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Effects of increasing tile drainage and seasonal weather patterns on phosphorus loading from three major Canadian Lake Erie tributaries

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ABSTRACT

Tile-drainage area has expanded across the Canadian Lake Erie watershed in recent decades, and effects on phosphorus (P) loading are unclear. Eleven years (2010 to 2021) of daily P, total suspended solids (TSS), discharge, and climatological data were aggregated from three Canadian tributaries that form a gradient of tiled areas: East Sydenham River (ESR, 60% tile), Thames River (TR, 48% tile), and Grand River (GR, 23% tile). Instead of using traditional seasons (winter, spring, summer, fall), we classified seasons by air temperature to highlight hydrological periods of importance for P loss through tile drains. Seasons included frozen (<-3.2 °C), thawing ($-3.2 – 6.7$ °C), bare ($6.7 – 15.9$ °C), and growing (>15.9 °C). Nonparametric comparisons revealed that during every season, the ESR and TR had significantly higher soluble reactive P (SRP) and total P (TP) concentrations than the GR. For %SRP, the ESR was significantly higher than the other rivers during every season, while for TSS, the GR was significantly higher than the other rivers during every season. Only during the thawing season were positive relationships observed in every river between year-over-year tile-drainage proportion and associated P loadings and concentrations. The ESR was the only river to yield significant relationships between tile drainage and P in all seasons except the frozen season. Our findings suggest that increases in tile-drainage area can lead to increases in SRP loading to Lake Erie from Canadian tributaries, especially during the thawing season. However, effects of tile drainage are moderated by differences in soil texture, land-use-land-cover, climate, and point sources.

1. Introduction

Protecting water quality in Lake Erie under the Great Lakes Water Quality Agreement (International Joint Commission, 1972) necessitates a holistic understanding of phosphorus (P) loading from tributaries across the binational (Canada and U.S.) watershed. In U.S. tributaries of the Lake Erie watershed (LEW), the National Center for Water Quality Research at Heidelberg University has recorded daily P data since the 1970s (e.g., Daloğlu et al., 2012; Kane et al., 2014; Jarvie et al., 2017; Stow et al., 2015), while in Canadian LEW tributaries, no comparable record of P data exists. This paucity of long-term water-quality data has manifested in knowledge gaps surrounding the status and trends of P loading from Canadian tributaries to Lake Erie.

In the U.S. LEW, an uptick in the implementation of agricultural tile drainage has been identified as a contributing factor of increased soluble reactive P (SRP) loading to Lake Erie (Jarvie et al., 2017). Tile-drainage implementation has also increased in the Canadian LEW in recent years (Fortier, 2022), enabling farmers to take advantage of the yield-boosting benefits tile drains can provide. Currently, most of Canada's tile-drained land exists in the southern Ontario region (Eimers et al., 2020; Smith, 2015). Most of the landscape in southern Ontario drains into Lake Erie (Statistics Canada, 2019; Valayamkunnath et al., 2020), yet few studies have documented the effects of tile-drain expansion on P loading from this region.

In addition to recent expansion in tile-drainage area across the binational LEW, changes in seasonal patterns have too been recorded. Rising air temperatures during the colder periods of the year have altered typical weather patterns, as the proportion of winter precipitation falling as rain increases and the duration of snow and ice cover declines (Bosch et al., 2014; Hayhoe et al., 2010; Li et al., 2016; Wuebbles et al., 2018; Zhang et al., 2018). In U.S. tributaries of Lake Erie's western basin, effects of these climate-mediated seasonal changes on P loading from agricultural fields are well-documented (Daloğlu et al., 2012; Smith et al., 2015; Stow et al., 2015; Williams and King, 2020) and have been linked to an increase in harmful algal bloom biomass (Dove and Chapra, 2015; Kane et al., 2014; Michalak et al.,

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2013; Wilson et al., 2019).

A key objective of tile drainage implementation is to remove excess water from agricultural fields (Ghane, 2018; Kokulan, 2019). As such, tile drains increase the connectivity between agricultural landscapes and tributaries, allowing P that would have formerly been retained in the soil to be transported to surface waterbodies (Blann et al., 2009; King et al., 2015). Typically, spring is recognized as the most active period for tile drains as they operate to remove excess soil moisture from snowmelt and precipitation events. During winter, tile drains are recognized to be separated from the soil surface by a snowpack; however, winter temperatures continue to rise and the duration of snow cover continues to decline in the Great Lakes Region (Wuebbles et al., 2018). The emergence of a "late-winter-early-spring" season, which covers the months of February, March, and April, has been proposed in the literature as a critical period for P loading to Lake Erie (Jarvie et al., 2017; Stow et al., 2015). This season has been characterized by earlier onset of snowmelt, mid-season thaws, rain-on-snow events, and freeze–thaw-cycles due to rising winter air temperatures that hover around 0 °C (Jarvie et al., 2017).

Water quality studies typically categorize seasons in two general ways: (1) winter (January, February, March), spring (April, May, June), summer (July, August, September), and fall (October, November,

