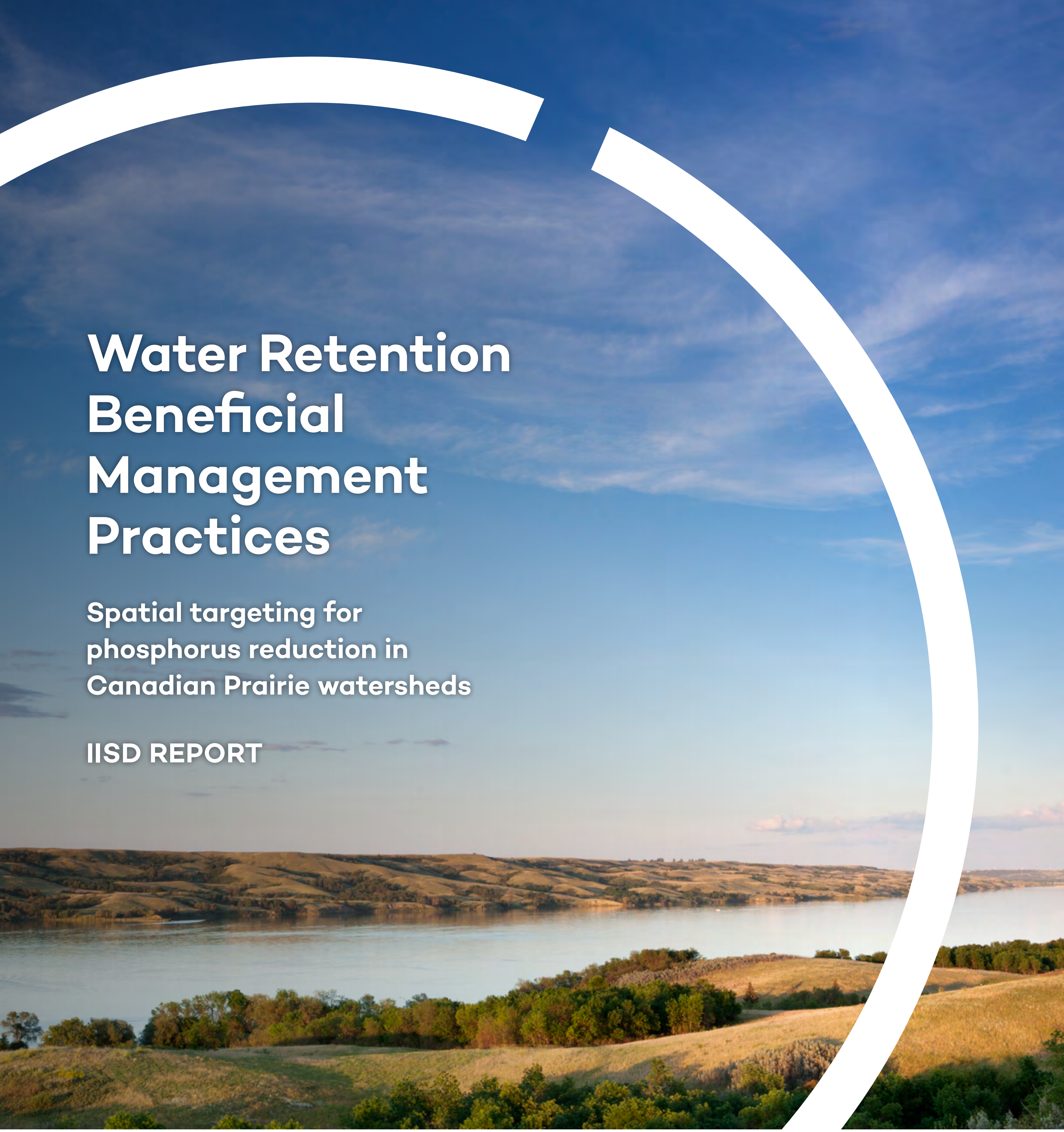

Water Retention Beneficial Management Practices

Spatial targeting for phosphorus reduction in Canadian Prairie watersheds

IISD REPORT

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Water Retention Beneficial Management Practices: Spatial targeting for phosphorus reduction in Canadian Prairie watersheds

May 2025

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Photo: iStock

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Indigenous Lands and Cultures

The region we refer to as the Canadian Prairies is home to an incredible diversity of Indigenous cultures. Indigenous Peoples of the Prairie region are rightsholders with robust knowledge, a close connection to their traditional lands, and jurisdiction over their territories.

The region of focus for IISD's Natural Infrastructure for Water Solutions (NIWS) initiative spans over 200 traditional territories and homelands across the provinces we call Alberta, Saskatchewan, and Manitoba—including the Indigenous territories of the Nêhiyaw-Askiy (Plains Cree), Woodland Cree, Iyarhe Nakoda (Stoney Nakoda), Anishininiimowin (Oji-Cree), Niitsítapi (Blackfoot), Tsuut'ina, Očhéthi Šakówiŋ, Nakoda Oyadeb (Nakota), Lakota, Dakota, Anishinaabe (Ojibwe), Anisininew (Ojibwe Cree), and Salteaux, alongside Métis Nations, including the Otipemisiwak Métis, Métis Nation–Saskatchewan, and Red River Métis.

At IISD, we uphold the agency and autonomy of Indigenous Peoples, supporting their efforts to revitalize and engage with their heritage across traditional, contemporary, and future contexts. We offer respect to those who have long lived with and stewarded lands and waters across the Prairies and recognize the ongoing leadership of First Nations and Métis communities.

We encourage everyone to visit native-land.ca to learn more about traditional lands and treaties across the Prairies.

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Abbreviations and Acronyms

3D	3-dimensional
AAFC	Agriculture and Agri-Food Canada
BMP	beneficial management practice
CaPA	Canadian Precipitation Analysis
DEM	Digital Elevation Model
DWM	drainage water management
ECCC	Environment and Climate Change Canada
HEC-HMS	Hydrologic Engineering Center – Hydrologic Modeling System
HEC-RAS	Hydrologic Engineering Center – River Analysis System
HUC	Hydrologic Unit Code
IDF	Intensity–Duration–Frequency
IISD	International Institute for Sustainable Development
LLEP	Living Lab Eastern Prairies
NASA	National Aeronautics and Space Administration
NLCD	National Land Cover Database
NRCS	Natural Resources Conservation Service
MRLC	Multi-Resolution Land Characteristics Consortium
PHyDAP	Prairie Hydrology Design and Analysis Product
PTMApp	Prioritize, Target, and Measure Application
SCS	Soil Conservation Service
SLC	Soil Landscapes of Canada
SRO	spring runoff
SWAT	Soil and Water Assessment Tool
TN	total nitrogen
TP	total phosphorus
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture

WASCoB	Water and Sediment Control Basin
WFDEI	WATCH-Forcing-Data-ERA-Interim
WSC	Water Survey of Canada

1.0 Background and Objectives

Beneficial management practices (BMPs) are widely recognized by watershed practitioners for reducing negative impacts and risks to the environment while being economically viable for implementation within the agricultural context. For example, downstream agricultural BMPs deployed on marginal lands such as wetlands can offset increased nutrient losses occurring from croplands that have been drained to improve their productivity. However, without guidance, it is challenging to target locations for BMP implementation with the objective of maximizing return on investment. Existing monitoring and modelling efforts have supported the identification of nutrient hotspots in the Canadian Prairies (Lake Winnipeg Foundation, 2019; Robertson et al., 2019), but the application of spatial targeting models for BMP evaluation has been limited or has not comprehensively considered the context of Canadian Prairie hydrology (Houston Engineering Inc. et al., 2019).

To address the stated needs, this report provides background on the unique features of Canadian Prairie hydrology and the Swan Lake study area, a watershed within the Living Lab Eastern Prairies (LLEP), as well as an overview of some prominent BMPs for nutrient reduction and current implementation practices (Section 1). This background provides justification for the methods recommended for strategic Canadian Prairie BMP spatial targeting using the Prioritize, Target, and Measure Application (PTMApp) model within the Swan Lake study area (Section 2). The strategy considers a reduction in nutrient loads during spring runoff and the identification of non-contributing areas, which were both found to be a priority through consultation with project stakeholders such as the Government of Manitoba and Manitoba Watershed Districts. This report also shares insights about spatial targeting methods from different end users through a review of several different practical applications of model outputs for BMP assessment (Section 3).

These guidelines for spatial targeting model development and the insights about their application provided by end users are intended to provide a foundation for streamlining future modelling efforts and to suggest strategies for producing model outputs that are more useful to their end users. A sufficiently trained hydrologic modeller or water resources engineer should be able to use the provided information to replicate the presented modelling strategy to produce similar-quality results that are adapted to their own study area. This report also informs governments, watershed managers, and other project developers of both the capabilities and limitations of these methods, with the intent of increasing their adoption. As this document is meant to serve these two audiences, readers with less technical knowledge of watershed modelling may wish to only skim Sections 2.1, 2.3, and 2.4 of this report.

1.1 Canadian Prairie Hydrology

This section reviews the physical characteristics of the Canadian Prairies, including unique water quantity and quality considerations, as well as projected climate change impacts on hydrology, to identify and justify the use of a BMP spatial targeting model appropriate to the given context.

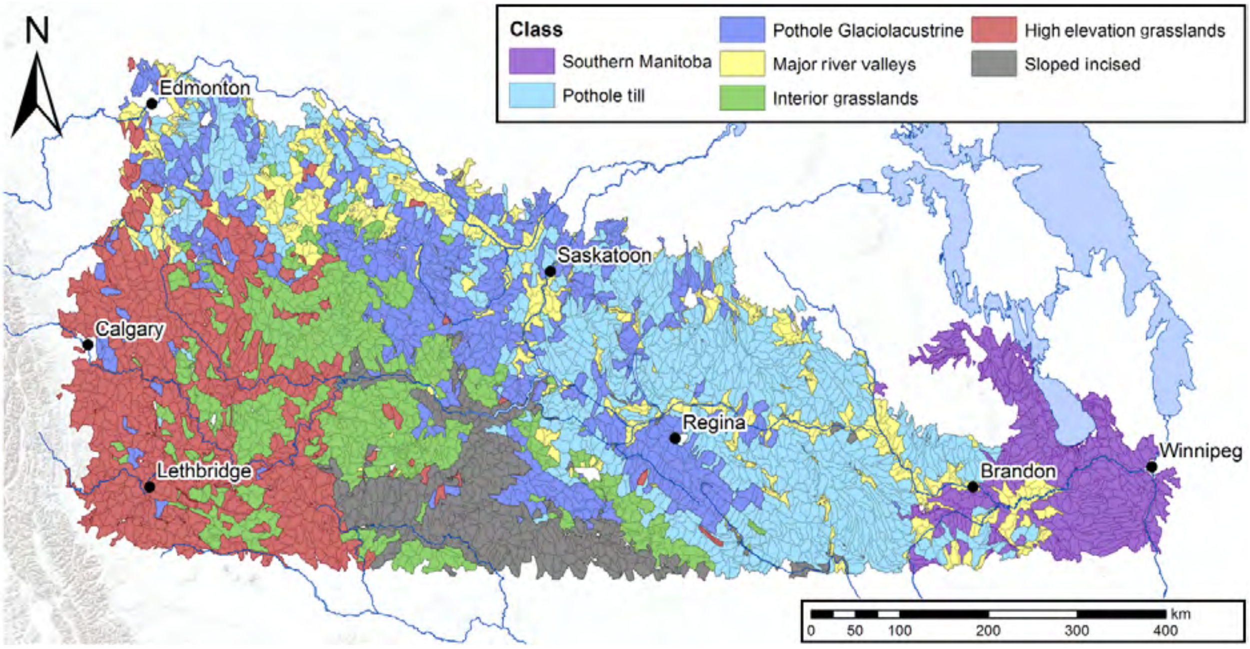
Physical Characteristics

The Canadian Prairie region has a cold semiarid climate and extends across 470,000 km^2 from Alberta to Manitoba. Wolfe et al. (2019) characterized the region using four main categories based on climate, physiography, wetland, and land-cover variables:

- **Grasslands:** The southwestern region (southern Alberta and western Saskatchewan) consists mainly of unmanaged grasslands, low wetland density, and an arid climate with a strong moisture deficit. Three classes were defined in this category: Interior Grasslands, High-Elevation Grasslands, and Sloped Incised Watersheds.
- **Major river valleys:** Watersheds surrounding major rivers (e.g., North and South Saskatchewan, Qu'Appelle, Assiniboine, Pembina) and large lakes. These watersheds are typically fluvial environments with high slope variations.
- **Prairie potholes:** This category represents the largest area, extending from northern Alberta to southeastern Saskatchewan. Annual precipitation is relatively high, with a slight moisture deficit. The high levels of land in annual crops compete with a high density of wetlands. These watersheds have a large fraction of non-contributing areas (intermittent connectivity of water flow between landscape depressions). Two classes were defined: Pothole Till and Pothole Glaciolacustrine.
- **Southern Manitoba:** Located south of Lake Winnipeg, this region is associated with cropland, low mean elevation, level topography, and high annual precipitation and potential evapotranspiration (no moisture deficit).

The area of study for this project, the Swan Lake study area (further discussed in Section 1.2), fits into the Major River Valleys class, and it is surrounded by Pothole Till and southern Manitoba classes' watersheds. This particular geographical context suggests that this area is a mesh of several characteristic clusters, namely: riverine environment (enlargement of the Pembina River), low and flat land, high density of wetlands with non-contributing areas, annual cropping, and relatively high precipitation.

Figure 1. Classification of Prairie ecozone watersheds



Source: Wolfe et al., 2019.

Flooding

Several major floods have occurred in Manitoba since the early 1800s, particularly within the Red and Assiniboine river basins. These events occur primarily during spring (April–May) when specific conditions are met: heavy rainfall during fall and/or spring, above-average snowpack in the basin combined with rapid snow melt, ice jams at critical river locations, unusual ice and cold conditions that affect drainage systems, and a high degree of ground-level frost that prevents ground water infiltration for spring runoff (Government of Manitoba, 2022a). In order to reduce the impacts of flooding, several measures have been put in place across the Prairies, including spillways, dams, land-use changes, and predictive modelling initiatives.

During the last several decades, the transformation of wetlands and grasslands to cropland has increased drainage and the transportation of nutrients (e.g., phosphorus and nitrogen) from fields to rivers and lakes. This land-use change also increases spring runoff event discharge and, therefore, nutrients and sediment exports, which compromises the water quality of downstream water courses (Painter et al., 2021). In the Canadian Prairie region of southern Manitoba, snowmelt may contribute up to 80% of annual total phosphorus (TP) and total nitrogen (TN) loads to connecting water bodies. A unique feature of this region is that its surface water network is mostly interconnected during the snowmelt period when flows are high, but it becomes disconnected during the rest of the year when precipitation is lower (Rattan et al., 2017). In addition to the environmental impact, spring flooding results in less farmland being utilized, lowering overall yields and income (Brimelow et al., 2014), and causes significant damage to infrastructure.

Drought

Drought is characterized by a lack of precipitation during winter and/or summer, above-average temperatures during summer, the drying up of agricultural soils, a drop in groundwater reserves, and the depletion of surface water supplies. The Canadian Prairie landscape, characterized by several depressions and wetlands, has water recharge that is strongly dependent on cold-season precipitation and hydrological processes (Fang & Pomeroy, 2008).

Although southern Manitoba is often affected by floods, the climate is highly variable and can also be extremely dry in some years (Brimelow et al., 2014). More recently, southern Manitoba had an exceptional drought (D4 intensity, 50-year recurrence) during the growing season of 2021, whereas some years recently were just abnormally dry (D0 intensity, 3-year recurrence) (Agriculture and Agri-Food Canada [AAFC], 2022). Events like these have led the Government of Manitoba to place greater emphasis on managing its water resources to improve drought resiliency, as evidenced by its recently released drought management strategy (Government of Manitoba, 2016).

Water Quality

The rapid transitioning of pluvial and drought regimes, along with increases in extreme hydrologic event frequency and intensity, are concerning for southern Manitoba. These factors have significant impacts on water supply and quality for both agricultural and other uses (Brimelow et al., 2014). The enrichment of water with nitrogen and phosphorus can lead to increasingly frequent and severe algal growth and eutrophication in rivers and lakes. Algae blooms can impair fish and wildlife habitats, cause taste and odour issues in drinking and recreational water, and increase the potential of toxins excreted from some species of algae, which can affect the health of humans, livestock, aquatic life, and wildlife (Bourne et al., 2002).

The Government of Manitoba established an Integrated Watershed Management Planning program to help regulate nutrient application while restricting development in environmentally sensitive areas. They also used the Canadian Council for Ministers of the Environment Water Quality Index to summarize large, complex water quality datasets and communicate water quality changes to the public (Government of Manitoba, 2022c).

Impacts of Climate Change and Future Trends

According to Sauchyn et al. (2020), predicted changes for the Canadian Prairie's agricultural region over the next decades include an increase in total annual precipitation with a shift in when they occur (slightly more in winter than in summer); more extreme conditions like drought, heat waves, heavy and frequent precipitation events and flooding, fewer extreme cold spells, more intense winter storms, and more liquid precipitation during winter rather than snow. Climate models show that a warming climate will increase the magnitude and frequency of consecutive years of drought in summer and fall (Bonsal et al., 2019).

These climatic changes will have direct and indirect impacts on future trends for agricultural production. For example, a direct impact will be the increase in temperature and atmospheric carbon dioxide that could improve yields for crops such as spring wheat and canola but may adversely affect corn yield (Qian et al., 2019). On the other hand, shifts in drought and precipitation patterns will likely increase the variability of crop yields between years. Indirect impacts include damage from biotic stresses and soil characteristics (Sauchyn et al., 2020).

In the Canadian Prairies, future surface and soil water deficits will significantly impact the availability and quality of both surface and groundwater reserves (Bonsal et al., 2019). As mentioned above, negative impacts on water quality will also result from extreme rainfall or snowmelt events, which increase runoff and result in significant nutrient and sediment exports and accumulations. The magnitude of runoff events and their impacts on downstream waterbodies are also correlated with land use and management practices.

Canadian Prairie Hydrologic Modelling

In the Prairie Pothole Region, spring runoff provides significant volumes of annual discharge and nutrient and sediment loading. However, Prairie watersheds are challenging to model due to their topography and non-contributing areas, especially during low-to-average flow periods. For this reason, particular attention needs to be paid to the hydro-conditioning of digital elevation models through the manipulation of topography using field data such as culvert surveys. It is also important to validate satellite-derived land use, which significantly affects incoming nutrient loads and rainfall–runoff relationships and can vary over time.

Given the Canadian Prairie landscape and its sensitivity to extreme climatic events, there is a need to develop and adopt mitigation and adaptation strategies that address both water quantity and quality issues. For a modelling approach with this context in mind, it is important to consider an ensemble of solutions to agri-environmental problems that are based on accurate geospatial analysis and field data and that consider both technical and socio-economic constraints.
In this study, the PTMApp has been identified for its ability to spatially target BMPs that mitigate nutrient and sediment exports while also assessing cost-effectiveness. This event-based hydrological model was developed by the International Water Institute in cooperation with the Red River Watershed Management Board, Minnesota Board of Water and Soil Resources, and Houston Engineering Inc. The processes built into the PTMApp can be tailored to the Canadian Prairie context, making the model an excellent candidate for addressing the challenges mentioned above. This model, our development strategy, interpretations of model outputs, evaluations, input data alternatives, and insights are provided in Section 2.

1.2 Living Labs Initiative

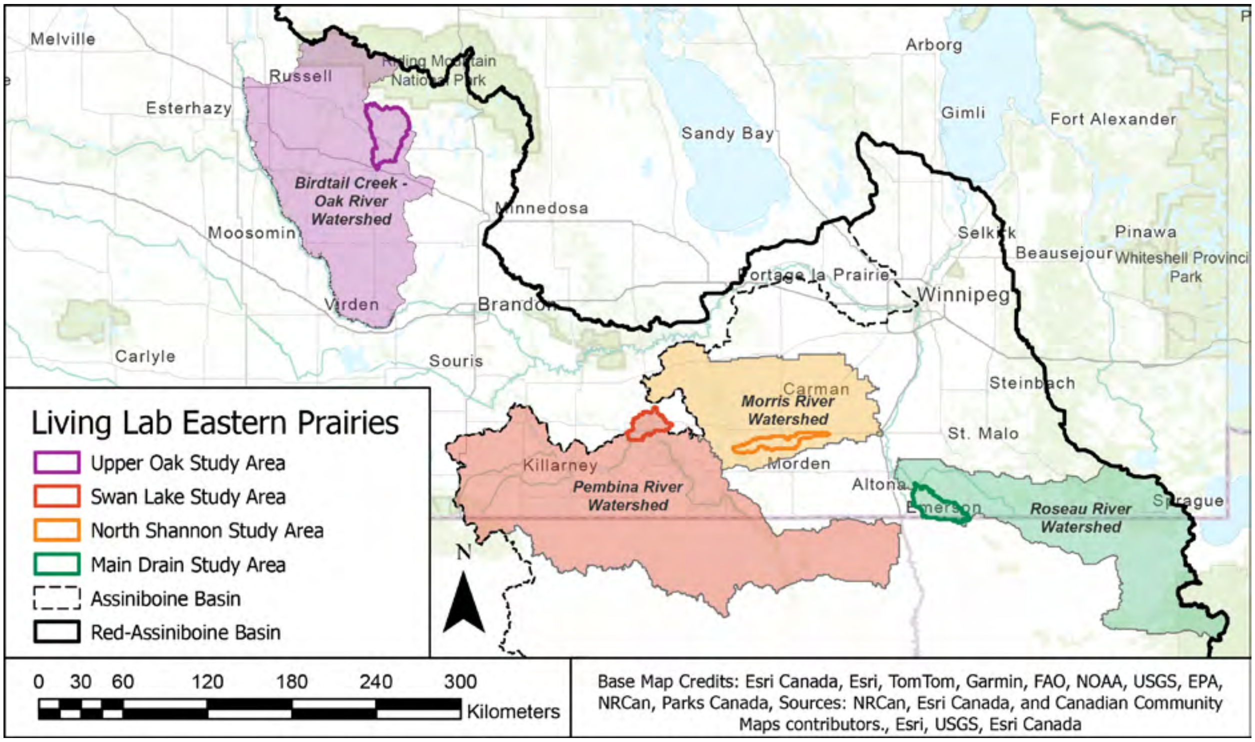
AAFC launched the Living Laboratories Initiative in 2018 to address significant environmental challenges and build resilient agricultural landscapes. The goal of the initiative was to establish a coordinated, long-term, nationwide network of sites where partner agencies, landowners, and managers collaborate to co-design, assess, and implement innovative solutions that are rapidly adopted to address persistent agri-environmental issues. After a series of engagement workshops across Canada that included a broad range of partners (including various federal government departments, First Nations, provincial governments, municipalities, non-governmental organizations, industry, academia, and other research organizations), Living Lab projects were established in the Prairie region (LLEP), Atlantic Canada (Living Lab Atlantic), Quebec (Living Lab Quebec), and Ontario (Living Lab Ontario).

