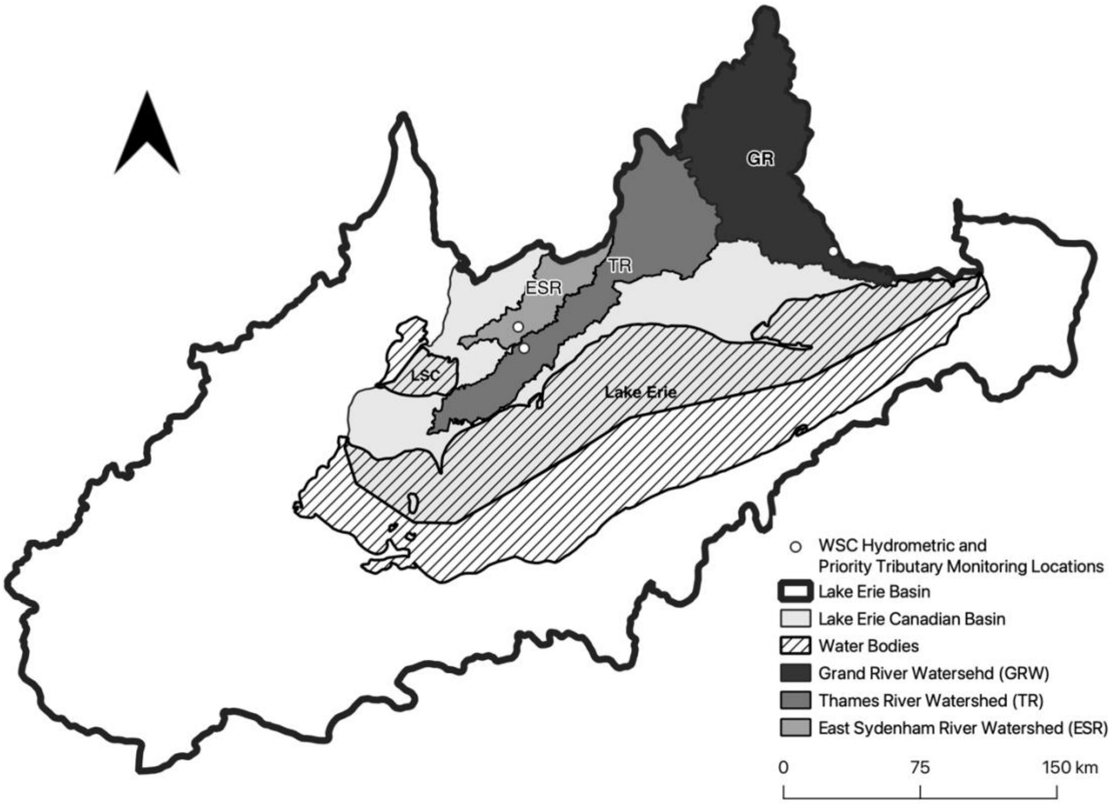

Figure 2.1. Locations of long-term monitoring stations on the East Sydenham River (ESR), the Thames River (TR) and the Grand River (GR) within the Lake Erie drainage basin. The monitoring stations are operated by Water Survey Canada (WSC) for hydrometric data and nutrient data for Environment and Climate Change Canada's Priority Tributary Monitoring Program for Lake St. Clair (LSC) and Lake Erie.