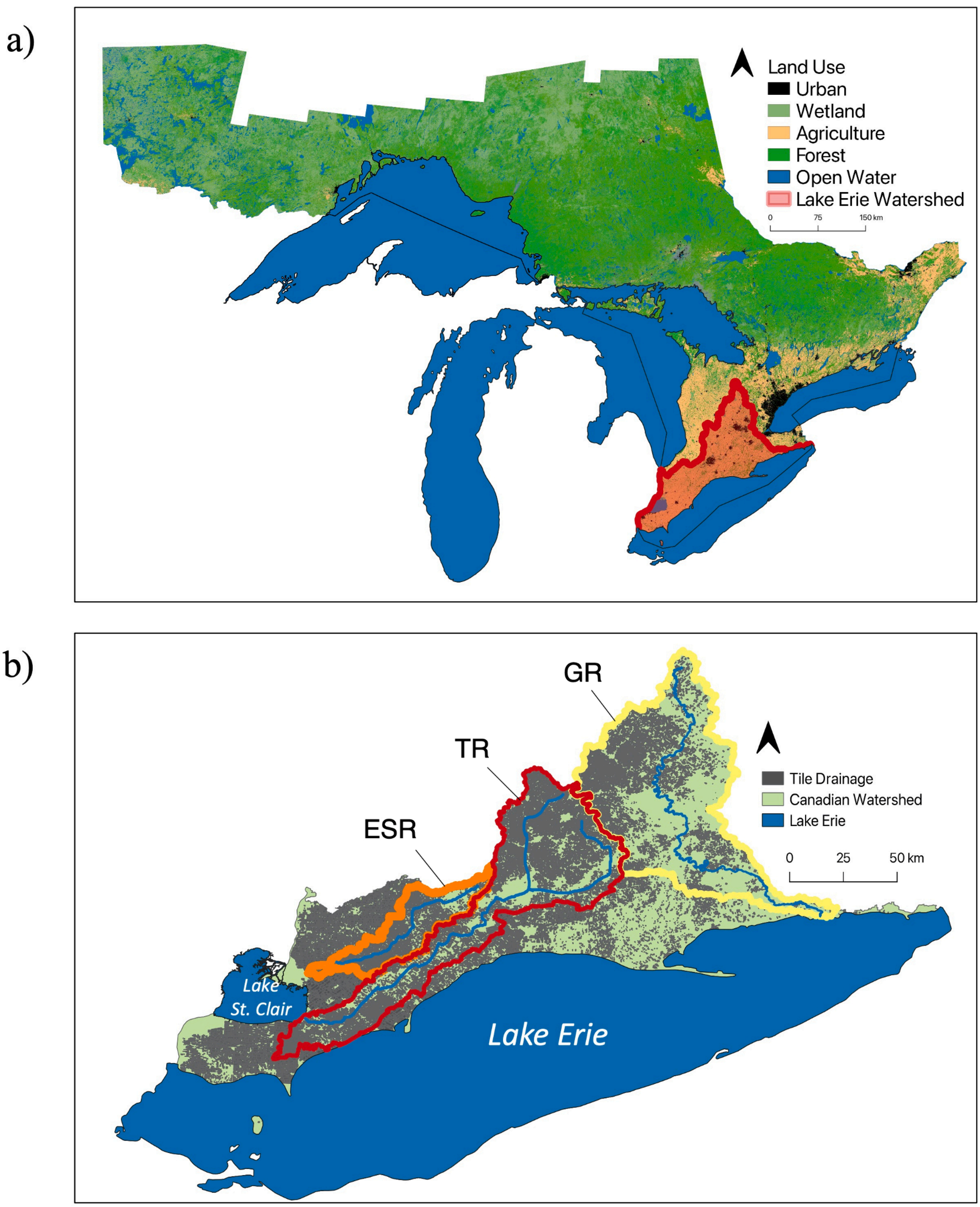

Fig. 1. Maps of the Canadian Lake Erie Watershed (LEW), and sub-watersheds studied. a) Land-use-land-cover map of central and southern Ontario with delineation of the Canadian LEW. b) Tile-drainage area map of the Canadian LEW and contiguous sub-watersheds of the East Sydenham River (ESR), the Thames River (TR), and the Grand River (GR).

December), or (2) the Growing Season (May to September) and the Non-Growing Season (October to April) (e.g., Irvine et al., 2019; Plach et al., 2019). There are, however, two main issues with typical seasonal classifications when studying the effects of agricultural tile drainage on P loading. First, the term "agriculture" is a conglomerate term that includes multiple agricultural sub-categories like row crop production, forage/pastureland, specialty crop production, and livestock production. Each of these agricultural sub-categories is associated with unique practices that can impact P runoff differently. Second, the "Non-Growing Season" bundles together multiple cold-season processes. From snowpack development to rain-on-snow events, to snow-cover and mid-season thaws, to the onset of snowmelt and thawing of soils, these various processes can have a range of effects on P loss from agricultural land. As such, when exploring the seasonal effects of tile drainage on P loading, the use of traditional seasons of winter, spring, summer, and fall could misrepresent what is actually occurring on the landscape, which is ultimately driven by regional nuances in climate and land-use-land-cover (Joosse and Baker, 2011), not solstices and equinoxes. Here, we reclassify seasons based on daily air temperature data to reflect hydrologically- and agriculturally-relevant periods in Canadian LEW, as well as to highlight periods of importance for tile-drain functioning and potential P loss.

The aim of this study is to explore how increased tile-drainage area in the Canadian LEW affects P loading to Lake Erie during seasons when agricultural soils are frozen, thawing, bare, and actively growing crops. Three contiguous subwatersheds of the Canadian LEW were studied: the ESR (East Sydenham River) watershed, TR (Thames River) watershed, and the GR (Grand River) watershed. Together, these watersheds account for 61% of the total Canadian LEW and hold most of the agricultural land in the province of Ontario (Fig. 1a). The ESR, TR, and GR watersheds drain a gradient of tile-drained areas (Fig. 1b), as well as distinct combinations of agricultural, urban, and natural land. The ESR has the smallest watershed size (1,537 km^2) but the highest proportion of tile drainage (60%), while the TR watershed is intermediate in both size (5,680 km^2) and in tile-drain proportion (48%), and the GR watershed is largest in size (6,786 km^2) but lowest in proportion of tile drainage (23%) (Agriculture and Agri-Food Canada, 2019). The total area of tile drainage (km^2) in the three watersheds has increased from 2004 to 2021; specifically, the ESR experienced an 84% increase in tile drainage area, while the TR and GR increased by 82% and 73% respectively (Fortier, 2022).

Here, we use publicly available historical datasets from the federal Priority Tributary Nutrient and Water Quality Monitoring Program (PTNWQMP) that provided SRP, total P (TP), and total suspended solids (TSS) data from 2010 to 2021. We investigate seasonal trends in water-quality concentrations, loadings, and river discharge, and test if annual increases in tile-drained areas have resulted in increases in P loading from these Canadian Lake Erie tributaries, particularly during hydrologically active periods like the late-winter-early-spring.