Although this report is focused on the Swan Lake study area of the LLEP, a brief overview of additional modelling efforts and the applicability of the PTMApp in Living Labs Atlantic, Quebec, and Ontario are each explored in Section 3.2.

1.2.1 Swan Lake Study Area of the LLEP

The LLEP included four watershed study areas that represent the distinct ecoregions that cover Manitoba's agricultural area (see Figure 2). These study areas include the Main Drain in the Roseau River watershed, North Shannon Creek in the Morris River watershed, Swan Lake in the Pembina River watershed, and the Upper Oak in the Birdtail Creek–Oak River watershed.

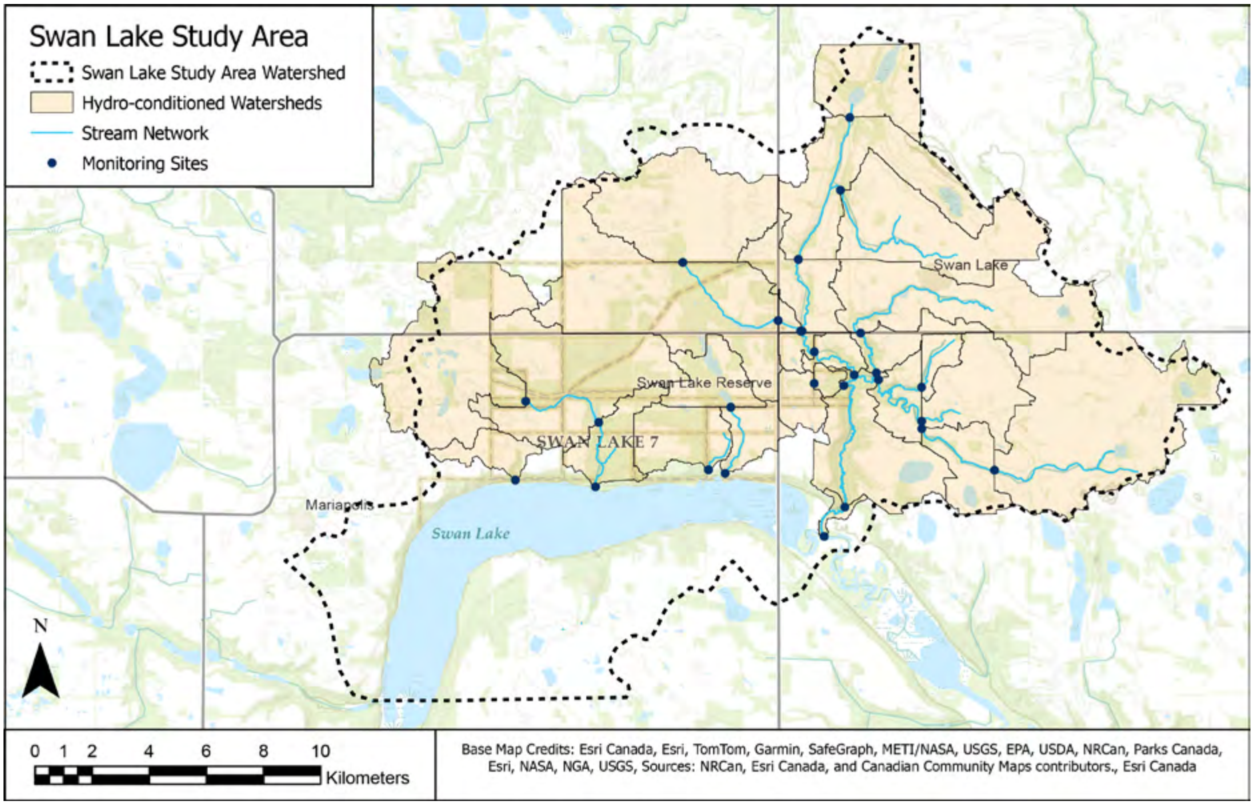
Figure 2. LLEP study areas and watersheds



Source: Author map based on AAFC, 2013a; Government of Manitoba, 2022b.

The Swan Lake study area was selected for model development because it had a strong community interest in water quality, specifically for Swan Lake itself, which suffers from eutrophication and frequent severe algae blooms. This study area also benefited from the existence of detailed model input data (e.g., culvert inventory, stream network, soil data, satellite imagery, and land use), as well as participating landowners and managers with BMPs, either planned or existing, that could be monitored for their performance to support model development, calibration, and evaluation. However, until this research program began, the study area was considered ungauged for long-term hydrometrics. Sub-watersheds and the stream network for the study area were also delineated based on a hydro-conditioned Light Detection and Ranging (LiDAR) digital elevation model (DEM) created using the available detailed model inputs mentioned previously (see Figure 3).

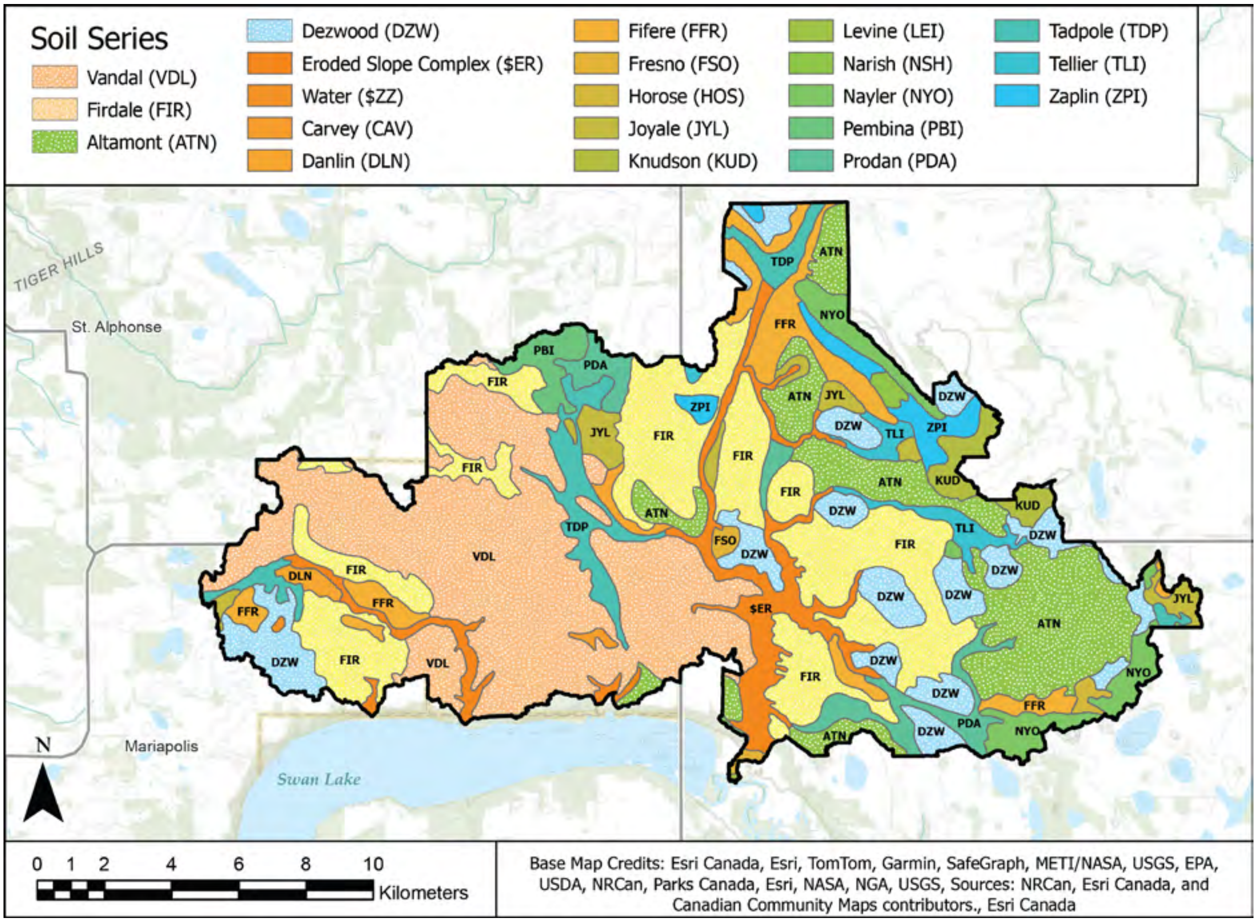
Figure 3. Swan Lake study area with hydro-conditioned watersheds, stream network, and monitoring stations



Source: Authors.

While the Swan Lake study area predictably shares many of the characteristics of the Canadian Prairies, additional physical characteristics should be described. First, the study area is generally hummocky, with the dominantly morainic landscape located in the Pembina Hills physiographic region within the Southwest Uplands Ecoregion of Manitoba. Figure 4 illustrates the various soil series of the region and highlights the Vandal, Firdale, Altamont, and Dezwood series, as they are the most common. These fine to coarse loamy dark grey soils range from moderately to well drained, and the corresponding higher infiltration rates can lead to less water ponding overtop of these areas. The Government of Manitoba (2010) provides more information on the stratigraphy of these soil series, including detailed morphological descriptions and the physical and chemical characteristics of each.

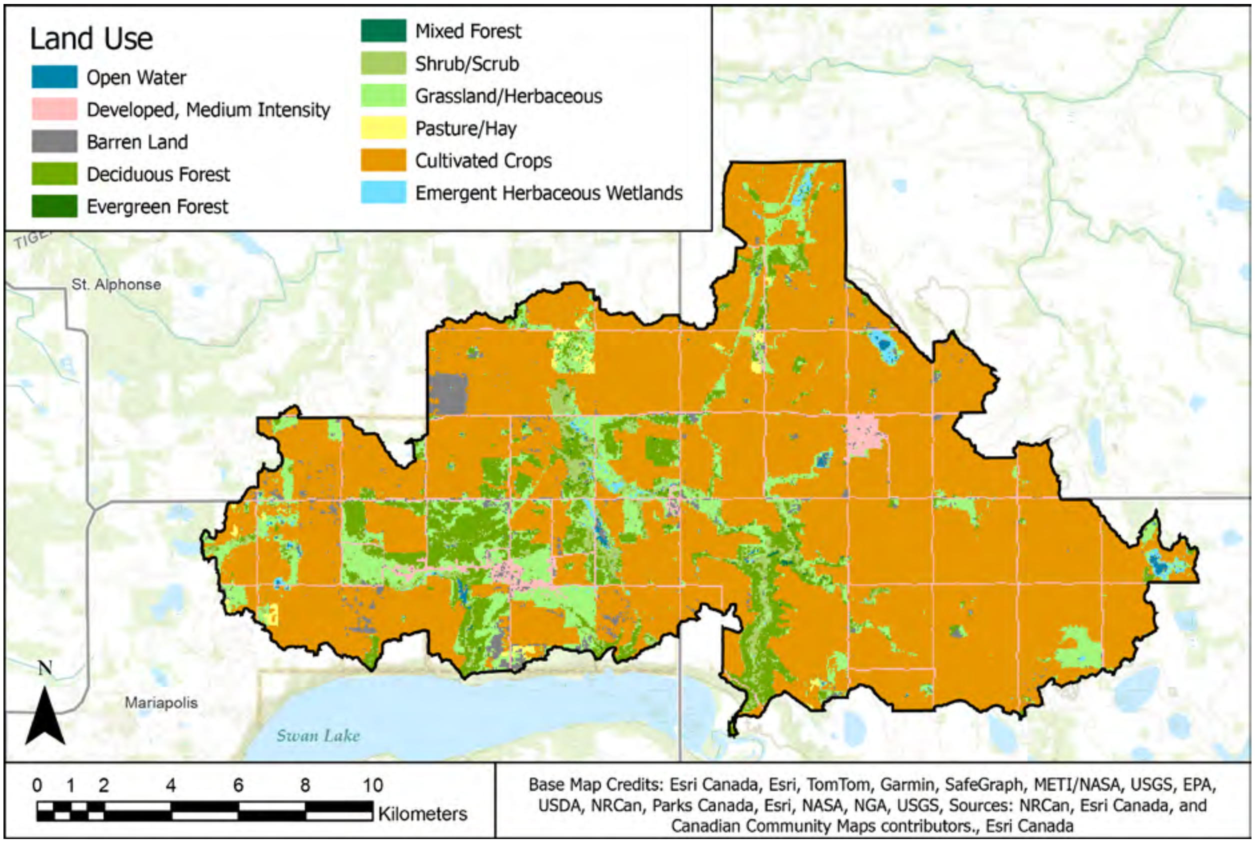
Figure 4. Swan Lake study area soil series



Source: Author map based on AAFC, 2019.

Land use across the watershed is also primarily agricultural, with 72% of its area being defined as cropland, according to the 2018 annual AAFC (2023) crop inventory data set acquired at the initiation of this project. As cropland is considered high value for agricultural production, it is less desirable for conversion to other uses (e.g., water storage projects) and BMPs that might affect productivity (e.g., reduced fertilizer or manure application rates). However, beyond other anthropogenic developments, like the Town of Swan Lake, natural land features in the watershed include forest, grassland, shrubland, and wetlands, as illustrated in Figure 5.

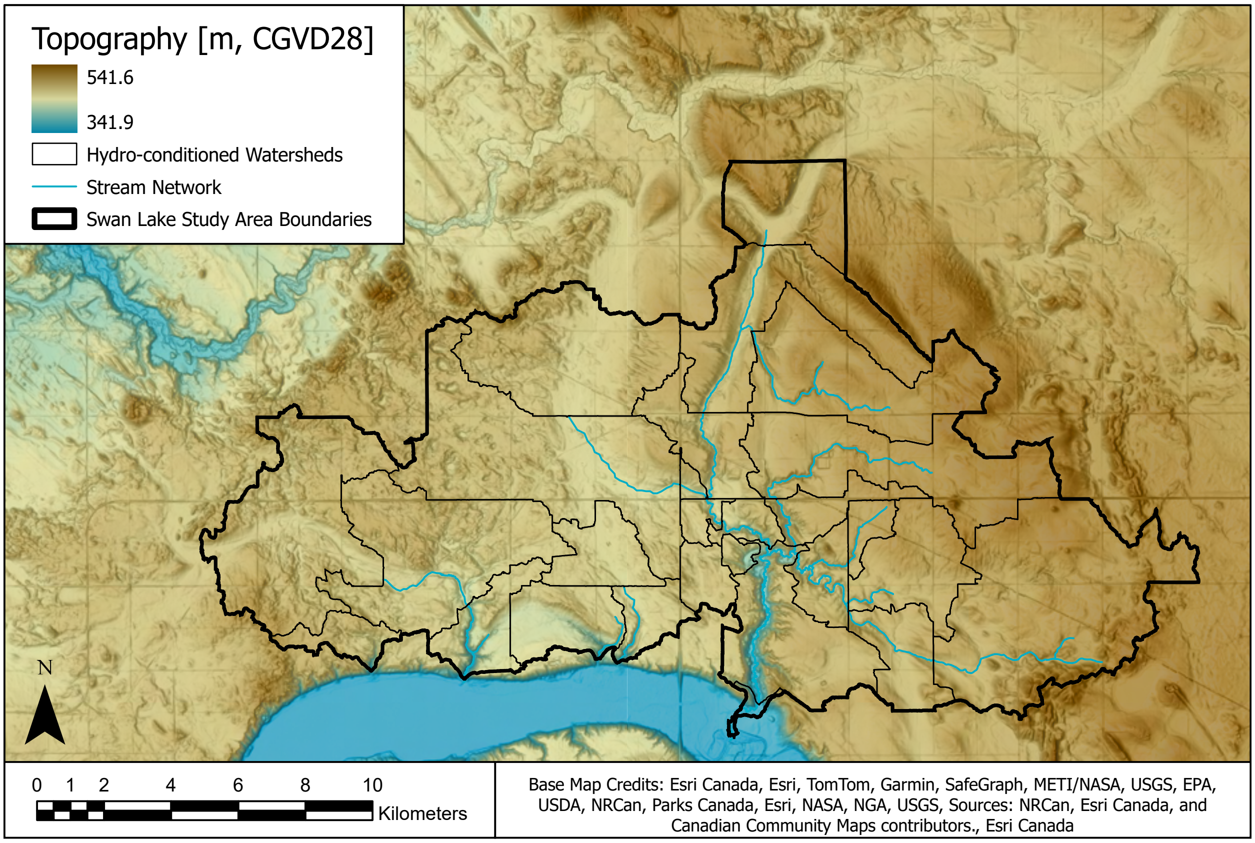
Figure 5. Swan Lake study area land use



Source: Author map based on AAFC, 2023; Multi-Resolution Land Characteristics Consortium (MRLC), 2021.

The Swan Lake study area topography can be characterized by "Prairie pothole" terrain, with rolling hills that have significant relief, as shown in Figure 6. Closed basins, or non-contributing areas, are therefore common, and catchments are often delineated by roads where there are no culverts to drain the land upstream. Steep ravines are also prominent features, formed by the creeks and intermittent streams flowing into the Pembina River Valley. These areas have historically been highly susceptible to erosion and gully formations, which can encroach into high-value cropland.

Figure 6. Swan Lake study area topography



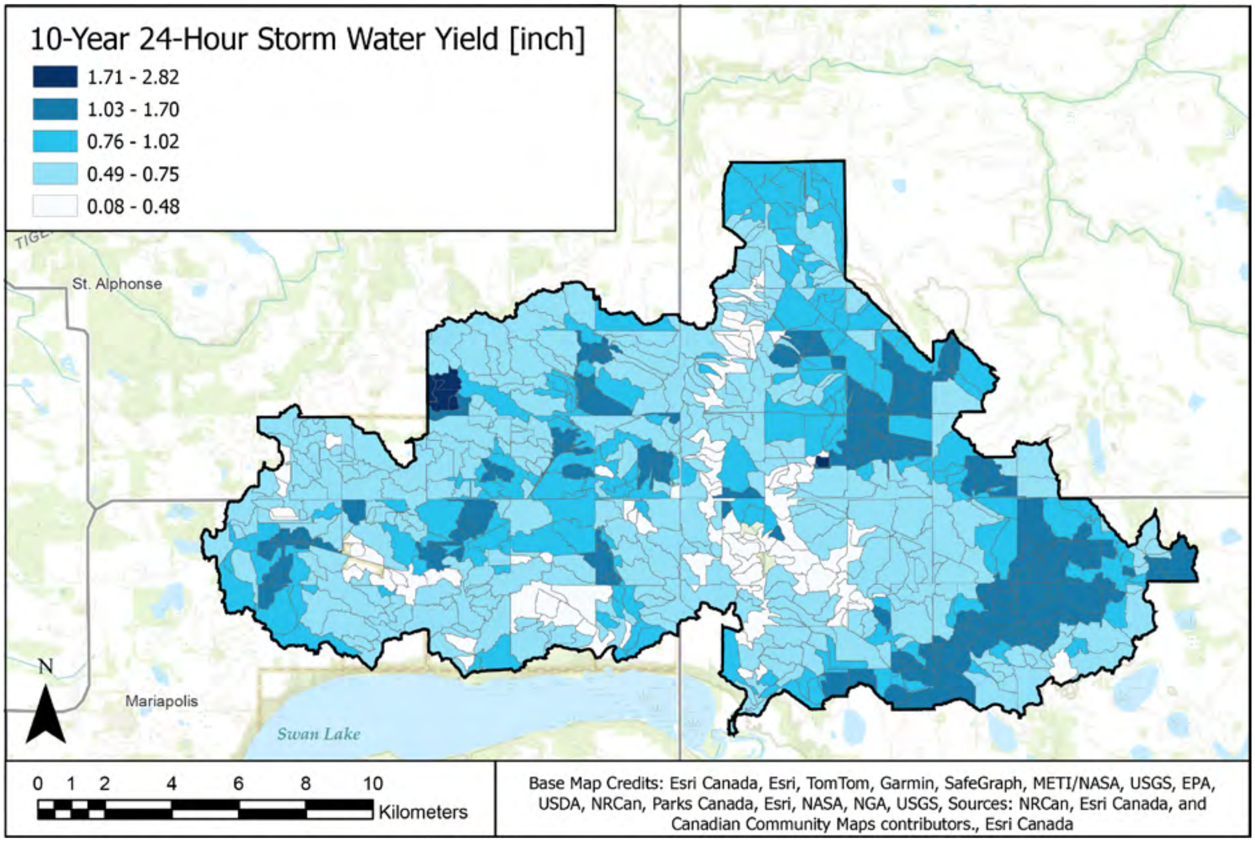
Source: Author map based on Government of Manitoba, 2022b.

Using land-use and soil data to derive inputs for the Soil Conservation Service (SCS) curve number method,[1] an uncalibrated water yield map was generated for the study area, as illustrated in Figure 7. The map was produced using a 10-year, 24-hour rainfall event (Environment and Climate Change Canada [ECCC], 2019), as it aligns with the suitability criteria for water storage BMPs explained in the following section. As can be noted, there are higher relative yields of water in the eastern headwaters of the study area than in the west, and expectedly, this has an influence on BMP performance, which will be discussed in greater detail within Section 2.

---

[1] The SCS curve number method is used to determine runoff depth generated from a rainfall event. The relationship of this function is defined using land-use and soil classifications within a watershed.

Figure 7. Water yield for a 10-year, 24-hour rainfall event



Source: Authors.

1.3 BMPs for Nutrient Loss Reduction and Current Implementation Strategies

According to AAFC (2006), "a 'Beneficial Management Practice (BMP)' is defined as any agricultural management practice which:

- mitigates or minimizes negative impacts and risk to the environment, by maintaining or improving soil, water and air quality, and biodiversity;
- ensures the long-term health and sustainability of land-related resources used for agricultural production; and
- does not negatively impact the long-term economic viability of producers and others in the agricultural industry."

The BMPs within this review were selected based on three additional factors:

1. They have strong scientific evidence to show that they reduce nutrient losses from agricultural lands in the Canadian Prairies (Mulla & Whetter, 2020).
2. They are supported within the identified spatial targeting model, the PTMApp (Houston Engineering, Inc., 2018).
3. They are presently supported and implemented through Watershed District programming in Manitoba (Pembina Valley Watershed District, n.d.).

Practices that increase water storage or reduce runoff from agricultural lands are considered best to reduce nutrient losses to downstream water bodies (Mulla & Whetter, 2020). Several BMPs related to water storage are supported within the PTMApp model and follow Conservation Practice Standard documentation of the Natural Resources Conservation Service (United States Department of Agriculture Natural Resources Conservation Service [USDA NRCS], n.d.), where available. The suitability criteria for these water storage BMPs are summarized in Table 1 and consider the following BMPs:

- **Water and sediment control basins (WASCoBs)** – a constructed earthen embankment or a combination of ridges and channels used across the slope of a minor drainage way (USDA NRCS, 2017).
- **Drainage water management (DWM) or controlled drainage** – the management of drainage volume and water table elevation by regulating the flow from a surface or subsurface agricultural drainage system (USDA NRCS, 2020).
- **Farm pond/wetland** – a created, restored, or modified pond, wetland, or impoundment made by constructing an embankment, excavating a dugout, or a combination of both.
- **Large wetland restoration** – a wetland ecosystem with hydrophytic vegetation for biological treatment of water (USDA NRCS, 2010). In the PTMApp, large wetland restoration has a larger drainage area and footprint than farm ponds or wetlands.
- **Regional wetland/pond** – similar to large wetland restoration but is typically shallow (more than 75% is less than 0.9 m deep), allowing it to perform better for nutrient reduction.