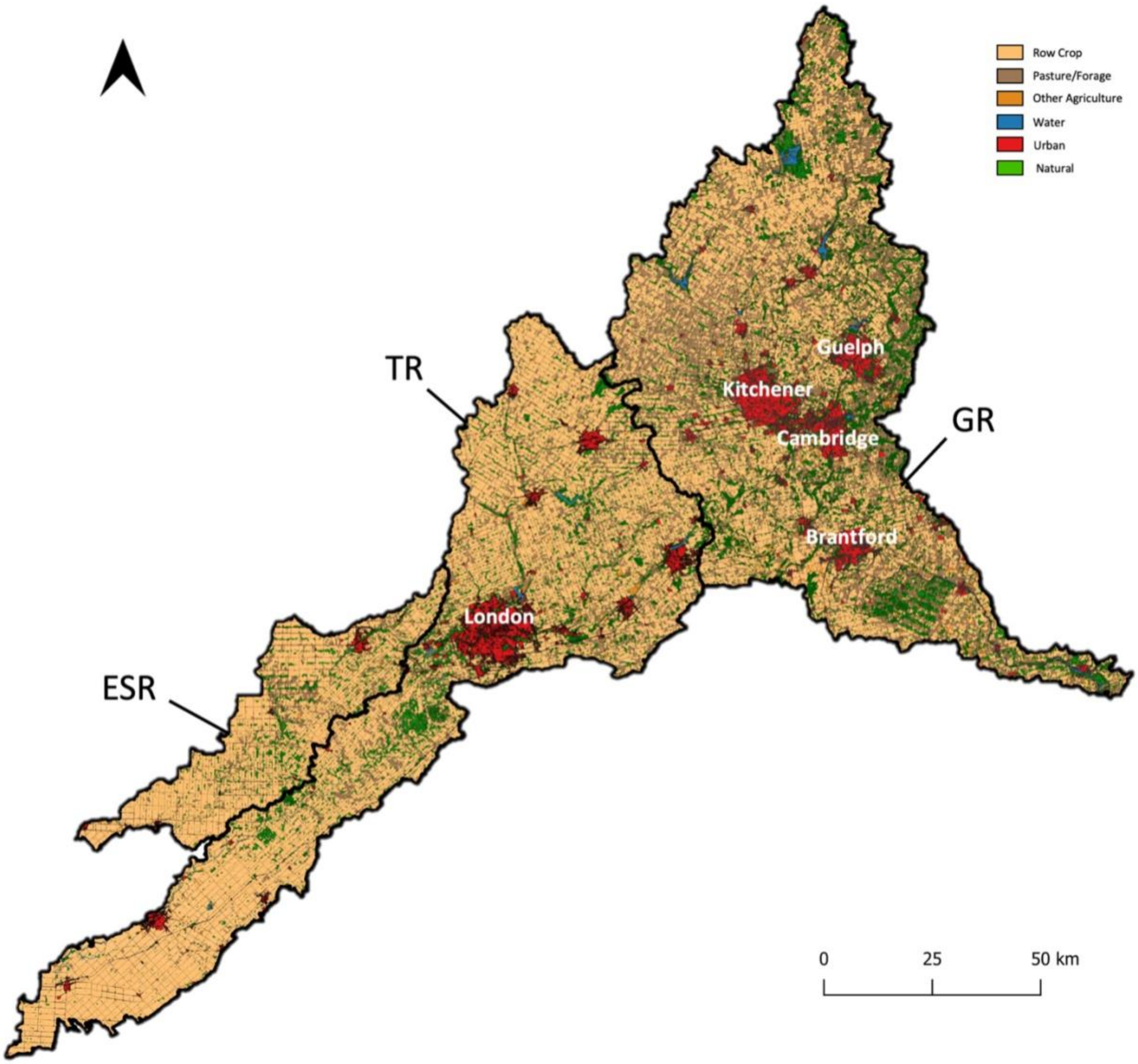

Figure 2.2. Visual depiction of land use/land cover data are from Agriculture and Agri-food Canada's (AAFC) Annual Crop Inventory (ACI) in 2019 for the East Sydenham River (ESR), the Thames River (TR) and the Grand River (GR).

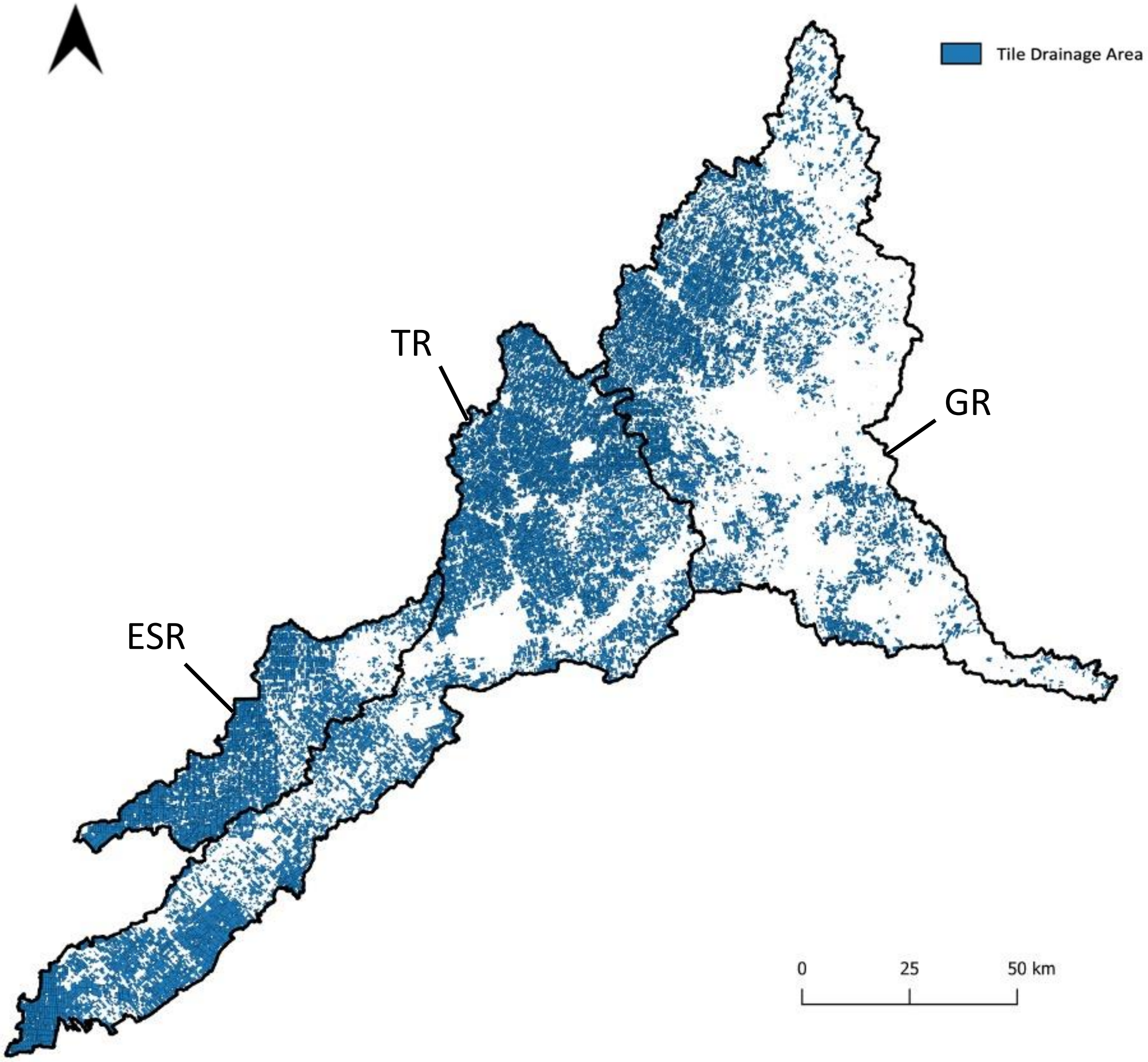

Figure 2.3. Visual depiction of tile drainage data are from Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) in 2021 for the East Sydenham River (ESR), the Thames River (TR) and the Grand River (GR).