2. Methods

2.1. Long-term nutrient, discharge data and load calculations

SRP (μg/L), TP (μg/L), and TSS (mg/L) data collected near the mouth of the ESR, TR and GR were aggregated between 2010 and 2021 from the Environment and Climate Change Canada's (ECCC) PTNWQMP (DataStream, 2022). Monitoring stations were located at, or near, the mouth of each river, and included East Sydenham River at Florence, Thames River at Thamesville, and Grand River at York. Samples were collected using automated samplers at irregular intervals, but on a minimum bi-weekly basis, and additional samples were taken during high-flow events (DataStream, 2022). Table 1 summarizes the number of days where a sampling point was collected from ECCC for each parameter in each river, as well as the number of days where a sampling point was missing during the sampling years. In cases where multiple samples were taken for one day (24 h), the daily mean concentration was taken.

Table 1
Observed and missing water-quality data. Sampling days for soluble reactive phosphorus (SRP) concentration (μg/L), total phosphorus (TP) concentration (μg/L), and total suspended solids (TSS) concentration (mg/L). Observed data points indicate days when a water-quality sample was collected and recorded by Environment and Climate Change Canada's (ECCC) Priority Tributary Nutrient and Water Quality Monitoring Program. Missing data points indicate days were there were no data collected by ECCC. Total sampling points refer to the number of days included in this study, from January 1st, 2010, to December 31st, 2021.

Parameter	Type	River		
		ESR	TR	GR
SRP	Observed	1425	1507	1283
	Missing	2958	2876	3100
	Total	4383	4383	4383
TP	Observed	1425	1510	1285
	Missing	2958	2873	3098
	Total	4383	4383	4383
TSS	Observed	1306	1339	1159
	Missing	3077	3044	3224
	Total	4383	4383	4383

Daily discharge (m^3/s) data were obtained from ECCC through the Water Survey of Canada (WSC) database (Environment and Climate Change Canada, 2022). Hydrometric gauging stations were chosen based on their proximity to the PTNWQMP sampling stations. Monitoring stations included the East Sydenham River at Florence station (#02GG003) and the Thames River at Thamesville station (#02GE003) (Environment and Climate Change, 2022). Since the WSC monitoring station on the GR (Grand River at York) has been inactive since 1923, daily discharge data (m^3/s) for the GR were obtained from the Grand River Conservation Authority at the York gauging station (#8731042) (Grand River Conservation Authority, 2022).

To obtain daily SRP, TP, and TSS concentration values, linear regression models were used to create nutrient-discharge curves for each parameter, in each river (Table 2). Daily SRP and TP loadings (kg/day) for each river were then calculated by multiplying the modelled daily concentrations (μg/L) with the measured daily discharge (m^3/s) values, and then multiplying the product of those values by 0.0864. To account for differences in watershed size, the loading data were standardized by size (as kg/day/km^2) for cross-site comparisons.

Table 2
Concentration-discharge linear regression models. For each river, linear regression models were derived for the concentration–discharge relationships for data collected between 2010 and 2021. $y = mx + c$, where y is the soluble reactive phosphorus (SRP; μg/L), total phosphorus (TP; μg/L), or total suspended solids (TSS; mg/L) concentration, x is the daily discharge in m^3/day; m is the slope, and c is the intercept.

River	*y*	*m*	*x*	*c*	*p*	R^2
ESR	SRP	0.8234	*x*	23.51	<0.0001	0.38
TR		0.1962	*x*	25.69	<0.0001	0.36
GR		0.1045	*x*	10.23	<0.0001	0.28
ESR	TP	2.587	*x*	68.18	<0.0001	0.45
TR		0.5658	*x*	101.4	<0.0001	0.24
GR		0.5226	*x*	26.71	<0.0001	0.38
ESR	TSS	2.343	*x*	43.84	<0.0001	0.19
TR		0.7179	*x*	82.37	<0.0001	0.14
GR		0.734	*x*	−20.53	<0.0001	0.28

2.2. Seasonal classification and nomenclature

Daily air temperature data were downloaded from the Historical Climate Data search from ECCC between 2010 and 2021. Daily minimum, mean, and maximum values were extracted. Climate stations were chosen based on proximity to the PTNWQMP sampling stations. For the ESR and TR, data were obtained from the Ridgetown station (#6137154), and in the GR, the Port Colborne (#6136606) station data were used. For all three rivers, there were a total of 917 missing values for daily air temperature. Missing values were replaced with the mean air temperature of the day before, and the day after the missing day. A freeze–thaw event was recorded on any day that had a minimum air temperature below 0 °C, and a maximum air temperature above 0 °C.

Typical seasons of winter, spring, summer, and fall were classified by solstices and equinoxes. Novel seasons that highlight hydrological periods of importance were classified by daily mean air temperature (°C) using Jenks natural breaks to create seasonal groups that maximize the differences between groups and minimize the difference within groups.

2.3. Delineation of tile drainage

Shapefiles for the three watersheds were obtained from the United States Geological Survey ScienceBase Catalog (Great Lakes and Watersheds Shapefiles; https://www.sciencebase.gov/catalog/item/530f8a0ee4b0e7e46bd300dd). Annual tile-drainage area in each of the watersheds for each of the study years was determined 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.

2.4. Statistical methods

Statistical analyses were performed with SAS JMP software version 16.2.0 for MacIntosh (SAS Institute Inc.). For regression analyses, proportions of tile drainage were arcsine-transformed, and water-quality parameters were log-transformed for normality. The Mann-Kendall test was used to evaluate long-term seasonal year-over-year trends. For nonparametric comparisons, the Kruskal-Wallis rank sum test and Wilcoxon Each-Pair method were used.