Table 1. PTMApp water storage BMP suitability criteria

BMP	PTMApp suitability criteria
WASCoBs	• Sediment delivered to flowline percentile rank greater than 0.75 • Drainage area less than 40 acres • Land use must be cultivated crops • Stream Power Index percentile rank greater than 0.80 • Upstream storage must be greater than 0.1 acre-ft

BMP	PTMApp suitability criteria
DWM or controlled drainage	• Land use must be cultivated crops • Slope less than or equal to 1% • Soil must be hydric • Depth to groundwater must be greater than or equal to 3 ft
Farm pond/ wetland	• Depressions determined from the difference between filled and raw DEMs • User-assigned value for minimum depressional depth; PTMApp default equals 0.5 ft • User-assigned value for minimum depression surface area; PTMApp default equals 1 acre • Must not be an existing functional or healthy wetland • Drainage area to the depression is less than 500 acres • Depression volume greater than 10-year, 24-hour design storm volume delivered • Depression's surface area must be larger than or equal to 1% of the drainage area
Large wetland restoration	• Depressions determined from the difference between filled and raw DEMs • User-assigned value for minimum depressional depth; PTMApp default equals 0.5 ft • User-assigned value for minimum depression surface area; PTMApp default equals 1 acre • Must not be an existing functional or healthy wetland • Drainage area to depression greater than or equal to 500 acres • Depression volume greater than 10-year, 24-hour design storm volume delivered • Depression's surface area must be larger than or equal to 1% of the drainage area
Regional wetland/pond	• Depressions determined from the difference between filled and raw DEMs • User-assigned value for minimum depressional depth; PTMApp default equals 0.5 ft • User-assigned value for minimum depression surface area; PTMApp default equals 1 acre • Must not be an existing functional or healthy wetland • Drainage area to the depression must be larger than 494 acres • Depression depth for no more than 25% of the depression area can be greater than 0.75 ft • Depression's surface area must be between 0.5%–2% of the drainage area

Source: based on Houston Engineering, Inc., 2018.

Watershed Districts, such as the Pembina Valley Watershed District and its Shallow Wetland Incentive Program, currently support the construction and protection of water storage BMPs, such as wetlands and ponds through financial and technical assistance. However, current BMP implementation programs like Watershed Districts in Manitoba are largely untargeted spatially. For the most part, funds and projects are not directed strategically to specific geographic areas to more efficiently achieve specific environmental targets, such as nutrient loss reduction from agricultural land. Programming and projects have broad targeting at best, are landowner driven, and are often first come, first served (Watershed District managers Justin Reid, Neil Zalluski, and Cliff Greenfield, personal communication, 2023).

Targeting BMPs where they are likely to be most cost-effective is a strategy that is widely supported but largely untested in the Canadian Prairies. This approach includes targeting based on land use and current management, environmental risk, and hydrological processes, such as erosion risk, potential for nutrient and sediment loss, runoff generation, stream power, catchment size, and location relative to the target water body. It is for this reason that spatial targeting using the PTMApp is currently being tested so extensively in the Swan Lake study area. An approach that satisfies the physical and climatic characteristics of the Canadian Prairies is shared in the following section.

2.0 PTMApp BMP Spatial Targeting

This section provides a review and general guidance on how to spatially target water storage BMPs like farm ponds and wetlands in the context of the Canadian Prairies using hydrologic models and geospatial analysis software. First, a review of the models and software selected to perform spatial targeting and how each has been used together are outlined in a model development strategy (Section 2.1). Next, considerations for the interpretation of model outputs are shared to help bridge the understanding of model developers and users (Section 2.2). A review of key changes to default modelling methodologies and their impacts on outputs are then shared (Section 2.3). Finally, a brief overview is provided for potential input data alternatives, and insights are shared to help identify future model development strategies that could improve functionality and accuracy (Section 2.4). For those data sets utilized in the development of the presented models, summary tables have been compiled within the Appendix of this document.

2.1 Model Development Strategy

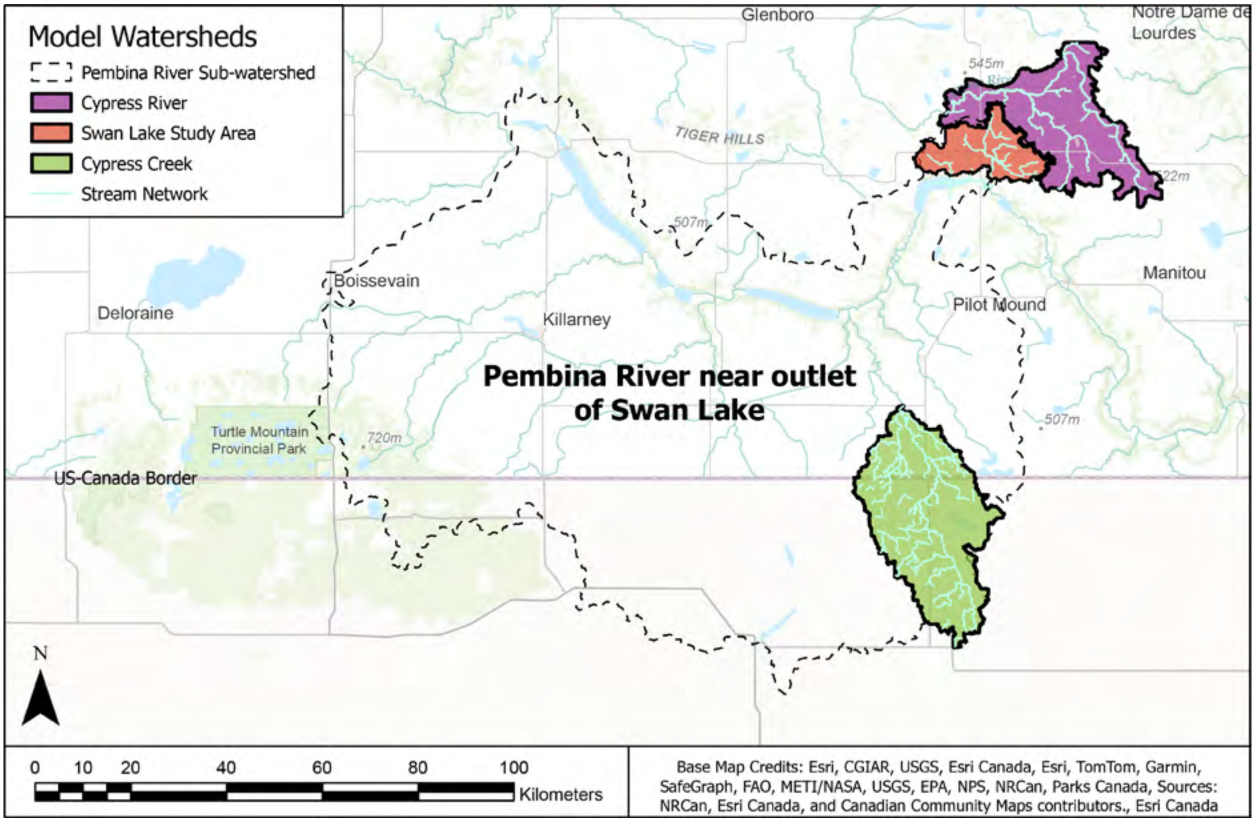
The PTMApp is a free-to-use hydrologic modelling platform that can determine the export and transport of non-point source nutrient and sediment loads, identify the locations of feasible BMPs, and assess the cost-effectiveness of those BMPs to address water quality concerns. The PTMApp model achieves these goals using a variety of geospatial input data such as DEMs, land use/cover, and soils in tandem with the outputs of hydrologic simulation. In this work, BMP spatial targeting in the LLEP Swan Lake study area has been performed using the PTMApp to demonstrate potential model development strategies that are applicable across the Canadian Prairies by considering its unique physical characteristics and climate. For example, in the Canadian Prairies, nutrient loads are greatest during spring runoff (Lake Winnipeg Foundation, 2019), and non-contributing areas impact the distribution of water across the landscape under typical flow conditions (AAFC, 2013b).

The PTMApp was developed by the International Water Institute in collaboration with the Red River Watershed Management Board, the Minnesota Board of Water & Soil Resources, and Houston Engineering Inc. Although this report does not intend to provide detailed step-by-step instructions on how to develop a PTMApp model, a sufficiently trained hydrologic modeller should be able to replicate the presented modelling strategy to produce results of similar quality, adapted to their own study area, with the provided information. Simoes and Vanrobaeys (2025) provided a more in-depth review on spring runoff modelling and statistical methods employed and their performance. Clear guidelines on how to develop a PTMApp model using default methodologies and its assumptions are also freely available on the Minnesota Board of Water and Soil Resources' (2022) website within the PTMApp Learning Center, and a review of that documentation should be considered a pre-requisite to replicating this modelling strategy.

2.1.1 Surrogate Watershed Modelling

As the LLEP Swan Lake study area is just one of several catchments within the basin delineated by the "Pembina River near outlet of Swan Lake" Water Survey of Canada (WSC) gauge (05OB019), hydrometrics and water quality data availability within the study area are limited to those that have been collected as part of the LLEP. As this modelling effort demonstrates what can be achieved for an ungauged basin, it is thought that the methods shared herein will be applicable wherever LiDAR (most importantly) and other needed data are available within the Canadian Prairies.

Figure 8. Swan Lake study area, Cypress River, and Cypress Creek modelling domains



Source: Author map based on WSC, 2020.

Due to the lack of available historic hydrometric data for the study area at the initiation of watershed modelling in 2020, surrogate modelling efforts were made to develop transferable modelling parameters to provide estimates of water quantity (Hydrologic Engineering Center – Hydrologic Modeling System [HEC-HMS] and Hydrologic Engineering Center – River Analysis System [HEC-RAS]) and quality (PTMApp) within the study area. The neighbouring WSC (2020) watershed, "05MH008 - Cypress River near Bruxelles," was selected as a surrogate watershed for modelling water quantity, and "05OB010 - Cypress Creek near Clearwater" was selected for water quality due to the availability of long-term historical hydrometrics and water quality sampling, geographic proximity, and its similar physical size and composition of land uses. Figure 8 illustrates the locations and approximate delineations of the Swan Lake study area within the greater Pembina River Valley basin (WSC watershed "05OB019 - Pembina River near outlet of Swan Lake"), delineated by the outlet of Swan Lake and the Cypress River and Cypress Creek surrogate modelling domains.

The size of the Swan Lake study area (112 km^2) is much smaller than an existing PTMApp model developed for the Roseau River watershed (5,306 km^2) in Manitoba (Houston Engineering Inc. et al., 2019), which could facilitate more rapid testing of alternative input data sets in the future. Houston Engineering Inc. et al. (2016) indicate that run-times for the PTMApp are estimated to be in the order of 1 month for hydrologic unit code 8 (HUC-8) watersheds[2] (average 1,400 mi^2). However, the developed Swan Lake study area model can be initialized and run to completion with a 1 m spatial resolution in just under 1 day (23 hours and 7 minutes) using a computer with an Intel Core i9 9900, 64 GB of RAM, and a PCIe 3.0 class NVMe storage solution (this is current as of writing this report). The acceleration of computations using a GPU is not currently possible with the PTMApp, and the storage speed has been noted to improve the run-time of some read/write intensive model functions. Because the Swan Lake PTMApp model can be run so quickly, some of the alternative input data sets currently in consideration for future evaluation are discussed in Section 2.4.

The strategy employed to spatially target BMPs using the PTMApp considers multiple hydrologic events, including both spring runoff and rainfall events. While only outputs for the 2-year spring runoff event are used in this report to quantify and assess BMP effectiveness in Section 2.2, similar outputs could also be generated for any of the other events considered. This narrowed focus on model output has been adopted to reduce the complexity of this report and to focus primarily on conservative evaluations of storage BMP types, which have been identified as key to addressing multiple water concerns within the Canadian Prairies (Government of Canada, 2022a; Government of Manitoba, 2020). Furthermore, there is evidence to suggest that vegetation-based BMPs, such as riparian buffers, are ineffective during snowmelt (Lobb, 2012; Vanrobaeys et al., 2019) and should instead be modelled following standard PTMApp modelling practices (i.e., using 2-year and 10-year 24-hour rain events). Therefore, modelling vegetation-based filtration and protection practices would require a re-evaluation of their performance statistics in order to match the spring runoff volume modelling considerations made in this Canadian Prairie application of the PTMApp.

The following list summarizes how each hydrologic event was used in this modelling strategy for clarity:

- The 2-year, 24-hour rainfall event has been used to estimate non-contributing areas using HEC-RAS (Section 2.1.2.2) and is shown to be used for BMP screening (Section 2.2.5).

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[2] The United States Environmental Protection Agency (2022) suggests that the area of HUC-8-level watersheds averages about 1,400 mi^2 (2,636 km^2).

- The 10-year, 24-hour rainfall event has been used to determine the feasibility of storage BMPs, such as farm ponds/wetlands (Section 2.2.2).
- The 2-year spring runoff event has been used to conservatively evaluate BMP performance for an average year and is applicable across the remaining PTMApp model outputs.

The peak flows and volumes of the spring runoff event were determined using the surrogate HEC-HMS model developed for the Cypress River and a frequency analysis of WSC flow data, which facilitated bias corrections to the model's output. The nutrient exports were determined using the surrogate PTMApp model developed for Cypress Creek. Finally, the HEC-RAS model was used to simulate two-dimensional hydrodynamics within the Swan Lake study area to determine non-contributing areas for a typical hydrologic event (2-year, 24-hour rainfall). ArcGIS Pro was used throughout model development to create input datasets, run PTMApp models, and develop the maps shared within this report. The following sub-sections provide a short summary of how PTMApp inputs were developed in each of the neighbouring watersheds using their respective surrogate models.

2.1.2 Water Quantity

Spring Runoff Hydrology

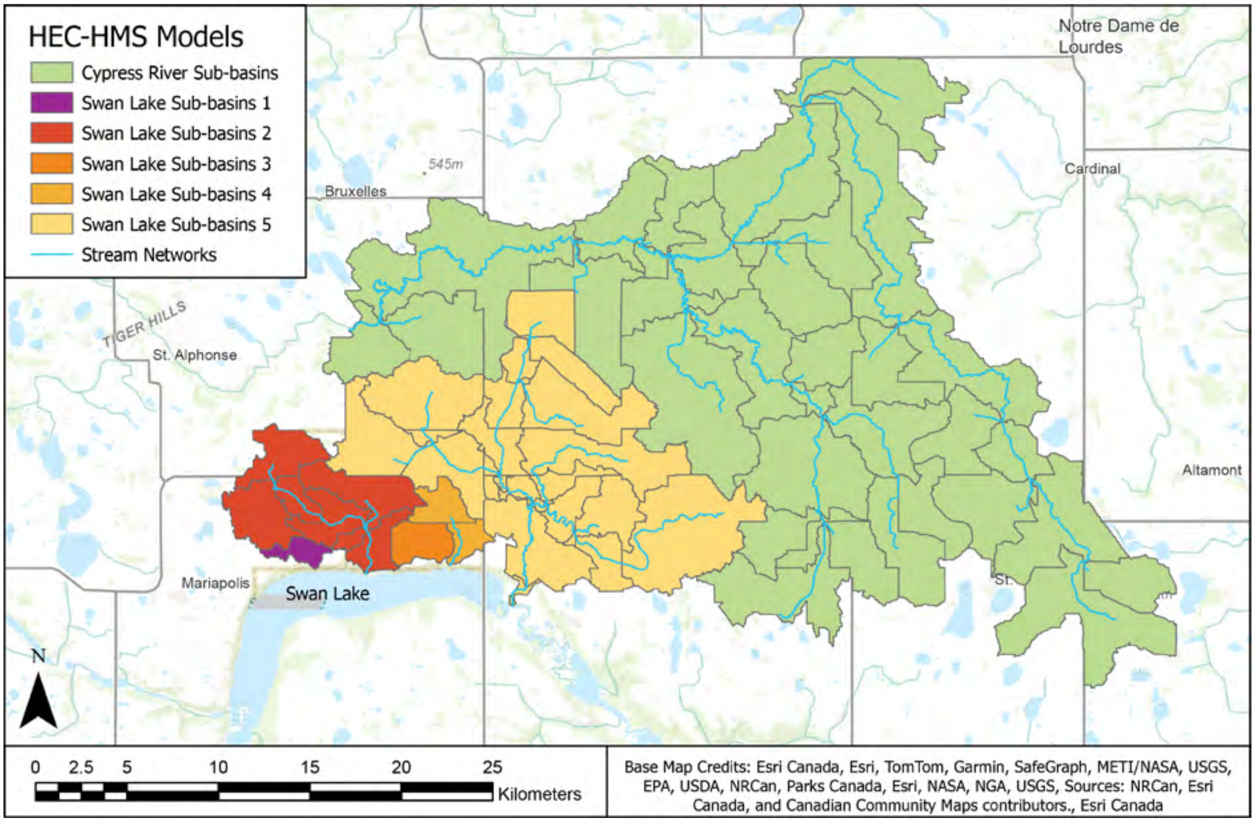
A HEC-HMS model was developed for the watershed delineated by the WSC (2020) gauge "05MH008 – Cypress River near Bruxelles," with parameters defined using a methodology transferable to the Swan Lake study area. HEC-HMS is a semi-lumped model capable of modelling the complete hydrologic cycle with various representations of watershed canopy and surface for interception and depressional water storage, infiltration losses with soil moisture accounting, unit hydrographs, and hydrologic routing (United States Army Corps of Engineers [USACE], 2022a). HEC-HMS provides the tools necessary to model components of a water balance, including direct runoff, infiltration, groundwater flows, and evapotranspiration, given climatic inputs such as precipitation, air temperature, and incoming solar radiation. The parameters transferred from the surrogate watershed included those used in canopy and surface storage, loss, transform, and baseflow methods. The HEC-HMS model was selected over other options in this application due to its high familiarity with most hydrologic modellers, but other more suitable models for simulating cold-region processes could similarly be used.

The objective of the developed HEC-HMS model was to determine the total volume and peak discharge of spring runoff events in the study area for 2- and 10-year return periods, in lieu of gauged data. The purpose of determining these quantities for the PTMApp model was to improve the accuracy of nutrient reduction calculations made for modelled storage BMPs during these spring runoff events, as their efficiency is a function of incoming flow volume and individual BMP storage volume (this mechanism is explored further in Section 2.1.3.2). The efficiency loss derived from this change to PTMApp input data is significant, as, for example, the 2-year spring runoff event in the study area is estimated to be approximately 78% larger in terms of total volume than the runoff generated from the uncalibrated 10-year 24-hour rainfall event using the SCS curve number method. This methodology employed the use of HEC-HMS 4.8 to generate model components and define their connectivity, as well as delineate the sub-basins for which initial parameter estimates of topographic features are made. Initial parameter estimates were also determined using ArcGIS Pro based on land use and soil type data for these sub-basins.

The HEC-HMS model was calibrated using the OSTRICH – Optimization Software Toolkit (Matott, 2017) by indirectly changing model parameters described previously using the Asynchronous Parallel Dynamically Dimensioned Search algorithm. Initial model parameter estimates were scaled using a set of global variables instead of those parameters being directly accessed as decision variables by the calibration software. The use of a set of global calibration parameters to scale initial parameter estimates reduced the number of unique variables exposed to the calibration algorithm, greatly reduced calibration complexity/run-time, and provided greater compatibility using the similarly developed Swan Lake study area model. As such, although just 30 decision variables were accessed by the calibration algorithm in this process, 420 unique parameters were ultimately adjusted within the Cypress River model. Likewise, when these 30 global parameters were transferred to the Swan Lake study area HEC-HMS model, 496 unique model parameters were ultimately informed by the Cypress River calibration. A graphical representation of the Cypress River and Swan Lake study area HEC-HMS models is illustrated in Figure 9, where each larger coloured polygon represents a HEC-HMS basin with a defined outlet, internal polygons represent sub-basins, and blue lines represent the defined stream network.

As the volumes and peak discharges for spring runoff events provided by the Cypress River HEC-HMS model, compared to WSC data, were not perfect, bias correction factors were developed to improve the accuracy of this surrogate modelling effort for the Swan Lake study area. A frequency analysis was performed using historical data for the Cypress River to determine the characteristics of the estimated 2- and 10-year spring runoff events. A synthetic hydrograph from the HEC-HMS model was then compared with the historical records to develop model correction factors. Next, historical events with characteristics closest to those derived from the frequency analysis were evaluated to develop event-based scaling factors. For example, it was determined that the combined model correction and event-based scaling factors should be used to scale the modelled 2007 spring runoff event volume down to generate a representation of the theoretical 2-year spring runoff. The same family of factors (determined for each event, volume, and peak discharge individually) were then applied to the Swan Lake study area model outputs in lieu of measured historical data to enable bias correction via the performed frequency analysis.

Figure 9. Swan Lake study area and Cypress River HEC-HMS models



Source: Author map.