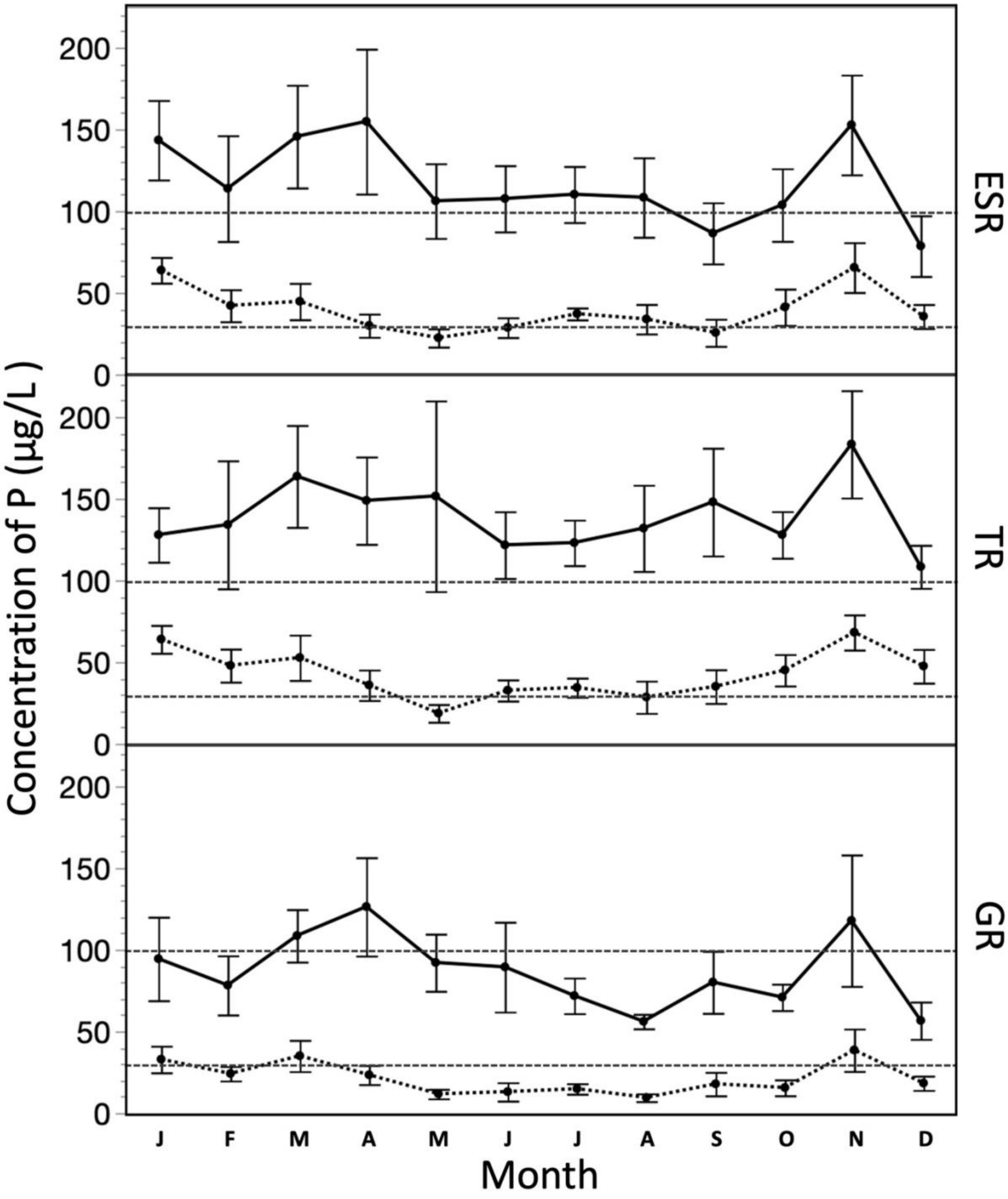

Figure 2.4. Mean (± SE) monthly soluble reactive P (dashed line) and total P (solid line) concentrations for the East Sydenham River (ESR), Thames River (TR) and Grand River (GR) watersheds. Means were calculated from data collected from 2012 to 2019 inclusive. The two reference (dotted) lines are 30 and 100 µg/L.