3. Results

3.1. Seasonal classification

During the study years, air temperatures in the winter rose above 0 °C often (Fig. 2a). In total, there were 383 days at the Ridgetown station and 427 days at the Port Colborne station when mean daily air temperature in the winter was above 0 °C. Maximum temperature in the winter was recorded at 17.3 °C for the Ridgetown station and 15.5 °C for Port Colborne station. In total, there were 449 freeze–thaw events in winter at Ridgetown, and 373 freeze–thaw events at Port Colborne in

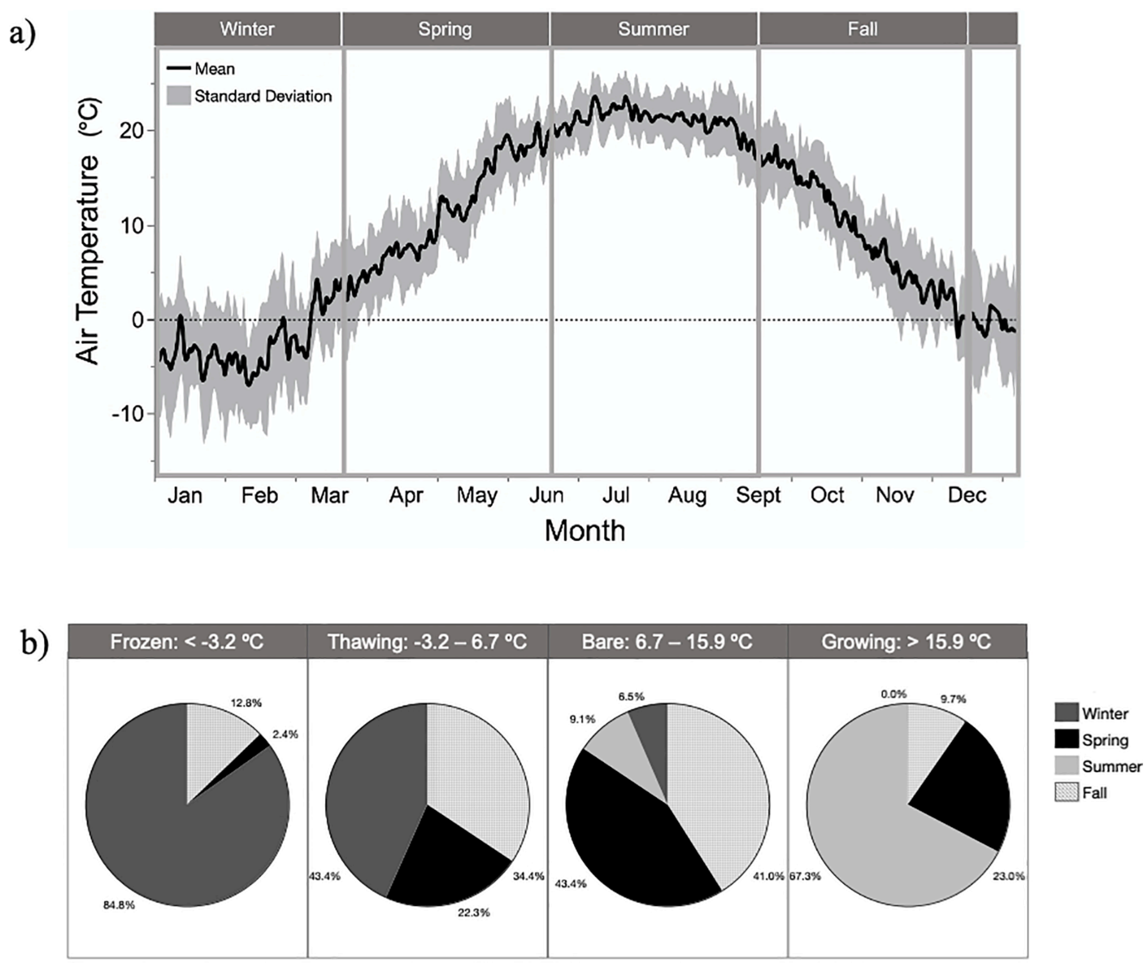

Fig. 2. Traditional and novel seasonal classifications. a) Mean daily air temperatures and standard deviation between 2010 and 2021. Traditional seasons of winter, spring, summer, and fall are defined by solstices and equinoxes. b) Novel seasons classified with Jenks natural breaks on daily air temperature data from 2010 to 2021. Proportions of traditional seasons (winter, spring, summer, and fall) captured within novel seasons are displayed.

winter. During spring, air temperatures varied considerably. While the mean air temperature of both climate stations was 11.6 °C, temperatures reached as low as −8.7 °C in March and as high as 41.8 °C in June. Even in spring, there were a total of 230 freeze–thaw events at Ridgetown and 89 at Port Colborne. Summer air temperatures varied the least, while fall air temperatures resembled those of spring (Fig. 2a). In Ridgetown, there were 316 freeze–thaw events recorded in fall, and in Port Colborne, there were 188 events.

Novel seasons were sorted into four air temperature categories and renamed as the frozen, thawing, bare, and growing seasons (Table 3). During the frozen season, 84% of the data were from the winter season, while the remainder of data mostly came from the fall (Fig. 2b). The thawing season was also comprised of data from mostly winter and fall; however, the data between the two typical seasons were in more equal proportion (43% winter, 34% fall), while the remainder were data from spring. The bare season captured data from every traditional season, yet the majority belonged to spring and fall. Two thirds of the data comprising the growing season were from summer, while the balance came from spring (Fig. 2b).

3.2. Discharge-concentration curves

The linear regression models between SRP concentration and discharge, TP concentration and discharge, and TSS concentration and discharge for each river are shown in Table 2. R^2 values were of low-to-moderate strength for all models, however, all models expressed *p*-values of <0.0001.

3.3. Soluble reactive phosphorus trends

In the ESR, the nonparametric Kendall's tau trend test revealed that modelled SRP concentrations significantly increased year-over-year during the thawing season and the growing (Table 4). For SRP loading from the ESR, trends were significant for year-over-year increases in every season except for the frozen season. In the TR, trend tests revealed no significant changes over time in any of the seasons for SRP concentration (Table 4). However, SRP loading was found to significantly increase over time in every season except the frozen season. In the GR, trends did not follow the other two rivers. SRP concentrations significantly decreased over time during every season in the GR, except during the thawing season where there was no trend detected. SRP loading trends differed from those of SRP concentration, as year-over-year increases were found during the thawing and growing seasons (Table 4).