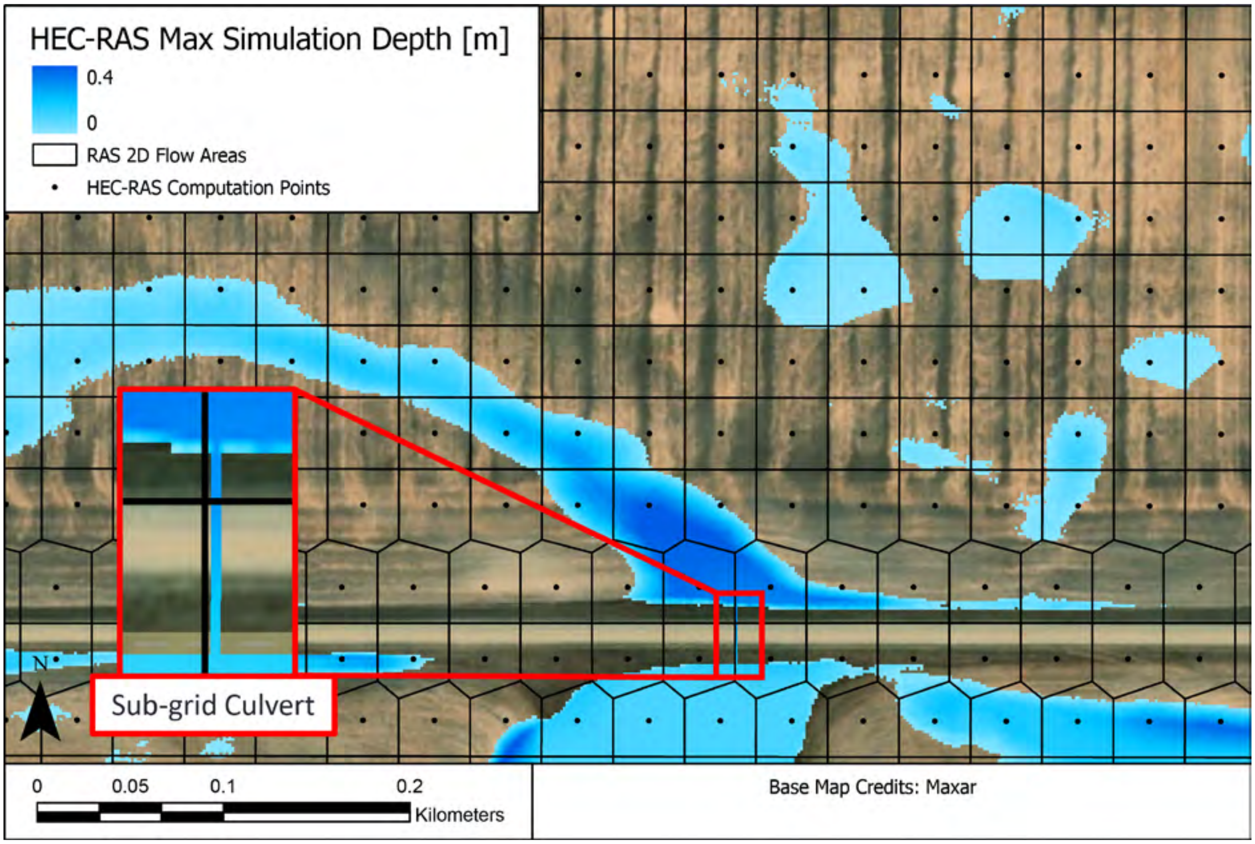
Inflows for the PTMApp model are defined using rainfall depth rasters and the SCS curve number method to determine runoff. Therefore, to represent the 2-year spring runoff, the 2-year, 24-hour rainfall input in the PTMApp was replaced such that the flow volumes produced at the five outlets of the Swan Lake study area in the PTMApp matched those from the bias-corrected HEC-HMS model results. The resulting increases in incoming flow volume to BMPs in the PTMApp model therefore decrease their effectiveness when storage volume to treat nutrient loads is exceeded. These decreases vary spatially with the precipitation–runoff relationships defined by the SCS curve number method used across the sub-basins. Although this representation does not model peak discharge or flow velocity accurately within PTMApp, these two hydrologic characteristics are not considered in the formulation for storage BMP performance in the PTMApp model by default.

Non-Contributing Areas

A two-dimensional HEC-RAS model was developed for the entire Swan Lake study area. HEC-RAS is a model that can perform steady or unsteady flow simulation across rivers and flood plains to estimate hydraulic characteristics, such as flood stage and flow velocities, or perform water quality assessments, including changes in both contaminant loads and temperatures (USACE, 2022b). The HEC-RAS software features an integrated GIS interface (RAS Mapper), which is also useful for viewing and exporting simulation results to more advanced geoprocessing analysis software, such as ArcGIS Pro. The purpose of HEC-RAS analysis was to determine which areas of the watershed contribute no or limited flow volume to the outlets of the study area on average years, which can be used to inform where BMP implementation may be of lower priority.

The modelling domain for the analysis was quite large; therefore, several concessions had to be made to achieve reasonable run-times for the model, and an understanding of the resulting limitations must be well understood by those seeking to replicate this analysis. Aspects of the produced model that contributed to improved run-time included 25 m resolution flow cells, the use of the diffusion wave instead of the shallow water computation scheme, and culverts that were not modelled using pipe flow representations. Flow cell edges were snapped to the top of flow boundaries, such as road and rail networks, to prevent leaking between these boundaries, while culverts were represented using burn lines in the hydro-conditioned DEM. As HEC-RAS 2D is a high-resolution sub-grid model, surface depressions inside of flow cells and the burn lines used for culverts are still represented in the model via detailed hydraulic property tables and cross-sections for the 2D flow areas, respectively.

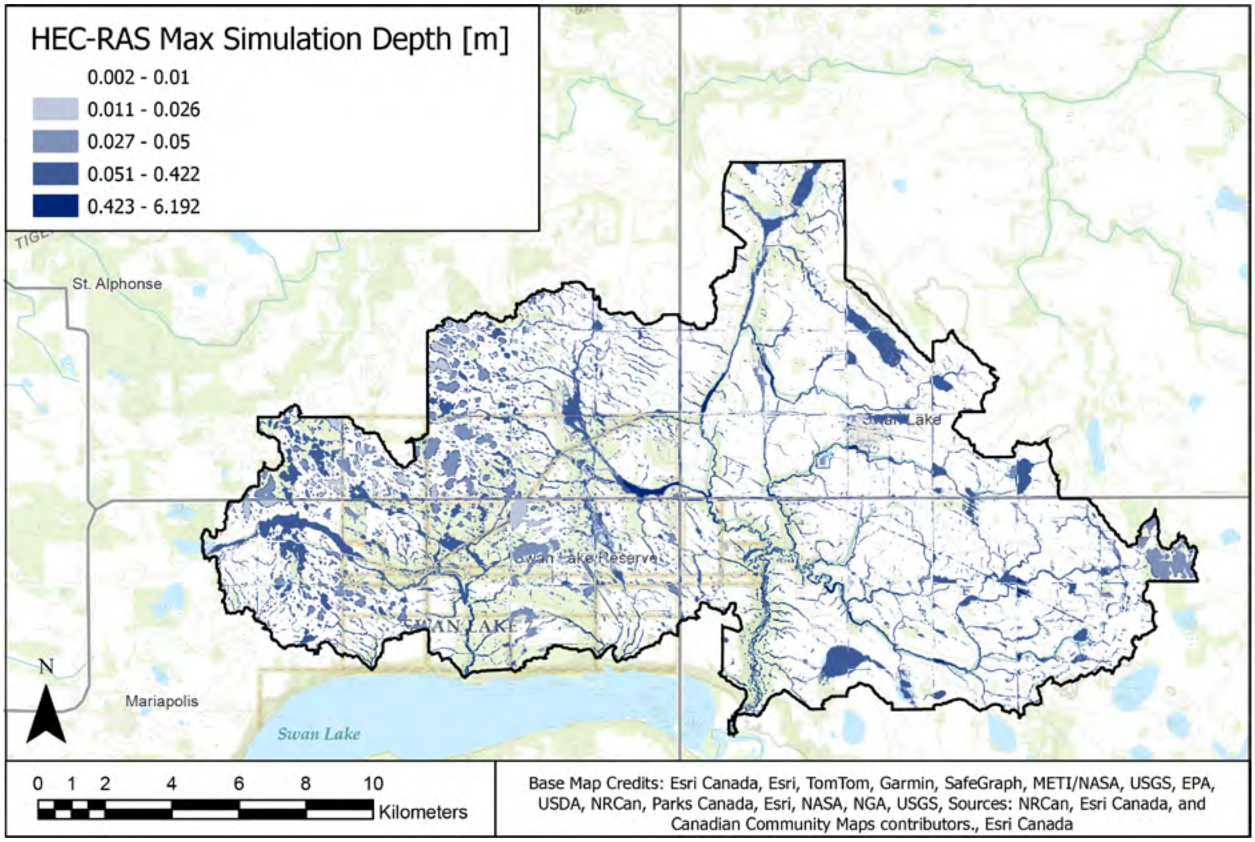
Figure 10. Typical field-scale representation of HEC-RAS model structure and output



Source: Author map.

Figure 10 illustrates the typical structure and output of the HEC-RAS model at field scale, including 2D flow cell size relative to smaller ponds, flow cells snapped to roads, and culvert flow utilizing the burn line methodology (e.g., simulation depth intersection with road). However, the result of this combination of model characteristics is such that the final HEC-RAS model would be unsuitable for more complex hydraulic calculations, such as the assessment of river stage and backwater effects upstream of culverts, but still satisfies water continuity throughout the modelling domain to facilitate non-contributing area delineation.

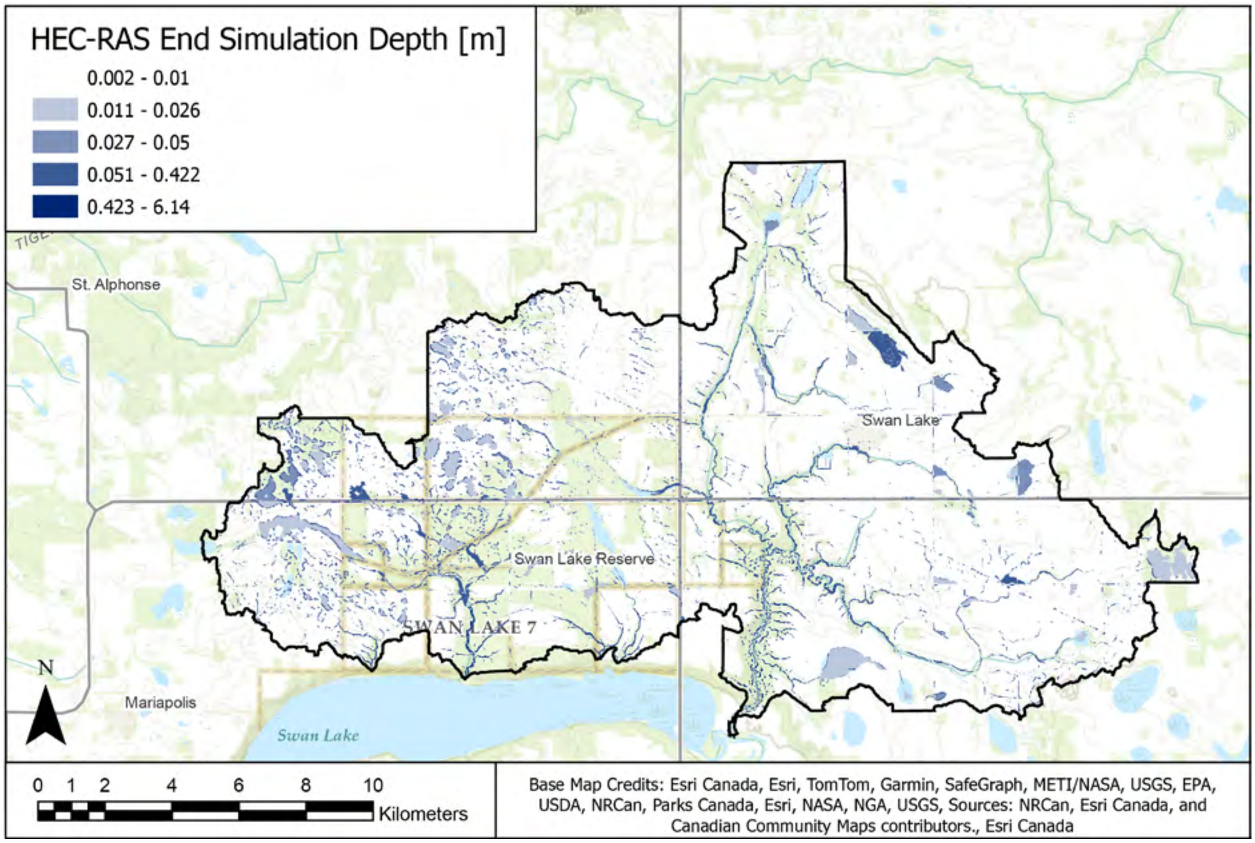
Figure 11. Swan Lake study area HEC-RAS max of simulation depth raster



Source: Author map.

A 2-year, 24-hour rainfall event was applied using the HEC-RAS model using the rain-on-grid approach and the rainfall–runoff relationship for different land uses and soils defined by the SCS curve number method. The rainfall and SCS curve number inputs for HEC-RAS are conveniently the same as existing raster datasets developed for the Swan Lake PTMApp model but are uncalibrated to measured or surrogate modelling data. A 3-month simulation period was used to allow the model excess time to fully drain surface runoff, and a dynamic time-step was implemented to optimize event run-time. Although the 3-month simulation time was found to be unnecessarily long, the use of a dynamic simulation time-step ensured that the extended simulation period did not contribute significantly to the total model run-time. Output rasters for the maximum and end-of-simulation depths, as illustrated in Figures 11 and 12, were then exported from HEC-RAS to be analyzed within ArcGIS Pro to identify the non-contributing areas. In these figures, darker blue areas on the landscape represent deeper depths of water in the simulation.

Figure 12. Swan Lake study area HEC-RAS end of simulation depth raster

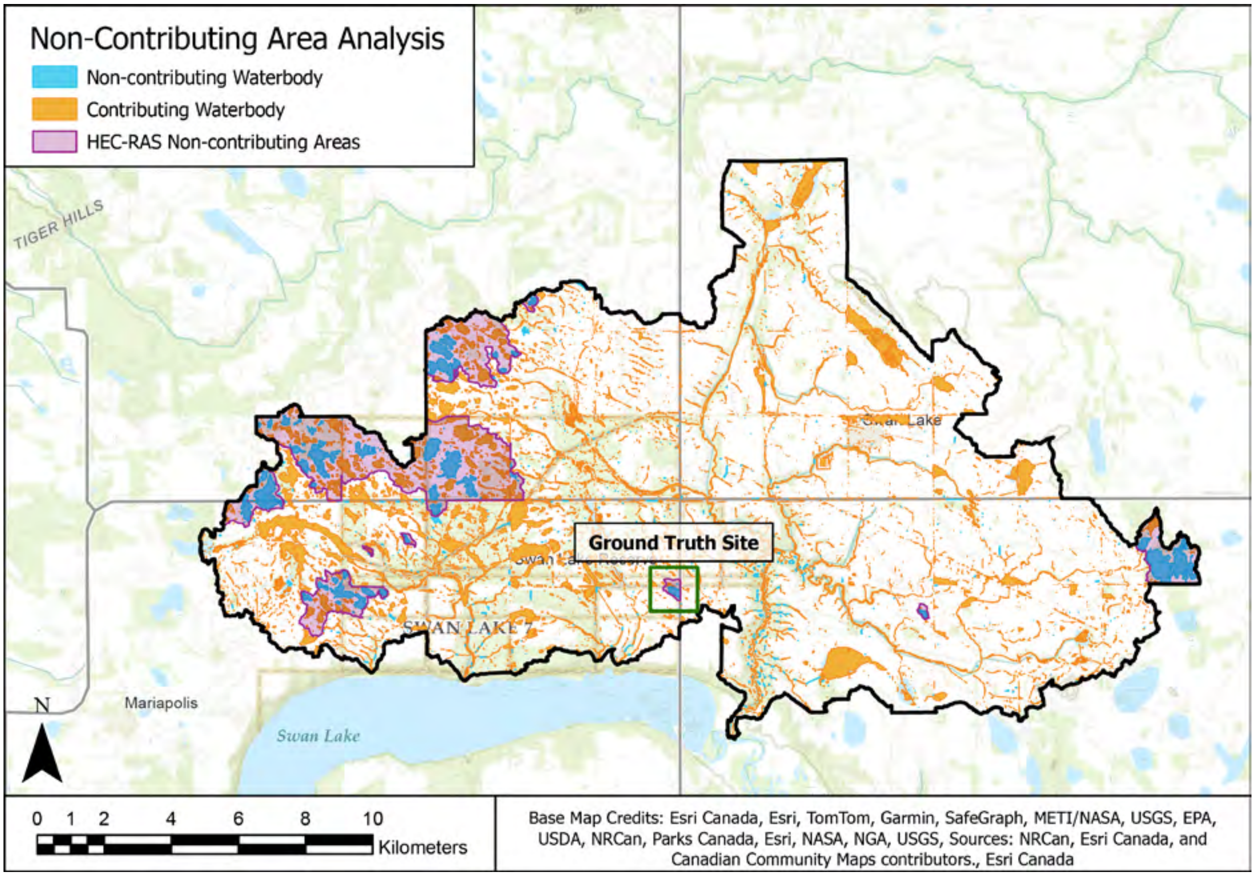


Source: Author map.

The tested method to identify non-contributing areas defined search criteria for waterbodies exported from HEC-RAS. Attributes for water body polygon depth and volume were calculated based on the max and end HEC-RAS simulation states and the percent change between them. Leveraging the knowledge of a local landowner, the calculated spatial attributes of a known non-contributing area were used to define thresholds for the acceptable percent change in depth and volume for a water body, should it be non-contributing. These thresholds were then applied to all other waterbodies to extrapolate additional non-contributing areas. The logic for defining these thresholds was that a non-contributing water body should not spill during the specified simulation and, therefore, should have similar depth and volume at its maximum and end-of-simulation states when ignoring other water losses like evaporation and infiltration of standing waterbodies over time (as was configured in HEC-RAS). It is also worth noting that accounting for evaporation and additional infiltration would only further reduce contributions from these waterbodies.

The non-contributing areas identified using this strategy are shown in Figure 13, which illustrates those waterbodies that were below the ground truth thresholds (non-contributing water body) and those that were above (contributing water body). Non-contributing areas were also only delineated upstream of non-contributing water bodies that met an additional catchment depressional storage criterion (the volume of the DEM fill must be greater than the total runoff volume of the catchment), which explains why not all waterbodies found below the depth and volume change thresholds have a final non-contributing area delineated upstream of them.

Figure 13. Swan Lake study area non-contributing areas and ground truth pond site



Source: Author map.

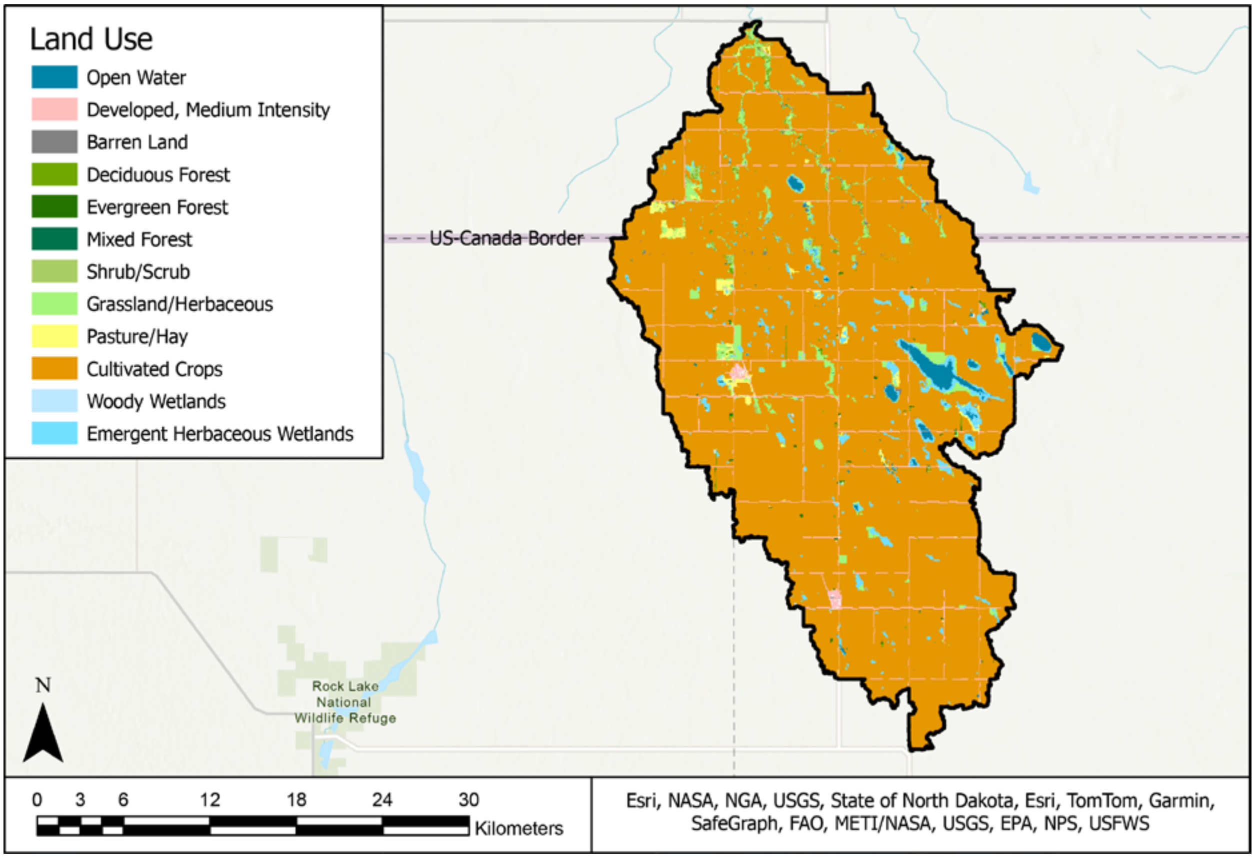
Perhaps unsurprisingly, most of the non-contributing areas found using this approach are in the western portion of the study area. This finding aligns with the water yield map that was presented in Section 1.2 (Figure 7), where the highest yields are estimated to be in the eastern portion of the study area. These delineated non-contributing areas were later used to deprioritize BMPs within or just downstream of them, as they would likely be lower contributors of load-to-downstream receiving water bodies during more typical flow conditions, like the 2-year, 24-hour rainfall event. Overall, the method tested for non-contributing area identification is imperfect but provides an additional filtering criterion for water retention BMP spatial targeting when there are potentially hundreds or even thousands of options presented by a PTMApp model.

2.1.3 Water Quality

Phosphorus Loading

By default, the PTMApp provides a table of nutrient export coefficients associated with different land uses to determine non-point source nutrient loads (Houston Engineering Inc. et al., 2016). These export coefficients define the input mass of phosphorus generated and transported throughout the model during a simulated spring runoff event. Because exports are based on land use alone, the model does not include discrete nutrient loads from point sources such as wastewater treatment plants or lagoons without manual intervention (a user could define custom land-use classifications and export coefficients for these, if desired). With the Swan Lake modelling effort being focused on an evaluation of spring runoff conditions, these default export coefficients were modified to better represent the conditions being modelled. This estimation of spring runoff loading was achieved by developing a surrogate PTMApp model for the Cypress Creek watershed and by using the Lake Winnipeg Foundation's Community-Based Monitoring Network (2019) and WSC data (2020) to perform a local calibration of the nutrient export coefficients. Figure 14 illustrates the National Land Cover Database (NLCD) land uses (MRLC, 2021) for Cypress Creek. It should be noted that there is a high degree of agricultural land in this watershed, similar to the Swan Lake study area, making it a suitable surrogate watershed for this application.

Figure 14. Cypress Creek land use



Source: Author map based on AAFC, 2023; MRLC, 2021; WSC, 2020.

A regression analysis was performed to relate the WSC instantaneous discharge and accumulated flow volume for spring runoff events to those concentrations of TP measured by the Lake Winnipeg Foundation. The regression was then applied to estimated hydrographs for 2- and 10-year spring runoff events, respectively, to determine the mass of nutrients carried to the outlet of the watershed resulting from each event. Although only the 2-year spring runoff was used for the models in this specific application, the 10-year spring runoff regression results are shared for posterity. These final outlet loads were then used to adjust the annual export coefficients and to test the sensitivity of the decay factor used to transport nutrients in the PTMApp model. It was found that for a watershed of this size, the model was not sensitive enough to the PTMApp nutrient decay factor to warrant using an alternative value from the default in this application. Although it may be the case that annual nutrient exports would not scale linearly for all land-use types, any error associated with this assumption is thought to be marginal in this scenario, considering the dominant cultivated crop land use in both watersheds. Table 2 details the export coefficients derived for each spring runoff event and have been shared as they may be applicable to other similar neighbouring watersheds. The adjustment factors presented provide the degree of scaling required to go from the annual average to the specified spring runoff off nutrient loading scenario.