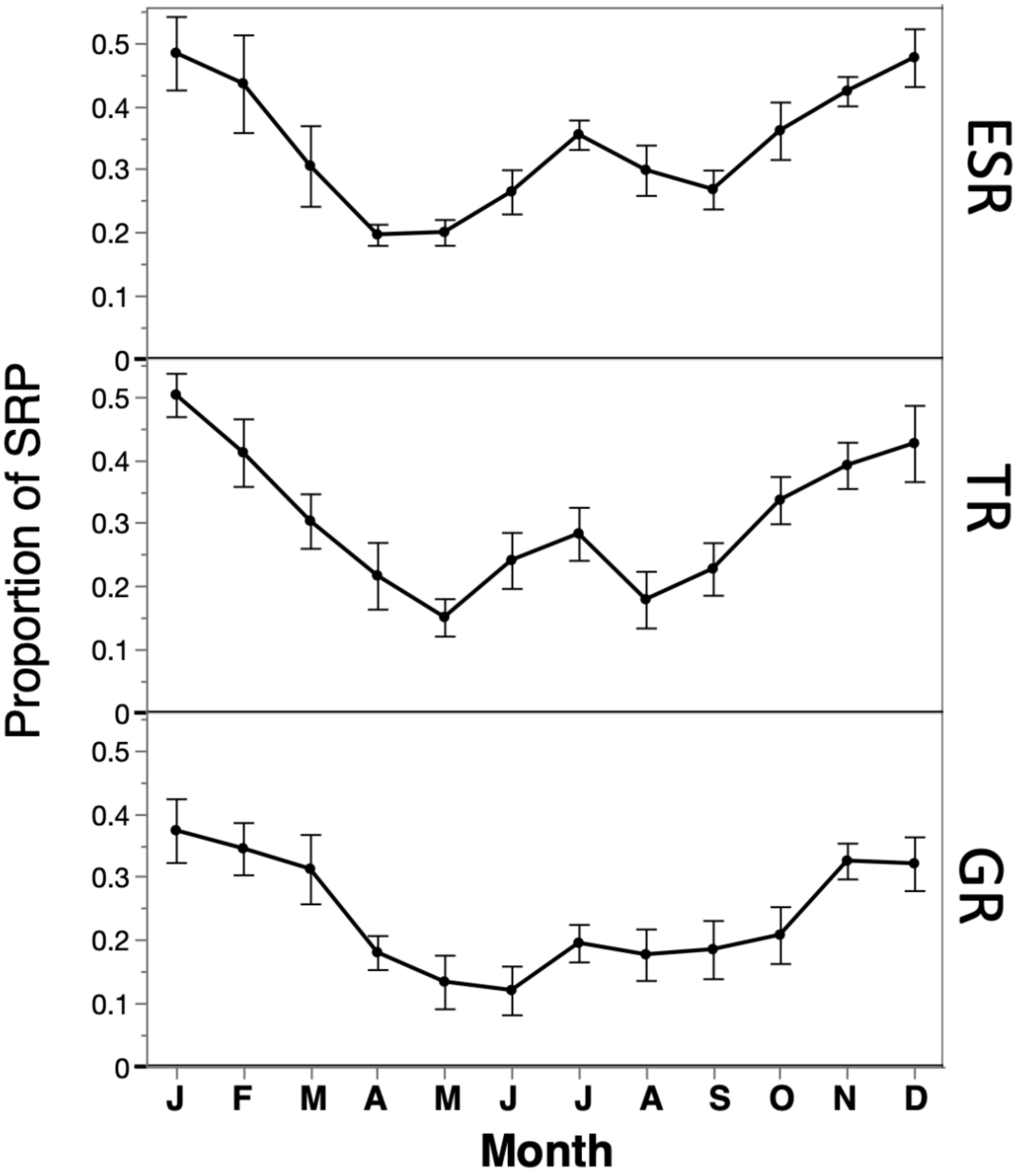

Figure 2.5. Mean (± SE) proportion of Total P that is soluble reactive P (SRP) from January to December calculated separately for East Sydenham River (ESR), Thames River (TR) and Grand River (GR) watersheds. Means were calculated from data collected from 2012 to 2019 inclusive.