3.4. Total phosphorus and total suspended solids trends

In the ESR, the nonparametric Kendall's tau trend test revealed that modelled TP concentrations and loadings significantly increased during every season except for the frozen season (Table 4). In the TR, trend tests demonstrated significant increasing trends of TP concentrations and loadings during one season only – the thawing season. While again, the GR exhibited a different trend from the rest. For TP concentrations and loadings, a significant decreasing trend was only found during the frozen season (Table 4). For TSS concentrations and loadings, the nonparametric Kendall's tau trends mirrored the year-over-year trends found for TP concentrations and loadings, and this was found to be true in every river (Table 4).

Table 3
Novel seasons classified by daily mean air temperature (°C) using Jenks natural breaks. The number of data points, or days, captured within each novel season across the study period (January 1st, 2010, to December 31st, 2021) is presented for each river: the East Sydenham River (ESR), Thames River (TR), Grand River (GR). The data used for the ESR and TR were obtained from the same climate station.

Novel Season	Air Temperature (°C)	Number of Days		
		ESR	TR	GR
Frozen	< −3.2	558	558	448
Thawing	−3.2 – 6.7	1318	1318	1323
Bare	6.7–15.9	1038	1038	1045
Growing	> 15.9	1469	1469	1567

Table 4
Kendall's tau (τ) trend test results. The τ statistic indicates a significant positive or negative temporal (2010 to 2021) trend in daily water quality and discharge parameters in the East Sydenham River (ESR), Thames River (TR), and Grand River (GR). SRP = soluble reactive phosphorus, TP = total phosphorus, and TSS = total suspended solids. Data were sorted by season according to air temperature, as classified in Table 3. "–" indicates a regression that was not statistically significant ($p > 0.05$).

River	Parameter	Season			
		Frozen	Thawing	Bare	Growing
ESR	SRP (µg/L)	–	0.06	–	0.07
	SRP Load (kg/day)	–	0.16	0.15	0.14
	TP (µg/L)	–	0.08	0.06	0.11
	TP Load (kg/day)	–	0.08	0.06	0.11
	TSS (mg/L)	–	0.07	0.05	0.11
	TSS Load (kg/day)	–	0.07	0.06	0.11
	Discharge (m^3/s)	–	0.06	–	0.08
TR	SRP (µg/L)	–	–	–	–
	SRP Load (kg/day)	–	0.11	0.09	0.11
	TP (µg/L)	–	0.05	–	–
	TP Load (kg/day)	–	0.05	–	–
	TSS (mg/L)	–	0.05	–	–
	TSS Load (kg/day)	–	0.05	–	–
	Discharge (m^3/s)	–	–	–	–
GR	SRP (µg/L)	−0.13	–	−0.05	−0.04
	SRP Load (kg/day)	−0.15	0.12	–	0.05
	TP (µg/L)	−0.11	–	–	–
	TP Load (kg/day)	−0.18	–	–	–
	TSS (mg/L)	−0.18	–	–	–
	TSS Load (kg/day)	−0.11	–	–	–
	Discharge (m^3/s)	−0.13	–	−0.05	−0.04

3.5. Water quality and tile-drainage proportion

When temperatures were within the thawing season, linear regression models between SRP variables and annual increases in tile-drain proportions were significant in all the rivers (Table 5). In the ESR, however, models were consistently stronger than the other rivers across all seasons. The ESR also exhibited strong and significant models between SRP variables and tile drainage during the bare and growing seasons (Table 5). In TR, linear regression showed no evidence of significance between SRP concentration and tile drainage, but SRP loading was found to significantly increase with tile-drainage proportion during the bare and growing seasons (Table 5). In the GR, SRP concentrations and loadings were negatively related to tile-drainage proportions during the frozen season (Table 5).

Linear regression models for TP variables and tile-drainage proportions reflected a similar pattern to those reported for SRP in every river. The same was true for TSS models in every river (Table 5). However, in the TR, only TP and TSS loadings yielded significant models with tile drainage, while the concentration values did not (Table 5).

3.6. Seasonal water quality comparisons among watersheds

When the modelled daily concentration data were aggregated and compared by river, seasonal nonparametric comparisons were conducted (Fig. 3). The TR consistently had the highest mean SRP concentration in every season, and the GR consistently had the lowest mean SRP concentration in every season. The TR also had the highest mean TP

Table 5
P-values from linear regression models between daily water-quality parameters (concentrations and loadings), and the annual proportion tile-drained areas in watersheds drained by the East Sydenham River (ESR), Thames River (TR), and Grand River (GR) from 2010 to 2021. SRP = soluble reactive phosphorus, TP = total phosphorus, and TSS=total suspended solids. Data were sorted by season according to air temperature, as classified in Table 3. "–" indicates a regression that was not statistically significant ($p > 0.05$).

River	Parameter	Season			
		Frozen	Thawing	Bare	Growing
ESR	SRP (μg/L)	–	<0.0001	<0.0001	0.0083
	SRP Load (kg/day)	–	<0.0001	<0.0001	<0.0001
	TP (μg/L)	–	<0.0001	<0.0001	0.0074
	TP Load (kg/day)	–	<0.0001	<0.0001	<0.0001
	TSS (mg/L)	–	<0.0001	<0.0001	0.0356
	TSS Load (kg/day)	–	<0.0001	<0.0001	<0.0001
	Discharge (m^3/s)	–	<0.0001	<0.0001	<0.0001
TR	SRP (μg/L)	–	0.0033	0.0374	–
	SRP Load (kg/day)	–	0.0004	0.0230	0.0017
	TP (μg/L)	–	0.0044	0.0421	–
	TP Load (kg/day)	–	0.0004	0.0230	0.0014
	TSS (mg/L)	–	0.0030	0.0360	–
	TSS Load (kg/day)	–	0.0004	0.0229	0.0018
	Discharge (m^3/s)	–	0.0002	0.0213	0.0006
GR	SRP (μg/L)	0.0013	0.0110	–	–
	SRP Load (kg/day)	0.0008	0.0021	–	–
	TP (μg/L)	0.0011	0.0054	–	–
	TP Load (kg/day)	0.0008	0.0018	–	–
	TSS (mg/L)	0.0014	0.0134	–	–
	TSS Load (kg/day)	0.0008	0.0022	–	–
	Discharge (m^3/s)	0.0006	0.0006	–	–

concentration during every season, while, again, the GR had the lowest mean TP concentration. In terms of mean TSS, nonparametric comparisons revealed that mean TSS concentration was consistently higher in the GR than the ESR and TR for all seasons (Fig. 3).