Table 2. Swan Lake TP land-use export coefficients

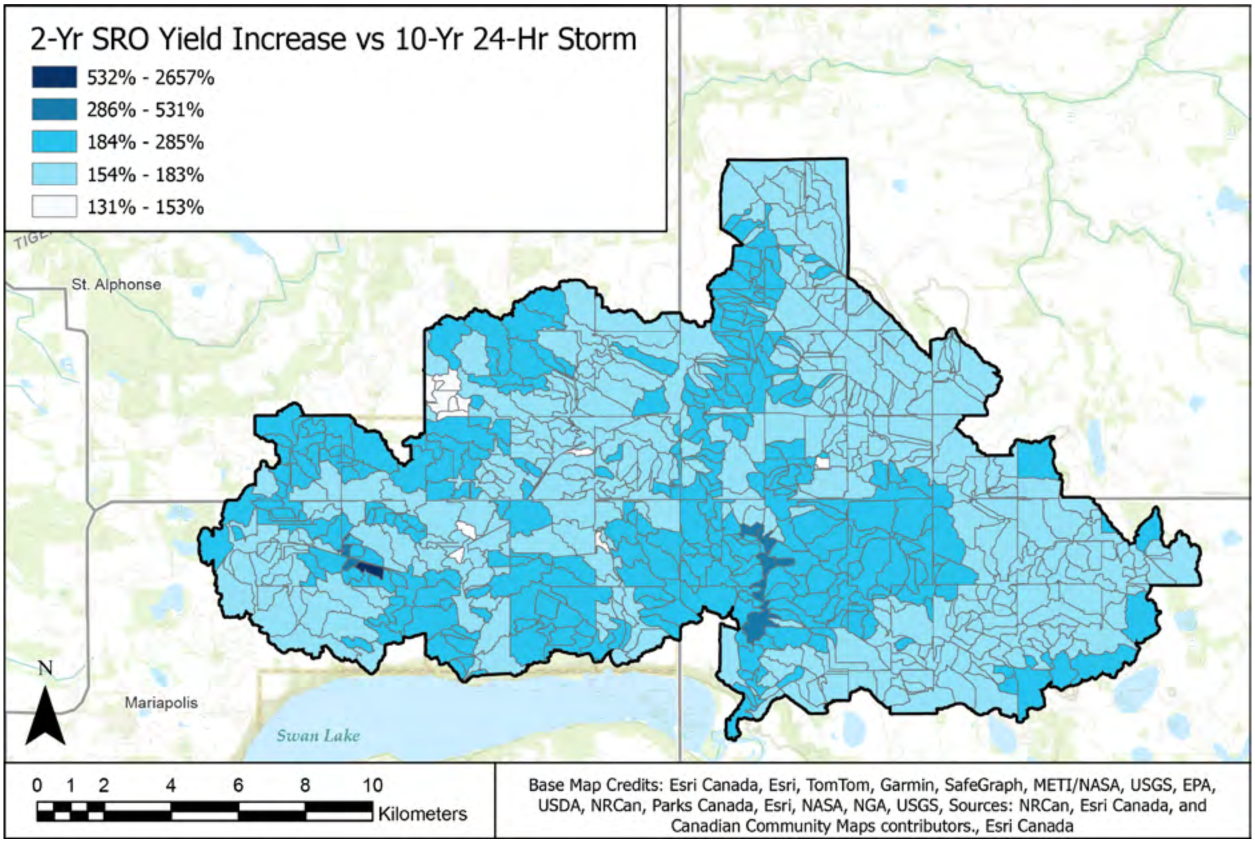
NLCD	**Default** (kg/ha/yr)	**2-yr SRO** (kg/ha/SRO)	**10-yr SRO** (kg/ha/SRO)
Open water	0.000	0.000	0.000
Developed, open space	1.000	0.387	1.784
Developed, low intensity	0.910	0.353	1.623
Developed, medium intensity	1.150	0.446	2.051
Developed, high intensity	1.500	0.581	2.676
Barren land	1.000	0.523	2.408
Deciduous forest	0.075	0.029	0.134
Evergreen forest	0.075	0.029	0.134
Mixed forest	0.075	0.029	0.134
Shrub/scrub	0.075	0.029	0.134
Grassland/herbaceous	0.170	0.066	0.303
Pasture/hay	0.170	0.066	0.303
Cultivated crops	0.380	0.147	0.678
Woody wetlands	0.000	0.000	0.000
Emergent herbaceous wetlands	0.000	0.000	0.000
Adjustment factor	**1.000**	**0.387**	**1.784**

Source: Author table based on Houston Engineering Inc. et al., 2016.
Note: SRO = spring runoff

Storage BMP Efficiency

In Section 2.1.2, it was noted that the 2-year spring runoff event is estimated to be approximately 78% larger in terms of total volume than the 10-year, 24-hour rainfall event, as represented at the outlets of the Swan Lake study area. The relative difference presented as a ratio for the water yield between these events is illustrated in Figure 15. The relative increase in yield for some catchments can be quite high, particularly in those where infiltration rates and vegetative canopy storage values are high; in these cases, the initial abstraction more greatly influences the rainfall–runoff relationship for the 10-year, 24-hour rainfall event. This increase in total water volume transported through the watershed has been modelled so that BMP efficiencies may be reduced under the assessed spring runoff scenario to provide more conservative estimates of nutrient reduction. However, the degree by which any BMP in the PTMApp may exhibit nutrient reduction efficiency loss is a function of several factors, which can vary across the model, as shown in Equation 1 (Houston Engineering Inc. et al., 2016).

Figure 15. Relative increase in water yield from the 10-year 24-hour storm to the 2-year spring runoff event



Source: Author map.

Equation 1. $R = ar^k$

Where:

R = final nutrient reduction (%)
a = remove coefficient (dimensionless)
r = reduction ratio (dimensionless)
k = decay factor (dimensionless)

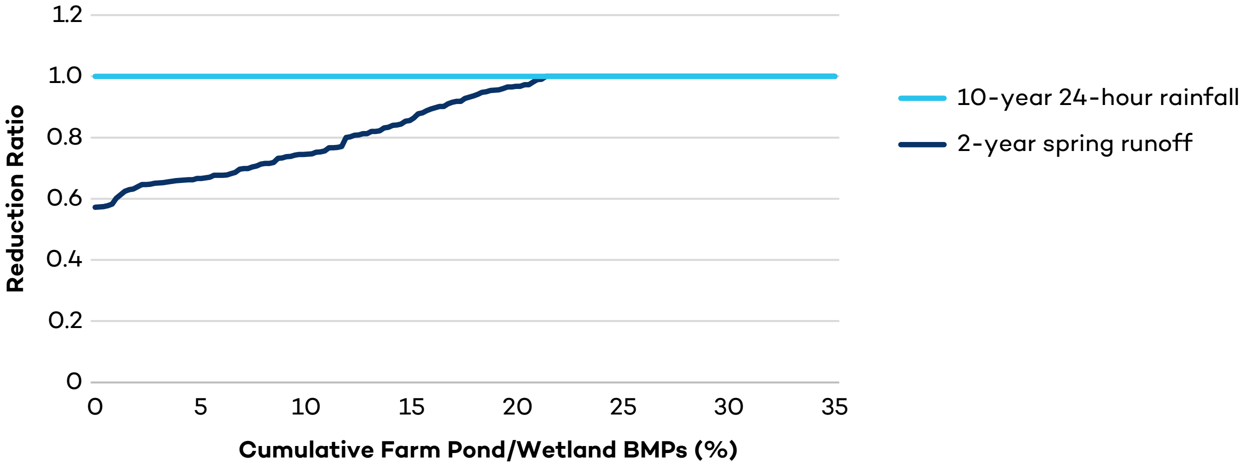
The primary factor influenced by the change in water yield from the spring runoff event is the reduction ratio "r," which for storage BMPs is the ratio of its own storage volume to the incoming flow volume ("r" set to 1.0, if found to be greater than 1.0). Other factors in the final nutrient reduction "R" include the decay factor "k" (calibrated using meta-analysis data and pre-defined in the PTMApp) and the removal coefficient "a," which is defined using a user-selected statistic from a five-number summary for the individual BMP type.

In the case of farm pond/wetland BMPs within the PTMApp, the median phosphorus removal coefficient "a" is 0.72, and the decay coefficient "k" for phosphorus treatment is 0.014. However, with such an exceedingly low decay coefficient, even a farm pond/wetland with a reduction ratio "r" of, for example, 0.1 (10× more incoming flow than pond/wetland depression volume) results in a similar final median phosphorus removal rate "R" of 70% (only a slightly less than the base 72% median removal coefficient "a"). In this example, the selected decay factor for the farm pond/wetland BMP type is undoubtedly inaccurate, as one would not expect 70% overall treatment efficiency when 90% of water passing through the system would immediately spill from the farm pond/wetland.

Although the above example for farm pond/wetland efficiency scaling accuracy is dubious for larger flow events, there are two conditions of the default PTMApp methodology that exempt it from posing any significant issues. The first is the feasibility criterion for farm pond/wetland BMPs, which requires depression volume to be greater than what a 10-year, 24-hour storm may provide. The second is that, by default, the maximum flow event assessed by the PTMApp model is that same 10-year, 24-hour storm event. As a result of these conditions, the reduction ratio "r" for all farm pond/wetland BMPs assessed by the PTMApp should be 1.0 and thus is not ultimately influenced by the decay coefficient "k" anyway. WASCoBs similarly have a relatively low decay coefficient "k" and are specified to have some minimum storage capacity to be deemed feasible. However, the defined minimum storage capacity for WASCoBs is not related to existing depression size or a specified rain event like it is farm ponds/wetlands and therefore is not impacted in the same way.

Figure 16 illustrates the cumulative percentage of farm pond/wetland BMPs in the Swan Lake study area with reduction ratios "r" at and below 1.0 for the 2-year spring runoff. As can be seen, 21.1% of farm pond/wetland BMPs (106 out of 503) have reduction ratios "r" lower than 1.0 for the 2-year spring runoff event, with the lowest reduction ratio "r" being 0.57. To address the issue of only marginal efficiency loss to farm pond/wetland BMPs under the spring runoff scenario assessed by the PTMApp, a conservative estimate for BMP efficiency loss has been used in the case that the reduction ratio "r" is less than 1.0. That is, the final nutrient reduction "R" has been determined by multiplying the reduction ratio "r" by the removal coefficient "a" without the use of the decay coefficient at all (i.e., setting the decay coefficient to 1.0). This conservatively assumes rapid snowmelt and that all water that exceeds the capacity of the storage BMP is both spilled and left untreated. A comparison between farm pond/wetland BMP performance using this methodology and the default methodology applied to spring runoff inputs has been evaluated in Section 2.3.2.

Figure 16. Farm pond/wetland BMP reduction ratio distribution over selected hydrologic model events



Source: Author chart.

2.2 Interpretation of Model Outputs

One of the suspected primary motivations for developing a PTMApp model is the identification and assessment of BMPs. There are four primary outputs that the PTMApp can generate to satisfy this motivation, but there are differences in the required effort to develop each. These outputs include maps of

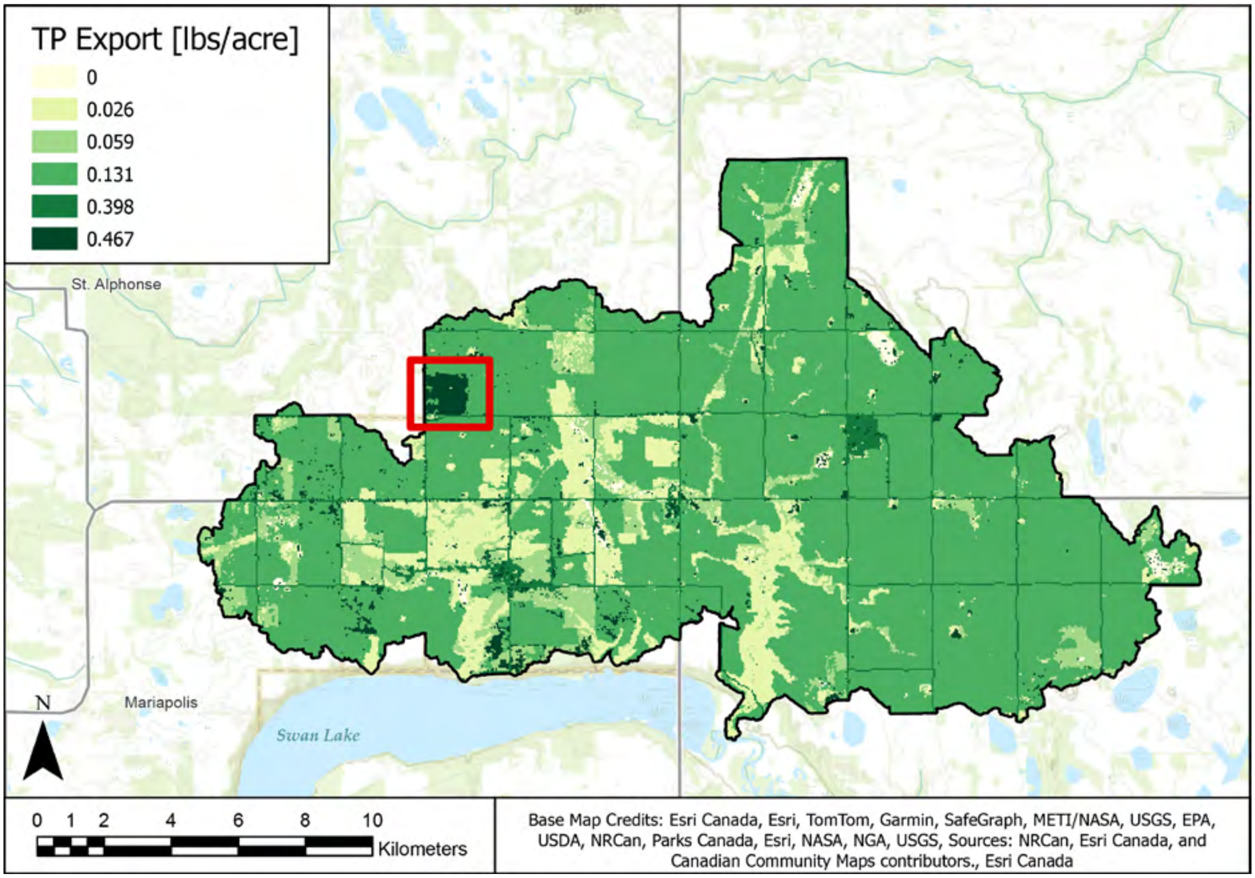
- nutrient export and load transport,
- BMP feasibility,
- BMP efficiency and load reductions, and
- BMP cost-effectiveness.

Provided the transferable parameters and considerations from the model development strategy detailed in Section 2.1, it is possible for the PTMApp to derive a package of standard model outputs that better account for the unique Prairie context. The simplest of these are the BMP feasibility maps, which can be created for individual BMP types from within six different treatment groups, including storage, infiltration, filtration, biofiltration, protection, and source reduction. To reduce the number of figures in this report and align with the BMP priorities for water-related objectives on the Canadian Prairies, only storage BMPs have been provided and only for farm ponds/wetlands for BMP efficiency (an exception has been made for DWM to better illustrate differences across the region due to water yield), load reductions, and cost-effectiveness. However, similar maps could be generated for any BMP type available within the PTMApp. The following subsections provide a brief overview of each of these PTMApp outputs and how they may be interpreted generally by end users.

2.2.1 Phosphorus Export and Transport

Rural non-point source nutrient hotspots generally arise from cropland and developed urban land, but the measurements used to derive these exports may be subject to greater degrees of uncertainty versus naturalized land cover. For cropland, this uncertainty may be the result of varying land management, such as fertilization and tillage practices, while for developed urban sources, the degree of transportation, industrial/municipal uses, and fertilized landscaping can be significant influences (Bar Engineering Company, 2004). The nutrient export coefficients used within the PTMApp generalize this variability, but a watershed modeller can re-evaluate these coefficients for Canadian Prairie conditions, as was considered somewhat simply in Section 2.1.3.1. A more detailed approach would be to reassess the distribution of these coefficients, in addition to scaling the original values to a specific watershed and hydrologic event. However, an extended analysis of this rigour was not completed for the Cypress Creek watershed, where the scaled coefficients were developed and transferred to the Swan Lake study area.

Figure 17. Map of total phosphorus export in the Swan Lake study area with incorrect cropland

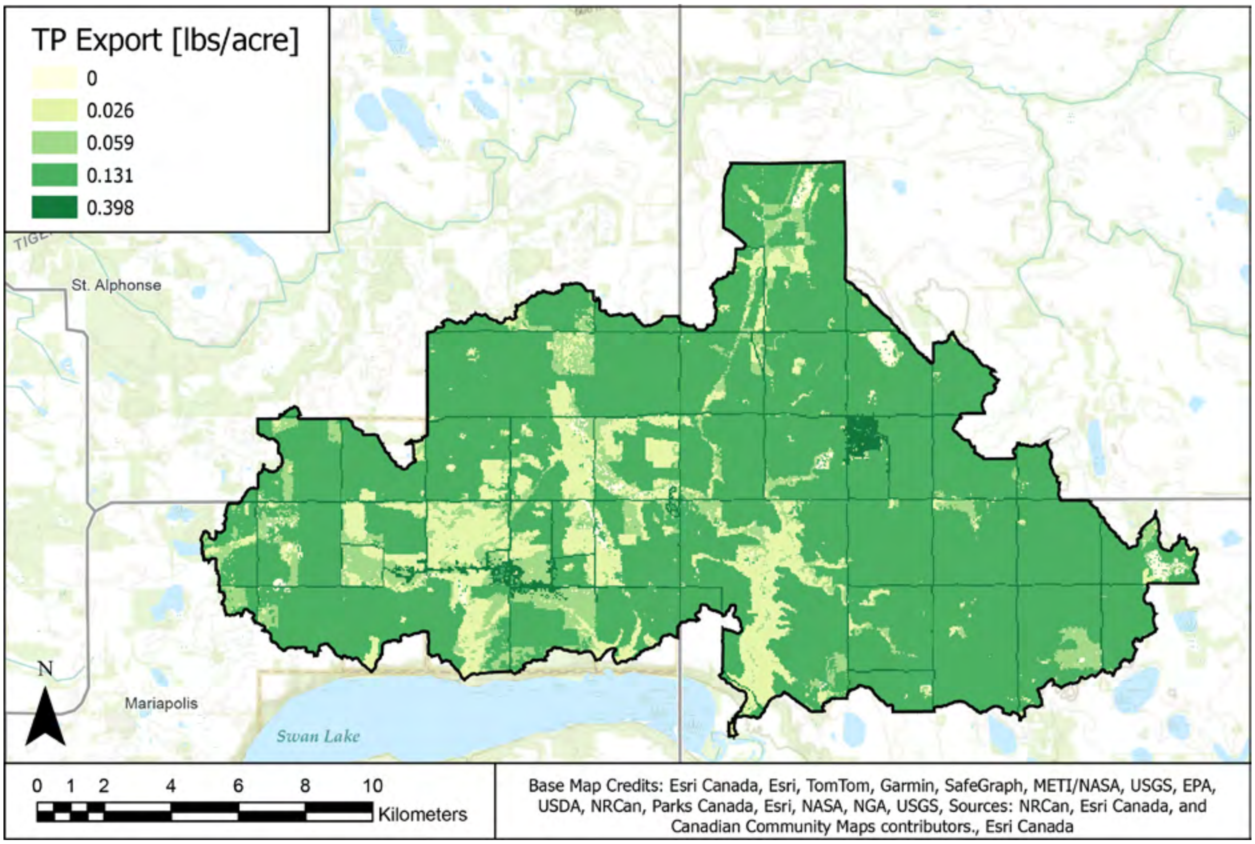


Source: Author map.

Note: The red square indicates the erroneous cropland assignments in the Swan Lake study area.

Nutrient export and transport can be illustrated for a watershed modelled with the PTMApp using two different styles of map. A nutrient export map can be useful for identifying where specific land-use change may be possible to reduce nutrient export or to help identify locations where areas of excess nutrient export may be erroneous in the model. For example, in the northwest of the Swan Lake study area shown in Figure 17, an entire quarter section of high nutrient export (darker green area highlighted with a red box) was identified due to the erroneous classification as barren land from the 2018 annual AAFC (2023) Crop Inventory dataset. This region should instead be properly classified as cropland and not result in such an extreme phosphorus hotspot. For instances of errors within an input data set such as this, a modeller should either be made aware of the error and any impacted downstream BMP assessments or simply correct for it. Figure 18 illustrates the same model output but with an erroneously identified barren land set to use cropland nutrient export values instead.

Figure 18. Map of TP export in the Swan Lake study area with corrected cropland

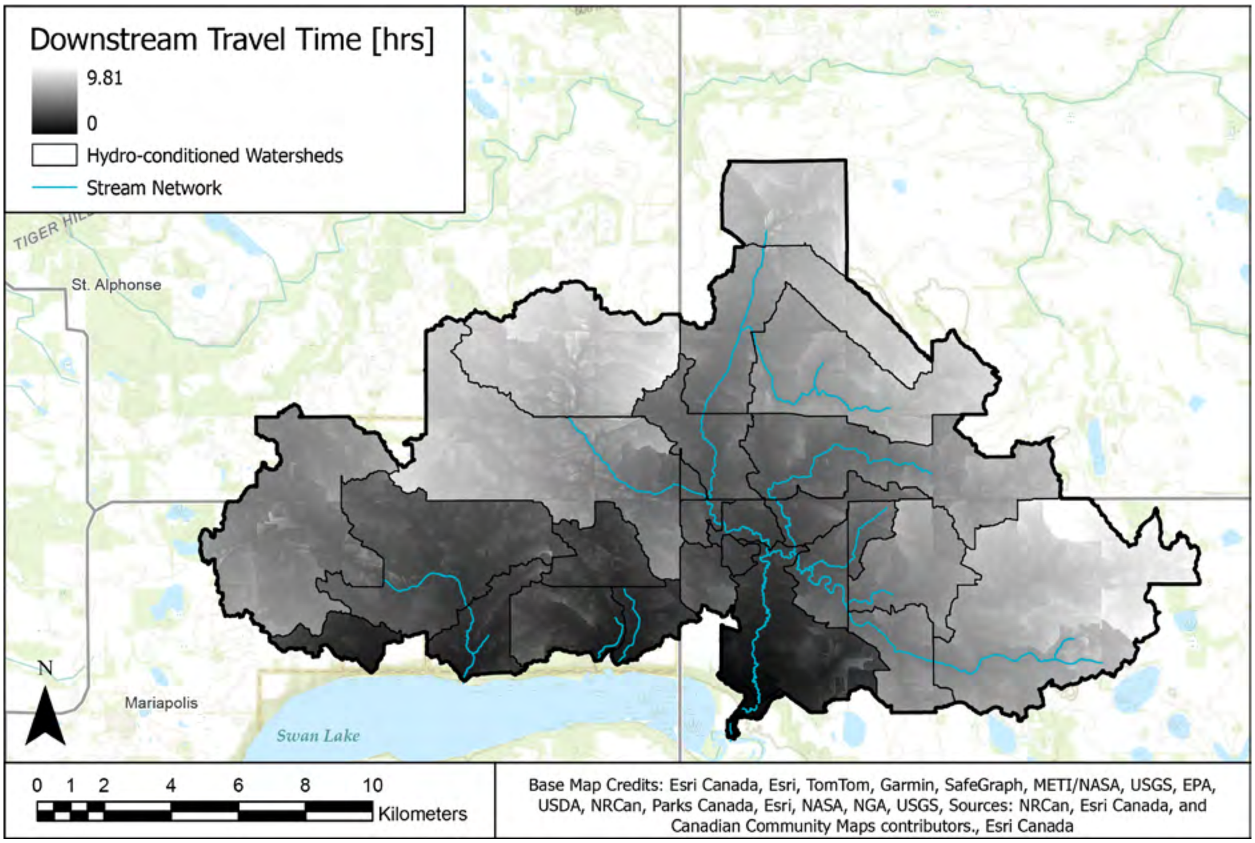


Source: Author map.

