Evaluating best management practices for nutrient load reductions in tile-drained watersheds of the Laurentian Great Lakes Basin: A literature review

Supplementary information

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Contents

1. Abbreviations used throughout this article

ADAPT - Agricultural Drainage and Pesticide Transport Model

AL - Alternative Land Management

AnnAGNPS - Annualized Agricultural Non-Point Source Pollution Model

APEX - Agricultural Policy Environmental eXtender Model

BMPs - Best Management Practices

CC – Cover Crops

CD - Controlled Drainage

CDS – Controlled Drainage System with Sub-Irrigation

CT - Conventional Conservation-Till

DPSIR - Drivers, Pressure, State, Impact, Response

DRAIN-WARMF - DRAINMOD coupled with WARMF Model

DRP - Dissolved Reactive Phosphorus

EPIC - Environmental Policy Integrated Climate Model

ETa - Actual Evapotranspiration

GLB - Great Lakes Basin

ha - hectare

HSPF - Hydrologic Simulation Program–Fortran Model

ICECREAM - Integrated Catchment-based Eco-hydrology and Advanced Modelling

kg - kilogram

kg/ha - kilograms per hectare

kg/ha/yr - kilograms per hectare per year

LAI - Leaf Area Index

MACRO - Model of Assessing Contaminant Release of Organics

MIKE SHE - MIKE Hydro Systems Engineering Model

mm - millimeter

N - Nitrogen

NCC - No-till Cover Crop system

NO_3–N - Nitrate Nitrogen

OrthoP - Orthophosphate

P - Phosphorus

PD - Pumped Drainage

PLEASE - Phosphorus LEAching from Soils to the Environment

PP - Particulate Phosphorus

PRISMA - Preferred Reporting Items for Systematic Reviews and Meta-Analyses

RCP - Representative Concentration Pathways

RFD – Regular Free Drainage

RZWQM2 - Root Zone Water Quality Model 2

RZWQM2-P - Enhanced RZWQM2 for Phosphorus simulation

SRP - Soluble Reactive Phosphorus

SWAT - Soil and Water Assessment Tool

SWAT+ - Enhanced version of SWAT Model

SWATDRAIN - SWAT combined with DRAINMOD Model

SWAT-P - SWAT for Phosphorus simulation

TKN - Total Kjeldahl Nitrogen

TN - Total Nitrogen

TP - Total Phosphorus

TSS - Total Suspended Solids

U.S. - United States

USDA - United States Department of Agriculture

USGS - United States Geological Survey

WARMF - Watershed Analysis Risk Management Framework Model

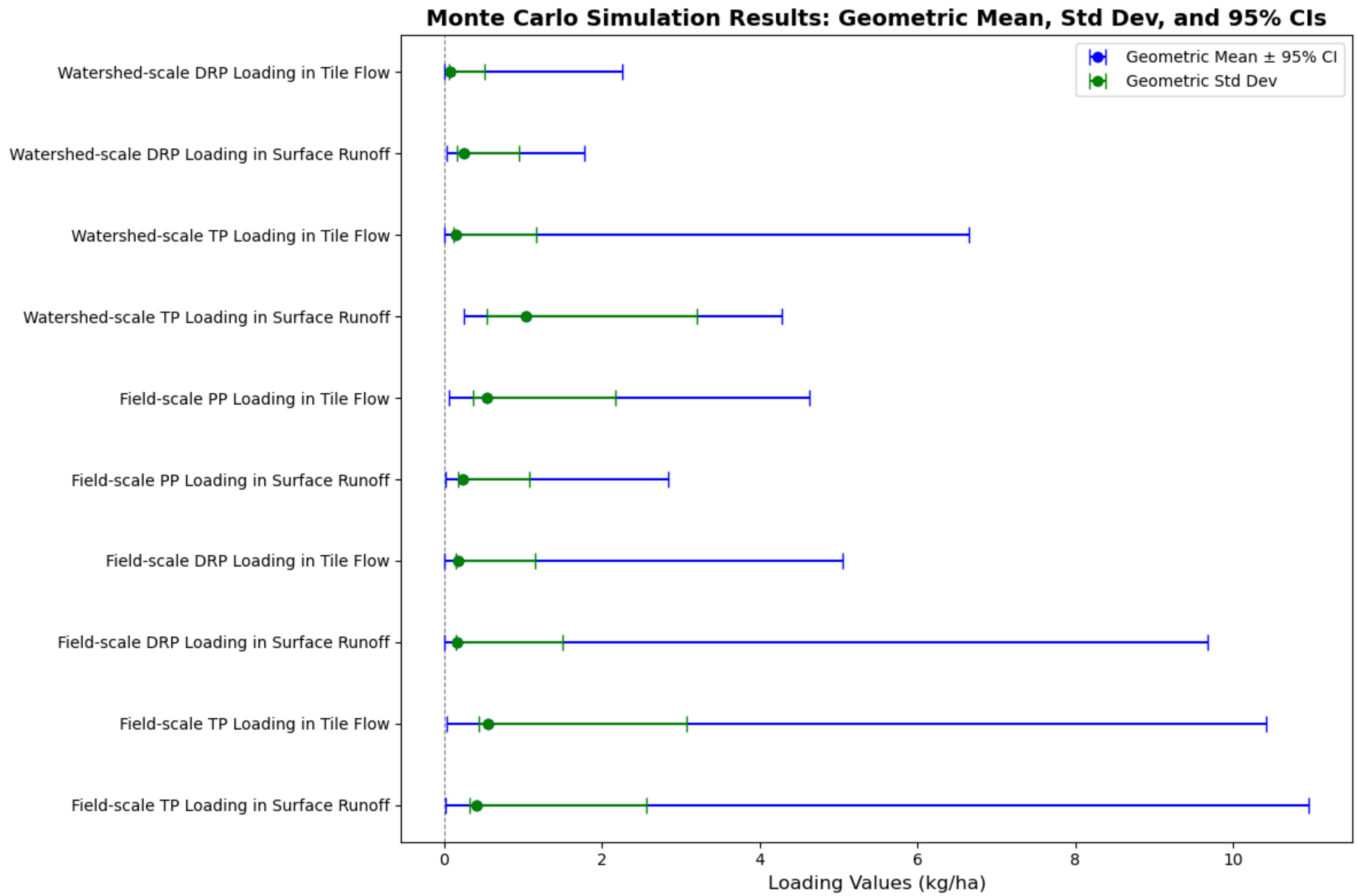
2. Defining different terms on the agricultural drainage system

- Drainage water management (DWM)
- Controlled Tile Drainage (CTD)
- Controlled drainage (CD)
- Controlled Drainage with Sub-irrigation (CDS)
- Pumped Drainage (PD)

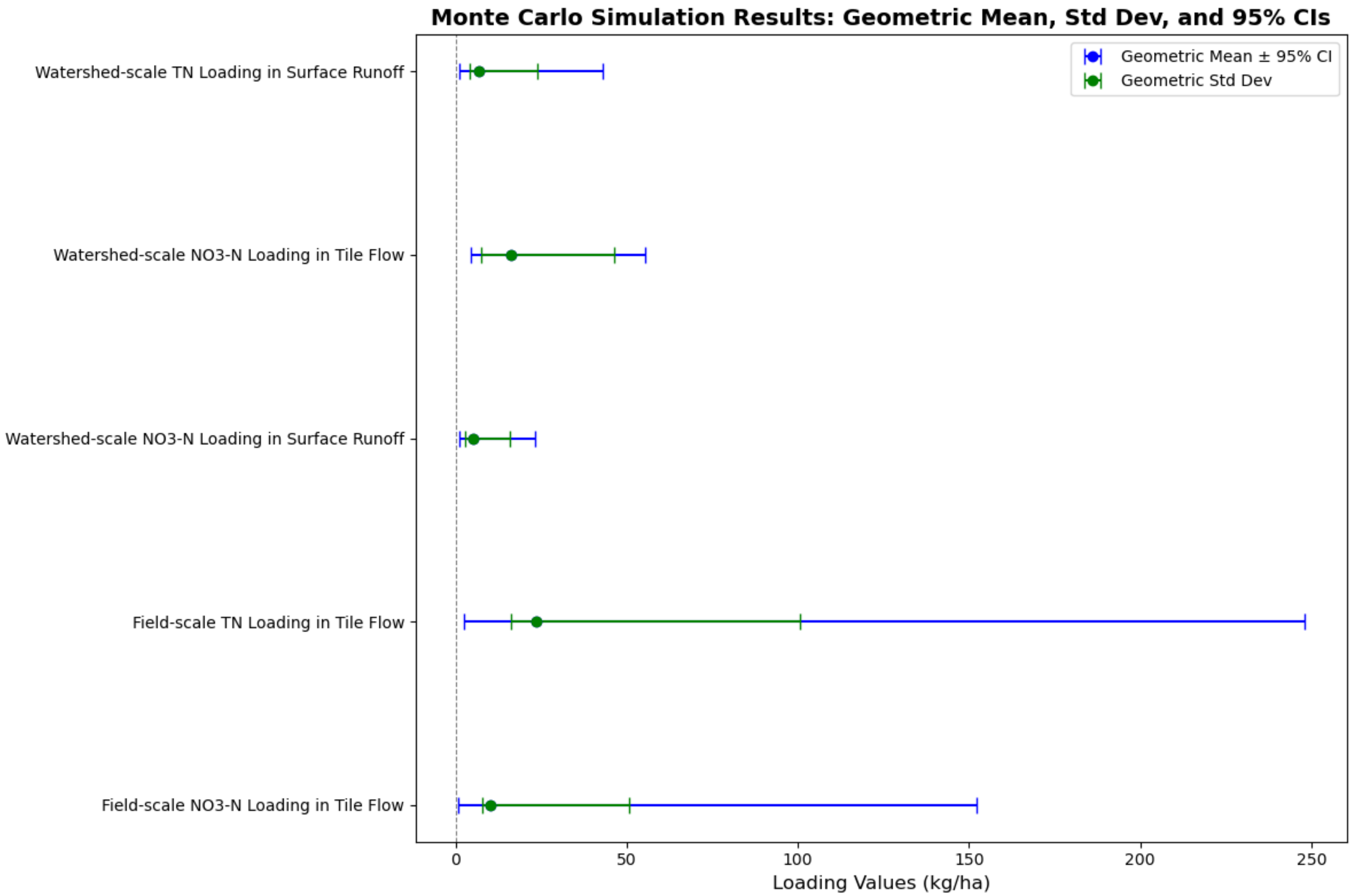
Agricultural **Drainage Water Management (DWM)** is an umbrella term encompassing various practices to control the timing and amount of water discharged from agricultural fields to enhance crop production and reduce nutrient loadings (Ross et al., 2016). According to Williams et al. (2015b) Drainage Water Management (DWM) involves seasonally adjusting the outlet elevation of a drainage system using a control structure, typically made of stackable boards or stop logs. The outlet elevation can be set at any level from the ground surface to the drainage depth. DWM helps manage excess and deficit soil–water conditions, ensuring adequate drainage during critical planting and harvesting operations. It also prevents excessive drainage of the crop root zone after planting or during winter periods when drainage is unnecessary.

Under DWM, methods like **Controlled Tile Drainage (CTD)** (Kęsicka et al., 2023) **and Controlled Drainage (CD)** (Carstensen et al., 2019) involve installing water control structures on subsurface drainage systems to regulate the water table by adjusting the water outflow. **Controlled Drainage with Sub-irrigation (CDS)** (Tan & Zhang, 2011) expands on this by using the same infrastructure to drain excess water and supply irrigation during dry periods, optimizing water availability for crops. Controlled Drainage with Sub-irrigation (CDS) advances regular free tile drainage by installing a "riser" on the tile outlet to manage the water table and sub-irrigate crops. The outlet riser has dual functions: controlling drainage outflow during periods of excess water and sub-irrigating crops under drought conditions by returning water to the tile lines. **Pumped drainage (PD)** (Grenon et al., 2023) is employed to remove excess water actively using pumps in regions with flat terrain or high-water tables. By integrating these practices, DWM allows farmers to efficiently manage soil moisture levels, improve crop yields, and minimize nutrient losses to surrounding water bodies.

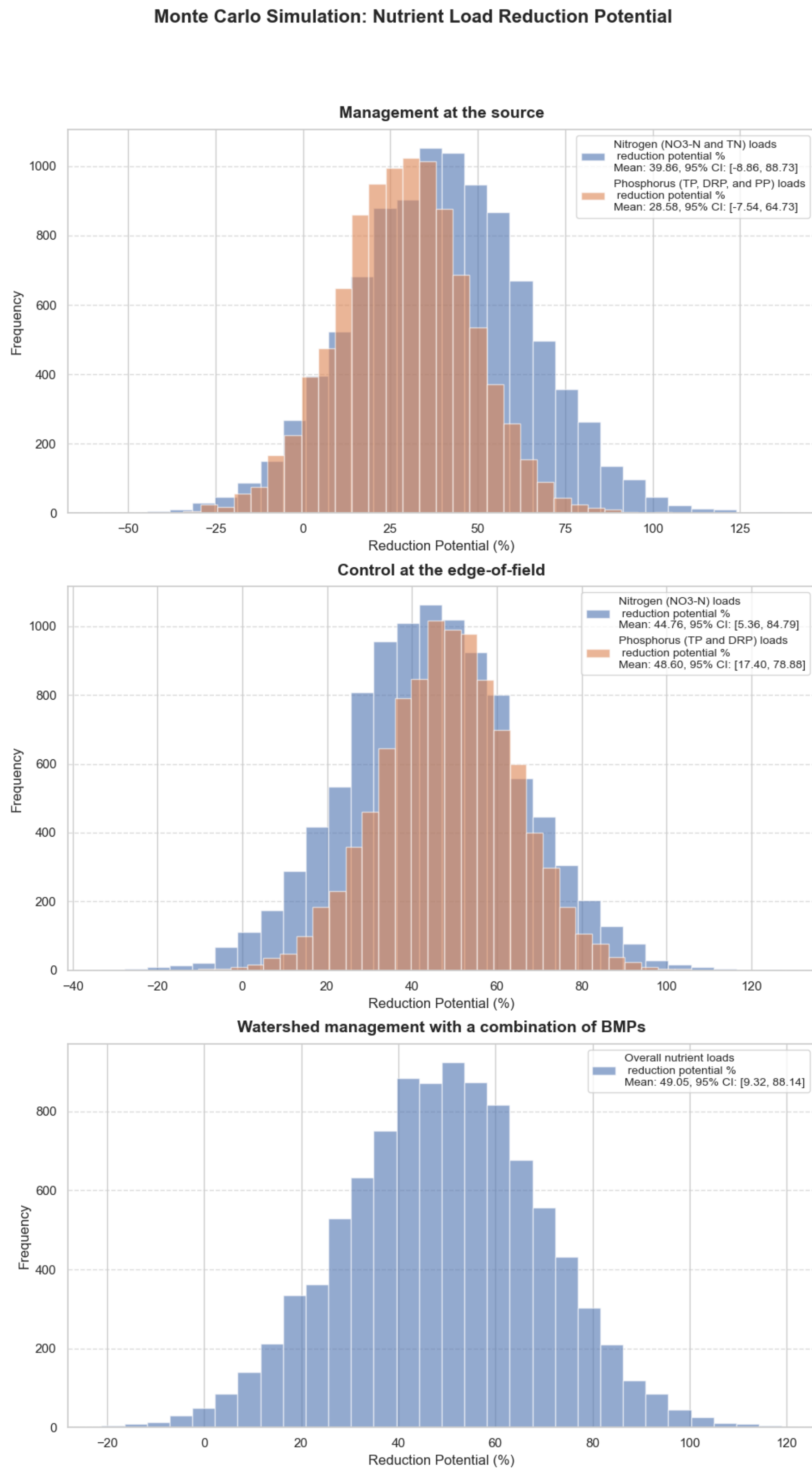
3. **Supplementary Figure S1:** Monte Carlo simulation for uncertainty analysis on phosphorus loadings from tile-drained fields and watersheds



4. **Supplementary Figure S2:** Monte Carlo simulation for uncertainty analysis on nitrogen loadings from tile-drained fields and watersheds



5. **Supplementary Figure S3:** Monte Carlo simulation for uncertainty analysis on nutrient load reduction potential of BMPs



6. **Supplementary Table S1:** The DPSIR (Drivers, Pressures, State, Impact, Response) framework of tile drainage in the Great Lakes Region

Framework component	Sub-components	Overview	Key facts	Examples
Drivers	• Agricultural intensification • Profitability and sustainability of farming • Climate variability	The adoption of tile drainage in the Great Lakes Region is primarily motivated by its potential to enhance agricultural productivity and economic outcomes. Tile drainage initially improves soil conditions, extends the growing season, and addresses the challenges of climate variability.	• Approximately 43 million hectares of U.S. cropland require artificial drainage (Boles et al., 2015). • 22.48 million hectares of U.S. croplands have tile drainage, predominantly in six Midwestern states (Boles et al., 2015; Valayamkunnath et al., 2020). • Around 50% of Ontario's arable land utilizes artificial drainage systems (Golmohammadi et al., 2021).	• Economic analyses suggest tile drainage can boost crop yields by 10-30% (Blann et al., 2009). • Predicted increases in precipitation in the Great Lakes region by 20-30% by the century's end highlight the need for efficient drainage systems (Bosch et al., 2014). • Tile drainage mitigates waterlogging and soil erosion risks, enhancing adaptability to increased rainfall intensity and frequency (Bailey et al., 2022).
Pressures	• Altered watershed hydrology • Increased nutrient loading	Tile drainage systems alter hydrological pathways, increasing nutrient loading in water bodies and impacting soil health. These systems enhance subsurface water flow and soil aeration, leading to faster runoff, changed groundwater recharge, and elevated nutrient runoff.	• Tile flow contribution: Averaged 29% of precipitation over five years in a free drainage system (Tan & Zhang, 2011). • Streamflow origin: 42% from drainage tiles in an Ontario watershed (Macrae et al., 2007). • Watershed discharge: 47% from tile drainage in a small Ohio watershed (King et al., 2014). • Phosphorus levels: Range from 0.01 to 8.0 mg/L, exceeding eutrophication thresholds of 0.02–0.03 mg/L (King et al., 2015).	• NO3-N loading: Tile drainage systems in the Midwest are significant pathways for NO_3-N reaching surface waters (David et al., 2010). • Lake Erie phosphorus loadings: Substantially linked to tile drainage systems (King et al., 2015). • Wisconsin phosphorus: Tile drainage water flow contributed 17–41% of cumulative total phosphorus and 16–58% of dissolved phosphorus loadings (Ruark et al., 2012). • Phosphorus leaching: 95–97% of P leached to subsurface drains in southern Ontario (Tan & Zhang, 2011).