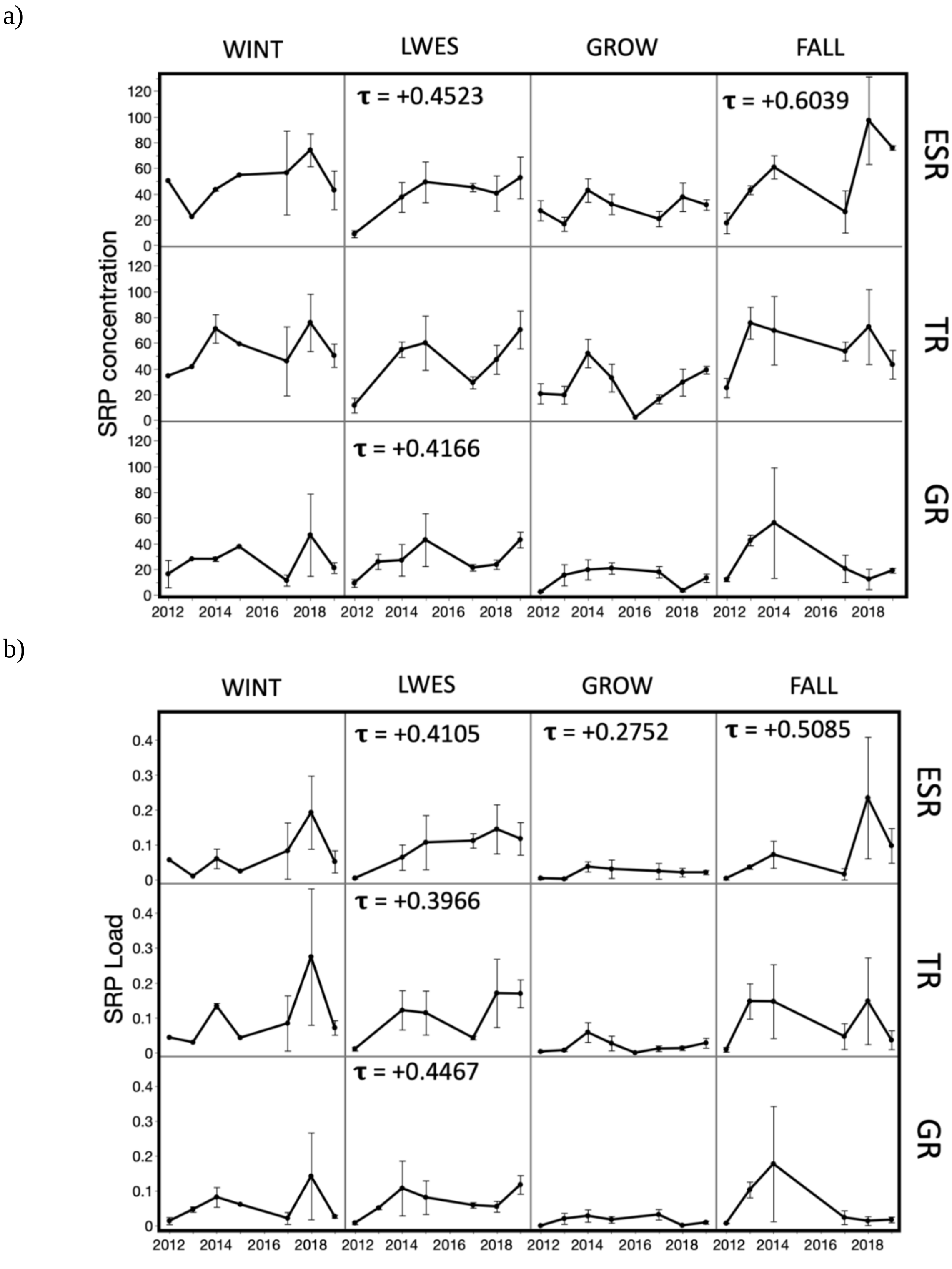

Figure 2.6. Change in mean seasonal a) Soluble Reactive P (SRP) (µg/L) and b) standardized Soluble Reactive P (SRP) load (kg/day/km^2) from 2012 to 2019 in the East Sydenham River (ESR), the Thames River (TR) and the Grand River (GR). The Mann Kendall statistic (τ) is presented for all significant ($p<0.05$) temporal trends.

a)

b)