A nutrient load transport map is useful for identifying catchments contributing the most nutrient load to downstream receiving water bodies after both accumulation and transportation decay have been considered by the model. Compared to a map of nutrient exports alone, nutrient load transported from the outlets of catchments to priority resource points like Swan Lake is more applicable for informing watershed management. That is, a user may find the nutrient load transport map useful for identifying the locations where nutrient interception actions are most suitable to take place along waterways, but not necessarily what those actions may be.

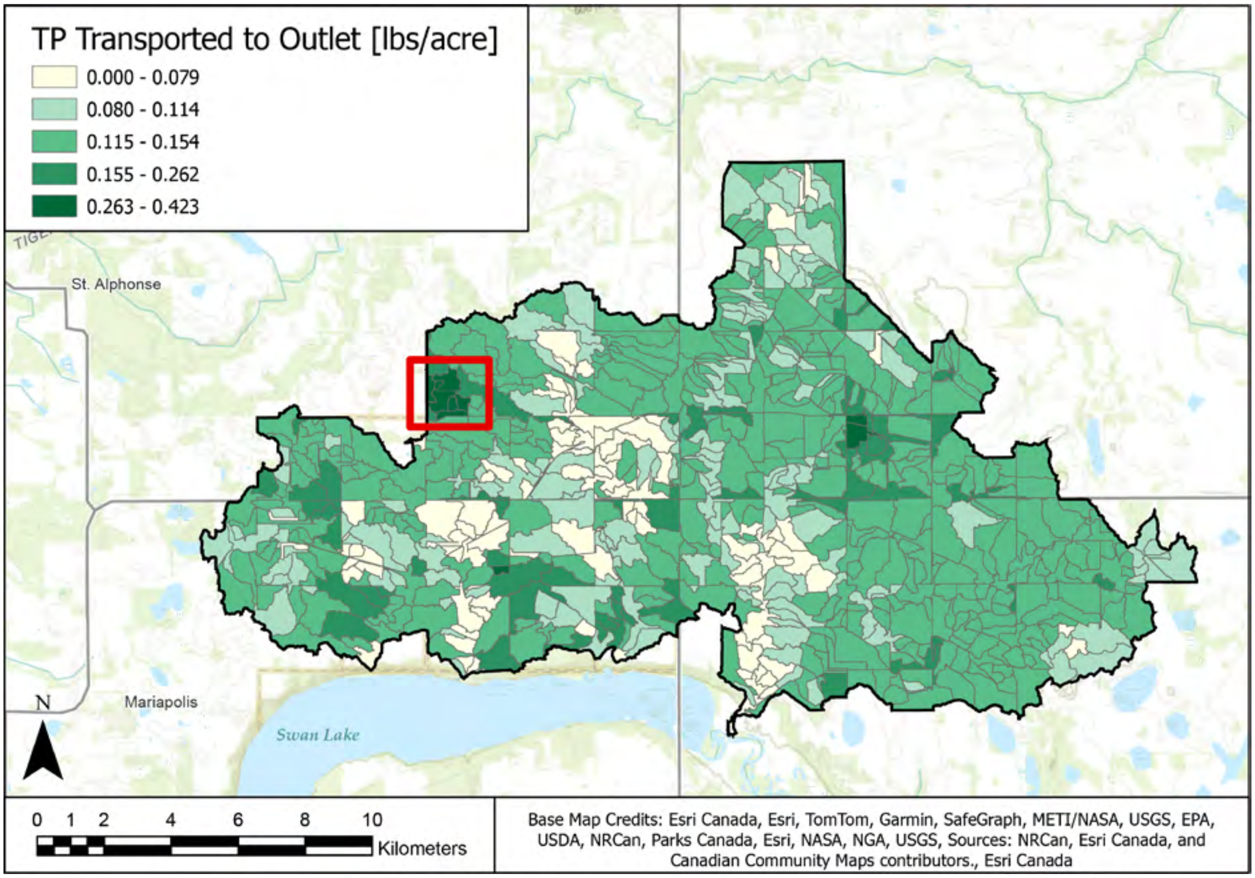
To accurately develop nutrient transport outputs, the PTMApp requires nearly all of its possible inputs to be developed (e.g., flow direction, accumulation, and travel time rasters). Therefore, there is little reason not to take a PTMApp model run to completion to assess BMP feasibility and performance, for which these export and transport outputs are simply intermediary calculations. Figure 19 illustrates the travel time for water within the study area to arrive at Swan Lake and has been developed using the Minnesota Department of Natural Resources (2019) DNR Toolbox for ArcGIS. Building on the travel time, Figure 20 demonstrates the nutrient transport from various catchments of the Swan Lake study area with the erroneous cropland assignments, as shown previously in Figure 17 (highlighted in red), while Figure 21 shows the transport with the cropland assignments corrected.

Figure 19. Map of downstream travel time for water transport in the study area to Swan Lake



Source: Author map.

Figure 20. Map of TP transported to Swan Lake with incorrect cropland

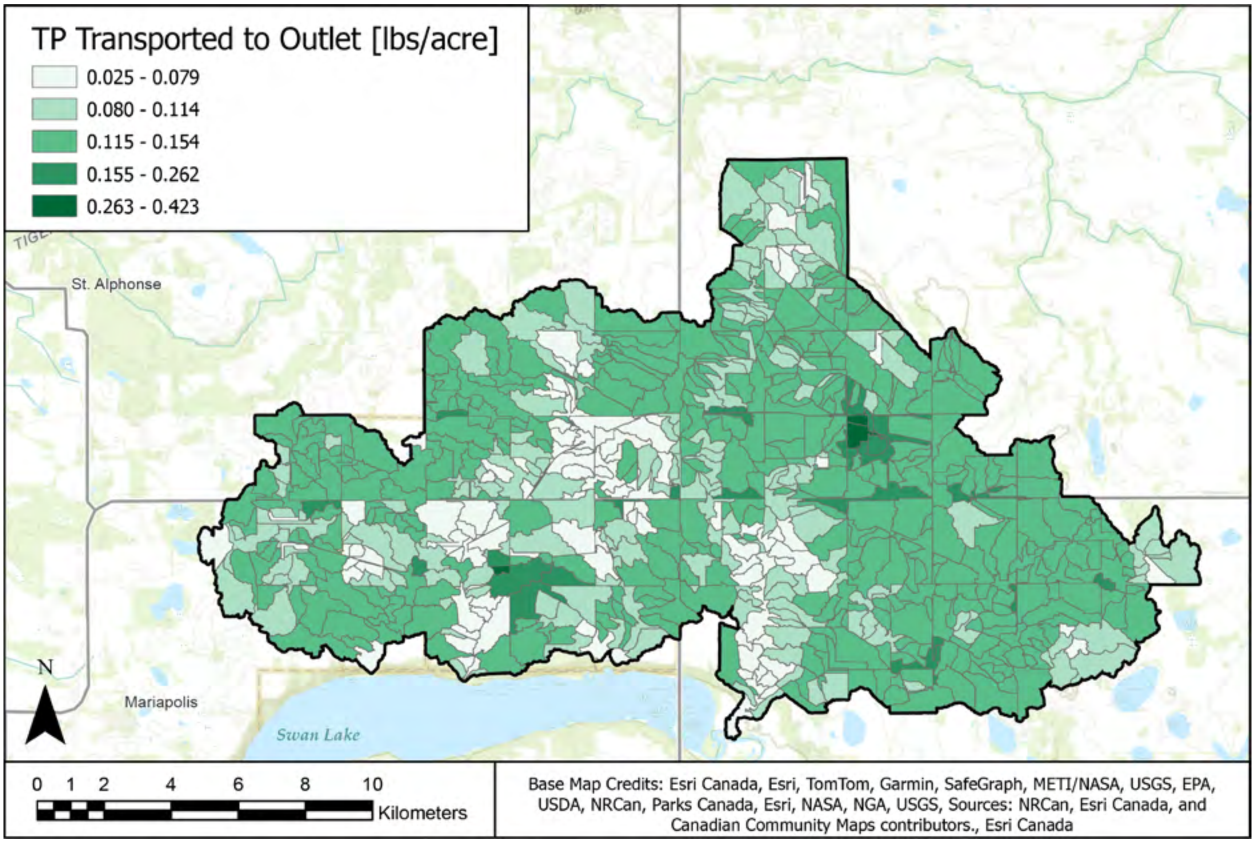


Source: Author map.

Note: The red square indicates the erroneous cropland assignments in the Swan Lake study area.

As noted in Figure 17, the nutrient hotspot generated by erroneous barren land use is still present in Figure 20, and its impact is visible in the neighbouring downstream catchments. BMPs in the path of this higher-than-expected nutrient accumulation are likely to demonstrate a higher mass of phosphorus removal than other comparable regions of the watershed (and the reverse could happen if nutrient export were underestimated). This error should therefore be accounted for in BMP comparison and selection, or the input data should be corrected, as also shown. Although the input data has been corrected in the final outputs shared in this report, the error is demonstrated here to better communicate the impact of input data quality on BMP spatial targeting efforts. Examples of BMP performance differences affected by this correction are explored in Section 2.3.1 to help users evaluate this type of input data error.

Figure 21. Map of TP transported to Swan Lake with corrected cropland

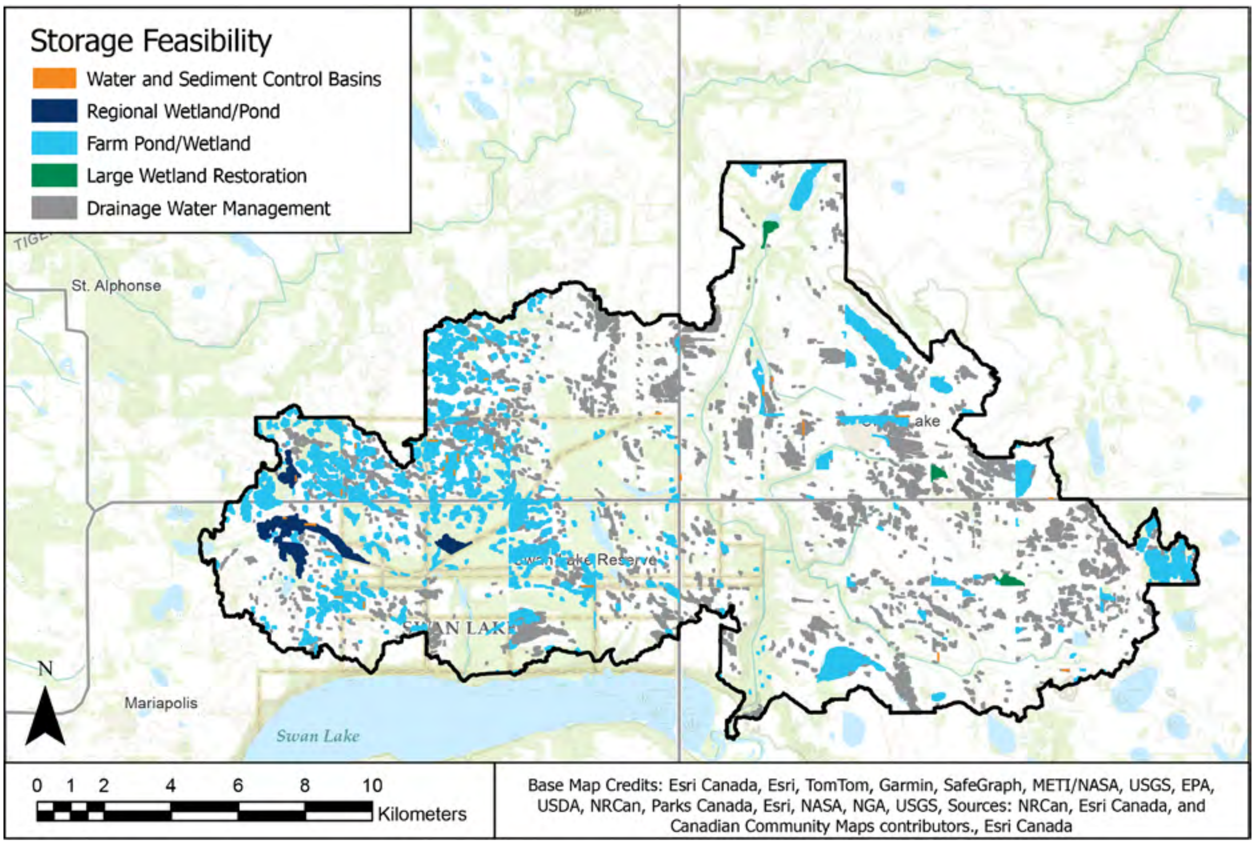


Source: Author map.

2.2.2 BMP Feasibility

Figure 22 illustrates the locations of all feasible BMPs identified by the PTMApp within the Swan Lake study area for the storage treatment group, which includes WASCoBs, regional wetlands/ponds, farm ponds/wetlands, large wetland restoration, and DWM. This feasibility is based on the criteria shared within Section 1.3, Table 1. The BMP feasibility maps that may be generated from the PTMApp are generally recognized to be the most innovative product of the PTMApp and, perhaps unsurprisingly, are one of the more computationally expensive outputs to generate by the model (behind catchment delineation). Although feasibility maps such as this do not quantify the benefits of individual practices, at a minimum, they can inform watershed managers where opportunities for development may lie for investigation by other means. Accordingly, the BMP feasibility map does not require that an assessment of the watershed spring runoff volumes or loading be completed; it can be generated without the entire model development strategy outlined in Sections 2.1 for spring runoff water quality and quantity. While non-contributing areas may still be important to consider in the Canadian Prairies, they may also be identifiable without modelling, using local knowledge if available.

Figure 22. Map of feasible storage BMPs in the Swan Lake study area

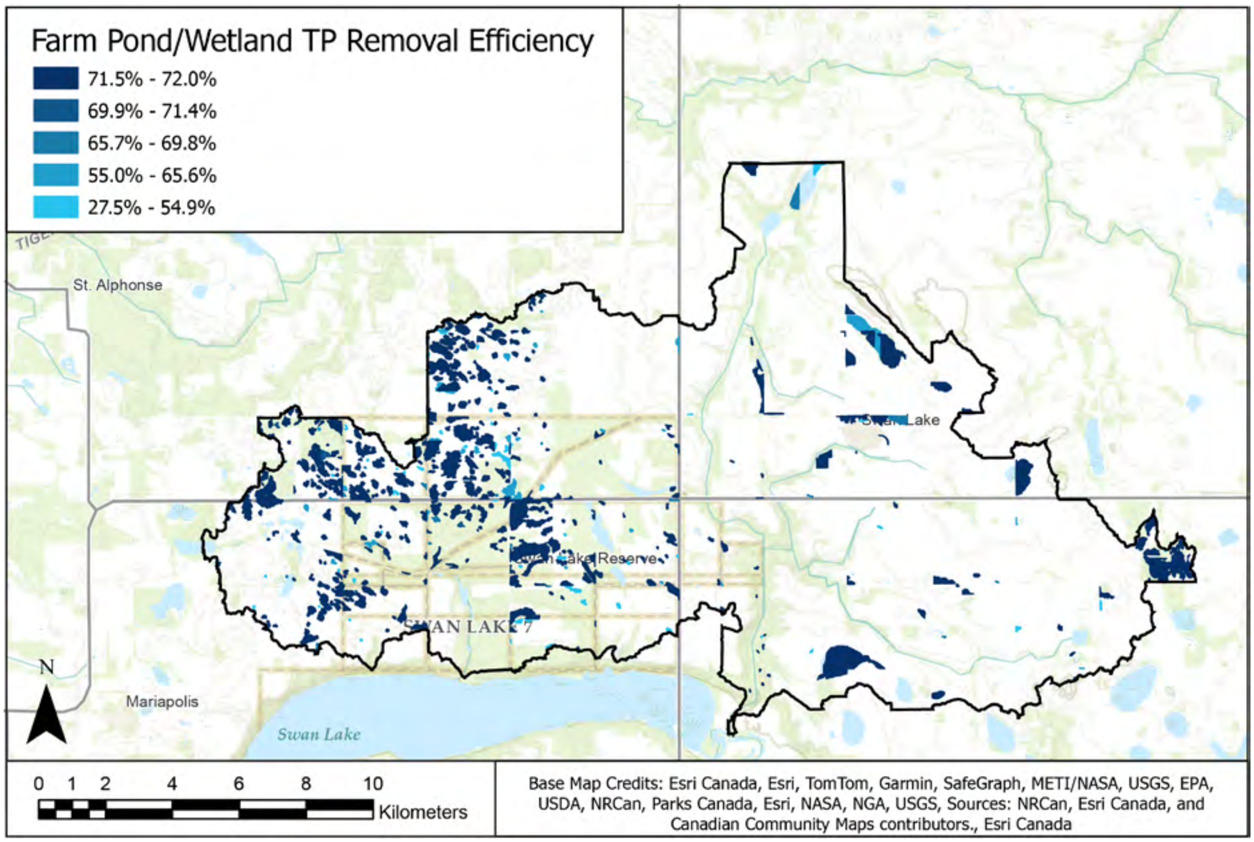


Source: Author map.

2.2.3 BMP Efficiency and Load Reductions

BMP nutrient removal efficiency calculation methods in the PTMApp only differ by treatment group. For storage BMPs, the nutrient removal efficiency is based on a reduction ratio defined by the incoming flow volume of water and the volumetric capacity of the BMP itself to hold and treat that water, as was described previously using Equation 1 in Section 2.1.3.2. For other BMPs, like those in the protection group (e.g., grassed waterways or critical area planting areas), this reduction ratio is developed using estimates of flow velocity and predefined velocity design standards. The reduction ratio in any nutrient removal efficiency calculation method is used to modify a five-number summary of BMP performance statistics derived from a meta-analysis of BMPs, which do differ between BMPs, even within the same treatment group. The results of nutrient removal efficiency calculations for farm ponds/wetlands within this application of the PTMApp model are shown in Figure 23.

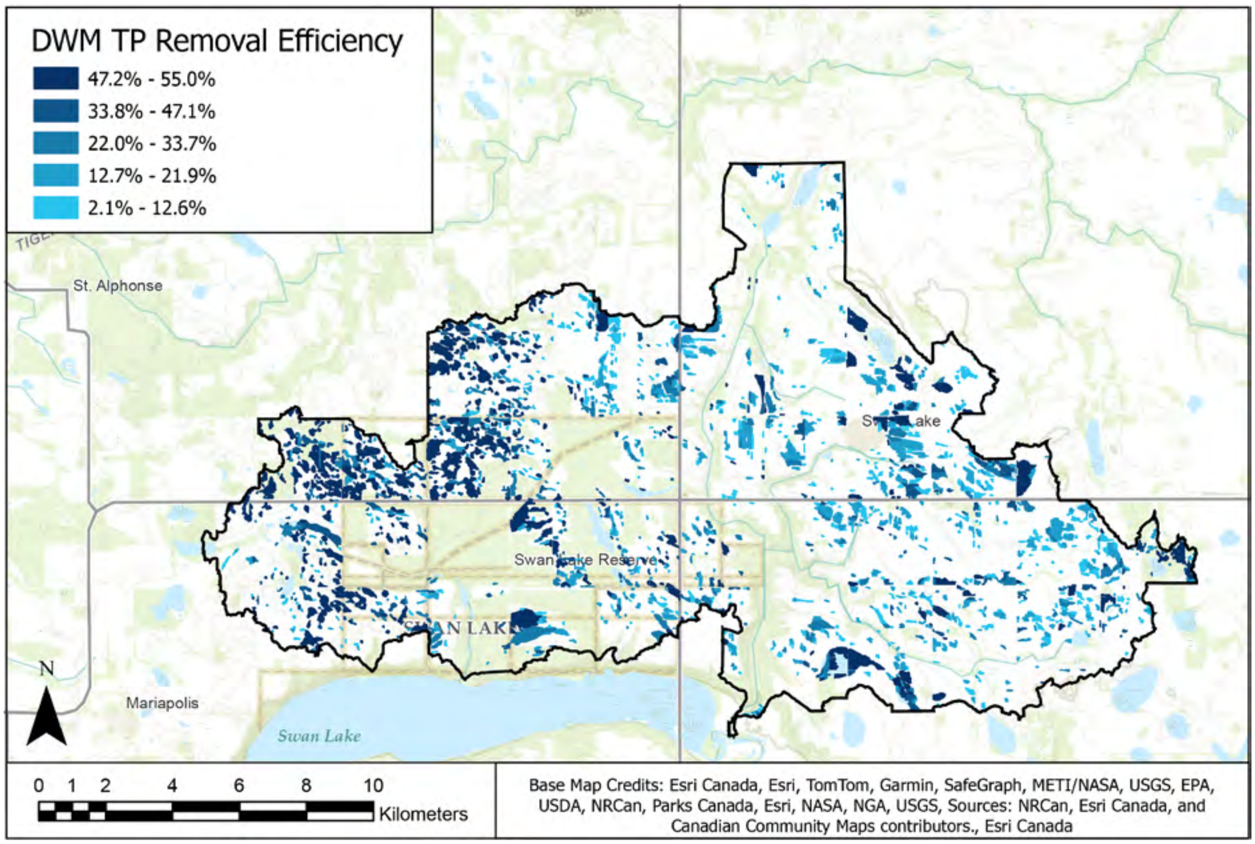
Figure 23. Map of total phosphorus removal efficiency for ponds/wetlands under a 2-year spring runoff event in the Swan Lake study area



Source: Author map.

As can be noted from Figure 23, many of the feasible farm pond/wetland BMPs are highly efficient at reducing TP for the 2-year spring runoff event. This high performance for the assessed farm ponds/wetlands is largely related to the criteria by which these BMPs are defined to be feasible. That is, farm ponds/wetlands in the PTMApp are only identified for those potential depressions that are greater than what a 10-year, 24-hour storm may provide. Accordingly, only those farm ponds/wetlands exposed to spring runoff volumes greater than their storage capacity (21.1% of them) have treatment efficiencies that become sensitive to the spring runoff inflow scenario (see Section 2.1.3.2 for a more detailed explanation). Therefore, Figure 24 has also been provided to demonstrate the possible range of efficiencies that can be observed in the model for an alternative BMP type, such as DWM, which is more sensitive to the incoming flow volume of the given scenario.