Framework component	Sub-components	Overview	Key facts	Examples
State	• Water quality degradation • Impacted aquatic ecosystems	The environmental resources of the Great Lakes region face significant challenges from deteriorated water quality and disrupted aquatic ecosystems, primarily due to increased runoff and nutrient inputs from agricultural runoff from tile drains and overland flow. These runoffs contribute to nutrient loading and variability in streamflow, complicating compliance with water quality standards and leading to severe periodic algal blooms.	• Phosphorus loadings: Lake Erie receives 2.4 kilotons TP annually; Lake Michigan receives 2.3 kilotons TP annually (King et al., 2015). • Nitrogen loadings: Lake Michigan receives 62.9 kilotons TN annually; Lake Erie receives 61.5 kilotons TN annually (King et al., 2015). • Nutrient loading uncertainties: Standard deviations for TN are 864 tons/year (Lake Michigan) and 910 tons/year (Lake Erie) (King et al., 2015). • Tile drainage impact: Tile drainage significantly contributes to nutrient loading in Lake Erie and Lake Michigan through agricultural runoff.	• Exceeding standards: Nitrates in tile drainage often surpass the drinking water standard of 10 mg/L NO_3-N (Frank et al., 1991). • Algal blooms: Phosphorus runoff from tiled fields contributes to recurrent algal blooms in Lake Erie (Scavia et al., 2014). • Eutrophication effects: It reduces biodiversity and increases turbidity in aquatic ecosystems (Smith et al., 2014). • Aquatic life impact: Changed water chemistry alters species composition and reduces fish populations (King et al., 2015). • Hypoxic conditions: Increased frequency affects aquatic life adversely (Watson et al., 2016).
Impact	• Agricultural impacts • Ecological degradation • Economic consequences	Tile drainage in the Great Lakes region enhances agricultural productivity by improving soil conditions and extending growing seasons, leading to higher crop yields and farm profitability (Blann et al., 2009). However, it also contributes to ecological degradation through nutrient pollution, affecting 40 million residents dependent on the Great Lakes for clean drinking	• Economic losses from HABs: Estimated at $4.6 billion annually in the U.S. due to impacts on water quality and aquatic health (Kudela et al., 2015; Miller et al., 2021). • Nutrient loadings: High phosphorus levels from agricultural runoff are linked to recurrent algal blooms in Lake Erie (Michalak et al., 2013). • Hydrological changes: Tile drainage modifies key hydrological processes, reducing the effectiveness of conservation	• Agricultural benefits: Improved farm operations and increased crop yields from better field conditions (Fausey et al., 1995). • Economic offsets: Benefits from increased agricultural output are counterbalanced by water treatment costs and ecological restoration costs (Nickerson et al., 2012; Christianson et al., 2015). • Recreational impact: Recurrent algal blooms in Lake Erie impair drinking water and recreational activities, affecting tourism and local

Framework component	Sub-components	Overview	Key facts	Examples
		water. Ecological impacts include fish kills and reduced biodiversity, affecting local ecosystems and economies. Economically, the region experiences declines in tourism and recreational activities due to periodic algal blooms, related health advisories, and increased water treatment and ecological restoration costs.	practices to lower surface runoff and nutrient loading (King et al., 2015). • Biodiversity reduction: Altered water chemistry and nutrient loadings disrupt ecosystems, leading to declines in fish and invertebrate populations (Scavia et al., 2014).	economies (Michalak et al., 2013; Scavia et al., 2014). • Regulatory and management costs: Financial investments are required for nutrient management and implementing Best Management Practices (BMPs) (Ohio EPA, 2010). • Long-term ecological effects: Include altered hydrological cycles and increased nutrient loadings, impacting overall ecosystem health (Giri et al., 2014).
Response	• Policy and regulation • Best Management Practices (BMPs) • Technological innovations	Responses to environmental challenges from tile drainage include policy and regulatory measures, implementation of BMPs, and technological advancements. The Great Lakes Water Quality Agreement (GLWQA) and other initiatives aim to reduce nutrient loadings from agriculture. Advancements such as controlled drainage systems are being adopted to minimize nutrient loading, supported by collaborative efforts that involve education and voluntary conservation practices.	• The Great Lakes Restoration Initiative supports projects to reduce nutrient runoff. • Controlled drainage systems can cut nutrient outflows by up to 50% (Skaggs et al., 2012). • Significant funding is allocated for research and development to enhance tile drainage efficiency and lessen environmental impacts (Bosch et al., 2013).	• Education and outreach: Programs enhance farmer participation in BMPs. • Incentive programs: The Conservation Reserve Program encourages runoff-reducing practices. • Community engagement: Local watershed groups and community involvement in management planning focus on improving agricultural practices and reducing ecological impacts (Fales et al., 2016). • Regulatory efforts: The Great Lakes Water Quality Agreement aims to reduce phosphorus loadings by 40%, highlighting the importance of managing tile drainage (IJC, 2017).

7. **Supplementary Table S2:** A systematic literature search strategy (Adapted from Bramer et al. 2018)

Search Step	Description
Focused Research Question	How can BMPs be optimized in tile-drained agricultural watersheds of the GLB to effectively reduce nutrient loadings, particularly phosphorus and nitrogen , while balancing agricultural productivity with water quality protection under varying hydrological, soil, and climatic conditions?
Relevant Literature Types	Reviews, research articles, field experiments, modeling exercises, and case studies that evaluate BMP effectiveness in nutrient reduction, optimization of BMPs under different environmental conditions, and their impacts on water quality and agricultural productivity in tile-drained landscapes.
Key Concepts	- Tile drained watershed - Tile drained fields - Tile drainage systems - Tile drainage design - Drainage water management - Controlled tile drainage - Nutrient management - Best Management Practices (BMPs) - Agricultural productivity - Water quality - Nutrient loading (Nitrogen, Phosphorus) - Nutrient dynamics - Hydrological modeling - Water quality modeling - Soil characteristics - Land use and agricultural management - Climatic change impacts on BMPs - Hydrology and subsurface runoff - Agricultural runoff and eutrophication
Search Strategy	Combined key concepts for targeted results, such as 'Tile-drained fields and watersheds', 'Best management practices and agricultural conservation', 'BMP effectiveness monitoring and modeling'.

Search Step	Description
Initial Databases	Scopus, Web of Science, Google Scholar, and Omni Academic Search, were selected for their comprehensive coverage of environmental, watershed management, geospatial modeling science, and agricultural studies.
Documentation of Search Process	Documented search engines/databases used, search keywords, Boolean operators (AND, OR, NOT), date of search, number of results, filters applied (e.g., publication date range, article type, language), articles reviewed and selected from initial results, reasons for exclusion, refining search strategy, and managing citations using Zotero.
Index Terms and Synonyms	Identified index terms and synonyms in the database thesaurus to ensure comprehensive search coverage: - BMPs = "Best Management Practices", "conservation practices" - Tile drainage = "subsurface drainage", "drainage systems" - Nutrient loading = "nutrient leaching", "nutrient runoff"
Search Syntax	Used database-appropriate syntax with parentheses, Boolean operators, and field codes to construct precise queries, e.g., Topic Search (TS)=("Best Management Practices" OR BMPs) AND TS=("tile drainage" OR "subsurface drainage") AND TS=("nutrient loadings" OR phosphorus OR nitrogen) AND TS=("water quality" OR "agricultural productivity") AND TS=(hydrology OR "soil characteristics" OR climate)
Optimization and Testing	It began with broad terms and was refined based on initial results; adjusted terms and added specifics related to hydrological and climatic factors influencing BMP effectiveness. Reiterated search based on results from different databases to include the most comprehensive and relevant set of articles.
Evaluation and Error Checking	Evaluated the relevancy of the first 30 results to ensure the search was on track and checked for syntax errors or Boolean operators' incorrect use.

8. **Supplementary Table S3:** An overview of the inclusion and exclusion criteria for identifying literature

Inclusion criteria	**Exclusion criteria**
Geographic Scope: • Studies must be conducted within the North American Great Lakes Basin (GLB) or in regions that exhibit similar climatic, soil, and agricultural landuse characteristics to the GLB. We use the Great Lakes drainage basin map to identify our geographic focus and the US and Canadian states connected with the GLB.  Figure: Extent of the Great Lakes drainage basin (Adapated from Neff & Nicholas 2005)	**Geographic Scope**: • Studies conducted outside the Great Lakes Basin (GLB) and regions that do not share similar climatic and agricultural conditions with the GLB are excluded. **Focus of Study**: • Research that does not specifically address tile-drained agricultural fields and watersheds will be excluded. **Interventions Analyzed**: • Studies that do not evaluate agricultural BMPs or focus on practices irrelevant to nutrient runoff and water quality in tile-drained systems are excluded. **Outcomes of Interest**: • Research lacking quantitative assessments of phosphorus (P) and nitrogen (N) loading reductions. • Studies that do not examine changes in hydrological processes due to BMP implementation. • Research that does not include assessments related to eutrophication mitigation or the reduction of harmful algal blooms. **Types of Studies**: • Theoretical papers, opinion pieces, and editorials that do not provide empirical data or modeling results. • Preliminary reports, conference abstracts, or poster presentations that have not undergone peer review. **Syntheses of Research**:

Inclusion criteria	Exclusion criteria
The rationale for the inclusion of studies to both in- and out-of-the GLB basin is to: • Demonstrate the consistency (or differences) of findings across regions. • Highlight innovative practices or outcomes that might be adapted for GLB conditions. • Provide a more comprehensive overview of tile drainage and BMP performance in regions with similar agricultural activities or climatic trends. **Focus of Study**: • Research should specifically focus on tile-drained agricultural fields and watersheds. **Interventions Analyzed**: • Studies must evaluate agricultural BMPs designed to mitigate nutrient runoff and improve water quality. **Outcomes of Interest**: • Research must quantitatively assess reductions in phosphorus (P) and nitrogen (N) loadings. • Studies should examine changes in hydrological processes due to BMP implementation. • Assessments related to the mitigation of eutrophication and the reduction of harmful algal blooms are required. **Types of Studies**: • Empirical studies, including field experiments and monitoring studies. • Modeling studies that employ watershed-scale hydrologic and nutrient transport models.	• Reviews or meta-analyses that do not specifically focus on BMP effectiveness in improving water quality or are not based on systematic review methodologies. **Publication Standards**: • Non-peer-reviewed articles, including newsletters, personal blogs, and most types of grey literature. • Studies published in languages other than English without an available and reliable English translation. **Publication Date Range**: • Studies published before the year 2000 that are not cited within included studies for historical context or foundational background. • Research that does not provide contemporary insights into BMP practices, especially those failing to account for recent changes in climate and agricultural technologies. **Climate Change Considerations**: • Studies that ignore the impact of climate variability and change on BMP effectiveness and nutrient loadings.

Inclusion criteria	Exclusion criteria
• Comparative analyses focusing on the comparison of multiple BMPs or the comparison of BMPs versus conventional agricultural practices. **Syntheses of Research**: • Literature reviews and meta-analyses that evaluate the effectiveness of BMPs and their impact on water quality through monitoring and modeling efforts. **Publication Standards**: • Only peer-reviewed articles published in recognized scientific journals will be included. • All included studies must be available in English. **Publication Date Range**: • Research published from the year 2000 to 2024 is included to ensure relevance to current agricultural practices and climatic conditions. • Citations within these articles that refer to foundational studies published before 2000 are also considered for inclusion to capture seminal work and historical context. **Climate Change Considerations**: • Studies must address how climate variability and change impact the effectiveness of BMPs and influence nutrient loadings.	

9. **Supplementary Table S4:** A description of study sites cited in this study

Location		Site description	Reference
Canadian portion of GLB	Pike River watershed, southern Quebec	• Study area of 3 km^2 features four fields labeled A-D, each investigated for phosphorus transport • Drainage systems differ with subsurface drainage in Fields A and B and natural drainage in Fields C and D • Soil composition varies between fields, with clay loam present in Fields A and C and sandy loam in Fields B and D • Crop rotations include corn, soybeans, mixed cereals, and hay • Climate data indicates an average temperature of 6.8°C and an annual precipitation of 958 mm • Growing season spans from May to September • Runoff measurements show significant variation from 56 mm to 737 mm, influenced by both the type of drainage and soil characteristics	Eastman et al. (2010)
	Innisfil, Ontario, south of Kempenfelt Bay in Lake Simcoe	• The study area is within the Lake Simcoe watershed covers 3,557 km^2 with the lake itself covering 722 km^2 • Agricultural fields utilize perforated pipes about 1 meter underground, spaced 12.2 meters apart, for excess water management during heavy precipitation and snowmelt • Crop rotations of corn, soybean, and winter wheat • Soils primarily from the Grey–Brown Luvisol Great Group, stony and range from imperfectly to well-drained • Average temperatures of −7.7°C in January and 20.8°C in July • Annual precipitation averages 933 mm, with 22% as snow, suitable for warm summers and cool, snowy winters with mid-winter thaws	Lam et al. (2016)
	Essex Region Conservation Authority Demonstration Farm, Holiday Beach, Southern Ontario, within the Lake Erie basin	• Study site features two tile drainage systems, Regular Free Drainage (RFD) with tiles at 0.6 m depth and 4.6 m spacing and Controlled Drainage with Sub-irrigation (CDS) which adjusts water levels to optimize usage and minimizes runoff • Site uses no-till corn-soybean rotation on Perth clay soil rich in sand, silt, and clay • Climate records an average annual precipitation of 858.5 mm • Surface runoff is significantly lower in Regular Free Drainage systems at 7.4 mm compared to 37.5 mm in Controlled Drainage with Sub-irrigation systems, highlighting controlled drainage effectiveness	Tan & Zhang (2011)
	Three sites across Ontario: Bainsville-BVL, Ilderton-ILD, London-LON	• Sites feature a humid continental climate with diverse soil types including Bainsville silt loam, Thorndale and Embro silt loams, and Perth clay loam • Tile drains installed at 0.9 meters depth with spacing of 9 to 14 meters	Esbroeck et al. (2016)

Location		Site description	Reference
		• All sites employ reduced tillage with a corn-soy-winter wheat rotation • Mean annual temperatures range between 7.0°C to 8.2°C • Annual precipitation varies with Bainsville at 1004 mm, London at 1024 mm, and Ilderton at 1247 mm, with 16%-30% as snow • From May 2012 to April 2013, runoff was 577 mm in Bainsville, 359 mm in Ilderton, and 375 mm in London, showing distinct surface runoff differences at each site	
	Chatham-Kent region, Ontario, on the northern boundary of Lake Erie	• Region features flat to gently undulating terrain, extensively using tile drainage on Brookston Clay soil • Warm summer continental climate with mean temperatures of 9.8°C and average annual precipitation of 882 mm • Study analyzed two systems, No-Till Cover Crop System (NTCC) with continuous no-till and cover crops, and Conventional Conservation-Till System (CT) involving shallow tillage. Both systems target a corn-soybean-soybean-winter wheat rotation	Macrae et al. (2023)
	Three agricultural fields on working farms in Midwestern Ontario	• Fields at Ilderton (ILD) and Londesborough (LON) have gently sloping loam soils; Essex (ESS) features flat, clay-textured soil • All fields are equipped with subsurface tile drainage systems spaced 10-15 meters apart and 60-90 cm deep • Common crop rotations include corn, soybeans, and winter wheat • Conservation tillage and varying fertilization techniques are implemented • Mean annual temperatures range from 6.7°C at Londesborough to 9.9°C at Essex • Precipitation varies from 935 mm at Essex to 1015 mm at Londesborough • Annual discharge at field edges ranges from 140 to 534 mm, about 33% of total precipitation	Plach et al. (2019)
	Londesborough, Southern Ontario, Canada	• Study focuses on an 8.66 ha field with a comprehensive tile drainage system • Drainage system embedded at 90 cm depth with 10-cm diameter laterals spaced 13.5 m apart, connected to a 20-cm diameter main tile • Field operates under a reduced tillage system cultivating soybeans, winter wheat, and grain corn on a strict schedule • Soils are part of the Perth Clay Loam association, featuring clay loam glacial deposits with imperfect drainage • Region experiences a mean annual temperature of 7.2°C, influencing crop growth cycles • Local climate station records a long-term average annual precipitation of 1247 mm • Field has a maximum surface storage capacity of 1.6 mm, critical for managing surface runoff	Golmohammadi et al. (2021)

Location		Site description	Reference
	Honorable Eugene F. Whelan Research Farm, South Woodslee, Ontario	• Experimental site includes 16 plots, each 67.1 meters by 15.2 meters • Conventional agricultural practices including chisel plow tillage • Tile drainage system set at 0.85 meters deep, spaced 3.80 meters apart • Features controlled drainage to manage water and nutrient outflow efficiently • Crop rotation system alternating annually between maize and soybean • Liquid cattle manure applied to maize plots providing 50 kg of phosphorus and 200 kg of nitrogen per hectare • Primary soil type is clay loam	Sadhukhan et al. (2019)
	Hon. Eugene F. Whalen Experimental Farm in Southwestern Ontario	• This study assessed impact of yard waste compost (YWC) and swine manure compost (SMC) on phosphorus loss in tile drainage • Compared free drainage to controlled drainage with subirrigation • Soil is a fine-textured, poorly drained Brookston clay loam • Tile drainage system comprised of perforated pipes at 0.6 to 0.7 meters deep and spaced 7.5 meters apart • Rotational cropping system of corn and soybean • Average annual air temperature was 8.9°C; average annual precipitation was 812.85 mm • Tile drainage volume averaged 166.67 mm, about 20% of the annual precipitation.	Zhang et al. (2015)
	Honorable Eugene F. Whelan Research Farm, South Woodslee, Ontario	• This study determined the individual and combined effects of drainage water management (DWM) and a winter wheat cover crop on phosphorus (P) losses via surface runoff and tile drainage in a fine-textured soil in the Lake Erie basin. • The design included eight treatment combinations of two drainage water management (DWM) systems (regular free drainage, RFD, versus controlled drainage with sub-irrigation, CDS) and two conditions of cover crop presence (no cover crop, NCC, versus winter wheat as cover crop, CC). • Winter wheat was used as the cover crop, seeded shortly after corn or soybean harvest each fall, using a no-till drill. Specific fertilization for corn and no additional fertilizers for soybeans, with detailed management of weed control.	Zhang et al. (2017)
	Honorable Eugene F. Whelan Research Farm near South Woodslee, Ontario	• Plot Configuration: 16 plots each measuring 67.1 meters by 15.2 meters, with regular chisel plow tillage before planting and after harvest. • Drainage System: Tile drainage installed at a depth of 0.85 meters and spaced 3.80 meters apart, including controlled drainage features to manage water and nutrient outflow. • Crop Rotation: Alternating annually between maize (Zea mays L.) and soybean (Glycine max (L.) Merr.).	Sadhukhan et al. (2019)

Location		Site description	Reference
		• Manure Application: Liquid cattle manure applied in maize planting years at rates of 50 kg of phosphorus per hectare and 200 kg of nitrogen per hectare. • Soil Type: Predominantly clay loam, with specific properties like field capacity, permanent wilting point, bulk density, and porosity documented.	
	Hon. Eugene F. Whelan Experimental Farm, Harrow Research and Development Center, South Woodslee, Ontario	• Field Configuration: Mineral-P-fertilized clay loam fields, each plot equipped with three tile drains at a depth of 0.85 m and spacing of 3.8 m. • Cropping System: Annual rotation between maize and soybean, with specific tillage and fertilizer application details reflective of typical agricultural land use. • Soil Type: Clay loam with detailed properties measured including texture, bulk density, porosity, field capacity, wilting point, and hydraulic conductivity. • Precipitation: Average annual precipitation reported at 990.9 mm. • Surface Runoff: Observed at 140.03 mm/yr, simulated at 90.72 mm/yr. • Tile Drainage: 43.2% to 43.6% of annual precipitation accounted for by tile drainage, with observed drainage at 428.49 mm/yr and simulated at 431.83 mm/yr.	Qi et al. (2018)
	Honorable Eugene F. Whalen Experimental Farm, Woodslee, Ontario	• The study was conducted over six years (1999–2005) across 16 0.1-ha field plots. • Tile-drained agricultural watershed in a corn-soybean rotation • Two drainage tiles per plot (10 cm diameter, 7.5 m apart, 0.6–0.7 m deep) • Soil: Brookston clay loam (Typic Argiaquoll or Orthic Humic Gleysol), 28% sand, 35% silt, 37% clay in the Ap horizon • Climate: Average annual temperature: 8.9°C and precipitation: 831 mm • Runoff: Cumulative runoff ranged from 365 mm (cover crops + UTD) to 590 mm (no cover crops + CDS) over the study period	Drury et al. (2014)
	Ewing Brook subwatershed, within the Pike River watershed, southern Quebec, Canada	• Ewing Brook subwatershed spans 32.2 km^2, predominantly flat with a mean slope of less than 1%. • Soils range from sandy Spodosols to clayey Inceptisols over poorly drained clay subsoils. • Tile drainage accounts for 42 to 60% of annual water discharge from agricultural lands in the Great Lakes region. • Agriculture covers 98% of the land. Main crops are corn in rotation with soybeans and small grains; hayfields with perennial forages make up 13% of agricultural use. • Temperature ranges from -10.0°C in January to 20.5°C in July. • Annual precipitation totals 932 mm of rain and 200 mm of snow	Michaud et al. (2019)
	Sydenham River watershed in Ontario	• The watershed covers 85% farmland with extensive tile drainage. • Features both closed (for annual crops) and open (for perennial and annual crops) tile systems, influencing sediment and nutrient runoff.	Coelho et al. (2010)