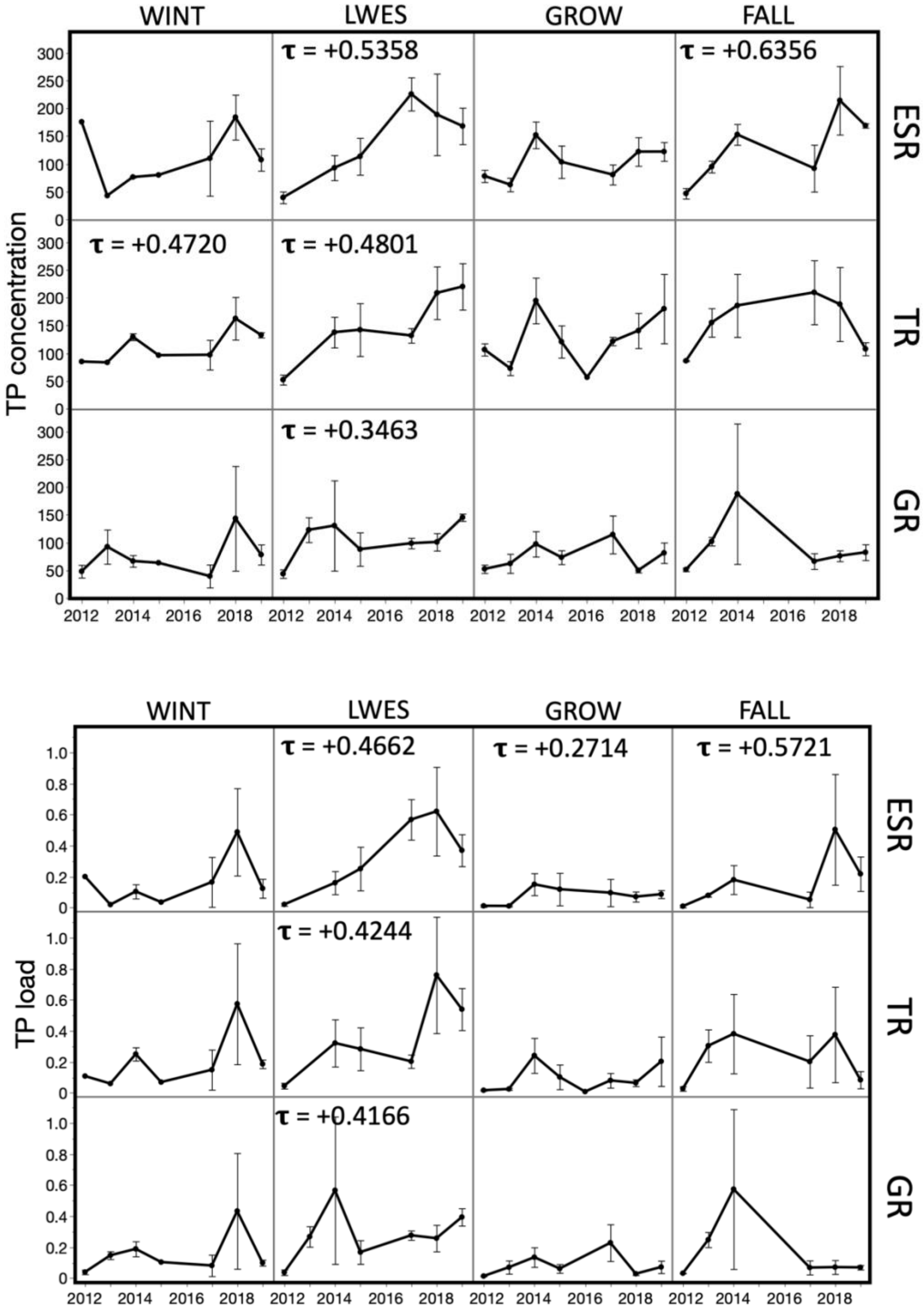

Figure 2.7. Change in mean seasonal a) Total P (TP) concentration (µg/L) and b) standardized Total P (TP) load (kg/day/km^2) from 2012 to 2019 in the East Sydenham River (ESR), the Thames River (TR) and the Grand River (GR). The Mann Kendall statistic (τ) is presented for all significant ($p<0.05$) temporal trends.

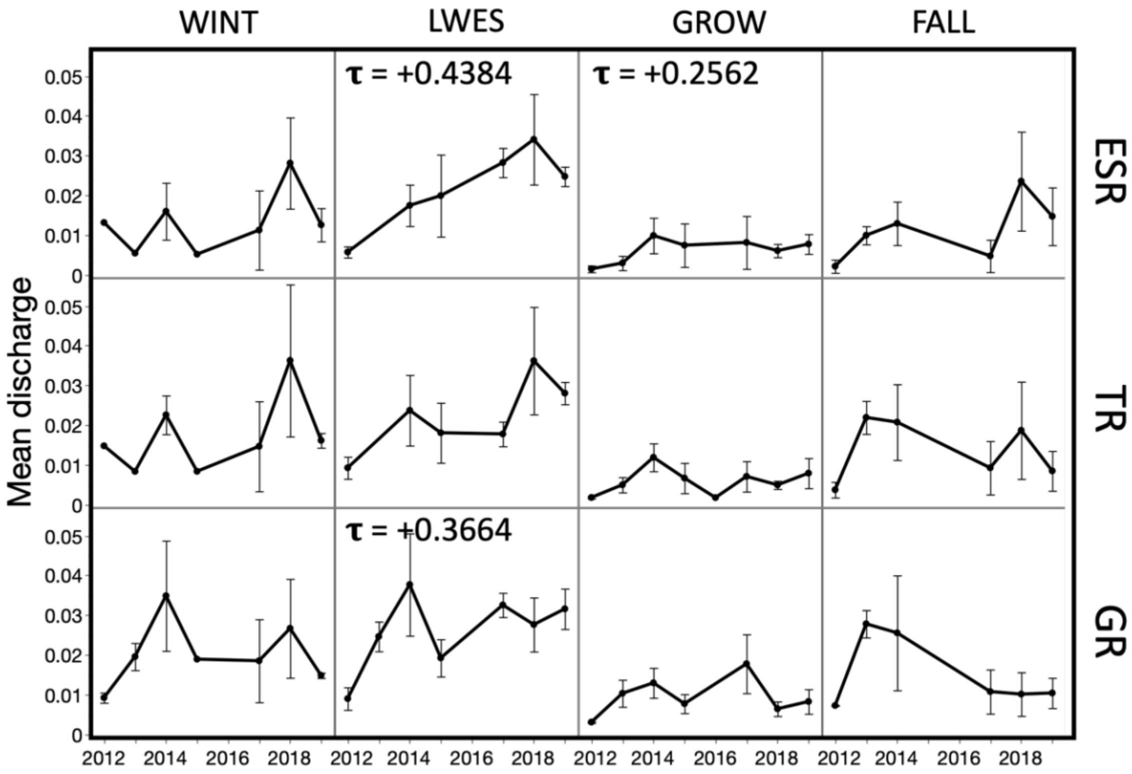

Figure 2.8. Change in mean seasonal discharge ($m^3/s/km^2$) from the East Sydenham River (ESR), the Thames River (TR) and the Grand River (GR) from 2012 to 2019. The Mann Kendall statistic (τ) is presented for all significant ($p<0.05$) temporal trends.