Figure 24. Map of TP removal efficiency for DWM under a 2-year spring runoff event in the Swan Lake study area

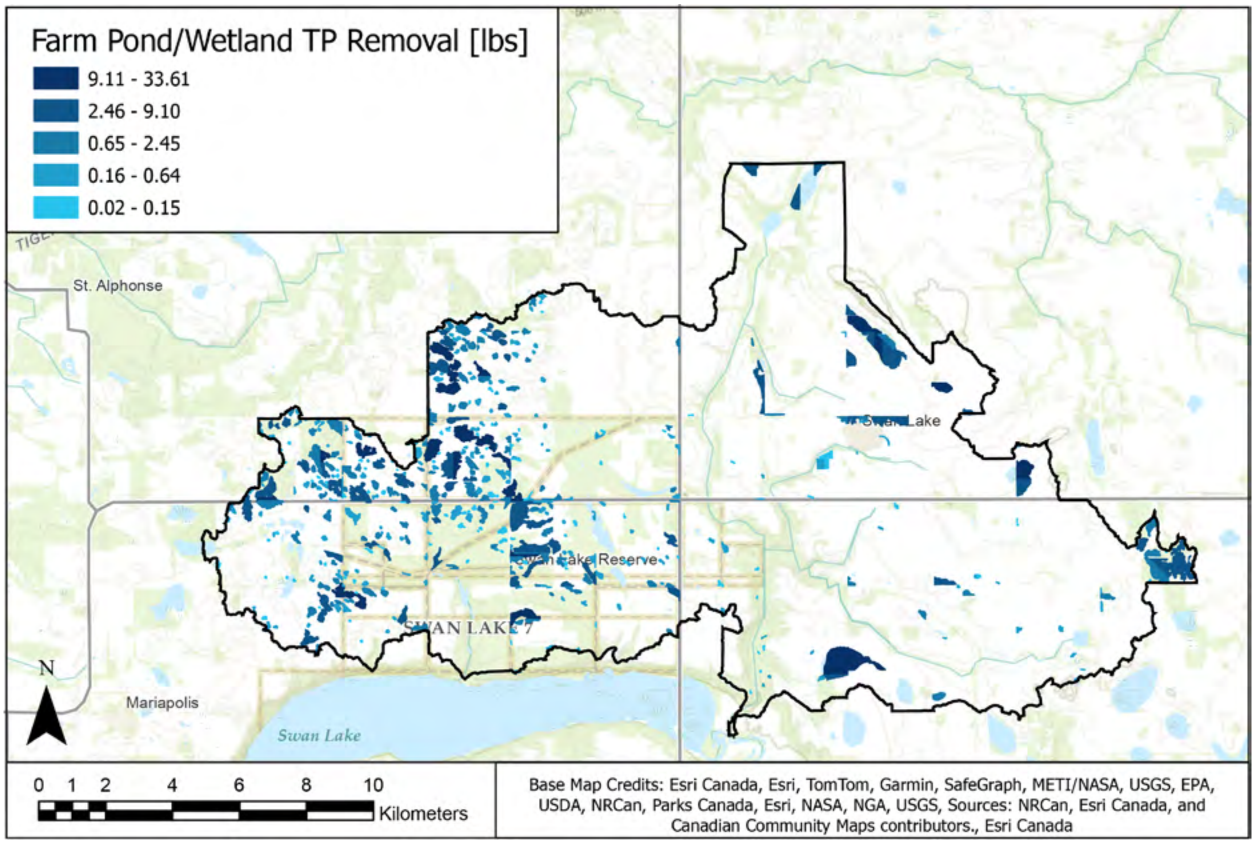


Source: Author map.

Although the DWM TP removal efficiencies in Figure 24 demonstrate a greater range of values across the watershed compared to farm ponds/wetlands, it should be emphasized that this figure has been provided for illustrative purposes only. That is, holding water back in tile drains increases the risk of wet field conditions at the time of seeding and is generally not recommended, making DWM a practice unlikely to be effective during spring runoff. However, from the 2-year spring runoff volume scenario, it can be seen that DWM performance is greater on the western side of the watershed, which again aligns with the water yield maps presented in Sections 1.2 and 2.1.3.2.

BMP nutrient removal efficiency does not tell the whole story, however, because BMP nutrient removal efficiencies on their own do not demonstrate the outcomes of these potential projects. Thus, it would not be wise to perform BMP prioritization and selection activities without considering their final load reduction and cost-effectiveness. With estimates for incoming nutrient loads and the efficiency of feasible BMPs available, it is then possible to combine these data sets to derive the nutrient load reductions for those BMPs. Figure 25 illustrates the estimated reductions of TP for the farm ponds/wetlands previously identified as feasible, considering both the incoming nutrient loads and the efficiency of these BMPs in treating them. It may be evident from the presented data, however, that farm pond/wetland phosphorus reduction is correlated with its water surface and contributing area, which is generally true. For this reason, it is also important to consider the cost-effectiveness of these BMPs, which considers the ratio of nutrient reduction to the construction size of the BMP, which is discussed further in Section 2.2.4.

Figure 25. Map of TP removed by ponds/wetlands under a 2-year spring runoff event in the Swan Lake study area

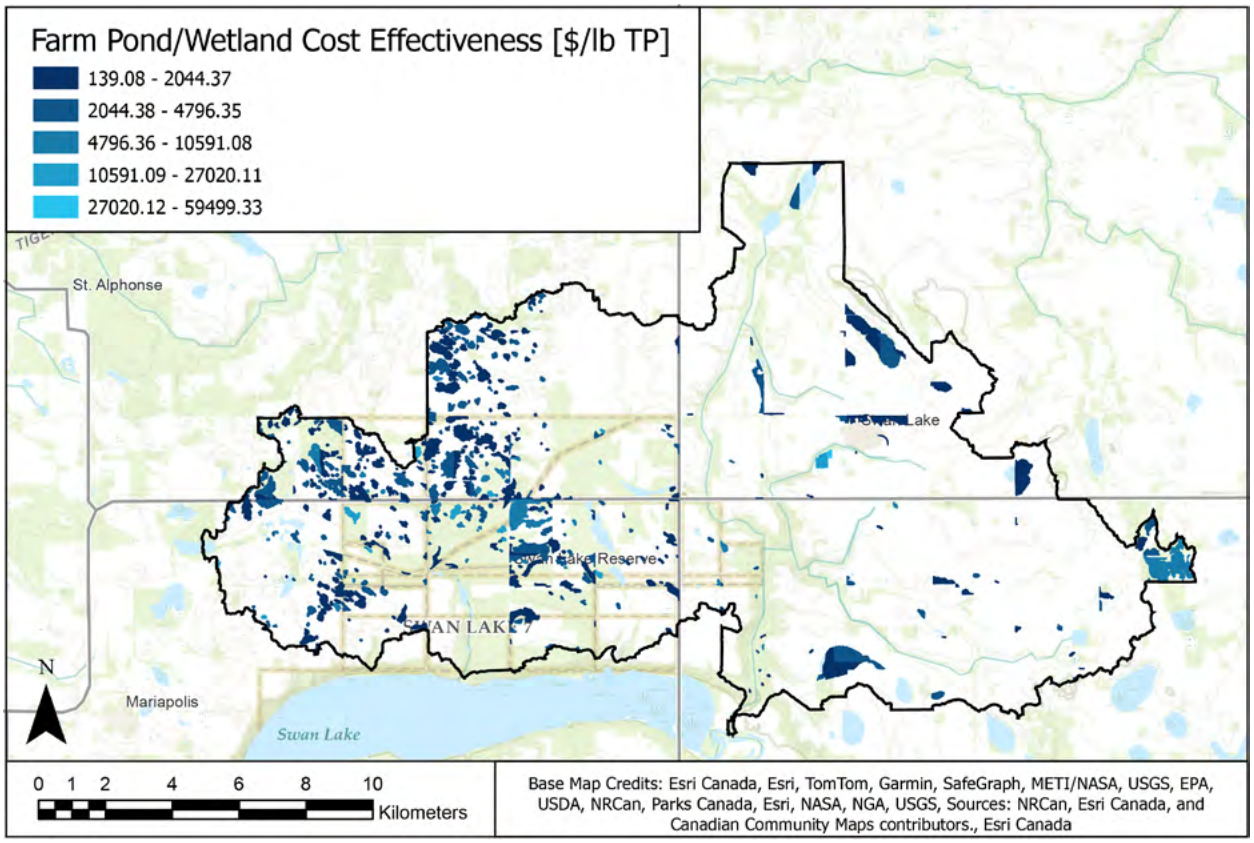


Source: Author map.

2.2.4 BMP Cost-Effectiveness

The final output that can be generated by the PTMApp without further external analysis is the cost-effectiveness of feasible BMPs based on estimated benefits and construction costs, as illustrated in Figure 26. This output combines all previous intermediary model outputs and provides information that can be directly interpreted by watershed managers to make more effective BMP comparison and selection decisions. As noted in Section 2.2.3, considering the size of farm ponds/wetlands in addition to the removal rate helps to improve the represented effectiveness of these BMPs. It was also previously noted that farm ponds/wetlands are only identified in the PTMApp if they are larger in volume than what a 10-year, 24-hour storm may provide. This results in most identified farm ponds/wetlands being, in general, highly efficient for treating the assessed 1-in-2-year spring runoff event. Therefore, one of the primary considerations impacting the cost-effectiveness of storage BMPs is their position within nutrient hotspots and whether they can sufficiently intercept resulting accumulated nutrient loads.

Figure 26. Map of TP removal cost-effectiveness for ponds/wetlands under a 2-year spring runoff event in the Swan Lake study area



Source: Author map.

To estimate the costs for any BMP, the PTMApp multiplies an assumed unit cost by the physical dimensions of that BMP. For farm ponds/wetlands, the unit cost is based on the area of the BMP, as are most others within the PTMApp; however, volumetric and per-practice estimates are also used for some BMP types. While the estimates for BMP cost-effectiveness in Figure 26 use the default PTMApp unit costs (in USD), it is simple to replace these values with those that may be more accurate in Canada, and within the Prairies more specifically, if they are known to the user. One concession to this method, however, is that it does not consider the value of cropland that a BMP may be replacing, which can be in the range of marginal to highly productive. Data, such as the crop productivity index, could be used to mitigate this concession if unit costs were also assigned to these land-use characteristics.

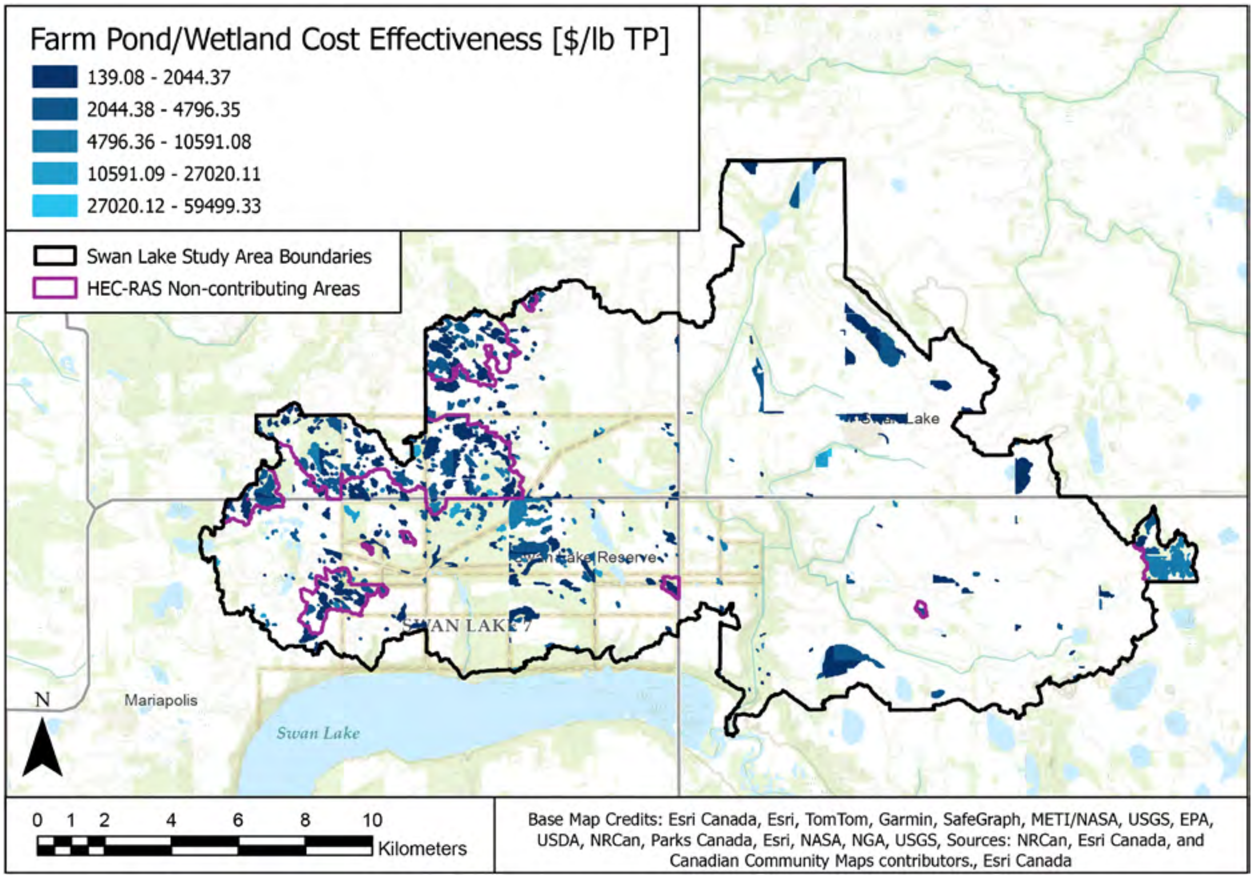
It may be reasonable to compare the effectiveness of different BMP types using these default values; however, if they are thought to be too inaccurate, the default values can still be used reliably to compare the effectiveness of BMPs against others of the same type. For example, the ranking of farm pond/wetland BMPs like those illustrated in Figure 26 would remain in the same order even if the unit cost was altered to be more accurate using the given methodology. Only the comparisons between different BMP types would result in different selection outcomes if the unit costs were updated using the built-in cost-effectiveness calculation methodology, and this should be recognized. Section 2.4.5 further explores BMP unit costs and function opportunities for the PTMApp model.

2.2.5 BMP Screening

To further improve BMP comparison and selection, non-contributing areas for a watershed can be layered onto maps to provide an additional filtering criterion. The non-contributing areas delineated under the 2-year, 24-hour rainfall event, developed using the HEC-RAS model discussed in Section 2.1.2.2, can be overlaid with the PTMApp results, as shown in Figure 27. Perhaps unsurprisingly, non-contributing areas are found to overlap many of those areas where farm ponds/wetlands are deemed to be both the most feasible and highly effective. This intersection results from existing depression-laden lands being well suited to hold water back on the landscape, which positively impacts water quality downstream but also limits flow contribution during low flow events to potential projects in these areas. These identified non-contributing areas also align well with estimated water yield maps for the watershed, where it was found that yield was lower in the western portion of the study area. However, despite the prevalence of non-contributing areas in the study area, it can be observed that there are many opportunities to construct farm ponds/wetlands that are simultaneously outside of these while still also being highly cost-effective.

Using a map with both above datasets presented together, a watershed manager can prioritize BMPs outside of identified non-contributing areas, which should be more effective under a larger range of hydrologic conditions, if desired. Although it may be preferred to select BMPs outside of an average annual non-contributing area, it should be understood that the concept of a non-contributing area is variable in nature. That is, non-contributing area delineations vary depending on the magnitude of the hydrologic event being assessed, as well as antecedent storage within existing landscape depressions and soil moisture conditions. Therefore, a BMP constructed within a non-contributing area can still provide significant water quality benefits to a watershed, though they may only deliver those benefits to the watershed outlet for larger hydrologic events. This is an important consideration, as it is expected that the resources needed to delineate non-contributing areas using the shared methods may not always be available to Watershed Districts.

Figure 27. Map of TP removal cost-effectiveness for ponds/wetlands under a 2-year spring runoff event in the Swan Lake study area with non-contributing areas



Source: Author map.

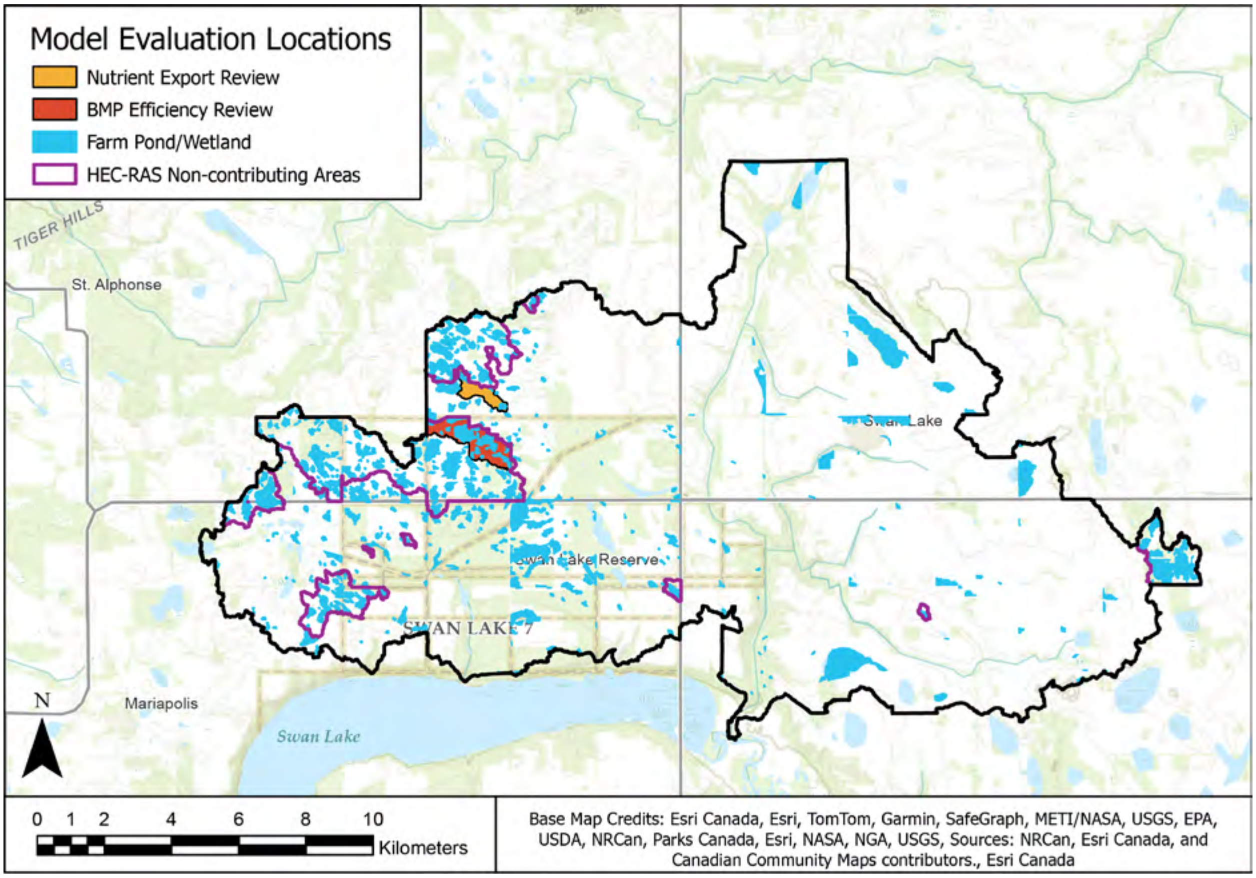
2.3 Model Evaluation

The output of any model is only as good as its inputs. For the PTMApp, many inputs can significantly alter the accuracy of model results, though only a few inputs impact the quantitative component of its outputs. That is, in the PTMApp, many inputs are used to identify feasible locations for BMPs but are not used to assess BMP benefits. For example, a depth-to-groundwater input data set impacts the assessment of feasibility for several different BMP types within the PTMApp but is not used in any calculations for flow, load, or nutrient reduction estimates. On the other hand, corrections made to input datasets like land use can have dramatic impacts on BMP performance, resulting from changes to incoming flow and load.

Trade-offs between model accuracy and complexity must be considered when defining model components, such as domain size and resolution, and when selecting input data sets. Chief among these accuracy and complexity trade-offs in the case of the Swan Lake PTMApp model was the increased level of effort required to achieve improved output confidence in the Prairies by modelling nutrient loading conditions for spring runoff. In this case, the input modelling scenario for the Swan Lake PTMApp model was developed using surrogate HEC-HMS and PTMApp models from neighbouring watersheds to provide more conservative nutrient loading and reduction estimates for storage BMP assessments versus the default PTMApp methodology. Non-contributing areas during a typical rainfall event were also identified using HEC-RAS and geospatial analysis to provide an additional filtering criterion for BMPs.

This section reviews the impacts that alterations to model input have had on its outputs in two key areas. The first is the impact of erroneous input land-use datasets, which govern nutrient exports and the incoming nutrient loads being assessed by BMPs in the PTMApp model. The second is the impact that modelling a 2-year spring runoff scenario had versus using the most extreme default, a 10-year, 24-hour rainfall event, on BMP evaluation. These impacts are explored for the model outputs of the two catchments highlighted in Figure 28 in Sections 2.3.1 and 2.3.2. Limitations of the PTMApp model and identified solutions for those limitations are also explored in these evaluations where appropriate.

Figure 28. Model evaluation catchments



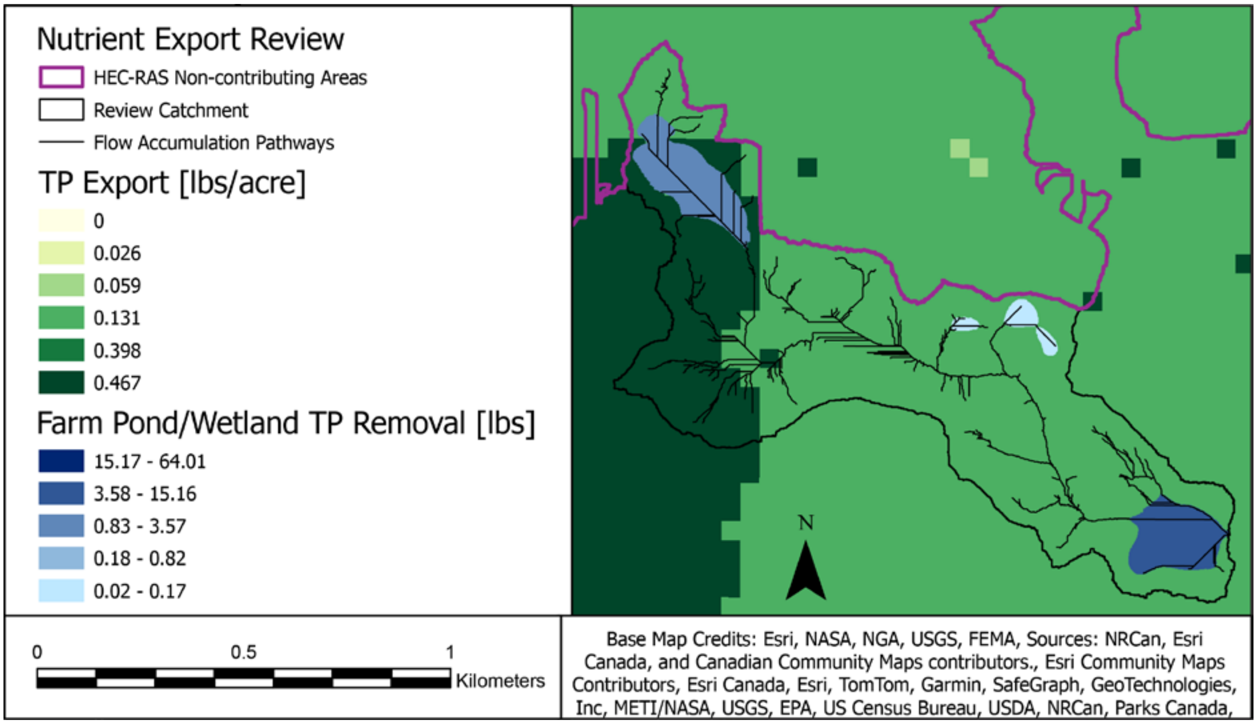
Source: Author map.