Location		Site description	Reference
		• Main crops include corn, soybeans, and alfalfa. • Soil types range from silty clay to sandy loam, affecting water dynamics and drainage efficiency. • Receives about 437 mm of precipitation from November to April, accounting for 47% of annual precipitation.	
	Holland Marsh, Ontario	• Two fields in a 5 km^2 area: a 4.2 ha field with controlled drainage (CD) and a 5.6 ha field with pumped drainage (PD). • Drained peatland with approximately 60% used for intensive, high-value crop production. • Water table maintained at 30-40 cm in winter and 70-80 cm during the growing season. • Growing season temperatures in 2015–2016 ranged from 14.6°C to 24.3°C, slightly above the 30-year average. • Precipitation was below the 30-year average, with 675 mm in 2015 and 630 mm in 2016.	Grenon et al. (2023)
	Hopewell Creek watershed, Ontario, Canada	• The 72 km^2 area encompasses 46% agriculture (24% tile-drained), 41% natural areas (forests and riparian zones), and 9% residential. • Predominantly sandy loam, including grey-brown luvisols, melanic brunisols, and humic gleysols. • Mean air temperatures range from -6.5°C in January to 20.0°C in July. • Average annual precipitation is 916.5 mm, with 17% falling as snow.	Irvine et al. (2019)
	Field site near Londesborough, Southern Ontario	• 8.66 ha agricultural field with both overland flow and tile drainage. • Tile drains embedded at 90 cm, with 10-cm diameter laterals spaced 13.5 m apart, linked to a 20-cm diameter main tile. • Agriculture under a reduced tillage system, growing soybeans, winter wheat, and grain corn, with a detailed management schedule. • Perth Clay Loam association, clay loam glacial deposits with imperfect drainage. Soil texture and hydraulic conductivity vary at different depths. • Mean annual temperature of 7.2°C with seasonal variations impacting crop cycles. • Long-term average annual precipitation is 1247 mm. • Annual average total tile flow was approximately 720 mm	Golmohammadi et al. (2021)
	Agriculture Agri-Food Canada (AAFC) experimental site near Harrow, Ontario	• The site comprises of 16 plots, treated with different fertilizer types and tile drainage depth. • Each plot is 67.1 m long and 15.2 m wide, and installed three tile drains at 0.85 m depth. Spacing between tile drains is 3.8 m.	Sadhukhan et al. (2019)

Location		Site description	Reference
		• The land use involved rotations of maize and soybean crops, with different plots receiving different fertilizer treatments. • The soil at the experimental site was described as clay loam • Observed and simulated surface runoff was 140.03 mm/yr and 20 mm/yr respectively • Observed and simulated tile outflow was 428.49 mm/yr and 419.06 mm/yr respectively	
	St. Esprit watershed, located northeast of Montreal, Quebec	• Size: 24.3 km^2. • Land Use: 64% agricultural (corn, cereals, soybeans, vegetables, hay, pastures), with the remainder consisting of forested, bare, and residential lands. • Drainage: Over 50% of the agricultural land is equipped with a subsurface drainage system. • Crops: Predominantly corn, followed by cereals, soybeans, vegetables, hay, and pastures. • Soil Types: Predominantly coarse-textured (sand and sandy loam), with significant areas of fine-textured soils (clay and clay loam). • Temperature: Average annual temperature is 5.2°C, with July temperatures ranging between 18 and 21°C. • Precipitation: Annual range from 860 to 1050 mm, with 20-25% as snow. • Observed and simulated surface runoff is 199.33 mm and 181.33 mm respectively	Dayyani et al. (2010)
	Grand River watershed, Southern Ontario	• Area: Approximately 6800 km^2. • Population: About 1 million, with major urban centers including Kitchener, Waterloo, Guelph, Cambridge, and Brantford. • Tile Drainage: Approximately 36% of croplands utilize tile drainage systems, with an average depth of 0.9 m, 3-hour lag time, and 24 hours to drain soil to field capacity. • Cropland: 47.8%, Forest: 16.5%, Pasture: 8.3%, Grassland: 20.8%, Urban: 4.4%, Transportation: 0.5%, Open water: 1.7%. • Major Soil Types: Perth, Huron, Guelph, Burford, Brantford. • Climate: Moderate to cool temperate with four distinct seasons. • Simulated average flow at the outlet is 82.5 m^3/s with a runoff coefficient of 0.41.	Liu et al. (2016)
	St. Esprit watershed, southwestern Quebec	• Size: 24.3 km^2. • Topography: Predominantly flat to rolling, with slopes under 3% and mainly cultivated land. • Agriculture: Corn (26%), small grains (8.5%), soybeans (6.4%), vegetables (8.1%), hay (12%), pastures (2.9%).	Dayyani et al. (2012)

Location		Site description	Reference
		• Soil Types: Coarse-textured soils (sand and sandy loam) comprise 44%, and fine-textured soils (clay and clay loam) 39%, majority tile-drained due to poor natural drainage. • Temperature: Mean July temperature ranges between 18°C and 21°C. • Precipitation: Annual average between 860 mm and 1050 mm, with 20% to 25% falling as snow.	
	Two neighboring farm fields near South Woodslee, southern Ontario	• Soil Type: Brookston clay loam. • Tile Drainage: Five subsurface tile drains spaced 8.7 m apart, at a depth of 0.6 m. • Crop Rotation: Four-year rotation of maize and soybean, with detailed tillage practices. • Hydraulic Properties: Soil properties such as hydraulic conductivity and air entry pressure were calibrated for model accuracy.	Pan et al. (2023)
	Near Bedford, Southern Québec	• Two experimental fields in the Pike River watershed, Québec, 3 km apart. • Site A: Dairy farm, 6 ha drainage area, Rubicon sandy loam soil (59% sand, 10% clay), prone to matrix flow. • Site B: Swine and cash crop farm, 7 ha surface and 7.8 ha subsurface drainage areas, Sainte Rosalie clay loam soil (22% sand, 40% clay), susceptible to preferential flow paths during dry periods. • Drainage System: Plastic corrugated lateral pipes, 11 cm diameter, 21 cm outlet pipes, installed at 1 meter depth with 10 to 13 meters spacing using a trenchless plow. • Climate: Average annual temperature of 6.8°C, approximately 1,096 mm precipitation annually, significant snowfall.	Morrison et al. (2013)
	Greenbelt Research Farm, Ottawa, Ontario	• 14-ha (approximately 450 m × 315 m) watershed at the Greenbelt Research Farm of Agriculture and Agri-Food Canada used for corn cultivation • Soil Type: Typic Haplaquent with loamy-textured topsoil and silty clay subsoil at about 60 cm depth. • Tile Drains: Spaced 15 meters apart, installed 1 meter below surface. • NT practices led to 23% more tile flow than CT, averaging 15% more annually after excluding the year 1994.	Golmohammadi et al. (2016)
US portion of GLB	St. Clair-Detroit River system watershed, spanning Southeastern Michigan, U.S. and Southwestern Ontario, Canada	• Covering about 19,040 km^2 • Includes agricultural and urban areas, covering major hydrologic units and sub-watersheds in both countries. • 60% agriculture, 20% urban, and the rest comprising forests, open water, and wetlands.	Dagnew et al. (2019)

Location		Site description	Reference
		• Agricultural drainage: 67% in Canadian and 55% in U.S. areas use subsurface tile drains. • Drainage specifics: Depths vary by soil type and country, with uniform spacing in the U.S. (20 m) and varied spacing in Canada (8-15 m depending on soil type). • Period: 2001–2015, capturing normal, wet, and dry years with annual precipitation ranging from 740 mm to 1200 mm.	
	Eastern Wisconsin, across three farms.	• The study area has high clay-content soils and focuses on intensive dairy farming • Farming practices include chisel plowing, no-till farming, and significant manure use • Utilizes clay and plastic tiles at about 1 meter depth, ranging from randomly spaced to structured configurations • Cropping systems feature continuous corn and corn-soybean rotations • Temperate climate with distinct seasonal changes. Annual precipitation ranges from 760 to 890 mm • Mean surface runoff is 68.15 mm	Madison et al. (2014)
	University of Minnesota Southwest Research and Outreach Center, near Lamberton, MN, in the Cottonwood River watershed	• 130-hectare site divided into two parcels for different farming approaches • One parcel uses conventional farming with corn-soybean rotations and standard fertilizers • Another parcel adopts alternative methods with diverse crops like oats and alfalfa, using organic management and cover crops • Fields equipped with subsurface tile drains spaced 55 meters apart, installed 1.2 meters deep to enhance soil drainage • Soils are primarily loams and clay loams, key for studying subsurface water flow • Area receives average annual precipitation of 670 mm, mostly from April to September • Mean annual temperature is 7°C, with a range from -29°C in January to 21°C in July	Oquist et al. (2007)
	Different sites of Western Lake Erie Basin (WLEB), spanning northeastern Indiana and northwestern Ohio, USA, and southern Ontario, Canada	• Edge-of-field sampling sites located in the Western Lake Erie Basin • Terrain is flat to gently rolling • Extensive tile drainage systems • Soils are mainly loams and clays, typically poorly drained • Fields are predominantly used for cash crop rotations of corn, soybean, and wheat, managed under a mix of tillage practices including conventional, conservation, and no-till methods. • Average annual precipitation of 730.07 mm, with variations ranging from 587 to 1051 mm	Hanrahan et al. (2020)

Location		Site description	Reference
	St. Joseph River Watershed, Northeastern Indiana	• Monitored surface runoff and tile drainage discharge from four fields in the Maumee River basin • Agricultural land in the cool, humid climate primarily cultivating corn and soybeans • Tile drainage includes existing standard corrugated, perforated tile lines in the fields without supplemental surface connections such as tile risers or blind inlets.	Smith et al. (2015)
	St. Joseph River Watershed, U.S. Corn Belt, part of the Lake Erie basin; spans northeast Indiana, northwest Ohio, and south-central Michigan	• Watershed covers 2,815 km^2 with terrain ranging from flat to hilly and slopes between <2% to 5% • Land use distribution includes 51% agriculture, 20% pasture, 22% forest, and 6% urban • Over 95% of area is dedicated to corn and soybean crops • Region experiences average annual temperature of 9.6°C • Receives 992 mm of precipitation annually, mostly during the growing season • Tile drainage prevalent, affecting 50% of the watershed and 92% of corn-soybean areas • Surface runoff averaging 145 mm, representing 15% of total precipitation	Ren et al. (2022)
	Subwatershed of the Upper Big Walnut Creek, central Ohio.	• Watershed spans 389 hectares, predominantly used for agriculture (86%), with 6% woodland and 8% urban/farmstead • Features a corn-soybean rotation under a humid continental climate with hot summers • About 80% of the area (319 hectares) is covered by a tile drainage system with laterals 15 meters apart, installed at a depth of 0.9 meters • Decades-old tiles made from durable materials range from 0.2 to 0.6 meters in diameter, aiding in water removal from poorly drained clay and silt loam soils • Region largely covered by Bennington silt loam (52.9%, somewhat poorly drained) and Pewamo clay loam (46.2%, very poorly drained) • Has around 160 growing days annually, from late April to mid-October • Average annual precipitation of 985 millimeters, includes about 500 millimeters of snow from December to March • Precipitation during the 2005–2012 study period ranged from 773 to 1239 millimeters	King et al. (2015)
	Upper Big Walnut Creek located in central Ohio	• Watershed size 492 km^2 • This study used monitoring data from over seven years (2006–2012) to evaluate Drainage Water Management (DWM) effects • 73% agricultural (corn-soybean rotation), 6% woodland, 21% urban/farmstead	Williams et al. (2015)

Location		Site description	Reference
		• 52.9% Bennington silt loam (somewhat poorly drained) and 46.2% Pewamo clay loam (very poorly drained) • 80% of the area systematically tile drained, with laterals 15 meters apart and 1 meter deep • Climate: Humid continental with warm, humid summers and cold, dry winters • Average annual precipitation: 986 mm (2006–2012), consistent with the long-term average of 985 mm • 22% of annual precipitation discharged as tile flow, with higher flow in winter and spring	
	Matson Ditch Watershed, DeKalb County, northeastern Indiana, within the Western Lake Erie Basin.	• Matson Ditch Watershed spans 4610 hectares with flat topography and relies heavily on subsurface drainage systems in silt loam Alfisol and clay loam Mollisol soils to manage water flow and prevent waterlogging • Agriculture constitutes 67.8% of land use, with tile drainage systems crucial for crop productivity by managing soil water and aiding in nutrient transport to nearby water bodies. • Typical climate includes median daily minimum temperatures of 4.0 °C to 5.0 °C and maximum temperatures of 15.7 °C to 17.5 °C. • Annual precipitation from 2006 to 2012 ranged from 600 to 1200 mm according to local climate station records.	Mehan et al. (2019)
	South Fork Watershed (SFW), Central Iowa	• Watershed spans 583 km^2, agriculture occupies about 85% of the land with significant emphasis on corn-soybean rotations • Predominantly hydric soils with poor natural drainage, enhanced by artificial subsurface drainage systems • Widespread subsurface drainage necessary to manage water table and enhance crop productivity • Climate varies significantly with temperatures from -13°C in January to 29°C in July • Average annual precipitation of 750 mm, 60% of which occurs during intense summer precipitation	Bailey et al. (2022)
	Four catchments in Iowa	• Catchments range from 2.1 to 4.6 km^2 with a mean slop of 0.43% to 0.86% • Tile drainage coverage varies from 55% to 88% • Predominant land use is agricultural across all four catchments, mainly dedicated to corn-soybean rotations and continuous corn, covering over 80% of the land • Climate is temperate and humid continental with temperature ranges from -32°C to 38°C • Average annual precipitation across these catchments is about 1100 mm, reflecting significant climatic variation	Cao et al. (2023)

Location		Site description	Reference
	Raisin, Maumee, Sandusky, and Grand watersheds across Michigan, Indiana, and Ohio, draining into Lake Erie	• Watersheds vary in size from 1,896 km^2 to 17,030 km^2, predominantly agricultural with significant variations in land use and precipitation. • Raisin Watershed, covering 2,784 km^2, is primarily agricultural and forested, receiving the least annual precipitation at 861 mm. • Maumee Watershed is the largest at 17,030 km^2, heavily focused on row crops, with an annual precipitation of 934 mm. • Sandusky Watershed, similar in agricultural dominance, receives 962 mm of precipitation. • Grand Watershed, mostly forested, is the wettest with 1,093 mm of precipitation annually. • All watersheds feature extensive tile drainage systems crucial for managing water flow and nutrient leaching in mostly poorly drained soils.	Bosch et al. (2014)
	Matson Ditch watershed, DeKalb County, Indiana, part of the Cedar Creek sub-watershed draining into Lake Erie	• Watershed spans 4700 ha in DeKalb County, primarily agricultural. • Main crops are soybeans (37%) and corn (21%), with smaller areas for pasture/hay, winter wheat, and forest. • Receives about 1000 mm of precipitation annually, with variations from 329 to 625 mm. • Mean temperature around 15°C. • Dominant soils are Blount (silt loam Alfisol) and Pewamo (clay loam Mollisol), making up 48.8% of the landscape. • Hydrology significantly influenced by subsurface tile drainage systems	Boles et al. (2015)
	Upper Big Walnut Creek (UBWC) Watershed, Delaware County, Ohio	• This watershed is characterized by its humid continental climate. • Supports about 160 growing days annually, with temperatures ranging from -9.6°C in January to 33.9°C in July. • Receives an average annual precipitation of 985 mm, including 500 mm of snow primarily from December to March. • Relies significantly on tile drainage systems to manage hydrological conditions for row crop production, mainly corn and soybean rotations. • Soil types include Bennington silt loam, which is somewhat poorly drained, and Pewamo clay loam, which is very poorly drained.	King et al. (2016)
	Western Lake Erie Basin, within Huron/Erie Lake Plain and Eastern Corn Belt Plains ecoregions	• Watersheds located on fertile, flat plains characterized by relic sand dunes, beach ridges, and historically poor soil drainage enhanced by intensive artificial drainage. • Extensive tile drainage across the area, crucial for improving agricultural yield in soils with naturally poor drainage; significant in more than half of the land in some watersheds.	Miller & Lyon (2021)

Location		Site description	Reference
		• Dominated by agriculture (67% to 86% of land use), with corn, soybean cultivation, and livestock farming. • astern Corn Belt Plains feature loamier soils; Huron/Erie Lake Plain contains clay- and silt-size glaciolacustrine sediments. • Notable increase in heavy precipitation events affecting runoff and nutrient transport, with 2019 showing higher runoff and nutrient loadings compared to 2018 due to wetter conditions and extensive tile drainage.	
	Little Vermilion River (LVR) watershed, East Central Illinois	• 489 km^2 of watershed featuring predominantly flat terrain with slopes of about 1% or less. • Approximately 90% of land is used for agriculture, mainly row crops like corn and soybeans; the rest includes grassland, woodland, roadways, and farmsteads. • Intensively tile-drained with random or irregular subsurface drainage systems, with drains typically installed at depths of 1.0 to 1.1 meters and spaced at 28 meters. • Soil types include Drummer silty clay loam, Flanagan silty clay loam, Sabina, and Xenia silty loam. Moderately to poorly drained with low vertical and significant horizontal hydraulic conductivity. • Precipitation is generally below the long-term regional average of 1040 mm per year, except in 1998. • Subsurface drainage and surface runoff removed 16.1% and 2.6% of precipitation	Algoazany et al. (2007)
	Macatawa Watershed, West Michigan	• 450 km^2 of watershed, dominated by agriculture (45%), urban/residential/industrial areas (33%), and natural forest/shrub/grassland (20%). • Primarily row crops, mainly corn and some soybeans. • Tile Drains are primarily PVC outlets draining into ditches, with one site using plastic tubing for sampling from a tile drain vent. • Dominant hydrologic soil type was Type C, characterized by low to moderate infiltration rates. • Temperatures range from 11.0°C in spring to 26.6°C in summer, influencing seasonal variations in phosphorus dynamics and algal growth potential.	Clement & Steinman (2017)
	Eagle Creek Watershed in Ohio	• Watershed with a 125-km2 drainage area • Dominantly agricultural with over 80% used for crops, mainly corn and soybeans, with a two-year rotation system. Smaller proportions include 10% forest, 8% developed areas, and 7% pasture. • Soil Types: Predominantly mollisols and alfisols with up to 2.030 m deep soil profiles, characterized by 99% somewhat poorly to poorly drained conditions. • Extensive tile drainage (90% of the basin) across 107.5 km of the basin to manage water tables and enhance productivity.	Merriman et al. (2018)

Location		Site description	Reference
		• Temperate climate with annual precipitation of approximately 859 mm, plus an average snowfall of 559 mm from November through April, reflecting significant seasonal precipitation variations	
	Matson Ditch Watershed, DeKalb County, Indiana	• Approximately 4610 hectares of a watershed with flat topography and relies heavily on subsurface drainage systems for crop production • Predominantly agricultural (67.8%), with corn, soybeans, and winter wheat. • Silt loam Alfisol and clay loam Mollisol, primarily somewhat to poorly drained soil • Historical precipitation ranged from 600 to 1200 mm annually (2006-2012). • Subsurface drain flow was 8-12% of total annual precipitation. • Projected precipitation increase could lead to a rise in surface runoff and subsurface drain flow by the end of the 21st century.	Mehan et al. (2019)
	Upper East River watershed, Wisconsin	• The Upper East River is a 116.5-km^2 tributary watershed to Wisconsin's Green Bay, impaired for low dissolved oxygen and degraded biological community due to excess TP loadingand degraded aquatic habitat caused by suspended solids. • Dairy with significant confined animal feeding operations (CAFOs) and some cash grain rotations agriculture dominates the landscape. • Approximately 22% of the watershed is estimated to be drained by subsurface tiles, integrating poorly drained soils, agricultural land use, and low slopes (< 2%) to locate likely tile drainage installations. • Humid with long, snowy winters and warm summers. Temperature Range: Annual temperatures from -30°C to 39.4°C during the 2000–2014 modeling period. • Annual precipitation varied between 666.2 mm and 970.0 mm during the same period.	Merriman et al. (2019)
	Walworth Watershed and Green Lake Watershed, Wisconsin	Green Lake Watershed: Size: 790 ha. Land Use: 76% cropland, 15% grassland, 9% forest. Dominant Soils: Plano silt loam and Mendota silt loam. Climate: Average air temperature 6°C, annual precipitation 874 mm. Walworth Watershed: Size: 1124 ha. Land Use: 42% cropland, 10% grassland, 48% urban area. Dominant Soils: Pella silt loam and Elburn silt loam. Climate: Average air temperature 8°C, annual precipitation 897 mm."	Wang et al. (2018)