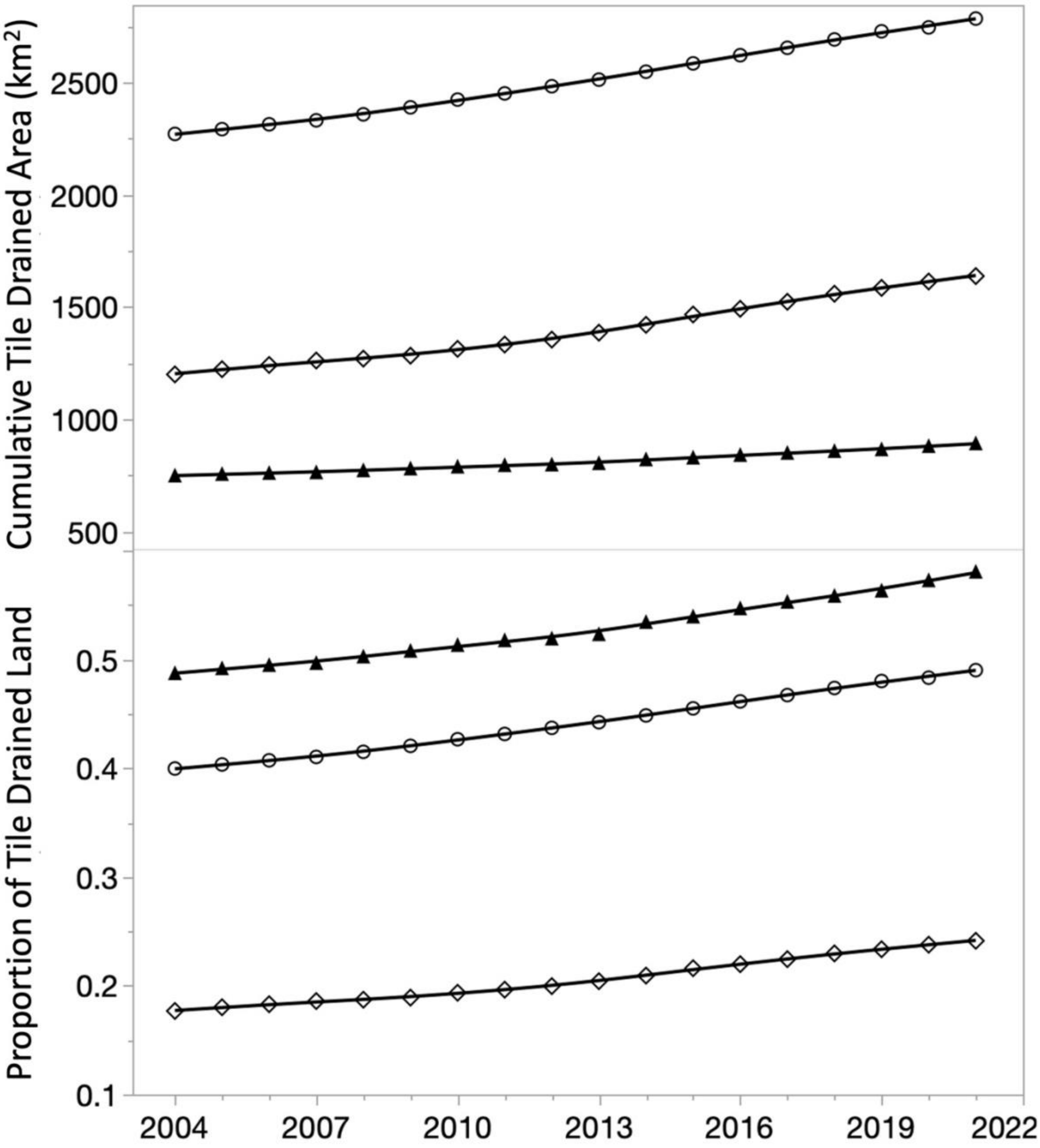

Figure 2.9. Change in a) total tile-drained area (km^2) and b) proportion of tiled-drained land from 2004 to 2021 in the East Sydenham River (ESR; triangle), the Thames River (TR; circle) and the Grand River (GR; diamond).