The proportion of SRP of the TP measured, an indicator of P bioavailability, varied for each river. Mean %SRP was also compared between the rivers during every season (Fig. 4). Mean %SRP was consistently and significantly highest in the ESR, measuring approximately 35% SRP during every season. When temperatures were cooler (i.e., frozen and thawing seasons) the GR had the lowest %SRP, but, when temperatures were warmer (i.e., during the bare and growing seasons), the TR had the lowest %SRP (Fig. 4).

4. Discussion

This study sought to explore the effect of tile-drainage expansion across the Canadian LEW on P loading to Lake Erie, and more specifically, to determine during which season tile drains have the greatest effect on P loading. We aimed to capture seasons that reflect hydrologically and agriculturally relevant periods for the Canadian LEW region. Within the ESR, TR, and GR, we explored year-over-year water-quality trends, as well as tri-watershed comparisons in water-quality during seasons when soils were presumed to be frozen, thawing, bare, and covered with growing crops.

4.1. *The frozen season: < −3.2 °C*

The Canadian portion of the LEW occupies the coldest region of the binational LEW and experiences more annual snowfall and snowpack development than any other region of the LEW (Macrae et al., 2021). We believe that in this study, the frozen season represented the period of the year when agricultural fields were covered with a snowpack. In the

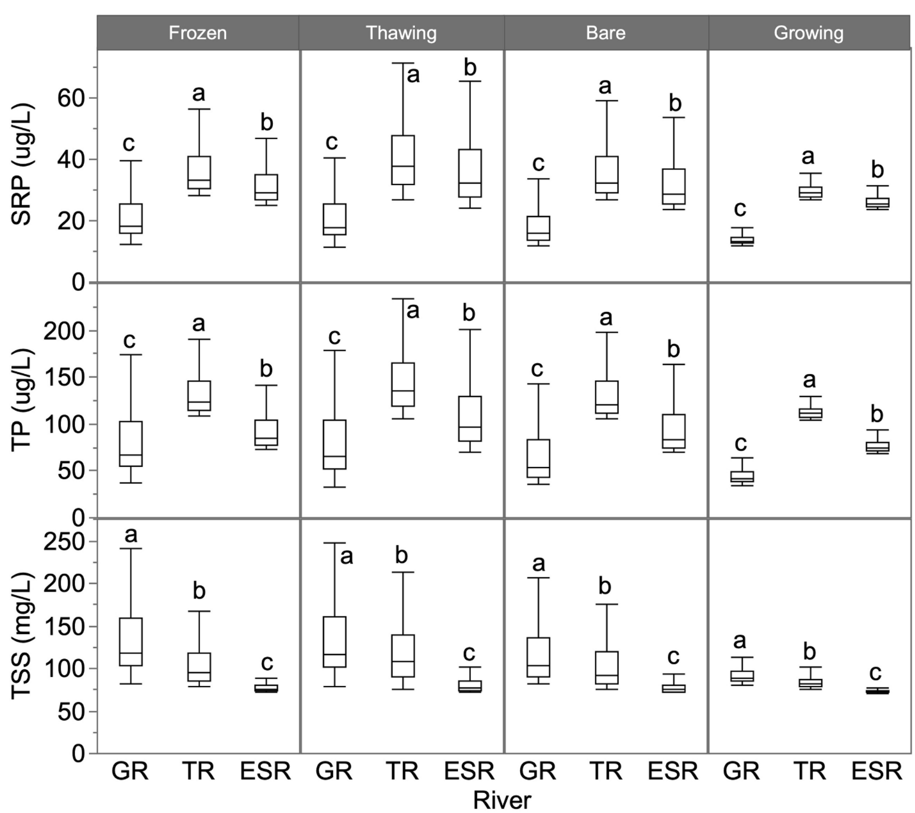

Fig. 3. Seasonal mean values for concentrations of soluble reactive phosphorus (SRP; μg/L), total phosphorus (TP; μg/L) and total suspended solids (TSS; mg/L) in the East Sydenham River (ESR), the Thames River (TR), and the Grand River (GR) from 2010 to 2021. Seasons were classified according to air temperature, as listed in Table 3. Statistically different means (as indicated by Kruskal-Wallis test and Wilcoxon Each Pair method) are denoted by the different letters (a, b, and c).

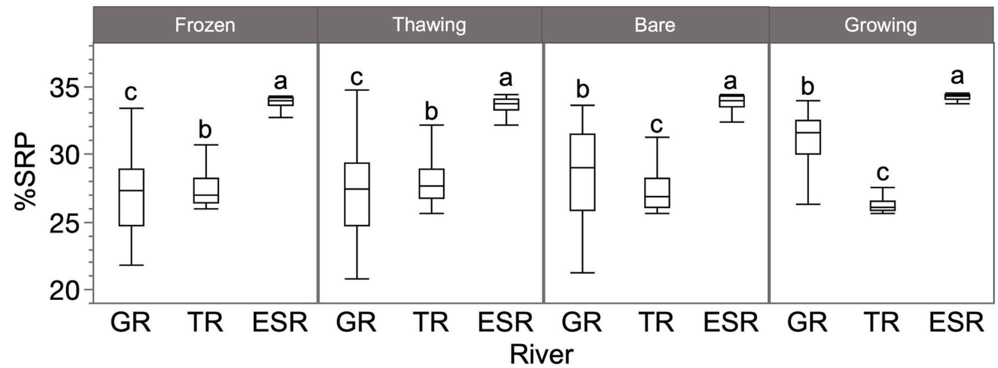

Fig. 4. Seasonal mean values for the percentage of soluble reactive phosphorus (%SRP) measured in the East Sydenham River (ESR), the Thames River (TR) and the Grand River (GR) from 2010 to 2021. Seasons were classified according to air temperature, as listed in Table 3. Statistically different means (as indicated by Kruskal-Wallis test and Wilcoxon Each Pair method) are denoted by the different letters (a, b, and c).

event where a snowpack was absent, this period also covered the time when soils would be frozen (Macrae et al., 2021; OMAFRA, 2010). In this season, we assumed that tile-drainage networks were disconnected from the soil surface due to snowpack development or the frozen state of the soil.