Location		Site description	Reference
	Eastern Corn Belt (ECB) monitoring program area, Northwestern Ohio	• This study utilized data from a four-year period from a drained field in northwestern Ohio for model validation. The field features tile drains with a depth of 60 cm and spacing of 12.2 m. • The field is primarily used for agriculture, rotating crops of corn, soybean, and wheat. • Soil Types: Predominantly Paulding clay and Roselms silty clay, known for low hydraulic conductivity and high clay content, which are prone to cracking • The annual precipitation was measured at 923 mm, closely matching the model prediction of 915 mm. Surface runoff was recorded at 59 mm. Additionally, the measured and simulated tile outflow volumes were 715 mm and 659 mm, respectively.	Askar et al. (2021)
	US coastline of the Great Lakes Basin, encompassing Lakes Superior, Michigan, Huron, Erie, and Ontario	• The watershed spans parts of eight US states, featuring a mix of urban, agricultural, and industrial landscapes that significantly impact the ecosystems of the Great Lakes. • Soil and Drainage: Focuses on regions with low permeability soils (Ksat < 14.4 mm/hr) and low slopes (< 1.2%), typically associated with tile-drained agricultural areas. • Predominantly agricultural, especially in areas with tile drainage, which are crucial for studying nutrient transport dynamics. • Temperature: Averages between 3 to 10°C. • Precipitation: Ranges from 500 to 1600 mm annually across the basin.	Wan et al. (2023)
	Four catchments in Iowa, Midwestern US: RS and KS in Story County, and LP and WW in Floyd County	• The catchments cover areas ranging from 2.1 to 4.6 km^2, featuring varied climates, catchment characteristics, and agricultural management practices. • Extent of Tile Drainage: Significant variability in tile coverage; RS and KS have 55% and 62% coverage, respectively, while LP and WW have 89% and 88%. • Predominantly agricultural across all four catchments, with more than 80% land used for corn-soybean and continuous corn cropping systems. • Soil and Slope: Coarse-textured and fine-textured soils dominate, with varying mean slope percentages, notably influencing nutrient dynamics and management efficiency. • Climate: Temperate, humid continental with extensive temperature variations from -32°C to 38°C. • Precipitation: Average annual precipitation around 1100 mm, with substantial contributions to hydrology and nutrient transport. • Dominance of Subsurface Flow: Subsurface flow (tile flow + lateral flow) predominantly governs discharge (70-75%).	Cao et al. (2023)

Location		Site description	Reference
	Little Vermillion River (LVR) watershed, east-central Illinois	• Area: 489 km^2. • Topography and Land Use: Predominantly flat with 91.1% agricultural land use, of which 85.8% is assumed to be tile-drained. • Cropping System: Crop rotation predominantly between corn and soybeans. • Soil Types: Mainly Drummer silty clay loam and Flanagan silt loam, classified in hydrological soil groups B and C. • Configuration at Site A: Tile spacing of 48.0 m, depth of 1.1 m, and drainage area of about 4.86 ha. • Scenario Analysis: Explored impacts of different tile depths (0.6 m to 1.2 m) on nitrate dynamics in both tile flow and surface runoff. • Temperature: Average annual air temperature was 11.61 °C from 1990 to 2018. • Precipitation: Average annual precipitation was 982.12 mm over the same period.	Kim et al. (2023)
	Grand Lake Saint Mary's Basin, Western Ohio	• 9.2 ha field, systematically drained, used for corn-soybean-wheat rotation. • Soil: Brookston clay loam; soils include Blount, Glynwood, and Pewamo. • Drainage System: Tile drains spaced at 9 meters, 0.6 m deep. • Temperature: Ranges from −20.6°C in winter to 31.9°C in summer. • Annual Precipitation: 1040 mm. • Cumulative tile drainage was 768 mm over 31 months, constituting 98% of total field discharge.	Ford et al. (2017)
	Maumee River Watershed (MRW): Located in northwest Ohio, northeast Indiana, and southwest Michigan	• Size: Over 17,000 km^2 spanning 253 HUC-12 units across 27 counties. • Land Use: Dominantly agricultural with over 70% being row crops including corn, soybean, and wheat. • Predominantly poorly drained soils from the historic Great Black Swamp area. • Extensive use of tile drainage, especially in areas with very poorly drained soils. • Observed discharge was 76.00 mm, while modeled discharges by Kalcic, Kujawa, and Apostel were 102.29 mm, 73.23 mm, and 115.32 mm, respectively. Tile flow rates followed a similar pattern with observed at 177.40 mm, and the models reporting higher rates: Kalcic at 264.51 mm, Kujawa at 260.01 mm, and Apostel at 229.56 mm.	Apostel et al. (2021)
	Shatto Ditch Watershed, Kosciusko County, Indiana, draining into the Tippecanoe River	• Quantify changes in tile drain loading and watershed export of nitrate (NO_3^--N) after establishing cover crops on over 60% of croppable acres in a small agricultural watershed. • 1333 hectares, with approximately 75% used for row-crop agriculture (corn and soybeans). • Varied soil composition including organic muck, loam, and sandy loam	Hanrahan et al. (2018)

Location		Site description	Reference
		• Subsurface tile drains are prevalent, with sizes ranging from 0.1–0.3m in diameter to accommodate drainage capacity. • Average runoff from 2008 to 2013 (pre-cover crop conditions) was 316 mm and from 2014 to 2016 (post-cover crop conditions) was 285.33 mm.	
	Six small, agricultural watersheds in the Conesus Lake catchment, New York	• These watersheds are characterized by agricultural land use, constituting more than 70% of the area. • The terrain includes deep, well-drained, glacially derived limestone soils, supporting diverse agricultural activities such as dairy farming and crop production (corn, forages, wheat, soybeans, and vegetables). • Intensive stream water monitoring and analysis of covariance were employed over a 5-year period to estimate marginal means of concentration and loading for each year, weighted by covariate discharge.	Makarewicz et al. (2009)
	South Nation River Basin, eastern Ontario	• Watershed area: ~3900 km^2 • Land use: 60% agriculture, 5% urban, 34% wooded/shrub lands • Agriculture: Cash and livestock cropping practices • Tile Drainage Depth: 1100 mm for unrestricted drainage (UCTD) as a reference condition, 200 mm (CTD200) as aggressive drainage control, 600 mm (CTD600) as recommended for growing season • Soil: Varied, including up to 17 m thick varved clay • Climate: Temperature: -15°C to 26°C, Average annual precipitation: ~940 mm	Que et al. (2015)
	Tile drainage experimental site near Waseca, southern Minnesota	• Plot-level study with implications for poorly drained agricultural watersheds in the Upper Midwest U.S., known for high NO3-N loading • Tile Drain Configurations: Depths 0.9 m to 1.5 m, Spacings: 15 m to 60 m • Continuous corn, representing typical agricultural practices in southern Minnesota • Soil: Webster clay loam, fine-loamy, mixed, superactive, mesic Typic Endoaquoll	Moriasi et al. (2013)
	Illinois State University Nitrogen Management Research Field Station, Lexington, Illinois	• Field Characteristics: Flat terrain (0–2% slopes), Drummer and El Paso silty clay loam soils, Equipped with a tile drainage system (13.7 m apart, 0.9 m deep) • Maize-soybean rotation from September 2014 to October 2018 • 12 experimental plots (0.65 ha each), with three replications of four treatments	Gupta et al. (2022)
	Raccoon River Watershed, west-central Iowa	• Draining a 9,393 km^2 area from 17 counties. Comprises the North Raccoon and South Raccoon watersheds, located primarily in the Des Moines Lobe (Flat landscapes, poor surface drainage) and Southern Iowa Drift Plain (Rolling hills, well-drained landscapes) regions • Land Use: Agricultural land: 79%, Pasture: 10%, Developed areas: 6%, Forest: 4.4%, Water bodies: 0.5%	Teshager et al. (2017)

Location		Site description	Reference
		• Tile Drainage: 57% of the watershed (72% of agricultural land) has tile drainage (1,200 mm depth)	
	McLean County, Illinois	• 110-ha farm in McLean County, Illinois, owned by the Franklin family since 1851 • Cattle production for 100 years, converted to corn and soybean production in the 1950s. • 75–90% row crop (corn and soybean); 52–82% of land tile-drained. • Wetlands built in 2006 with three series (East, West, Gully), each containing three cells. • Wetland soils: Flanagan silt loam and Drummer silty clay loam (poorly drained). • Tiled farmland soils: LaRose silt loam (well-drained) and Saybrook silt loam (moderately drained). • Wetland vegetation developed naturally, with occasional management for invasive species control.	Lemke et al. (2011)
	Shatto Ditch Watershed (SDW) and Kirkpatrick Ditch Watershed (KDW) in Indiana	• SDW 1333 ha and KDW 2630 ha • SDW and KDW are small, agriculturally-dominated watersheds with predominantly corn-soybean rotations. SDW has 85% cropland and 79% tile drainage coverage, while KDW has 94% cropland, with extensive tile drainage • The tile drainage systems included field drains (diameter <0.3 m) and larger county drains (diameter ≥0.5 m) • SDW soils are primarily Alfisols (77%) and Mollisols (13%), while KDW soils are mostly Mollisols • Midwestern US climatic conditions • SDW runoff ranging from 323 to 618 mm annually, and KDW from 334 to 487 mm	Speir et al. (2022)

10. **Supplementary Table S5:** An overview of tile drainage design characteristics focusing on depth, spacing, soil, and land use.

Site/Location	**Landuse and cropping system**	**Soil**	**Tile Depth (m)**	**Tile Spacing (m)**	**Remarks**	**Reference**
St. Joseph River Watershed in the U.S. Corn Belt region which is part of the Lake Erie basin and located in northeast Indiana, northwest Ohio, and south-central Michigan - Total drainage area of approximately 2815 km2, Slope: with 52% of the area having less than 2% slope, 35% with 2-5% slope, and 13% with larger than 5% slope.	51% agricultural, 20% pasture, 22% forest, and 6% urban, Crops: Main crops: Corn and soybean, Corn-soybean rotation system constituted 659 HRUs in the watershed and accounted for 48	Main soil textures: Silt loam, silty clay loam, clay loam	1	Not specified	50% of watershed, 92% of corn-soybean rotation estimated as tile-drained.	Modeling study by Ren et al. (2022)
Pike River watershed region of southern Quebec. Four fields (referred to as sites A, B, C and D) were selected and situated on privately owned farm lands within a 3 km2 radius of each other. Sites A and B have subsurface drainage installed, whereas sites C and D are naturally drained.	Crops grown in 2005 at sites A and C were corn, followed by soybean and mixed cereals in 2006	Soil types included clay loam at sites A and C and sandy loam at sites B and D	1	10.0 (Site A), 13.0 (Site B)	Plastic corrugated pipes used.	Monitoring study by Eastman et al. (2010)

Site/Location	Landuse and cropping system	Soil	Tile Depth (m)	Tile Spacing (m)	Remarks	Reference
Innisfil, Ontario, directly south of Kempenfelt Bay in Lake Simcoe - Lake Simcoe Watershed in Ontario, Canada, which encompasses a total area of 3,557 km2	Predominantly agricultural, accounting for approximately 47% of the total area, Crops: This agricultural activity primarily includes a rotation of corn, soybean, and winter wheat, managed under varying tillage practices	Grey–Brown Luvisol Great Group and of the Bondhead and Guerin series (sandy loam)	1	12.2	Networks of perforated pipes installed	Monitoring study by Lam et al., (2016)
Essex Region Conservation Authority Demonstration Farm at Holiday Beach, Southern Ontario within the Lake Erie basin	The cropping system was a corn-soybean rotation	Perth clay soil (Gleyed Grey Brown Luvisol)	0.6	4.6	Two types: Regular Free Drainage and Controlled Drainage with Sub-irrigation. 104-mm diameter subsurface tile drains with less than 0.1% slope.	Monitoring study by Tan & Zhang, (2011)
Three sites (Bainsville-BVL, Ilderton- ILD, London- LON) across Ontario - Characterized by a humid continental climate with warm summers and cold, snowy winters	All sites use reduced tillage systems and follow a corn-soy-winter wheat rotation	Bainsville Silt Loam at the BVL site, which is poorly drained with a clay layer at about 1 meter depth on flat terrain; Thorndale and Embro Silt Loams at the ILD site, characterized by imperfect drainage and hummocky topography; and Perth Clay Loam at the LON site,	0.9	9 to 14	Equipped with flow monitoring and water quality sampling systems.	Monitoring study by Esbroeck et al., (2016)

Site/Location	Landuse and cropping system	Soil	Tile Depth (m)	Tile Spacing (m)	Remarks	Reference
		also imperfectly drained but situated on gently undulating terrain				
Hon. Eugene F. Whalen Experimental Farm in Southwestern Ontario - The farm covers an area typical of southwestern Ontario's agricultural landscape, featuring a temperate climate with distinct seasonal variations	Rotational cropping system of corn and soybean	Brookston clay loam is a fine-textured soil prevalent in Southwestern Ontario	0.6 to 0.7	7.5	Controlled drainage plots used outlet risers to manage water table.	Monitoring study by Zhang et al., (2015)
University of Minnesota Southwest Research and Outreach Center near Lamberton, MN, within the Cottonwood River watershed. The site encompassed a total of 130 hectares, split into two adjacent 65-hectare parcels	One parcel employed conventional farming methods with rotations of corn and soybean, using standard applications of inorganic fertilizers and pesticides typical of intensive agriculture. The other parcel utilized alternative farming practices, incorporating diverse crop rotations that included oats and alfalfa, minimized synthetic inputs, and used organic management strategies	Characterized by glacial till soils predominantly fine-loamy, mixed, and mesic, with some clay loam and sandy loam textures, which influence water retention and drainage properties	1.2	55	Designed for early spring planting and crop growth enhancement.	Monitoring study by Oquist et al., (2007)

Site/Location	Landuse and cropping system	Soil	Tile Depth (m)	Tile Spacing (m)	Remarks	Reference
	with cover crops to enhance soil health and reduce environmental impact.					
Subwatershed of the Upper Big Walnut Creek watershed, located in central Ohio - The watershed covers a drainage area of 389 hectare. This watershed is characterized by its humid continental climate, supporting approximately 160 growing days annually	Predominantly agricultural, making up 86% of the total area, Crops: This agricultural land was primarily utilized for a corn-soybean rotation	Bennington silt loam and Pewamo clay loam	0.9	15	Tile drainage covers 80% of the area, aged over 50 years, varying in diameter from 200 to 600 mm	Monitoring study by Williams et al., (2015)
Midwestern Ontario, - three agricultural fields located on working farms in southern Ontario, Canada, characterized by diverse soil textures and topographical features	Agricultural fields with typical crop rotations, including corn, soybeans, and winter wheat	Loam-textured and clay-textured soil	0.6 to 0.9	10 to 15	Tile drainage was the primary pathway for runoff in the non-growing season	Monitoring study by Plach et al., (2019)

Site/Location	Landuse and cropping system	Soil	Tile Depth (m)	Tile Spacing (m)	Remarks	Reference
Eastern South Dakota - located near Alexandria, South Dakota. The total drained area of the experimental site was 26 hectares, split into two halves with distinct drainage management practices.	Predominant agricultural use is focused explicitly on corn and soybeans, which are cultivated from May to October	Poorly drained soil	0.9	18	127 mm diameter tiles installed. The system utilizes control structures at the edge of the field, equipped with adjustable weir boards. These boards can be inserted or removed to retain or release water according to the crop's water needs and the seasonal requirements, such as during planting or harvest times.	Modeling study by Sharma et al., (2024)
Southern Ontario, Canada, specifically 8.66 ha agricultural field with both overland flow and tile drainage site near Londesborough	Utilized for agriculture, specifically under a reduced tillage system. The crops grown include soybeans, winter wheat, and grain corn	Perth Clay Loam association, developed on clay loam glacial deposits	0.9	13.5	The tile drains in the field are systematically placed with 100mm diameter laterals connected to a larger main tile of 200mm diameter at the field's edge.	Modeling study by Golmohammadi et al., (2021)
Various sites representing different climate scenarios and crop growing conditions in the eastern U.S.	Continuous corn	Drummer silty clay loam, Normania clay loam, Two Rains sandy loam, Portsmouth sandy loam	0.75 to 1.25	17 to 28	Developed empirical equations to estimate site-specific design drainage rate	Modeling study by Ghane et al., (2021)

Site/Location	Landuse and cropping system	Soil	Tile Depth (m)	Tile Spacing (m)	Remarks	Reference
Agriculture Agri-Food Canada (AAFC) experimental site located near Harrow, Ontario	Rotations of maize and soybean crops	Clay loam	0.85	3.8	The site comprises of 16 plots, treated with different fertilizer types and tile drainage depth	Monitoring study by Sadhukhan et al., (2017)
Edge-of-field (EOF) research network established at the Eastern Corn Belt (ECB) Northwestern Ohio	Corn–soybean–wheat rotation	Paulding clay, Roselms silty clay	0.6	12.2	Tile drained field with relatively flat slope. Field characterized by macropore flow, very poor drainage, high clay content, severe cracking	Modeling study by Askar et al., (2020)
University of Minnesota's Southern Research and Outreach Center near Waseca, southern Minnesota	Continuous corn cultivation with conventional tillage practices	Webster clay loam soil, poorly drained	1.2	27	Drains isolated with plastic sheeting to limit lateral water movement.	Modeling study by Ale et al., (2013)
Little Vermillion River (LVR) watershed located in east-central Illinois - The LVR watershed has a drainage area of 489 km2, with flat topography and predominantly agricultural land use	crop rotation between corn and soybeans	Drummer silty clay loam and Flanagan silt loam	1.1	48	Extensive tile drainage impacts nitrate loadings and water management.	Modeling study by Kim et al., (2023)

Site/Location	Landuse and cropping system	Soil	Tile Depth (m)	Tile Spacing (m)	Remarks	Reference
Honorable Eugene F. Whelan Research Farm near South Woodslee, Ontario	Maize-soybean rotation, manure application	Clay loam	0.85	3.8	Includes controlled drainage features to manage water and nutrient outflow.	Modeling study by Sadhukhan et al., (2019)
Two Farm Fields, South Woodslee, Ontario	Four-year rotation of maize and soybean, varying tillage practices	Brookston clay loam	0.6	8.7	Tile drainage with the automatic water sampling system	Modeling study by Pan et al., (2023)
The St. Clair-Detroit River system watershed is situated between Southeastern Michigan, U.S. and Southwestern Ontario, Canada, draining areas of about 19,040 km2 - The watershed includes both significant agricultural and urban areas	About 60% of the watershed is covered by agriculture, 20% by urban areas, and the rest by forests, open water, and wetlands	Clayey, loamy, and sandy soil types	0.65 to 1.0	8 to 15	Intensive drainage in Canadian and U.S. agricultural areas; drainage depth and space vary by soil type.	Modeling study by Dagnew et al., (2019)
Tile drainage experimental site near Waseca, in southern Minnesota	Continuous corn cultivation	Webster clay loam soil, characterized as fine-loamy, mixed, superactive, mesic Typic Endoaquoll	0.9 to 1.5	15 to 60	Drain spacing that is too narrow leads to increased drainage intensity.	Modeling study by Moriasi et al., (2013)

Site/Location	Landuse and cropping system	Soil	Tile Depth (m)	Tile Spacing (m)	Remarks	Reference
Illinois State University Nitrogen Management Research Field Station, Lexington, Illinois	Maize-soybean rotation with cereal rye as a winter cover crop	Drummer and El Paso silty clay loam	0.9	13.7	Installed to manage water drainage in soils with poor natural drainage.	Modeling study by Gupta et al., (2022)
Greenbelt Research Farm near Ottawa, Ontario, Canada	The study area consists of a 14 ha field within the agricultural landscape, primarily used for corn cultivation with no tillage (NT) and conventional tillage (CT) methods	Typic Haplaquent with loamy-textured Ap and B horizons, underlain by silty clay	1	15	Typical setup for managing water table depth in the region.	Modeling study by Golmohammadi et al., (2016)
Near Bedford, Québec	Corn and alfalfa; Conventional tillage with mouldboard plough	Rubicon sandy loam and Sainte Rosalie clay loam	1	10 to 13	Tile drainage diameter between 110 (laterals)mm and 210 (outlet); studies indicate high drainage density impacts N and P losses.	Modeling study by Morrison et al., (2013)
South Nation River Basin, eastern Ontario, Canada - Area: Approximately 3900 km2, predominantly flat landscape	Agriculture (60%), urban (5%), wooded/shrub lands (34%)	Varied, includes varved clay up to 17 m thick	0.2 to 1.1	Not specified	Studies controlled tile drainage scenarios at 200 mm and 600 mm depths.	Modeling study by Que et al., (2015)