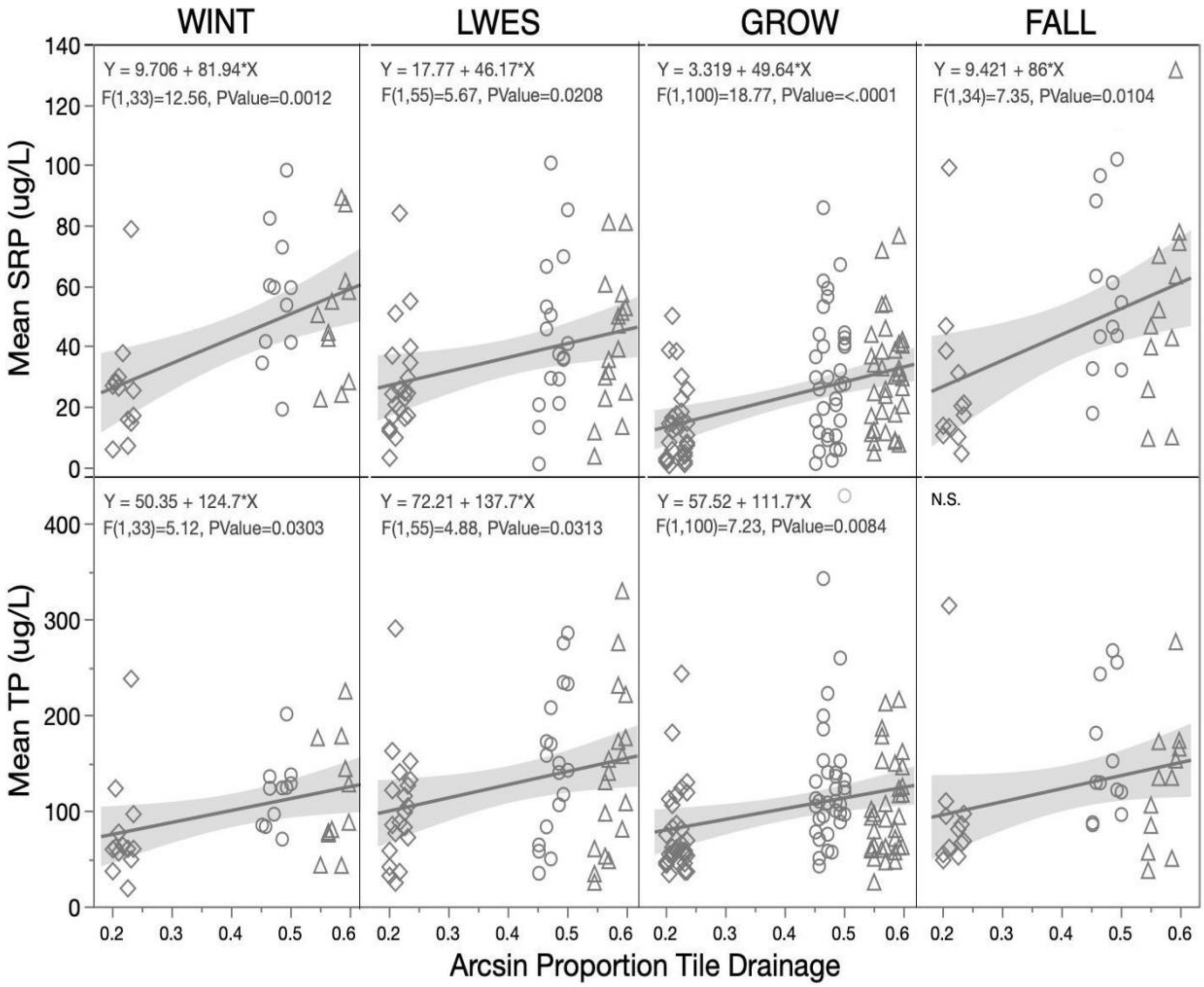

Figure 2.10. Relationship between mean monthly concentration (µg/L) of soluble reactive P (SRP) and total P (TP) versus Arcsine-transformed proportion of tile drainage in watersheds (calculated for each year from 2012 to 2019). Data are for all three tributaries (the East Sydenham River [triangle], the Thames River [circle], the Grand River [diamond]).

Chapter 3: CONCLUSION

Our study confirms that SRP loading from the CLEB tributaries has been increasing over the past decade, especially during LWES. We have significantly related these seasonal increases to an increased presence of tile drainage across the CLEB; however, it is likely that the effects of on seasonal P export varies across seasons and tributaries. In addition to the LWES, both winter and fall were critical times in the ESR and TR for P export, especially SRP. In the most heavily tile-drained watershed, the ESR, tile drainage is likely the reason for increases in TP and SRP loading during the growing season and fall since the most significant linear relationships with tile drainage were seen in these seasons and it was the only tributary to increase in SRP and TP load outside of LWES. Our findings suggest that P loading in the growing season may be influenced by increased water flux, while P loading in the fall may be a caused by increased P availability. Overall, variations in LULC characteristics, topography, soil texture, and climate across the CLEB tributaries affect the contribution of P to the Lake Erie basin from each tributary, and this variation highlights that tile drainage does not uniformly affect P transport across the CLEB. Our results emphasize that there is not a “one-size-fits-all” solution for P management across the Lake Erie basin, especially in the CLEB.

Summary and Future Research Needs

Although there is a wealth of knowledge on factors influencing P export via agricultural drainage, fully understanding trends in P transport in tile-drained systems is difficult. Field and watershed scale losses are highly variable spatially and temporally. The rate, magnitude, timing, and form of P that is lost through tile drains is highly dependent on a multitude of environmental and management factors. It is evident that there is not one specific factor driving SRP loading.

Most published research involving P export and tile drains has been focused on discharge after precipitation or snow melt events at the edge-of-field scale, as SRP and TP export from tile drains is known to be episodic. More research should be done to look at seasonal influences of tile drains at the watershed, or even headwater stream scale, to fully understand what LULC factors are in influencing P export from tile drains at the watershed scale. In addition, the literature has demonstrated that the lack of vegetative cover throughout the non-growing season has a significant influence on SRP; therefore, more research into the effectiveness of cover crops on tile-drained fields across various soil textures, tillage and fertilization practices is necessary.

It is also evident that research around effects of tile drainage on P is lagging behind current policy and decision making. Current research is starting to illuminate the impacts of some of the BMP that were implemented to help improve soils, crops and the environment, leaving land use managers and farmers in an interesting position. There is now a kind of "Farming vs the Environment Conundrum", as many farms have taken steps and invested heavily to improve their soil quality, reduce erosion and increase carbon storage by adopting no-till practices and tile drainage; however, we are now seeing that these BMPs are likely exacerbating some of the issues they were implemented to solve. Tile drainage is almost essential for profitable yields across much of southern Ontario, so further adopting of tools like "Environmental Farm Plans" could help identify farms that are more at risk of nutrient losses through tile drains and create nutrient management plans tailored to specific field characteristic (Smith et al., 2020)

This study is also the first time SRP and TP loading trends have been compared across the CLEB tributaries in this way, as prior to now, these types of data were not available. The PTNWQMP is one of the first in Ontario to collect both TP and SRP data on a regular, long-term basis across multiple major tributaries, compared to some other regions in the WLEB that have been collecting these data since the 1970’s (Jarvie et al., 2017, Stow et al., 2015). This is one of the leading reasons why our understanding of P trends is not as strong for CLEB compared to the WLEB. This study highlights the benefits and need for continuous and robust long-term nutrient monitoring in Canada. While the sample period for these PTNWQMP is relatively short, we were still able to paint a picture of P trends in the CLEB, and continued monitoring will only increase this knowledge. Overall, this study highlights the complexity of P transport via tile drains and that specific P management likely needs to be tailored to site conditions for best results.

Literature

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