4.2. The thawing season: −3.2 to 6.7 °C

We believe this class of air temperatures represented not only the period that has been highlighted in the literature as late-winter-early-spring, but also similar conditions during the late-fall-early-winter months. This particular period captures hydrologically active conditions characterized by large amounts of runoff (Macrae et al., 2007; Macrae et al., 2021; Plach et al., 2019; Van Esbroeck et al., 2016), frequent freeze–thaw events (Rowlandson et al., 2018), increased precipitation as rain (Li et al., 2016; Wuebbles et al., 2018), as well as major snowfall and subsequent snowmelt events (Macrae et al., 2021; Stow et al., 2015). Here, we assumed this period to be the time when tile drains are operating to their fullest capacity, fulfilling their role in preventing oversatured soil-moisture conditions.

4.3. The bare season: 6.7 to 15.9 °C

We suggest that this bare season encapsulated periods of the year when agricultural fields were bare and uncovered. Given that data originating from the spring and fall seasons were largely represented within the bare season (Fig. 2b), we characterized conditions during this time as post-harvest and pre-planting. After primary crops were harvested, agricultural fields were assumed to be left bare and devoid of canopy (OMAFRA, 2016). However, this is not necessarily true in regions where cold-hardy cover crops are commonly used. Nutrient application is also likely to have occurred during this season (OMAFRA, 2016).

4.4. The growing season: > 15.9 °C

This warmest season reflected the period when the temperature warmed sufficiently for the dominant row crops to be planted in the region (i.e., corn [*Zea mays* L.] and soybean [*Glycine max* (L). Merr.]; Macrae et al., 2021). During this time, we assumed there was a crop canopy that covered the soil throughout the whole season, actively uptaking water and nutrients (Macrae et al., 2021; OMAFRA, 2016).

4.5. Seasonal water quality trends and relationships

In all rivers between 2010 and 2021, we observed trends and relationships during the thawing season that were indicative of increased P loading to Lake Erie from increased tile-drainage area. We found consistent year-over-year increasing trends in P variables during the thawing season in the ESR and TR, which have 60% and 48% tile drainage in their watersheds, respectively. However, when we looked at the GR, which has 23% tile drainage, there were no increasing trends in P variables (Table 4). By contrast, linear regression models between P variables and year-over-year increases in tile-drainage proportion were significant across all three watersheds, including the GR. This means that even though P variables did not increase year-over-year in the GR, tile-drainage area still influenced P loading during the thawing season, even at a relatively low proportion of 23%.

In the context of traditional seasons, snowmelt and precipitation events are known to occur in the spring. However, warmer and wetter winter conditions in southern Ontario have begun to cause shifts in the timing of snowmelt and freeze–thaw events (Déry et al., 2009; Shinker et al., 2010; van Vliet et al., 2013). When we sorted the data according to air temperature instead of traditional seasons, we were able to isolate for all study days where wet, thawing, and freeze–thaw conditions would have occurred. This allowed us to target the days when tile-drainage networks would have been actively operating to remove water from agricultural fields. As such, our findings suggest that the most appropriate time to implement P-reduction measures in the Canadian LEW would be during the period when air temperatures range between −3.2 – 6.7 °C (i.e., the thawing season), especially in heavily tile-drained areas like the ESR, but also in less tile-drained regions like the GR where networks are still expanding.

We found that the river with the highest proportion of tile drainage also happened to be the only river to yield increasing trends for all water-quality parameters during the warmer periods of the year (i.e., the bare and growing seasons) (Table 4). Linear regression models between water-quality parameters and tile drainage suggest that tile drainage was a stronger predictor of SRP, TP, and TSS loading, as opposed to concentrations, during these warmer periods in the ESR. As such, we attribute increases in nutrient loading values to increases in discharge, and this is supported by the highly significant models generated between discharge and tile drainage in the ESR during the warming seasons (Table 5). We speculate that the macropores in clay-rich soils of the ESR created preferential flow paths for water to travel through and reach tile-drain networks while bypassing the natural buffering capacity of the soil matrix and active plant uptake (Kokulan, 2019). During summer precipitation events, tile drains work together with soil macropores to enhance the overall movement of water from the soil matrix, exacerbating sub-surface water flux and increasing landscape-tributary connections (King et al., 2015; Van Esbroeck et al., 2016). Therefore, effects of soil texture may act cumulatively with tile drainage to increase discharge and associated loading values in the ESR, but more research should be done to explore this.

In the season that broadly represented post-harvest and pre-planting, which we assumed to be the bare season, linear regression models between water-quality concentrations and tile drainage in the ESR were stronger than those observed during the growing season. We believe that this is likely due to the application of fertilizer during the bare season. Rising air temperatures in the spring and fall within the Canadian LEW region (Wuebbles et al., 2018) have potentially created more favourable conditions for fertilizer application on agricultural fields. In fact, windows for fertilizer application have likely extended into late-fall-early-winter, as well as late-winter-early-spring.

When we sorted the data by river to compare water-quality parameters based on the tile-drain gradient between the three watersheds, we expected the ESR to have the highest mean SRP and TP concentrations across all seasons (Fig. 3). The fact that the TR had the highest P concentrations points to the potential role of cumulative impacts of P sources from the watershed. The TR watershed is not only highly tile-drained (48%) and dominated by row-crop agriculture (Agriculture and Agri-Food Canada, 2019), but it also contains major cities like London, Stratford, and Woodstock, Ontario. Urban pressures on P loading from these cities likely arise from wastewater treatment plant outflows and general overland runoff from impervious surfaces across the major cities.