Site/Location	Landuse and cropping system	Soil	Tile Depth (m)	Tile Spacing (m)	Remarks	Reference
Vermont, USA, particularly focusing on Lake Champlain Basin's western side, notably within Addison County. The watersheds are situated in areas with fertile, nearly flat plains featuring relic sand dunes and beach ridges, historically poor soil drainage, and intensive artificial drainage.	Corn silage production, previously hay; manure injection and light chisel tillage	Vergennes clay, Covington, Panton silty clay loams	1	7.62	Recent tile drainage networks established, impacts water management.	Monitoring study by Ruggiero et al., (2022)
Lower Great Lakes Region, Ontario, Canada	Crop rotations (corn, soybeans, wheat, oats, other grains)	Varied (clay loam, silt loam, sandy loam)	0.9	12 to 18	Consider phosphorus transport pathways to improve Total Maximum Daily Load (TMDL) estimation	Monitoring study by Plach et al., (2018)
Across 38 edge-of-field research sites in Ohio, within the Eastern Corn Belt (ECB), part of the Lake Erie watershed	Corn, soybean, and wheat rotation	Silt loam, silty clay, clay (poorly drained)	0.6 - 0.9	7 to 15	Quantify the impact of agricultural crop production on surface and subsurface water quality	Monitoring study by Pease et al., (2018)
Leary Weber Ditch, Sugar Creek Watershed, Indiana, USA	Corn and soybean rotation; conventional tillage	Crosby–Brookston association; silty clay loam in top 30 cm	1.2	20.3	Tile diameter was 203mm and the tile length was between 660 and 719m	Monitoring study by Vidon & Cuadra (2011)

11. **Supplementary Table S6:** Specific studies representing the effect of tile drainage on surface and subsurface discharge at the field and watershed scale

Location	Tile discharge and subsurface outflow	Reference
Tile discharge and subsurface flow at the field scale		
Pike River watershed, southern Quebec	Subsurface outflow as a percentage of annual precipitation ranged from 24% to 66% across different sites.	Eastman et al. (2010)
Innisfil, Ontario, south of Kempenfelt Bay in Lake Simcoe	Approximately 220 mm of runoff was exported via the drainage tiles in 2011 (22% of precipitation), 121 mm in 2012 (16% of precipitation), and 229 mm between January and June 2013 (41% of precipitation)	Lam et al. (2016)
Essex Region Conservation Authority Demonstration Farm, Holiday Beach, Southern Ontario, within the Lake Erie basin	Subsurface runoff contribution to total flow: 80% under the controlled drainage with sub-irrigation and 97% under the regular free drainage system	Tan & Zhang (2011)
Three sites across Ontario: Bainsville-BVL, Ilderton-ILD, London-LON	Annual tile runoff was 505 mm at the BVL site (87% of total runoff), 322 mm at the ILD site (90% of total runoff), and 294 mm at the LON site (78% of total runoff).	Esbroeck et al. (2016)
Chatham-Kent region, Ontario, on the northern boundary of Lake Erie	Average water drained through tiles was about 202 mm at the Conventional Conservation-Till (CT) site and 183 mm at the No-Till Cover Crop (NTCC) site. More water drained in the wetter years (about 250 mm) compared to drier years (about 195 mm). Each year, event-related runoff losses accounted for more than 90% of annual subsurface runoff losses.	Macrae et al. (2023)
Eastern Wisconsin, across three farms.	The average amount of water flowing out through the tiles is 210.3 mm per year. For fields used to grow corn, this outflow is about 11-40% of the annual precipitation. For pasture lands, it's about 17-22% of the annual precipitation.	Madison et al. (2014)
University of Minnesota Southwest Research and Outreach Center, near Lamberton, MN, in the Cottonwood River watershed	Subsurface runoff as a percentage of annual precipitation ranged from 13.7% to 21.9% for alternative practices and 17.5% to 32.0% for conventional practices, highlighting that conventional farming typically results in higher drainage proportions in wetter years.	Oquist et al. (2007)
Three agricultural fields on working farms in Midwestern Ontario	Tile drainage was the dominant pathway for flow across sites, contributing 81%, 96%, and 84% of the yearly runoff at the Essex (ESS), Ilderton (ILD), and Londesborough (LON) sites, respectively.	Plach et al. (2019)
Different sites of Western Lake Erie Basin (WLEB), spanning northeastern Indiana, northwestern Ohio, and southern Ontario	Tile outflow ranges from about 11% to 39% of the annual precipitation, with an average of about 25%.	Hanrahan et al. (2020)
Londesborough, Southern Ontario	From 1960 to 1990, the average yearly water flow through tiles was about 720 mm. This is expected to increase to about 1000 mm from 2011 to 2040, then to 1250 mm	Golmohammadi et al. (2021)

Location	Tile discharge and subsurface outflow	Reference
	from 2041 to 2070, and finally to about 1450 mm by the end of the century, from 2071 to 2100.	
Honorable Eugene F. Whelan Research Farm, South Woodslee, Ontario	On average, 68% of the water left the field through tile drainage, mostly during the non-growing season from December to May.	Sadhukhan et al. (2019)
St. Joseph River Watershed, Northeastern Indiana	Surface runoff ranged from 4.32% to 40.78% of total precipitation, while tile discharge varied between 13.36% and 22.16%, reflecting variability in runoff and tile discharge under different climate and management conditions.	Smith et al. (2015)
Tile discharge and subsurface flow at the watershed scale		
St. Joseph River Watershed, U.S. Corn Belt, part of the Lake Erie basin; spans northeast Indiana, northwest Ohio, and south-central Michigan	In the watershed, 8% of precipitation drained through tiles. From areas with corn-soybean rotation, tile drainage represented 15% of total precipitation.	Ren et al. (2022)
Subwatershed of the Upper Big Walnut Creek, central Ohio.	Over the study period, tile outflow was about 34.14% of annual rainfall and 47% of the average monthly watershed discharge.	King et al. (2015)
Matson Ditch Watershed, DeKalb County, northeastern Indiana, within the Western Lake Erie Basin.	From 2006 to 2012, subsurface drainage was 8-12% of annual precipitation. It is projected to increase by 11% to 50% under RCP 4.5 and could rise to 67% under RCP 8.5 by 2070-2099.	Mehan et al. (2019)
South Fork Watershed (SFW), Central Iowa	From 2002 to 2012, subsurface drainage accounted for 45% of the water yield from the watershed. This percentage varied from 37% in wet years, when surface runoff increased due to higher rainfall, to 54% in dry years.	Bailey et al. (2022)
Four catchments in Iowa	Subsurface flow was found to dominate the discharge (70-75%) across the catchments.	Cao et al. (2023)
Raisin, Maumee, Sandusky, and Grand watersheds across Michigan, Indiana, and Ohio, draining into Lake Erie	Future climate change is expected to increase tile drain flow across all watersheds. For instance, the Maumee watershed model predicted a 71% rise in tile drain flow from December to February under a future climate scenario.	Bosch et al. (2014)
Matson Ditch watershed, DeKalb County, Indiana, part of the Cedar Creek sub-watershed draining into Lake Erie	Simulated tile flow ranged from 85 to 172 mm per year, which represents 8.5% to 16.2% of annual precipitation.	Boles et al. (2015)
Ewing Brook subwatershed, within the Pike River watershed, southern Quebec, Canada	Tile drainage represented between 53 and 80% of water discharged from agricultural fields.	Michaud et al. (2019)

12. **Supplementary Table S7:** Specific studies representing field-scale phosphorus loading from tile-drained fields- Major Findings from monitoring studies

Location	Phosphorus loading (kg/ha) from tile-drained fields	Reference
Pike River watershed, southern Quebec	• Loading in surface runoff: TP 0.40 to 1.90, DRP 0.17 to 0.43, PP 0.08 to 0.73 • Loading in tile flow: TP 0.30 to 2.30, DRP 0.21 to 0.53, PP 0.09 to 1.77	Eastman et al. (2010) conducted the research from October 2004 to September 2006, covering two hydrologic years.
Sydenham River watershed in Ontario	• Loading in tile flow: DRP 0.01 to 0.03	Based on the monitoring data in 2003 and 2004 by Coelho et al. (2010)
Innisfil, Ontario, south of Kempenfelt Bay in Lake Simcoe	• Loading in tile flow: TP 0.01 to 0.46, DRP 0.003 to 0.10	Based on the monitoring data by Lam et al. (2016) in the year between 2011 and 2013
Essex Region Conservation Authority Demonstration Farm, Holiday Beach, Southern Ontario, within the Lake Erie basin	• Loading in surface runoff in CDS system: TP 0.05 to 0.56 (Mean: 0.30), DRP 0.01 to 0.08 (Mean: 0.04), PP 0.04 to 0.51 (Mean: 0.23) • Loading in surface runoff in RFD system: TP 0.01 to 0.13 (Mean: 0.07), DRP 0.001 to 0.01 (Mean: 0.01), PP 0.01 to 0.10 (Mean: 0.06) • Loading in tile flow in CDS system: TP 0.14 to 1.62 (Mean: 0.70), DRP 0.01 to 0.15 (Mean: 0.07), PP 0.10 to 1.33 (Mean: 0.57) • Loading in tile flow in RFD system: TP 0.21 to 2.14 (Mean: 1.09), DRP 0.01 to 0.12 (Mean: 0.08), PP 0.19 to 1.82 (Mean: 0.89)	Based on the monitoring data from spring 2000 to December 2004 by Tan & Zhang (2011).
Three sites across Ontario: Bainsville-BVL, Ilderton-ILD, London-LON	• Loading in surface runoff: TP 0.08 to 0.25, DRP 0.01 to 0.08, PP 0.07 to 0.20 • Loading in tile flow: TP 0.17 to 0.26, DRP 0.02 to 0.02, PP 0.15 to 0.23	Based on the monitoring data from May 2012 to April 2013 by Esbroeck et al., (2016)
Hon. Eugene F. Whalen Experimental Farm in Southwestern Ontario	• Loading in tile flow: TP 0.73 - 8.36, DRP 0.19 - 6.28, PP 0.46 - 1.46 • The higher phosphorus content in swine manure compost, compared to yard waste compost, led to greater concentrations and losses of DRP, PP, and TP in tile drainage water, regardless of water table management strategies.	Based on monitoring data over a four-year period from late 1999 to October 2003 by Zhang et al., (2015)
Honorable Eugene F. Whelan Research Farm, South Woodslee, Ontario	Loading in surface runoff: • CDS-NCC: TP 0.51 to 1.38 (Mean: 1.02), DRP 0.26 to 0.34 (Mean: 0.30), PP 0.46 to 0.99 (Mean: 0.71) • CDS-CC: TP 0.41 to 0.49 (Mean: 0.46), DRP 0.11 to 0.21 (Mean: 0.17), PP 0.14 to 0.29 (Mean: 0.23) • RFD-NCC: TP 0.45 to 0.89 (Mean: 0.68), DRP 0.18 to 0.24 (Mean: 0.21), PP 0.23 to 0.58 (Mean: 0.38)	Based on monitoring data over a four-year period from late 1999 to October 2003 by Zhang et al., (2017)

Location	Phosphorus loading (kg/ha) from tile-drained fields	Reference
	• RFD-CC: TP 0.37 to 0.92 (Mean: 0.71), DRP 0.15 to 0.38 (Mean: 0.23), PP 0.17 to 0.47 (Mean: 0.35) Loading in tile flow: • CDS-NCC: TP 0.60 to 0.93 (Mean: 0.73), DRP 0.06 to 0.28 (Mean: 0.19), PP 0.33 to 0.64 (Mean: 0.46) • CDS-CC: TP 0.64 to 1.47 (Mean: 0.86), DRP 0.14 to 0.32 (Mean: 0.27), PP 0.23 to 1.15 (Mean: 0.69) • RFD-NCC: TP 0.66 to 1.34 (Mean: 1.00), DRP 0.19 to 0.55 (Mean: 0.35), PP 0.24 to 1.27 (Mean: 0.69) • RFD-CC: TP 0.58 to 1.47 (Mean: 1.05), DRP 0.24 to 0.51 (Mean: 0.34), PP 0.17 to 0.98 (Mean: 0.58)	
Chatham-Kent region, Ontario, on the northern boundary of Lake Erie	Loading in tile flow: • Conventional Conservation-Till (CT) system: TP 2.02 to 3.21 (Mean: 2.39), DRP 0.18 to 0.90 (Mean: 0.52) • No-Till Cover Crop (NTCC) system: TP 1.04 to 3.45 (Mean: 1.83), DRP 0.29 to 2.43 (Mean: 0.93)	Based on monitoring data over a four-year period from 2017 to 2021 by Macrae et al., (2023)
Eastern Wisconsin, across three farms.	Loading in surface runoff**:** • Chisel-plowed sites: TP 0.60 to 4.55 (Mean: 1.89), DRP 0.22 to 0.95 (Mean: 0.51) • No-till: TP 1.05 to 8.73 (Mean: 4.45), DRP 0.52 to 7.84 (Mean: 3.66) • Grazed pasture: TP 3.32 to 8.91 (Mean: 5.30), DRP 3.32 to 7.84 (Mean: 4.57) Loading in tile flow: • Chisel-plowed sites: TP 0.24 to 1.53 (Mean: 1.12), DRP 0.22 to 0.95 (Mean: 0.51) • No-till: TP 0.49 to 6.93 (Mean: 2.24), DRP 0.36 to 5.86 (Mean: 1.83) • Grazed pasture: TP 0.27 to 2.63 (Mean: 1.32), DRP 0.13 to 2.08 (Mean: 0.99)	Based on monitoring data between 2005 and 2009 by Madison et al., (2014)
University of Minnesota Southwest Research and Outreach Center, near Lamberton, MN, in the Cottonwood River watershed	Loading in tile flow: • Alternative (AL) Farming: TP 0.01 to 0.08, DRP 0.01 to 0.06 • Conventional (CN) Farming: TP 0.01 to 0.19, DRP 0.01 to 0.15	Based on monitoring data between 2002 and 2004 by Oquist et al., (2007)

Location	Phosphorus loading (kg/ha) from tile-drained fields	Reference
Upper Big Walnut Creek (UBWC) Watershed, Delaware County, Ohio	• Loading in tile flow: TP 0.44 to 0.75 (Mean: 0.57), DRP 0.36 to 0.61 (Mean: 0.46)	Based on monitoring data between 2005 and 2012 by King et al., (2016)
Three agricultural fields on working farms in Midwestern Ontario	• Loading in surface runoff: TP 0.02 to 0.34 (Mean: 0.22), DRP 0.01 to 0.12 (Mean: 0.05) • Loading in tile flow: TP 0.15 to 0.72 (Mean: 0.33), DRP 0.02 to 0.20 (Mean: 0.10)	Based on monitoring data between 2013 and 2017 by Plach et al., (2019)
Different sites of Western Lake Erie Basin (WLEB), spanning northeastern Indiana and northwestern Ohio, USA, and southern Ontario, Canada	• Loading in tile flow: TP 0.10 to 0.90 (Mean: 0.42), DRP 0.10 to 0.20 (Mean: 0.10)	Based on monitoring data between 2012 and 2017 by Hanrahan et al., (2020)
Holland Marsh, Ontario	Loading in tile Flow: • Controlled Drainage (CD): TP 0.58 to 0.60, DRP 0.28 to 0.34 • Pumped Drainage (PD): TP 0.18 to 0.90, DRP 0.06 to 0.69	Based on monitoring data between 2015 and 2016 by Grenon et al., (2023)

13. **Supplementary Table S8:** Specific studies representing field-scale nitrogen loading from tile-drained fields-Major Findings from monitoring studies

Location	Nitrogen loading (kg/ha) from tile-drained fields	Reference
Sydenham River watershed in Ontario	NO3-N Loading in Tile Flow: 3.10 to 3.80	Based on the monitoring data in 2003 and 2004 by Coelho et al. (2010)
Chatham-Kent region, Ontario, on the northern boundary of Lake Erie	NO3-N Loading in Tile Flow: • Conventional Conservation-Till (CT) System: 1.0 to 18.40 (Mean: 11.25) • No-Till Cover Crop (NTCC) System: 3.6 to 15.4 (Mean: 7.83)	Based on monitoring data over a four-year period from 2017 to 2021 by Macrae et al. (2023)
University of Minnesota Southwest Research and Outreach Center, near Lamberton, MN, in the Cottonwood River watershed	NO3-N Loading in Tile Flow: • Alternative (AL) Farming: 2.88 to 8.34 • Conventional (CN) Farming: 5.71 to 42.95	Based on monitoring data between 2002 and 2004 by Oquist et al. (2007)
Upper Big Walnut Creek (UBWC) Watershed, Delaware County, Ohio	• NO3-N Loading in Tile Flow: 23.9 to 56.8 (Mean: 39.57) • TN Loading in Tile Flow: 28.3 to 64.2 (Mean: 45.17)	Based on monitoring data between 2005 and 2012 by King et al. (2016)
Different sites of Western Lake Erie Basin (WLEB), spanning northeastern Indiana and northwestern Ohio, USA, and southern Ontario, Canada	• NO3-N Loading in Tile Flow: 2.9 to 153 (Mean: 26.68) • TN Loading in Tile Flow: 6.6 to 97.7 (Mean: 25.8)	Based on monitoring data between 2012 and 2017 by Hanrahan et al. (2020)
Holland Marsh, Ontario	NO3-N Loading in Tile Flow: • Controlled Drainage (CD): 24.63 to 43.76 • Pumped Drainage (PD): 0.67 to 5.88 • Observation: Higher average NO3-N concentrations during winter than in the growing season under CD. Peaks in NO3-N and TN during high rainfall periods under CD compared to PD. TN Loading in Tile Flow: • Controlled Drainage (CD): 34.73 to 52.86 • Pumped Drainage (PD): 2.09 to 20.63 • Observation: TN concentrations positively correlated with discharge.	Based on monitoring data between 2015 and 2016 by Grenon et al. (2023)

14. **Supplementary Table S9:** Specific studies representing watershed-scale loading of nutrients from tile-drained fields to watershed- Major findings from monitoring studies

Location	Major findings on nutrient loading (kg/ha)	Reference
Subwatershed of the Upper Big Walnut Creek, central Ohio.	This study used monitoring data from 2005 to 2012 and evaluated long-term phosphorus (P) movement through tile drainage and its manifestation at the watershed outlet. **Loading in surface runoff in watershed outlet:** TP 0.52 to 1.85 annually (mean: 0.98), DRP 0.33 to 1.26 annually (0.66 kg/ha) **Loading in tile flow:** TP 0.28 to 0.92 (mean: 0.48), DRP 0.22 to 0.84 (mean: 0.39) **Contribution of Tile Drainage:** Accounts for 48% of dissolved P and 40% of total P exported to the watershed outlet **Temporal Dynamics:** The most significant P loading in tile drainage occurs in late fall, winter, and early spring. Tile drainage significantly contributes to P export in tile-drained watersheds, emphasizing the need for targeted P loading mitigation during peak loading seasons.	King, Williams, & Fausey (2015)
Western Lake Erie Basin, within Huron/Erie Lake Plain and Eastern Corn Belt Plains ecoregions	Assessed the impact of tile drainage on hydrologic responses and nutrient export, utilizing data from 16 USGS gages during 2018 and 2019. Loading in surface runoff: DRP 0.471 kg/ha, NO3-N 15.54	Miller & Lyon (2021)
Ewing Brook subwatershed, within the Pike River watershed, southern Quebec, Canada	The study conducted between October 2008 and May 2009 found that tile drainage significantly contributes to TP loading in agricultural subwatersheds. **TP loading:** Significant during peak flow events. 46 to 67% of TP at the outlet originates from surface runoff during these events. **SRP/DRP loading:** Dominant in tile drainage during winter and spring, indicating seasonal prevalence of dissolved forms. **PP loading:** Concentrations increase in summer due to soil cracks acting as preferential flow pathways, enhancing PP loss through tile drainage. **Seasonal and Hydrological Variation:** TP, SRP/DRP, and PP concentrations vary seasonally, affected by hydrologic conditions and soil properties. Transition between phosphorus forms from dissolved to particulate highlights the impact of soil structure and moisture.	Michaud et al. (2019)

Location	Major findings on nutrient loading (kg/ha)	Reference
	Hydrologic Pathways: Matrix flow: Moves dissolved phosphorus through micropores. Preferential flow: Transports both dissolved and particulate phosphorus through macropores, particularly when soil cracks are present.	
Hopewell Creek watershed, Ontario, Canada	This study collected data from four monitoring sites in a watershed, each with slightly different land uses, monitored from November 2014 to October 2015. **Loading in Surface Runoff:** TP 0.94, DRP 0.10 to 0.15, NO3-N 9.15 to 11.55 **Annual Nutrient Export by Land Use:** Natural sites include forests and riparian zones: DRP 0.001, TP 0.01, NO3-N 0.04 Agricultural and mixed-use sites: DRP 0.10 to 0.15, 0.70 to 0.94, 9.15 to 11.55	Irvine et al. (2019)
Little Vermilion River (LVR) watershed, East Central Illinois	This study used the collected monitoring data from 1994 to 2000, capturing changes in P transport due to management practices Loading in surface runoff: DRP 0.046 to 0.125 Loading in tile flow: DRP 0.113 to 0.226	Algoazany et al. (2007)
Macatawa Watershed, West Michigan	Assess the significance of tile drain effluent as a phosphorus source in the watershed using the monitoring data from March 2015 to February 2016 **Loading in Tile Flow:** TP 0.003 to 0.322 annually, DRP 0.002 to 0.248 annually	Clement & Steinman (2017)

15. **Supplementary Table S10:** Modeling approaches to represent tile-drained dominated fields and watersheds in different studies

Location	**Modeling approach**	**Model used, scale of the study and Reference**
St. Joseph River Watershed, U.S. Corn Belt, part of the Lake Erie basin; spans northeast Indiana, northwest Ohio, and south-central Michigan	The SWAT model was improved to take into account all nutrient loss paths from soil. Calibrated and validated SWAT model for simulating monthly stream flow, total suspended solids (TSS), nutrient loadings (including total Kjeldahl nitrogen (TKN), nitrate and nitrite nitrogen (NOx-N), total phosphorus (TP) and orthophosphate phosphorus (orthoP)), actual evapotranspiration (ETa), leaf area index (LAI) and annual crop yields in the watershed from 2011 to 2019. The SWAT 2012 (Revision 681) source code was improved to consider additional forms of phosphorus and nitrogen lost through lateral soil flow, tile drainage and percolation.	Watershed scale modeling using SWAT by Ren et al. (2022)
Eagle Creek Watershed in Ohio	The SWAT model in ArcSWAT 2012 (Revision 665b) interface was specifically modified for this study to measure the DRP in tile drainage to the hydrologic response unit and subbasin output. The model was also enhanced to develop several conservation practice scenarios and conduct field-scale simulations.	Watershed scale modeling using SWAT by Merriman et al. (2018)
Matson Ditch Watershed, DeKalb County, Indiana	SWAT 2012 Rev. 666 was used and improved to a new version of SWAT 2012 Rev. 670 to evaluate the impacts of changing climate on hydrology and nutrient loadings in an agriculture-dominated, subsurface-drained watershed. This was specifically examined under two greenhouse gas emission scenarios, RCP 4.5 and RCP 8.5. SWAT was configured to accurately simulate the hydrological processes and nutrient transport mechanisms, integrating climate projections from various models and assessing the potential range of outcomes.	Watershed scale modeling using SWAT (version 666) by Mehan et al. (2019)
Field site near Londesborough, Southern Ontario	The study utilized the DRAINMOD 6.1 model, which was chosen due to its applicability in cold regions like Ontario, and its capabilities in modeling winter-season soil hydrology and nitrogen dynamics. The methodology involved the calibration and validation of the model using field data, followed by simulations to estimate future impacts on tile discharge and nitrate loading under different climate change scenarios.	Field scale modeling using DRAINMOD by Golmohammadi et al. (2021)

Location	Modeling approach	Model used, scale of the study and Reference
Upper East River watershed, Wisconsin	The study used SWAT model, calibrated at the monthly time-step for flow, sediment, dissolved reactive phosphorus (DRP), total phosphorus (TP), nitrate, and total nitrogen (TN). ArcSWAT2012 for ArcGIS 10.3 Rev. 665b was used for this analysis and field-scale simulation. The model evaluated the impact of 74 BMP combinations on dairy and cash grain rotations.	Watershed scale modeling using SWAT by Merriman et al. (2019)
Walworth Watershed and Green Lake Watershed, Wisconsin	The Water Erosion Prediction Project-Water Quality (WEPP-WQ) model was used to quantify the impacts of climate change on nutrient (Phosphorus and Nitrogen) losses from the two small watersheds against the historical nutrient estimation data from 1985 to 2008). WEPP model provides hydrological inputs and sediment to the water quality model, which then returns nutrient stresses and estimates nutrient concentration in surface runoff, infiltrated flow, tile drainage, and base flow. This study also utilized downscaled and bias-corrected future climate forcing from two General Circulation Models (GFDL, HadCM3).	Watershed scale modeling using WEPP-WQ by Wang et al. (2018)
Agriculture Agri-Food Canada (AAFC) experimental site near Harrow, Ontario	Root Zone Water Quality Model (RZWQM2) enhanced with a newly developed phosphorus module. Incorporates detailed simulations of various soil phosphorus pools and processes affecting phosphorus movement and transformations. Model calibration and validation were based on data collected from June 2008 to May 2012 from tile-drained corn-soybean fields.	Field scale modeling using RZWQM2 by Sadhukhan et al. (2019)
St. Esprit watershed, located northeast of Montreal, Quebec	The study used a combination of the watershed-scale model WARMF for surface flow and the field-scale model DRAINMOD 5.1 for subsurface flow, focusing on subsurface-drained shallow water table fields. The watershed was subdivided into uniform cells, and DRAINMOD was run on each cell with specific hydrologic characteristics. DRAIN–WARMF was used to simulate hydrological processes and nitrogen transport in small, predominantly subsurface-drained agricultural watersheds that experience periodic freezing and thawing conditions	Watershed scale modeling by combining WARMF and DRAINMOD (DRAIN-WARMF) by Dayyani et al. (2010)
Eastern Corn Belt (ECB) monitoring program area, Northwestern Ohio	The study involves the development and testing of the DRAINMOD-P model which incorporates simulations of hydrology, macropore flow, soil erosion, phosphorus cycling, and transport dynamics. The model incorporates hydrological and biochemical	Field scale modeling using DRAINMOD-P by Askar et al. (2021)

Location	Modeling approach	Model used, scale of the study and Reference
	processes affecting P cycling. Data from a four-year period of a drained field in northwest Ohio was used for validation.	
Grand River watershed, Southern Ontario	Model Used: SWAT, adapted to Canadian conditions. Data Used: Geospatial, climate, management, flow, and water quality data. Calibration Stations: Eight flow gauging stations and seven water quality stations. BMP Evaluation: Nutrient management, buffer strip, cover crop, and wetland restoration.	Watershed scale modeling using SWAT by Liu et al. (2016)
St. Esprit watershed, southwestern Quebec	Model Used: DRAIN-WARMF, combining field-scale subsurface flow (DRAINMOD) and watershed-scale surface flow (WARMF). Climate Data: Projections for 1961 to 2100 from the CRCM, examining changes in temperature and precipitation. Integration: Surface flow and nitrate-N transport simulated using WARMF; subsurface flow and NO3-N fate/transport modeled with DRAINMOD. Scaling: Upscaled field-scale model to watershed scale through a distributed parameter approach, dividing the watershed into field-sized units, with DRAINMOD run on each based on specific soil type, land use, and drainage system.	Watershed scale modeling using DRAIN-WARMF by Dayyani et al. (2012)
US coastline of the Great Lakes Basin, encompassing Lakes Superior, Michigan, Huron, Erie, and Ontario	Model Used: Spatially Explicit Nutrient Source Estimate and Flux model (SENSEflux). Key Features: SENSEflux simulates total annual phosphorus and nitrogen loadings, identifies nutrient delivery hotspots, and quantifies contributions from different sources and pathways, including tile-drained agricultural fields, overland runoff, groundwater flow, and septic plumes within groundwater, with a high resolution of 120 m. Calibration and Optimization: The model is calibrated for phosphorus (P) and nitrogen (N) separately, employing global optimization techniques to refine model parameters and evaluate uncertainties.	Watershed to Basin scale modeling using SENSEflux by Wan et al. (2023)
Four catchments in Iowa, Midwestern US: RS and KS in Story County, and LP and WW in Floyd County	Dynamic Land Ecosystem Model 2.0 (DLEM 2.0), adapted as DLEM-catchment to better represent management practices and specific water and nitrogen transport features through farmed potholes and tile lines. Spatially distributed, process-based model	Watershed scale modeling using DLEM by Cao et al. (2023)

Location	Modeling approach	Model used, scale of the study and Reference
	that integrates unique landscape and management characteristics, focusing on flow-specific nutrient transport.	
Little Vermillion River (LVR) watershed, east-central Illinois	Model Used: SWAT model, specifically revised tile drainage module referred to as SWAT-tile. Data Utilization: The study incorporated field and watershed scale data on tile flow and nitrate loadings for both sensitivity and scenario analyses. Analysis Focus: Effects of varying tile depths on nitrate loadings were extensively analyzed to understand their impact on water and nitrate transport.	Field to watershed scale modeling using SWAT by Kim et al. (2023)
Honorable Eugene F. Whelan Research Farm near South Woodslee, Ontario	Model Used: Root Zone Water Quality Model version 2–Phosphorus (RZWQM2-P), a field-scale phosphorus management model in simulating phosphorus losses (dissolved reactive phosphorus [DRP] and particulate phosphorus [PP]) in surface runoff and tile drainage from a manure-amended field, and identify effective manure management practices to mitigate phosphorus losses. Data and Validation: Evaluated against data collected from a field where liquid cattle manure was applied, assessing the model's capability to simulate phosphorus losses and testing different manure management practices for phosphorus reduction.	Field scale modeling using RZWQM2-P by Sadhukhan et al. (2019)
Hon. Eugene F. Whelan Experimental Farm, Harrow Research and Development Center, South Woodslee, Ontario	Model Used: ICECREAM model, version 3.1.9, developed by the Swedish University of Agricultural Sciences. Processes Simulated: Includes surface runoff, matrix and macropore flow, evapotranspiration, and nutrient losses. Calibration and Validation: Conducted detailed monitoring and calibration of the ICECREAM model to accurately simulate phosphorus losses in both surface runoff and tile drainage, focusing on dissolved reactive phosphorus (DRP) and particulate phosphorus (PP) based on field data.	Field scale modeling using ICECREAM by Qi et al. (2018)
Two neighboring farm fields near South Woodslee, southern Ontario	Model Used: RZWQM2-P, a comprehensive agricultural model simulating water, nutrient, and pesticide dynamics along with crop growth. Treatments Evaluated: A factorial combination of two compost treatments (0 or 75 Mg dry weight per hectare) and two tillage	Field scale modeling using RZWQM2-P by Pan et al. (2023)

Location	Modeling approach	Model used, scale of the study and Reference
	practices (no till- NT and conventional tillage- CT), resulting in four treatment scenarios: NTCMP0, NTCMP75, CTCMP0, CTCMP75. Simulation Focus: Long-term impacts of varying tillage and compost application on phosphorus losses.	
St. Clair-Detroit River system watershed, spanning Southeastern Michigan, U.S. and Southwestern Ontario, Canada	Modeling Tool: SWAT2012 rev635, calibrated and validated from 2001 to 2015	Watershed to basin scale modeling using SWAT by Dagnew et al. (2019)
Greenbelt Research Farm, Ottawa, Ontario	Model Used: DRAINMOD 6.1. Approach: The study used climate scenarios from the Providing REgional Climates for Impacts Studies (PRECIS) to simulate the future impact of tillage practices on hydrology and nitrogen loss.	Field scale modeling using DRAINMOD by Golmohammadi et al. (2016a)
Grand Lake Saint Mary's Basin, Western Ohio	Model Used: APEX-MACRO, enhanced to simulate macropore flow dynamics. Integrate macropore flow in the APEX model to enhance DRP model connectivity with P-rich surface soils. Data Application: 31-month surface and subsurface monitoring data for model calibration and validation.	Field scale modeling using APEX-MACRO by Ford et al. (2017)
Maumee River Watershed (MRW): Located in northwest Ohio, northeast Indiana, and southwest Michigan	Ensemble of SWAT (Soil and Water Assessment Tool) models with different parameterizations: Kalcic Model: Adapted for soluble phosphorus movement through subsurface drains. Kujawa Model: Similar to Kalcic in phosphorus handling but varies in management inputs and structure. Apostel Model: Latest iteration with refined parameterization, particularly in HRU delineation and management practices integration.	Watershed to basin scale modeling using SWAT by Apostel et al. (2021)

16. **Supplementary Table S11:** Specific studies representing nutrient loading from tile-drain dominated fields and watersheds- Major findings from modeling studies

Location	Major findings on nutrient loading (kg/ha/yr)	Model used, scale of the study and Reference
St. Joseph River Watershed, U.S. Corn Belt, part of the Lake Erie basin; spans northeast Indiana, northwest Ohio, and south-central Michigan	**Nutrient loading at watershed outlet:** Surface Runoff: TP 0.77, DRP 0.34, PP 0.07, TN 6, NO3-N 2.4 Tile Flow: TP 0.18, DRP 0.1, TN 7.6, NO3-N 6.5 **Nutrient loading from corn system:** Surface runoff: TP 0.61, TN 4.3 Tile flow: TP 0.34, TN 17.8 **Nutrient loading from soybean system:** Surface runoff: TP 0.55, TN 4 Tile flow: TP 0.38, TN 12.6 **Corn-soybean rotation system (CSRS) contributions to watershed:** Accounts for approximately 49% of the watershed area. Contributes 83% of the total nitrogen and 88% of total phosphorus inputs. Key contributor to nitrogen losses (64%) and phosphorus losses (46%) to the water system.	Watershed scale modeling using SWAT by Ren et al. (2022)
Eagle Creek Watershed in Ohio	Average annual loading by row crops landuse with the all BMP constructed scenario: TP 1.44, DRP 0.18, TN 4.27, NO3-N 1.81	Watershed scale modeling using SWAT by Merriman et al. (2018)
Matson Ditch Watershed, DeKalb County, Indiana	Increased precipitation and flow are projected to increase total nitrogen, total phosphorus, and mineral phosphorus losses. Surface runoff soluble phosphorus loadings (Baseline 0.051 kg/ha) could increase up to 70% under RCP 4.5 and 75% under RCP 8.5. Soluble phosphorus via subsurface drains (Baseline 0.017 kg/ha) is projected to decrease by 35% to 60%. Nitrates in surface runoff are projected to increase by 5% to 50% under RCP 4.5 and 50% to 100% under RCP 8.5. Subsurface drain nitrate-N loadings (Baseline 0.549 kg/ha) could decrease by 25% to 75% mid-century under medium emissions scenarios.	Watershed scale modeling using SWAT (version 666) by Mehan et al. (2019)
Field site near Londesborough, Southern Ontario	Annual average total NO3-N loss during 1960-1990 was approximately 17 kg/ha. Projected NO3-N losses are: About 23 kg/ha for 2011-2040.	Field scale modeling using DRAINMOD by Golmohammadi et al. (2021)

Location	Major findings on nutrient loading (kg/ha/yr)	Model used, scale of the study and Reference
	Around 30 kg/ha for 2041-2070. Approximately 37 kg/ha for 2071-2100. Nitrate losses are expected to increase significantly (about 50%) under future climates due to elevated tile flows. Climate change will significantly affect field hydrology and water quality in tile-drained agricultural regions.	
Upper East River watershed, Wisconsin	Under the all BMP constructed scenario at the watershed scale, the average annual loadings from different land uses: Dairy: TP 1.11, DRP 0.34, TN 9.90, NO_3-N 1.21 Cash Grain: TP 0.99, DRP 0.82, TN 16.35, NO_3-N 2.78 Continuous Corn: TP 1.85, DRP 0.63, TN 15.11, NO_3-N 1.69 Additional key points: SWAT estimated that 0.023 kg/ha DRP is exported with tile drainage. Field monitoring showed an average of 7% of TP left the Tile field through tile drainage annually, with phosphorus distributed as 60% DRP and 40% particulate phosphorus (PP). Other edge of field monitoring in eastern Wisconsin found TP export through tile drainage ranged from 17% to 41% of the total TP load.	Watershed scale modeling using SWAT by Merriman et al. (2019)
Walworth Watershed and Green Lake Watershed, Wisconsin	In the base period, annual losses from Green Lake watershed TP 1.1, NO3-N 2.6, and from Walworth watershed TP 3.3, NO3-N 1.5 Projected increases due to increased precipitation, extreme storm events, and higher air temperatures in Green Lake watershed TP loss increases by 28% to 89% and NO_3-N loss increases by 1.1% to 38%. From Walworth watershed, TP loss increases by 25% to 108% and NO_3-N loss increases by 8% to 95%	Watershed scale modeling using WEPP-WQ by Wang et al. (2018)
Agriculture Agri-Food Canada (AAFC) experimental site near Harrow, Ontario	Surface Runoff: Observed and simulated DRP 0.390 and 0.346, Observed and simulated PP 1.290 and 1.143 Tile flow: Observed and Simulated DRP 0.890 and 0.789, Observed and Simulated PP 2.111 and 2.104	Field scale modeling using RZWQM2 by Sadhukhan et al. (2019)
St. Esprit watershed, located northeast of Montreal, Quebec	Observed and Simulated NO3-N in surface runoff 5.27 and 4.67	Watershed scale modeling by combining WARMF and DRAINMOD (DRAIN-WARMF) by Dayyani et al. (2010)

Location	Major findings on nutrient loading (kg/ha/yr)	Model used, scale of the study and Reference
Eastern Corn Belt (ECB) monitoring program area, Northwestern Ohio	Most P losses through drainage discharge and surface runoff were in the particulate form, as DRP represented less than 20% of the TP load. More than 80% of predicted surface and subsurface P losses were in the particulate form. Surface runoff was the major pathway for P loss, contributing 78% of predicted total P (TP) loading. On average, predicted macropore flow represented about 15% of drainage discharge and contributed 21% of DRP loss via subsurface drains.	Field scale modeling using DRAINMOD-P by Askar et al. (2021)
Grand River watershed, Southern Ontario	Simulated TP loading at the outlet 0.18 to 1.80 and TN loading 0.93 to 6.40	Watershed scale modeling using SWAT by Liu et al. (2016)
St. Esprit watershed, southwestern Quebec	Nitrate-N (NO_3-N) Loading in Surface Runoff 1961-1990: 33.84, 2011-2040: 33.60, 2041-2070: 32.40, 2071-2100: 31.68 Nitrate-N (NO_3-N) Loading in Tile Flow 1961-1990: 27.36, 2011-2040: 26.04, 2041-2070: 24.60, 2071-2100: 22.80 The subsurface flow contribution to annual nitrate loadings was 14% of total loadings in 1961-1990, whereas it increased to 39.3% during 2071-2100.	Watershed scale modeling using DRAIN-WARMF by Dayyani et al. (2012)
US coastline of the Great Lakes Basin, encompassing Lakes Superior, Michigan, Huron, Erie, and Ontario	TP Load: Averages 0.217 kg/ha/yr from tile-drained agricultural fields, overland runoff, and groundwater phosphorus movement. Tile field pathway contributes 0.2771 kg/ha/yr. TN Load: Averages 5.99 kg/ha/yr across the US Great Lakes Basin (US-GLB) from tile-drained fields, overland runoff, groundwater flow, and septic plumes. In Southern Lake Michigan, Saginaw Bay, western Lake Erie, and Lake Ontario basins, tile field pathway contributes significantly, delivering 10.53 kg/ha/yr.	Watershed to Basin scale modeling using SENSEflux by Wan et al. (2023)
Four catchments in Iowa, Midwestern US: RS and KS in Story County, and LP and WW in Floyd County	Subsurface flows, including tile flow and lateral flow, are the primary contributors to in-stream NO_3-N loadings. 77-82% of NO_3-N loading is governed by subsurface flows. 77-81% of annual NO_3-N loadings from four catchments are carried by subsurface flows, with tile flow delivering 53-76% of these loadings.	Watershed scale modeling using DLEM by Cao et al. (2023)
Little Vermillion River (LVR) watershed, east-central Illinois	Nitrate loading s in surface runoff slightly decreased from approximately 0.132 kg/ha at 0.6 m depth to 0.127 kg/ha at 1.2 m depth. Nitrate loadings in tile flow Increased with deeper tiles, from approximately 9.2 kg/ha at 0.6 m to 11.4 kg/ha at 1.2 m depth.	Field to watershed scale modeling using SWAT by Kim et al. (2023)
Honorable Eugene F. Whelan Research	Surface Runoff and Tile Drainage Losses During Nongrowing Seasons: 53% of total surface runoff-bound DRP and 68% of total tile drainage-bound DRP lost. 56% of total surface runoff-associated PP and 65% of total drainage-associated PP lost.	Field scale modeling using RZWQM2-P by Sadhukhan et al. (2019)