While the ESR did not exhibit the highest SRP concentrations across the seasons, the river did have the highest mean %SRP during every season (Fig. 4). Together with this is the observation that the GR had the highest mean TSS concentration in every season. Being that these watersheds are on opposite ends of the tile-drainage gradient tested in this study, these findings likely illustrate one of the benefits of tile drain networks – the reduction of particulate P loss from overland flow. However, the trade-off presented here is that, although pervasive tile-drain networks can lower particulate losses from agricultural fields, they can also cause an increase in soluble P losses.

In southern Ontario, contribution of P to surface water from tile drainage and overland flow can differ from region-to-region (Plach et al., 2019). Regional variation in glacial deposits from flat and clay-textured in the southwest to hummocky and loam-textured soils in the north (Plach et al., 2018) can determine the amount of P exported via overland flow versus tile-drain flow. Many studies have claimed that snowmelt processes in the GR watershed almost always lead to overland flow instead of tile flow due to the strong buffering potential of the loamy-textured soils (Macrae et al., 2021). In this northern region, soils have the capacity to efficiently retain water, resulting in high-moisture conditions. P losses through tile drains in the GR have been shown to be lower than those from overland flow across the saturated soils of the GR watershed (Grant et al., 2019; Macrae et al., 2021; Plach et al., 2019; Pluer et al., 2020; Van Esbroeck et al., 2016). We believe this suggests that surface-flow dominated losses occurred in the GR, which resulted in the high TSS concentrations and low %SRP that we observed from the river.

In the frozen season, we found that year-over-year water-quality trends were consistently negative in the GR. This is in addition to the significantly negative linear models observed between water-quality parameters and annual tile-drainage proportion in the GR. Such negative trends and models likely suggest that tile drainage plays a limited role on water quality in the GR when temperatures are colder and below freezing. Given the GR's northernmost position in the Canadian LEW, it would be safe to assume the snowpack developed during the colder periods of the year acted as a barrier between tile drains and the soil surface, thus eliminating any tile-to-soil-surface connections.

One limitation of our study was our inability to apportion tile-P contributions from overland-P contributions. Flow-apportion studies have been conducted in smaller sub-watersheds (e.g., King et al., 2015; Plach et al., 2019; Van Esbroeck et al., 2016); however, takeaways from smaller sub-watershed studies are difficult to apply across scales as broad as the Canadian LEW. In Ontario, Van Esbroeck et al. (2016) reported that tile drains export proportionally less P compared to water export, while surface-flow dominated processes export proportionally more P compared to water export. While the data used in our study provide knowledge of cumulative surface and sub-surface processes, the fact that regression models between annually increasing tile drainage and discharge were stronger in the ESR than the GR (Table 5) is suggestive of the influence of dense tile-drainage networks on water export in flat and clay-dominated landscapes like the ESR.

Another limitation of our study is that water-quality data were collected at the mouth of every river. The issue with sampling at a single location near the mouth of a major tributary is that the data do not accurately capture the effect of smaller-scale regional differences in land-use-land-cover on water quality. As pointed out in the literature, riverine water quality regimes are difficult to measure and interpret in contemporary mixed-use watersheds where different land-use-land-cover types can confound observations (Hubbart et al., 2019; Kellner and Hubbart 2017; Poff et al., 2006). For instance, the GR watershed is recognized as a mixed-use watershed. It has relatively large proportions of natural land, pastureland, and urban land within the predominately-agricultural landscape, as well as a distinct north-to-south transition of glacial till and loamy soils to flat clay plains. It is very likely that trends observed in this study largely reflect water quality from the southern clay plains of the GR, thus masking P conditions from upstream areas of the watershed where the landscape supports more pastureland and well-drained soils.

Tile-drainage area continues to expand in the province of Ontario (Fortier, 2022), as programs like the Tile Loan Program (OMAFRA) provide farmers with competitive financing options for tile-drain implementation (https://www.ontario.ca/page/tile-loan-program). Given the concomitant increasing trends in tile-drainage area and P loading presented in this study, we suggest that financial-assistance programs adopt a more rigorous evaluation process for program eligibility on a farm-by-farm basis. Factors to be considered by financial-assistance programs should include soil texture, regional climate, crop rotation, and surrounding land-use-land-cover characteristics of the watershed like proportion of wetlands and forests.

Controlled tile drainage (CTD) involves installing flow control systems at the outlet of tile drains. CTD may be an effective practice for farmers to adopt to reduce the impact of their tile drains on water quality during the thawing season while still reaping the benefits of increased field drainage during the growing season. The management practice of CTD should continue to be researched at watershed scales to evaluate its effectiveness on reducing P runoff from tile-drained fields during critical seasons for P loss.

While this study sheds light on the potential role of tile-drainage expansion and seasonality changes on P loading across the Canadian LEW, we believe this study also speaks to the importance of long-term, high-resolution water-quality data collection. Due to the low-resolution nature of the Canadian water-quality dataset used in this study, the daily SRP, TP, and TSS concentrations, and associated loading values were estimated with low-to-moderate accuracy. High-resolution data are imperative to accurately identify, document, and model seasonal trends in water-quality variables across Canadian tributaries. Investment in government programs that collect high-resolution data should not only be continued, but also prioritized as climate-mediated seasonal changes continue to emerge over time.

5. Conclusion

In the Canadian LEW, this study has demonstrated that increased tile-drainage area can lead to increased P loading during the thawing season; however, effects of tile drainage are moderated by differences in soil texture, land-use-land-cover, regional climate, and watershed point sources. While more years of consistent data are critical to better delineate and analyze long-term P loading trends from the ESR, TR, and GR, the increasing trends we observed from 2010 to 2021 during the thawing season are consistent with the literature across the binational LEW. We believe that as climate change and agricultural practices continue to transform seasonal characteristics, the classification of seasons should be dynamic when investigating seasonal P export. In the Canadian LEW, the thawing season should be further explored as a regionally important period for increased P loading to Lake Erie.

CRediT authorship contribution statement

Alana C. Tedeschi: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rachelle A. Fortier:** Writing – review & editing, Investigation, Data curation. **Patricia Chow-Fraser:** Writing – review & editing, Supervision, Methodology, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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