Location	Major findings on nutrient loading (kg/ha/yr)	Model used, scale of the study and Reference
Farm near South Woodslee, Ontario	Annual Average TP Loss: 54% through tile flow, with 75% of that as PP. DRP Loadings: Surface runoff 0.29 kg/ha/yr, Tile flow 0.53 kg/ha/yr. Field Experiment and Model Simulation Results: 74% of total P lost as PP, with tile drainage and surface runoff contributing almost equally. Model simulation showed 75% of total simulated P loss as PP, with half of the total PP loss via tile drainage.	
Hon. Eugene F. Whelan Experimental Farm, Harrow Research and Development Center, South Woodslee, Ontario	TP Loss Through Tile Drainage: Measured 2.85 kg/ha, representing 65.4% of total annual TP loss (4.36 kg/ha). Simulated 53.8% of total TP loss from the field. PP Dominance in TP Losses: Observed annual PP loss 3.14 kg P/ha (72.0% of TP losses). Simulated PP loss 69.1% of TP losses. DRP Loadings: Observed 0.38272 kg/ha/yr, Simulated: 0.34369 kg/ha/yr. PP Loadings: Observed 1.12542 kg/ha/yr, Simulated: 1.20102 kg/ha/yr.	Field scale modeling using ICECREAM by Qi et al. (2018)
Two neighboring farm fields near South Woodslee, southern Ontario	CT-CMP75 (Conservation Tillage, 75% Compost Mix): Observed TP 0.555, Simulated TP 0.571, Observed DRP 0.182, Simulated DRP 0.220, Observed PP 0.347, Simulated PP 0.277 NT-CMP75 (No Tillage, 75% Compost Mix): Observed TP 0.761, Simulated TP 0.689, Observed DRP 0.362, Simulated DRP 0.262, Observed PP: 0.323, Simulated PP: 0.339 CT-CMP0 (Conservation Tillage, No Compost Mix): Observed TP 0.331, Simulated TP 0.429, Observed DRP 0.046, Simulated DRP 0.165, Observed PP 0.274, Simulated PP 0.209 NT-CMP0 (No Tillage, No Compost Mix): Observed TP 0.434, Simulated TP 0.514, Observed DRP 0.057, Simulated DRP 0.196, Observed PP 0.362, Simulated PP 0.253 Key Findings: Increasing tillage intensity and compost mix efficiency reduces DRP by 48.12% and PP by 30.29% under intensive tillage and moderate soil mixing conditions.	Field scale modeling using RZWQM2-P by (Pan et al. (2023)
St. Clair-Detroit River system watershed, spanning Southeastern Michigan, U.S. and Southwestern Ontario, Canada	TP loading across the watershed: 1116 metric tons per annum (MTA) approximately 0.586 kg/ha/yr DRP loading across the watershed: 414 metric tons per annum (MTA) approximately 0.217 kg/ha/yr	Watershed to basin scale modeling using SWAT by Dagnew et al. (2019)
Greenbelt Research Farm, Ottawa, Ontario	No-Till (NT) practices resulted in 15% higher NO3-N loss compared to Conservation Tillage (CT) during the study period. Under future climatic conditions, both NT and CT are expected to show significant increases in flow and NO3-N losses, with NT showing comparatively higher increases.	Field scale modeling using DRAINMOD by Golmohammadi et al. (2016a)

Location	Major findings on nutrient loading (kg/ha/yr)	Model used, scale of the study and Reference
Grand Lake Saint Mary's Basin, Western Ohio	Median Annual DRP Load: 0.68 kg P/ha/yr. Contributions to DRP Load: Macropore pathways: 44% (0.30 kg P/ha/yr). Matrix percolation: 56% (0.38 kg P/ha/yr). Seasonal Contributions to Macropore DRP Loading: Winter: 0.19 kg P/ha/yr. Spring: 0.17 kg P/ha/yr.	Field scale modeling using APEX-MACRO by Ford et al. (2017)
Maumee River Watershed (MRW): Located in northwest Ohio, northeast Indiana, and southwest Michigan	The observed TP in surface runoff was noted at 0.37 kg/ha, whereas models showed higher values with Apostel recording the highest at 2.68 kg/ha. In tile flow, Apostel reported the lowest TP at 0.04 kg/ha. DRP observations for surface runoff were at 0.15 kg/ha, with Apostel again being the highest at 0.29 kg/ha, contrasting with its minimal contribution in tile flow at 0.04 kg/ha. For TN and NO_3-N, the surface runoff values were significantly varied among models, with Kujawa showing exceptionally high TN at 12.67 kg/ha and Kalcic marking the highest in tile flow for both TN and NO_3-N at 36.44 kg/ha. These comparisons illustrate significant disparities in nutrient handling and management practices are evident among the models in both surface runoff and tile flow scenarios.	Watershed to basin scale modeling using SWAT by Apostel et al. (2021)

17. **Supplementary Table S12:** Specific studies representing BMP effects on nutrient reduction in tile-drained fields and watersheds- Major findings from monitoring studies

Location	**BMPs in the tile-drained landscape**	**Effectiveness**	**Reference**
Honorable Eugene F. Whelan Research Farm, South Woodslee, Ontario	• Controlled Drainage with Sub-irrigation (CDS). • Overwinter cover crops (CC)	• P reduction potential in surface water runoff under CDS-CC vs. RFD-NCC: DRP 0.03, PP 0.15, TP 0.22 kg/ha/yr. • P reduction potential in tile drainage water runoff under CDS-CC vs. RFD-NCC: DRP 0.07, PP 0.12, TP 0.19 kg/ha/yr. • TP loss reduction under CDS-CC treatment compared to RFD-NCC: up to 23%.	Monitoring conducted at Field scale by Zhang et al. (2017)
Chatham-Kent region, Ontario, on the northern boundary of Lake Erie	• No-Till Cover Crop (NTCC) • Conventional Conservation-Till (CT)	• NTCC system reduced annual NO3-N losses by 3.425 kg/ha/year compared to the CT system. • NTCC system increased dissolved reactive phosphorus (DRP) losses by 0.4095 kg/ha/year compared to the CT system. • NTCC system reduced TP losses by 0.5575 kg/ha/year compared to the CT system. • Despite reductions in soil erosion, particulate phosphorus (PP), and possibly NO3-N at the NTCC site, increased DRP losses and insufficient soil P reduction hinder achieving water quality targets in tile drainage.	Monitoring conducted at Field scale by Macrae et al. (2023)
Upper Big Walnut Creek located in central Ohio	• Drainage Water Management (DWM)	• DWM reduced annual tile discharge by 11 to 178 mm, corresponding to an 8 to 34% decrease in flow. • DWM decreased annual NO3-N loadings by 1.3 to 26.8 kg/ha, resulting in an average reduction of 9.4 kg/ha (8 to 44%). • DWM cut annual dissolved P loadings by 0.04 to 0.51 kg/ha, averaging a 0.19 kg/ha reduction (40 to 68%). • While DWM reduced nutrient loadings in tile flow, it increased nutrient loadings in surface runoff, presenting water quality trade-offs. • Nutrient concentrations remained unchanged by DWM; reductions in nutrient loadings were primarily due to decreased tile discharge. • The study supports using DWM as a BMP to reduce N and P loadings in subsurface drain discharge in the U.S. Midwest.	Monitoring conducted at field scale by Williams et al. (2015b)
Shatto Ditch Watershed, Kosciusko County, Indiana, draining	• Cover crops, primarily annual ryegrass and some cereal rye, were	• Year-round sampling in tile drain outlets confirmed that cover crops retained nutrients applied to agricultural fields. • Median NO3−N losses from tile-drained fields with cover crops were 69–90% lower compared to those without cover crops during winter/spring.	Monitoring conducted at field and watershed

Location	BMPs in the tile-drained landscape	Effectiveness	Reference
into the Tippecanoe River	planted on 65-68% of croplands.	• Watershed level NO3−N export during elevated flows was 18–22% lower in years with watershed-scale cover crop planting compared to years without. • Even after adjusting for larger drainage areas, NO3−N yields from tiles with cover crops were still >60% lower than those without, demonstrating significant NO3-N reductions in working lands. • The study confirmed the high effectiveness of cover crops in reducing NO3-N loss at both tile and watershed scales, though translating results from field to watershed scale is complex due to varying management practices and other factors.	scale by Hanrahan et al. (2018)
Six small, agricultural watersheds in the Conesus Lake catchment, New York	• Structural BMPs included manure lagoons, terraces, buffer strips, and sediment control basins • Cultural BMPs involved cropping sequences, soil testing, fertilization rates, and tillage practices	• Significant reductions in TP, NO3-N, total Kjeldahl nitrogen, and total suspended solids were noted by the second and third years of implementation. • Greatest reductions observed at Graywood Gully with an average 55.8% decrease in pollutants following Whole Farm Planning. • BMPs proved more effective when integrated into comprehensive Whole Farm Planning rather than as isolated practices. • While effective locally, translating BMPs to broader ecosystem or watershed-wide reductions was challenging due to scale and existing practices. • Soluble reactive phosphorus concentrations in groundwater from managed field tiles were significantly lower (5.81 ± 3.4 µg P/L) compared to unmanaged areas (219 ± 162 µg P/L).	Monitoring conducted at watershed scale Makarewicz et al. (2009)
Honorable Eugene F. Whalen Experimental Farm, Woodslee, Ontario	• Cover crops + controlled drainage–subirrigation (CDS), • Cover crops + unrestricted tile drainage (UTD), • No cover crops + CDS, • No cover crops + UTD	• Cover crops (CC) decreased 5-year flow-weighted mean (FWM) NO3- concentration in tile drainage by 21 to 38% and cumulative NO3- loss by 14 to 16% compared to plots without cover crops (NCC). • Controlled tile drainage–subirrigation (CDS) reduced FWM NO3- concentration by 15 to 33% and cumulative NO3- loss by 38 to 39% relative to traditional unrestricted tile drainage (UTD). • Combining cover crops and controlled drainage–subirrigation reduced 5-year cumulative FWM NO3- concentrations and losses in tile drainage by 47% (from 9.45 to 4.99 mg N L-1 and from 102 to 53.6 kg N ha-1) compared to plots without cover crops and unrestricted drainage (NCC+UTD). • Cover crops increased corn grain yields by 4 to 7% in 2004 and soybean yields by 8 to 15% over three years, whereas CDS had no impact on corn or soybean yields over six years.	Monitoring conducted at field scale by Drury et al. (2014)

Location	BMPs in the tile-drained landscape	Effectiveness	Reference
		• The combination of cover crops and water-table management significantly reduced NO3- loss from cool, humid agricultural soils.	
Essex Region Conservation Authority Demonstration Farm, Holiday Beach, Southern Ontario, within the Lake Erie basin	• Controlled Drainage with Sub-irrigation (CDS)	• The Controlled Drainage with Sub-irrigation (CDS) system reported a mean TP (TP) loading of 0.699 kg/ha in tile drainage water, significantly lower than the 1.086 kg/ha observed in the Regular Free Drainage (RFD) system. • CDS increased Dissolved Reactive Phosphorus (DRP) and TP concentrations in surface runoff, and DRP in tile drainage, but decreased Particulate Phosphorus (PP) and TP concentrations in tile drainage water.	Monitoring conducted at field scale by Tan & Zhang (2011)
University of Minnesota Southwest Research and Outreach Center, near Lamberton, MN, in the Cottonwood River watershed	• Alternative farming practices featuring diverse crops such as oats and alfalfa, combined with organic management and the use of cover crops	• Alternative farming practices reduced subsurface drainage discharge by 41% compared to conventional practices. • These practices decreased NO3-N N losses by 59 to 62% in 2002 and 2004 compared with conventional methods. • Alternative farming significantly reduced both mean daily and annual losses of phosphorus and nitrogen in subsurface drainage, particularly in years with average or above-average precipitation.	Monitoring conducted at field scale by Oquist et al. (2007)
McLean County, Illinois	• Wetlands built in 2006 with three series (East, West, Gully), each containing three cells. Water flowed through tile drains between cells; berms prevented surface runoff.	• Wetlands treated runoff from 8 ha (East, West) and 4 ha (Gully), covering 3%, 6%, and 9% of tile-drained areas. • Wetlands covering 3% (W1) of tile-drained farmland reduced NO3-N export by 15–38%, with higher reductions observed in larger wetlands: 39–49% for 6% coverage (W2) and 49–57% for 9% coverage (W3). NO3-N mass removal efficiencies ranged from 28 to 52%. • For orthophosphate (ORP) or DRP, W1 achieved a 12-year total loading reduction of 53 to 81%, while W2 and W3 wetlands achieved 35–91% and 32–95% reductions, respectively, with mass removal rates between 71 to 85%.	Monitoring conducted at field scale by Lemke et al. (2022)
Shatto Ditch Watershed (SDW) and Kirkpatrick Ditch Watershed (KDW) in Indiana	• Cover crops	• Cover crops reduced tile drain NO3-N loss by 27–72% and DRP loss by 7–58% • NO3-N and DRP export were reduced at watershed scale by 2–67% and 31–88%, respectively.	Monitoring conducted at field to watershed scale by Speir et al. (2022)

18. **Supplementary Table S13:** Specific studies representing BMP effects on nutrient reduction in tile-drained fields and watersheds- Major findings from modeling studies

Location	BMPs in the tile-drained landscape	Effectiveness	Reference
Greenbelt Research Farm, Ottawa, Ontario	• Controlled drainage strategy applies from June 15 to August 15 during the crop season and from November 1 to April 1 in the non-growing season	• Controlled drainage implementation led to a 16% reduction in mean annual drain flow. • Surface runoff increased by approximately 71% due to controlled drainage. • A balance between conserving water and reducing pollution through controlled drainage is necessary to establish effective watershed management practices.	Field to watershed scale modeling using SWATDRAIN model by (Golmohammadi et al., 2016b)
South Nation River Basin, eastern Ontario	• Controlled Tile Drainage (CTD) is recommended for agricultural lands with surface slopes ≤1%. • The study tested CTD on growing season at two depths: 600 mm (CTD600) and 200 mm (CTD200) below the surface.	• Over five growing seasons, CTD600 reduced direct runoff by 6.6%, total nitrogen by 3.5%, and dissolved nitrogen by 13.7%. • However, CTD600 led to increases in total phosphorus (0.96%), dissolved phosphorus (1.6%), and total suspended solids (0.23%). • In a single season under corn crop, CTD600 resulted in a 55% reduction in dissolved nitrogen as predicted by AnnAGNPS.	Watershed scale modeling using AnnAGNPS model (version 5.2) by (Que et al., 2015)
Two neighboring farm fields near South Woodslee, southern Ontario	• Impact of tillage intensity and compost/manure application efficiency on reducing P losses	• Tillage can reduce both tile drainage and phosphorus loss compared to no-till management. • Increasing tillage intensity (TI) from no-till (0) to intensive tillage (0.93) using a moldboard plow decreases DRP losses by 48.12% and PP losses by 30.29%. • Enhancing manure/compost mix efficiency (ME) from 0 to 0.5 with moderate soil mixing via a Tandem Disk cuts DRP losses by 53.98% and PP losses by 30.95%.	Field scale modeling using RZWQM2-P model by (Pan et al., 2023)
St. Clair-Detroit River system watershed, spanning Southeastern Michigan, U.S. and Southwestern Ontario, Canada	• Fertilizer rate reduction and sub-surface placement substantially. Implementing filter strips, planting cover crops, and	• Filter strips achieved TP reductions between 20% and 39%, and DRP reductions between 18% and 37%, varying by sub-watershed. • Subsurface fertilizer placement cut TP and DRP loadings by up to 35% and 33% in certain areas.	Watershed scale modeling using SWAT2012 model (version rev635) by Dagnew et al., (2019)

Location	BMPs in the tile-drained landscape	Effectiveness	Reference
	increasing wetland drainage areas. • Combining practices like cover crops, subsurface fertilizer placement, filter strips, and wetland enhancement.	• Cover crops led to a TP reduction of 30% and DRP reduction of 24% in some regions, with lesser effects in others. • The most effective bundles, achieving up to 40% loading reductions, involved these practices in various combinations. • Specifically, the combination of cover crops, filter strips, and wetland enhancements performed best, reducing loadings by up to 80% with full implementation. • Controlled Drainage and No-Till Tillage practices Increased TP and DRP loadings. However, integrating controlled drainage with cover crops could reduce nutrient load.	
Hon. Eugene F. Whelan Experimental Farm, Harrow Research and Development Center, South Woodslee, Ontario	• Tillage timing and fertilizer application methods (injection vs. surface application)	• Shifting autumn tillage to spring results in a 10% reduction in total phosphorus (TP) losses. • Injecting fertilizer rather than broadcasting can reduce 25.4% TP losses. • About 86.9% of TP losses through tile drainage during the nongrowing season, highlighting the critical need for management strategies	Field scale modeling using ICECREAM model (version 3.1.9) by Qi et al., (2018)
Honorable Eugene F. Whelan Research Farm near South Woodslee, Ontario	• Manure injection, controlled drainage, and winter manure application.	• Compared to conventional practices, manure injection effectively mitigates P losses (DRP+PP) in subsurface-drained fields by 18%. • Controlled drainage, despite reducing total P loss via tile flow, leads to an overall increase in P loss by 13% due to enhanced surface runoff. • Winter manure application exacerbates P losses significantly, showing a 23% increase.	Field scale modeling using RZWQM2-P model by Sadhukhan et al., (2019)
Tile drainage experimental site near Waseca, southern Minnesota	• Effect of reducing nitrogen application rates and adjusting tile drain spacing and depth.	• Reducing tile drain depth from 1.5 to 0.9 meters led to an 8% reduction in tile flow (from 207 to 191 mm) and a 14% reduction in NO3-N losses (from 34.0 to 29.4 kg ha^{-1}). • Increasing tile drain spacing from 27 to 60 meters resulted in an 11% reduction in tile flow (from 205 to 182 mm) and a 16% reduction in NO3-N losses (from 33.8 to 28.4 kg ha^{-1}). • Halving the N application rate from 200 to 100 kg ha^{-1} led to a 67% decrease in NO3-N losses (from 33.8 to 11.1 kg ha^{-1}).	Field to watershed scale modeling using SWAT2012 which was revised by Moriasi et al., (2013)

Location	BMPs in the tile-drained landscape	Effectiveness	Reference
		• Significant reductions in nitrate-nitrogen (NO3-N) losses are more effectively achieved through reductions in nitrogen (N) application rates compared to adjustments in tile drain spacing and depth.	
Illinois State University Nitrogen Management Research Field Station, Lexington, Illinois	• Optimizing nitrogen application timings (fall and spring) with and without cereal rye cover crop	• Model predictions and observations indicated significant reductions in nitrate loss and tile drainage volumes with cereal rye: • Predicted reductions in nitrate loss were 43.6% and 45.4% for fall and spring N application treatments, respectively. Observed reductions in nitrate loss were slightly higher at 48.6% and 47.8%. • Predicted reductions in tile drainage volume were 21.3% and 21.0%, while observed reductions were 30.2% and 19.4%, respectively.	Field scale modeling using DSSAT model by Gupta et al., (2022)
Near Bedford, Southern Québec	• Optimal drain spacing	• Increasing drain spacing from 5 to 70 m at Site A reduced TP loadings in subsurface drainage from 0.5 to 0.2 kg/ha/yr and increased surface runoff TP loadings from 0 to 0.4 kg/ha/yr; • At Site B, it reduced subsurface TP loadings from 2.3 to 0.1 kg/ha/yr and increased surface runoff TP loadings from 0 to 4.5 kg/ha/yr.	Field scale modeling using DRAINMOD model coupled with developed regression model by Morrison et al., (2013)
Raccoon River Watershed, west-central Iowa	• Analyzed 14 management scenarios combining five strategies: fertilizer/manure management, perennial grass conversion, vegetative filter strips (VFS), cover crops, and shallower tile drainage.	• Conversion of hotspot areas to perennial grass reduced NO3 by 47% • Multiple management practices achieved a 38.5% NO3 reduction, while extensive perennial grass conversion could achieve up to 49.7%. • Reduced fertilizer/manure, shallower tile drainage, cover crops, and VFS achieved 38.5% NO3 reduction • Climate change may reduce the effectiveness of these practices by up to 65% for nitrate by the late 21st century.	Watershed scale modeling using SWAT model Teshager et al., (2017)
Raisin, Maumee, Sandusky, and Grand watersheds across Michigan, Indiana, and Ohio, draining into Lake Erie	• No-till, cover crops, and filter strips were analyzed under various climate scenarios	• BMP effectiveness varied with climate scenarios, generally becoming less effective under more pronounced climate changes due to increased precipitation and altered runoff patterns. However, higher implementation rates could still substantially offset increases in nutrient and sediment yields.	Watershed scale modeling using SWAT model to simulate various climate scenarios and BMPs by Bosch et al., (2014)

19. **Supplementary Table S14:** Key remarks by different studies related to tile drainage discharge, phosphorus, and nitrogen loading from tile-drained fields and watersheds, modeling and monitoring results of nutrient loading from tile-drain dominated fields and watersheds, and BMP effectiveness

Table Component	Key remarks by other studies
Tile discharge and subsurface outflow at the field scale	• Logan et al. (1980) monitored tile-drained fields across the midwestern United States, finding tile discharge as a fraction of precipitation to be 13% in Iowa, 17% in Minnesota, and 26% in Ohio, with precipitation recovery from individual tile drains ranging from 0 to 66%. • Baker and Johnson (1981) identified tile flow at an Iowa site varying between 9.5% and 23% of annual precipitation. • Lal et al. (1989) observed tile flow representing 28% to 59% of annual precipitation on poorly drained plots in northwest Ohio. • Kladivko et al. (1991) found tile flow ranging from 5.9% to 27% of annual precipitation in southern Indiana. • Jaynes et al. (2001) reported tile losses between 18 and 40% of total precipitation over four years in Iowa. • Tile drainage is the dominant hydrologic pathway, observed in edge-of-field studies (70 to 97%) and at the plot scale (Goulet et al., 2006). • Algoazany et al. (2007) found tile drainage contributing 83–90% of total basin drainage from nearly level fields in Illinois • Hernandez-Ramirez et al. (2011) reported an average tile flow of 23% of annual precipitation in central Indiana on corn-soybean rotations. • Across all sites, March and April had the highest tile drainage, consistent with other seasonal patterns reported in the Midwest and Ontario
Tile discharge and subsurface outflow at the watershed scale	• Algoazany et al. (2007) reported that 13–19% of annual precipitation was drained via tile lines over seven years in central Illinois. • Tile drains contribute approximately 40% of annual runoff in various sites across the Lake Erie watershed (Macrae et al., 2007b; King et al., 2014). • Boles et al. (2015) and Green et al. (2006) found that subsurface drain flow typically constitutes 4.7 to 18.5% of total annual precipitation in watersheds with about 50% of the area under subsurface drains. • Owens et al. (2008) reported that 46% of precipitation was recovered at the outlet of a 1.2-km^2 watershed in Ohio. • Larger watersheds have greater potential for water storage, affecting watershed response (Tomer et al., 2003; Schilling and Zhang, 2004). • Tile drainage has been estimated to equal up to half of annual watershed discharge, with 42% of discharge from tile drainage in a headwater watershed in Ontario, Canada (Macrae et al., 2007). • Culley and Bolton (1983) estimated that 60% of watershed discharge in the Big Creek watershed originated from tile drainage, and Xue et al. (1998) estimated 86% of stream flow was derived from tile drains. • Tile drainage tends to increase total water yield by 10-25% due to increased discharge to surface waters relative to storage, evaporation, or transpiration (Serrano et al., 1985; Magner et al., 2004; Tomer et al., 2005).

Table Component	Key remarks by other studies
	• King et al. (2014a) found that tile drainage contributed 51% of annual stream flow in a headwater watershed in Ohio, while 42% of annual discharge originated from tile flow in an Ontario watershed (Macrae et al., 2007). • Anticipated future climates are expected to increase tile drain flow and sediment export to streams, with higher annual precipitation, especially in spring, leading to increased surface runoff and tile drainage.
Field-scale phosphorus loading from tile-drained fields- Major Findings from monitoring studies	• Clay loam vs. sandy loam soils: Clay loam soils showed higher particulate phosphorus (PP) levels up to 1.77 kg/ha, while sandy loam soils had higher dissolved phosphorus (DP) levels up to 0.53 kg/ha (Eastman et al., 2010). • Seasonal phosphorus loading: High phosphorus loadings observed during the non-growing season with significant contributions from snowmelt, accounting for 23-52% of annual TP and DRP exports (Lam et al., 2016; Su et al., 2011; Macrae et al., 2007; Liu et al., 2014). • Tillage and phosphorus loss: No-till management increased stratification and migration of DRP into tile drains, enhancing phosphorus loss (Bertol et al., 2007; Fisher, 2014; Kleinman et al., 2015). • Tile drainage as a significant phosphorus pathway: Tile drains were major pathways for phosphorus loss, particularly in Western Lake Erie Basin, with TP losses ranging from 17% to 41% of the total (Pease et al., 2018; Madison et al., 2014). • Dissolved reactive phosphorus (DRP) export range: Annual tile drain DRP loadings varied from 0.08 to 2.7 kg/ha/yr in Ohio and 0.01–1.34 kg/ha/yr in Canada (King et al., 2015, 2016; Pease et al., 2018; Eastman et al., 2010; Lam et al., 2016). • Preferential flow and P transfer: Fine-textured, shrink–swell soils prone to preferential flow significantly contribute to P transfer into tile drains (Stamm et al., 1998; Grant et al., 2018). • Significant phosphorus losses during peak flow events: TP loadings during peak flows often contributed 46-67% of the total, with a high proportion originating from surface runoff (Michaud et al., 2019). • Comparative tile and surface runoff loadings: Tile drains can export comparable or greater amounts of P as surface runoff, with specific rain events significantly contributing to seasonal loadings (King et al., 2015; Ball et al., 2012).
Field-scale nitrogen loading from tile-drained fields- Major Findings from monitoring studies	• Dissolved nitrogen loadings vary across North America, with values from 14.4 kg/ha in Eastern Canada to 27.1 kg/ha in the American Southeast (Christianson et al., 2015). • Mean dissolved nitrogen loading in selected wet years was 35.8 kg/ha, compared to 33.9 kg/ha from pooled wet years, highlighting potential impacts of climate variability (Christianson et al., 2015). • Approximately 80% of nitrate nitrogen losses from tile-drained lands occur through tile drainage, particularly during fall and early spring in humid temperate regions (Drury et al., 1996; Tan et al., 1999, 2007; BallCoelho et al., 2012; Tan and Zhang, 2011). (Amado et al., 2017) found that subsurface tile drainage contributed to at least 50% of the watershed nitrogen loading from April 15 to November 1, 2015, delivering up to 80% of the stream nitrogen loading while accounting for only 15–43% of the streamflow, with quick flows playing a marginal role in nitrogen loading. • Annual runoff loadings averaged 14.2 kg/ha for total nitrogen across all land uses, representing 10-25% of applied fertilizer nitrogen (Harmel et al., 2008). • Average nitrogen loss in drainage from cornfields is around 20%, ranging from less than 10% to 40% of applied nitrogen (Christianson et al., 2015). • Excess nitrate is prone to leaching from artificially drained fields, with 42% more nitrogen lost in subsurface drainage from conventionally farmed land compared to organically farmed land in Norway (Korsaeth and Eltun, 2000).

Table Component	Key remarks by other studies
	• Annual tile drain nitrate loadings vary significantly: 0.1 to 133.2 kg N/ha/yr in Ohio and 0.4 to 49.9 kg N/ha/yr in Canada (King et al., 2016; Logan et al., 1994; Williams et al., 2015b; Bolton et al., 1970; Drury et al., 2009; Tan et al., 2002). • Nitrate levels in drainage water from agricultural organic soils can range from 37 to 245 kg/ha due to nitrogen fertilizer application (Miller, 1979).
Watershed-scale loading of nutrients from tile-drained fields to watershed-major findings from monitoring studies	• **Nutrient Loadings:** Tile drainage in watershed areas shows mean annual loadings of 0.39 kg ha-1 DRP and 0.48 kg ha-1 TP (King et al., 2015). These are similar to other studies in Ontario and Illinois, which report ranges from 0.24 to 0.38 kg ha-1 DRP and up to 0.50 kg ha-1 TP (Gaynor and Findlay, 1995; Gentry et al., 2007). However, these are lower than the 1.55 kg ha-1 TP found in a Quebec study (Eastman et al., 2010). In a headwater watershed in Ohio, annual watershed NO3–N loading varied from 12.4 to 39.6 kg/ha, with tile drainage contributing 44 to 82% (average: 62%) of the annual watershed NO3–N export (Williams et al., 2015a). • **Soil Composition and P Transport:** Clay-heavy soils like Pewamo clay loam, which predominates in certain watersheds, are more prone to developing preferential flow paths, increasing P transport to subsurface drains compared to soils like Bennington silt loam (Eastman et al., 2010; Simard et al., 2000). • **Seasonal and Event-based Losses:** A significant proportion of P transport occurs outside the growing season, with tile drains exporting 19-67% of total annual DRP loading. Notably, 78-90% of annual water export is carried by tile drains (Kerr et al., 2016; Van Esbroeck et al., 2016). Nutrient losses are highly episodic, with 70-88% of TP and 82-83% of DRP losses tied to storm events (Macrae et al., 2007a; Banner et al., 2009). • **Impact of Watershed Characteristics:** Land use, slope, soil texture, and tile drain density impact nutrient export, but it's unclear if these factors consistently lead to elevated loadings or if impacts are event-specific (Chen et al., 2015). • **Dissolved Reactive Phosphorus (DRP) Concerns:** DRP is a bioavailable form of phosphorus that is rapidly transported from tile drains to waterways, with tile drain density also influencing nitrogen (N) loadings through NO3- leaching (King et al., 2015; Vidon and Cuadra, 2011). • **Management Practices Affecting P Transport:** The rate, timing, and method of P application, along with rainfall intensity, are critical in influencing P transport. Land-management practices, including tillage and crop regime, also significantly impact P transport to tile drains. No-tillage management, for instance, reduces runoff but increases macropore formation, facilitating faster P transport (Culley et al., 1983; Edwards and Daniel, 1993; Sharpley et al., 1993; Daniel et al., 1994; Kinley et al., 2007).
Modeling of nutrient loading from tile-drain dominated fields and	• Tile drainage is a major pathway for nutrient delivery, particularly for nitrogen, to the US Great Lakes, influencing over 66% of TN and 76% of TP loadings with significant contributions in various Lake basins (Wan et al., 2023).

Table Component	Key remarks by other studies
watersheds- major findings from modeling studies	• Developed land, high tile-drainage, and low wetland densities increase dissolved nutrient concentrations in the Great Lakes Basin. Conversely, more silt-clay soils and low wetland densities increase particulate phosphorus (PP) concentrations (Basu et al., 2023). • Significant phosphorus losses occur during non-growing seasons, accounting for over 60% of total runoff and drainage-associated phosphorus losses (Sadhukhan et al., 2018). • Increasing tile drain spacing in sandy loam soils decreases total phosphorus (TP) loadings by 6% per 5-meter increase, while in clay loam soils, it increases TP loadings by 20%. Changes also affect TP loadings in surface runoff (Morrison et al., 2013). • A 122% increase in tile drain spacing reduces NO3-N losses by 16%, and a 40% decrease in drain depth reduces NO3-N losses by 14% (Moriasi et al., 2013). • By the 21st century's end, subsurface drain flow may increase by 70%, surface runoff by 10-140% under RCP 8.5. DRP yields could decrease by 30-60%, with annual variations expected under different RCP scenarios (Mehan et al., 2019). • Tile drainage significantly impacts soil water balance and nutrient losses, requiring improvements in SWAT models for better simulation of nitrogen and phosphorus losses (Boles et al., 2015; Guo et al., 2018; Bauwe et al., 2019). DRAINMOD drainage routines incorporated into SWAT, though verification is limited (Moriasi et al., 2012; Guo et al., 2018).
BMP effects on nutrient reduction in tile-drained fields and watershed-findings from monitoring studies	• Cover Crops: Studies show cover crops can reduce NO3-N loss by up to 84% in surface runoff (Sharpley and Smith, 1991) and up to 62% in tile drainage (Constantin et al., 2010). These reductions are attributed to biological nitrogen uptake during non-crop periods and improved water management strategies. (Drury et al., 2014; Kaspar et al., 2007, 2012). These crops not only decrease nutrient concentrations but also increase tile drainage volume, which can enhance crop yields by improving soil moisture retention (Strock et al., 2004; Qi and Helmers, 2010). Moreover, cover crops improve soil hydraulic properties like water storage and soil aggregate stability, leading to better overall water management within agricultural systems (Blanco-Canqui et al., 2015). • Controlled Drainage with Sub-Irrigation (CDS) and DWM: CDS systems have demonstrated effectiveness in reducing NO3-N losses by 38-39% and significantly decreasing TP (TP) losses, particularly when integrated with cover crops (Tan et al., 1993; Elmi et al., 2005). Such systems not only mitigate nutrient leaching but also adaptively manage water levels to support crop growth during dry periods, leading to yield improvements by 50-90% during drought conditions through enhanced water availability (Fisher et al., 1999; Ng et al., 2002). (Saadat et al., 2018) reported that compared to free draining, controlled drainage significantly reduced annual drain flow by 25-39% and NO3-N loading by 26-43% across different seasons and outlet levels, demonstrating that NO3-N loss reductions were primarily due to decreased flow rates. A review by (Ross et al., 2016) found that DWM significantly reduced nutrient losses via tile drainage, decreasing NO3-N loadings by 48%, TP loadings by 55%, and DRP loadings by 57%. • Wetlands: Over three years (Kovacic et al., 2000) found that constructed wetlands (ranging from 0.3 to 0.8 ha in surface area and 1200 to 5400 m^3 in volume) removed 37% of nitrogen and 2% of phosphorus from agricultural tile drainage systems. Coupling with a 15.3-m buffer strip increased nitrogen removal to 46%. • Emerging edge-of-field BMPs: (Zak et al., 2018) discussed the Integrated buffer zones (IBZs) as an edge-of-field BMP distinct from traditional riparian buffer strips. This system incorporates a combination of a pond and a flow-through filter

Table Component	Key remarks by other studies
	bed that can remove 10−67% of TN and 31−69% of TP loading. (Moorman et al., 2015) reported that denitrifying bioreactors, designed to intercept either tile drainage or lateral groundwater flow, can effectively reduce NO3-N losses by at least 20% to 30%, requiring only up to 0.27% of the watershed area for a cumulative volume with a half-day hydraulic retention time. Another management practice is the construction of two-stage ditches—small, constructed floodplains adjacent to the stream channel—that intercept sediment and nutrients and slow water velocity, thereby promoting in-stream denitrification processes (Davis et al., 2015; Speir et al., 2020). • No-till Management: While no-till practices are widely promoted to reduce erosion, it can increase dissolved reactive phosphorus (DRP) losses due to enhanced stratification of phosphorus in surface soils and the development of macropores that facilitate preferential flow pathways (King et al., 2015; Kleinman et al., 2015). (Christianson et al., 2016) reported that no-till practices resulted in higher dissolved P loadings in drainage compared to conventional tillage (0.12 vs. 0.04 kg P ha-1), underscoring the impact of tillage methods on P transport. Therefore, tillage techniques require careful integration with other BMPs to effectively reduce nutrient leaching. • Best Management Practices (BMPs) Efficacy: The success of BMPs varies significantly depending on regional and seasonal factors. Particularly in cool, temperate regions, managing phosphorus losses during the non-growing season (NGS) poses considerable challenges. BMPs must strategically address both the timing of phosphorus applications and the physical pathways of nutrient movement to mitigate losses effectively (Hansen et al., 2000; Tiessen et al., 2010). The incorporation of BMPs such as cover crops, controlled drainage, and precise nutrient management is critical to adapting to the hydrological and biogeochemical conditions specific to each agricultural setting. • Implementation and Stakeholder Cooperation: Effective conservation planning in tile-drained agricultural watersheds should integrate surface-runoff BMPs with conservation measures that intercept and retain subsurface agricultural runoff (Lemke et al., 2011). (Sunohara et al., 2016) found that CTD implemented during the growing season significantly reduced nutrient losses in tile effluent, achieving reductions of 51% for NO3-N, 66% for TP, and 66% for dissolved reactive phosphorus over 35 field-crop years. While these results highlight the effectiveness of CTD in mitigating nutrient fluxes, the study emphasizes that no single BMP is entirely sufficient. Therefore, combining multiple BMPs—such as nutrient management strategies, surface erosion control measures, end-of-pipe treatments like woodchip bioreactors, and downstream systems including wetlands and riparian protection—is recommended to enhance the environmental benefits of CTD. Achieving substantial improvements in water quality through conservation practices requires not only comprehensive farm planning but also robust cooperation among stakeholders. This includes coordinated efforts in BMP deployment and monitoring to ensure effective implementation at both the field and watershed scales (Fales et al., 2016).
BMP effects on nutrient reduction in tile-drained fields and watershed-findings from modeling studies	• Kęsicka et al. (2022) in a meta analysis reported that a range of practices like controlled drainage, tile drainage management, denitrifying bioreactors, and constructed wetlands effectively reduce nitrate loading from artificially drained agricultural lands. • Kęsicka et al. (2022) also reported that Controlled Drainage (CD) reduced drainage outflow and nitrate losses by 30.5% and 33.61% respectively, achieving reductions of 71.26 mm and 8.36 kg NO3-N ha^{-1} $year^{-1}$. However, nitrate reduction varied widely from 0.88 to 12.32 kg NO3-N ha^{-1} $year^{-1}$, with its effectiveness influenced by study duration and local

Table Component	Key remarks by other studies
	precipitation, showing greater reductions in longer studies and areas with lower rainfall. (Kęsicka et al., 2023) also found that CD can retain or reduce the discharge of NO3-N up to 22 kg/ha using DRAINMOD model. • Evans et al. (1991) reported a 30% reduction in total phosphorus (P) losses using Drainage Water Management (DWM) compared to free drainage, while Cooke et al. (2004) observed an 83% reduction in P losses following DWM implementation. • Singh et al. (2007) observed up to an 18% reduction in tile drainage outflow using controlled drainage in Iowa, while Ale et al. (2009) reported a 60% decrease in drain flows at Purdue University with a drainage management strategy. • Kleinman et al. (2015) highlighted the pronounced effects of Best Management Practices (BMPs) on phosphorus (P) losses in drainage, with reductions of 36% through wetland installation, 39 to 55% with structure liming, and 50% by incorporating liquid swine manure into clay soil. • Feyereisen et al. (2015) found that blind inlets, which replace open surface inlets with soil and gravel caps, reduced total P and dissolved P loadings by 66% and 50% respectively, over seven years in Indiana, with total suspended solids also reduced by 64%. Additionally, biochars used in bioreactors decreased dissolved P concentrations by 65% and nitrate concentrations by up to 97% compared to controls without biochar. • Merriman et al. (2018 and 2019) assessed the effectiveness of Best Management Practices (BMPs) in tile-drained agricultural watersheds using the SWAT model. The 2018 study highlighted that significant field-scale BMP investments are essential for improving water quality at the watershed level, with single BMPs rarely reducing dissolved reactive phosphorus (DRP) by more than 10%, even at high implementation levels. Filter strips were the most effective single BMP, especially when combined with other practices, and cover crops showed particular efficacy during winter months. The 2019 study demonstrated that a combination of BMPs—such as cover crops, crop rotation, nutrient management, reduced tillage, and filter strips—was more effective than individual practices in reducing DRP and total phosphorus on dairy fields in Wisconsin's Upper East River Watershed. Both studies noted potential increases in soluble nutrients through tile drains and highlighted the SWAT model's limitations in accounting for particulate phosphorus.

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