2.3.1 Nutrient Exports

One of the most widely available input data sets that may significantly alter spatial targeting results using the PTMApp is land use. Land use impacts the estimated rainfall–runoff relationships using the SCS curve number method (along with soils) and, more importantly, governs the spatially distributed estimates for nutrient export. In this evaluation of outputs from the Swan Lake PTMApp model, a comparison between TP reduction rates for farm ponds/wetlands is shared before and after the correction to upstream barren land-use assignments was made, as was discussed in Section 2.1.3.1.

Figure 29 illustrates the impact of the previously mentioned land-use changes and the TP reduction performance for several feasible BMPs within the nutrient export review catchment before modification. In the case of the downstream-most pond, whose outlet delineates the review catchment, there was a 10.0 lb reduction to TP before correction, which lowered to a 6.8 lb reduction after correction. This represents an overestimation of nutrient reduction for this selected storage BMP of 47.7% for a spring runoff event before correction, simply from an improper land-use assignment for only approximately one quarter of its total catchment area. This sensitivity in assessed BMP performance, without even considering its removal efficiency, therefore demonstrates the importance of high-quality input data sets for this type of modelling.

Figure 29. Nutrient export evaluation for farm pond/wetland TP removal



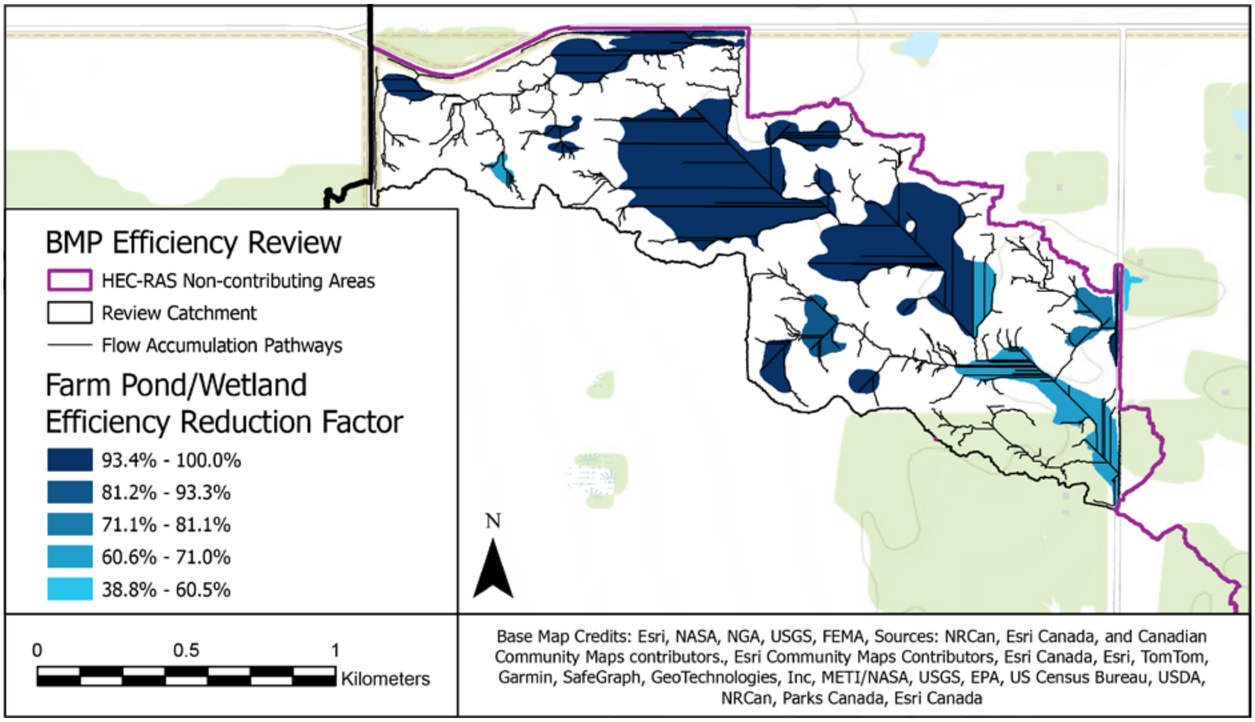
Source: Author map.

2.3.2 BMP Efficiency

The most significant alteration to inputs from this modelling exercise was the volume of water transported throughout the watershed and how that volume modified the efficiency of storage BMPs. This was achieved by simulating a 2-year spring runoff event as opposed to a 1-in-2-year or 1-in-10-year, 24-hour rainfall event and by modifying the BMP performance formulation of farm ponds/wetlands to only treat the volume that it can store under the more conservative inflow conditions.

Figure 30 illustrates the relative efficiency losses determined for select farm ponds/wetlands under the 2-year spring runoff compared to the 10-year, 24-hour rainfall event in the BMP efficiency review catchment, which itself is within and along the upper boundary of an identified non-contributing area. As can be noted, the downstream-most pond/wetland in the highlighted area achieves only 71% of the complete median TP reduction rate under the 2-year spring runoff scenario versus the 10-year, 24-hour rainfall event, resulting in a final TP reduction rate of 51% instead of 72%. However, because this series of potential ponds exists in a modelled non-contributing area, it is also the case that for smaller hydrologic events, this catchment may only negligibly contribute to nutrient loading to Swan Lake under average annual conditions. This contrasts the ponds within the nutrient export review catchment in Figure 29, which instead only neighboured an identified non-contributing area.

Figure 30. Farm pond/wetland 2-year spring runoff efficiency loss against the 10-year, 24-hour storm



Source: Author map.

Another noteworthy consideration when assessing performance for BMPs like farm ponds/wetlands in the PTMApp is evident within Figure 30, wherein it can be seen that, occasionally, a single pond/wetland may be broken up into two or more polygons with differing performance levels. While this artifact resulting from the BMP feasibility criteria appears to primarily affect larger ponds/wetlands, a user may still calculate an appropriate load reduction where this occurs manually if desired. Put simply, the incoming water volume and load from the downstream-most point of these separate polygons may be used from the original model results; however, the user must combine the separated polygon storage volumes to recalculate the reduction ratio, then finally reassess the TP reduction using the new calculated efficiency. Example results for this process using the split pond in Figure 30 are shown in Table 3, which illustrates a more accurate assessment that could be delivered by this pond and suggests that, in general, this error will result in an underestimation of BMP performance rather than an overestimation (assuming a user does not incorrectly add up the nutrient reductions).

Table 3. Combined farm pond/wetland example calculations

Data	Big pond fragment (left)	Little pond fragment (right)	Combined pond
Incoming volume (ft^3)	485,566	497,090	497,090
BMP volume (ft^3)	3,092,859	304,846	3,397,705
Incoming TP load (lbs)	16.6	17.1	17.1
Median TP reduction	72%	72%	72%
Reduction ratio (-)	1.000	0.614	1.000
TP reduction efficiency	72.0%	44.2%	72.0%
Load reduction (lbs)	11.96	7.55	12.31

Source: Author calculations.

2.4 Input Data Alternatives and Insights

In this section, additional insights are provided for selected model inputs used for Swan Lake and surrogate models, as well as potential alternatives. The sensitivity of PTMApp model outputs to some inputs was already demonstrated in Section 2.3, but an exhaustive comparison of many different inputs and their uncertainty is out of the scope of this report. The model inputs considered for discussion herein include climate data sets and other possible models to derive hydrologic forcing for spring runoff events, LiDAR data, and hydro-conditioning using culvert inventories, soils and land-use data sets, and BMP performance and unit costs.

2.4.1 Spring Runoff Data and Models

There are just two raster inputs within the PTMApp that govern the rainfall event that drives the hydrologic simulation. These are the rainfall depth rasters for the 1-in-2-year and 1-in-10-year, 24-hour events, which are varied spatially and can be estimated using known Intensity–Duration–Frequency (IDF) relationships derived from local weather stations. The Swan Lake models were developed by interpolating data from ECCC (2019) IDF curve stations. In this application of the PTMApp, 2- and 10-year, 24-hour rainfall depth rasters were developed using traditional means, but the 2-year, 24-hour rainfall raster was ultimately replaced to replicate the 2-year spring runoff event volume instead. This spring runoff event volume was derived from bias-corrected HEC-HMS model results developed from the neighbouring Cypress River watershed, as was discussed in Section 2.1.2.

Although there are many input data considerations for the HEC-HMS modelling effort, perhaps the most significant was the selection from available input precipitation data sets. Three different precipitation inputs were used in an attempt to calibrate the HEC-HMS model for the Cypress River, using only spring runoff discharge to evaluate model performance. These precipitation inputs were the Canadian Precipitation Analysis (CaPA) (Canadian Meteorological Centre, 2019), WATCH-Forcing-Data-ERA-Interim (WFDEI) (Weedon et al., 2014), and NASA (National Aeronautics and Space Administration, 2019). Of note for these precipitation input data sets is the temporal resolution provided, which for WFDEI, CaPA, and NASA were available in 3-, 6-, and 24-hour frequencies, respectively.

Although the temporal resolution of these three datasets may suggest that WFDEI may provide the greatest model performance, particularly due to the size of the study watersheds, this was not the case for the spring runoff-focused HEC-HMS model. Instead, CaPA performed the best. In fact, because the model evaluation criteria for this effort were just discharged following snowmelt, the temporal resolution of the input rainfall data was, in fact, unimportant. This contrasts with the importance of the temporal resolution of rainfall data for small watersheds, such as those being modelled in this study, due to the limited time required for runoff generated in headwaters through to termination at the outlet. Instead, the key component of the precipitation input effecting model performance is the total volume accumulated over the entire snowfall period, for which the CaPA dataset proved to be the most accurate. The CaPA dataset was the only input precipitation dataset that could result in, at minimum, satisfactory calibration and validation scores for Nash Sutcliffe Efficiency, root mean square error standard deviation, and percent bias (NRES-21 Hydrology Committee of ASABE, 2017) for the Cypress River model.

The timing of snowmelt is another important consideration for evaluating modelled spring runoff events using HEC-HMS, as the rate of melt can significantly impact peak discharge. In the case of HEC-HMS, the temperature index method is used for assessing the rate of snowmelt and relies on other climatic inputs, such as air temperature and incoming radiation (USACE, 2022a). As these inputs drive the timing of snowmelt from the volume of snowpack accumulated from precipitation, the temporal resolution of air temperature and incoming radiation is more important than the precipitation. However, experimentation with many different climatic datasets was not required to achieve satisfactory results (WFDEI used). Instead, it is suggested that the simplicity of the temperature index method may be a limiting factor for achieving higher performance within this component of the model. It is for this reason that an investigation was instead initiated to identify alternative methods for assessing snowmelt for future studies.

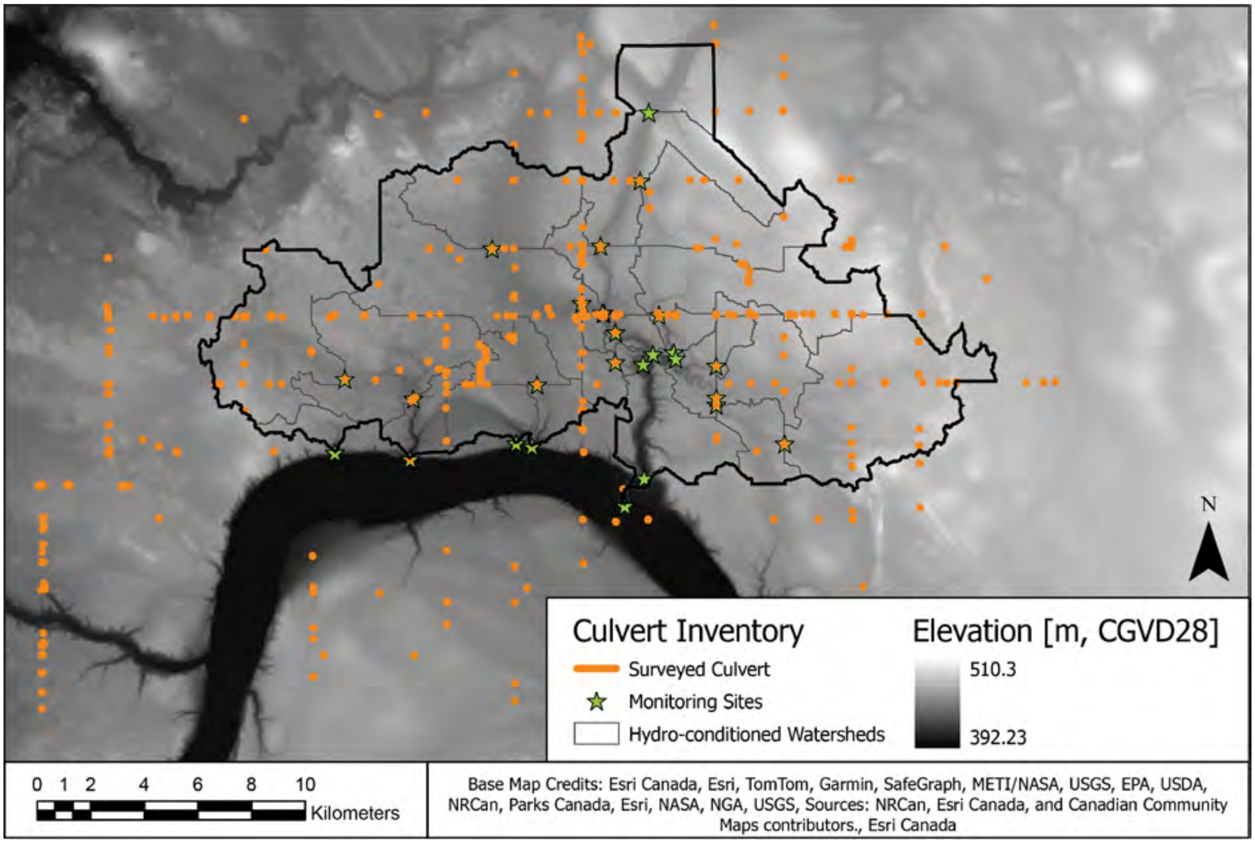
It has been proposed that spring runoff modelling performance for the Cypress River could be improved using an entirely separate model from HEC-HMS to generate snowmelt runoff. Two relevant ongoing model development efforts have been identified to serve this purpose: SNOWPACK (Richards et al., 2022) and PHyDAP (Global Water Futures, 2022), which is based on the Cold Regions Hydrological Model. One of the outputs of both investigated sources of output data is a snowmelt runoff depth time series that could replace the CaPA precipitation input in HEC-HMS and thus no longer require the implementation of the temperature index method. In this way, the precipitation input would be modified with snowmelt runoff depth in the spring, with no snow accumulation modelled explicitly in HEC-HMS for the winter, circumventing the need for traditional snow input data and defined snowmelt climatic variables. Just the basin transform and river routing components of the HEC-HMS model would be retained to facilitate hydrograph development for the modelled watershed in either of these cases. This strategy is currently being investigated by the International Institute for Sustainable Development (IISD) for feasibility and to test performance for future applications.

2.4.2 Digital Elevation Models and Hydro-Conditioning

The availability of LiDAR digital elevation models is arguably the most likely condition to govern the viability of PTMApp model development. Furthermore, high-resolution topographical data like that derived from LiDAR should be processed further before being used in the PTMApp to eliminate potential irregularities and errors in modelling results. The International Water Institute (2015) provides basic guidance on performing hydro-conditioning alongside other PTMApp documentation. Basic hydro-conditioning practices, such as burning in stream networks and filling depressions, are required to ensure the connectivity of a modelled basin from its headwaters to its outlet and to properly compute flow direction and accumulation rasters. However, in the case of the PTMApp, which can be used to evaluate BMPs at field scale, input data like culvert inventories can be more important than for larger-scale river basin models. Including culverts within the hydro-conditioning process will prevent potential short-circuiting and ensure that smaller-scale catchments are more accurately representing true flow accumulations.

In the case of the Swan Lake study area PTMApp model, an inventory of 363 culverts was collected by Swan Lake First Nation and AAFC for inclusion in hydro-conditioning and watershed delineation, as shown in Figure 31. This survey provided coordinates for both the inlets and outlets of culverts, which enabled the processing of burn lines through individual roads and highways in the modelling domain. This input data was also important for defining the non-contributing areas identified with HEC-RAS, as a known culvert can enable what would otherwise be modelled as a road-based dam to be drained as it does in reality. This hydro-conditioned LiDAR DEM is available to download freely from the Government of Canada's Open Government Portal (AAFC, 2024).

Figure 31. Map of culvert inventory collected by Swan Lake First Nation for LiDAR hydro-conditioning



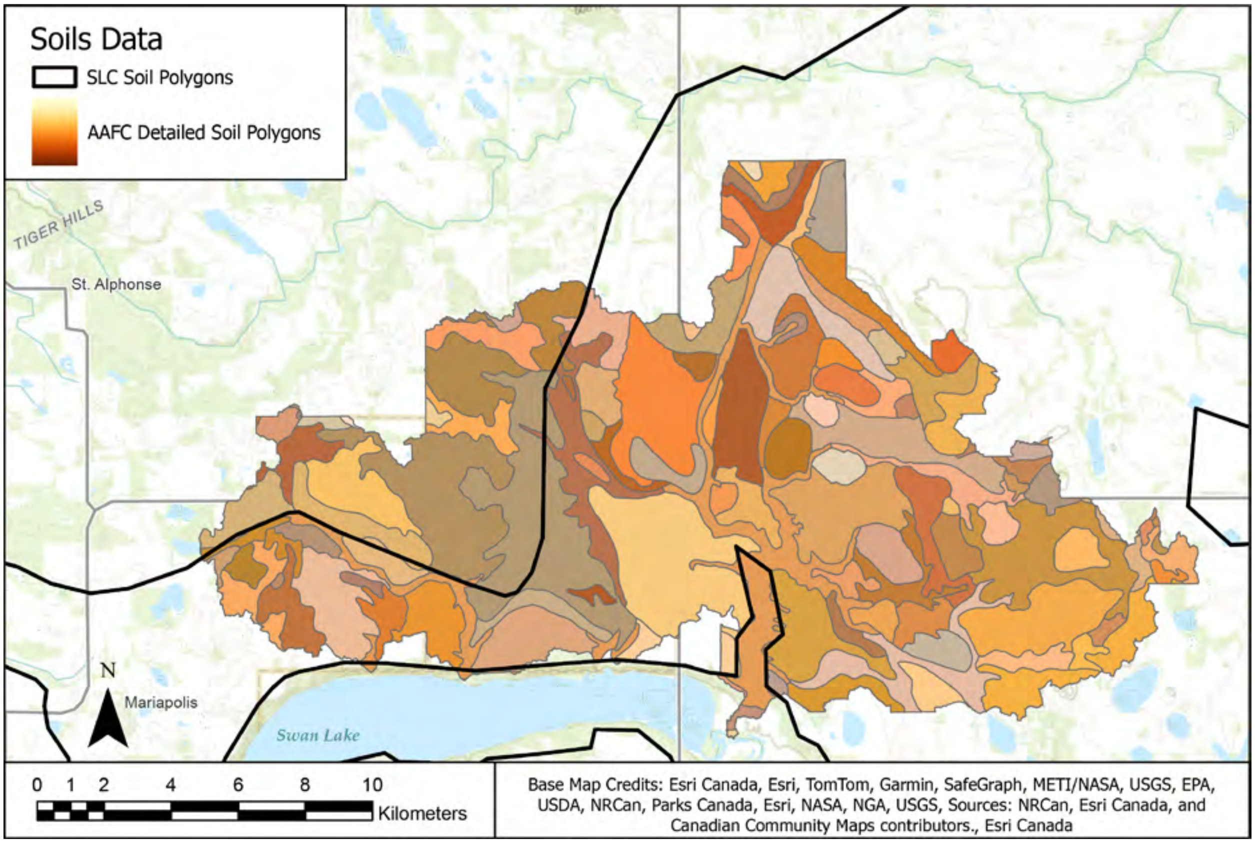
Source: Author map based on Government of Manitoba, 2022b.

Although the Swan Lake culvert inventory was extremely useful for determining culvert locations, it did not provide other information that could used for other purposes. To be most useful in modelling exercises, culvert inventories should include information about culvert inlet and outlet coordinates, including elevation, in addition to pipe diameter at a minimum. However, these inventories should also consider including material properties (e.g., corrugated metal pipe or smooth PVC), known obstructions (e.g., gravel or boulders), headwalls, and (if applicable) gate configurations. It is also important that these datasets be made publicly available. In Manitoba, the Assiniboine West Watershed District's (2023) culvert inventory provides a good example for others to follow.

2.4.3 Soil and Land-Use Data

Soil and land-use data sets are important within the PTMApp, as they define various hydrologic modelling and nutrient loading characteristics. Perhaps most importantly, soil and land-use data together form the basis for defined SCS curve numbers used to determine rainfall–runoff relationships, while land use alone defines the spatial distribution of nutrient exports. Both datasets are also important considerations for sediment transport functions, though erosion modelling considerations that utilize the Revised Universal Soil Loss Equation (RUSLE) method in the PTMApp have not been prioritized in this application of the model. Inventories for existing BMPs established in a watershed are also invaluable, as they can be used to better model the baseline conditions for a watershed. Although the choices available to the user for these inputs may not be vast, there are still important considerations that can be recognized for each.

Figure 32. Comparison of soil polygon density between SLC vs detailed municipal data



Source: Author map based on AAFC, 2011, 2019.

In the case of soil data, it is likely that a Canadian modeller may wish to use the national Soil Landscapes of Canada (SLC) dataset provided by AAFC (2011). This is especially true, as Cordeiro et al. (2018) derived a dataset for agriculturally relevant soils from the SLC database for use in Soil and Water Assessment Tool (SWAT) simulations. As the PTMApp shares some of the same inputs of the SWAT model, and these inputs are not available within the SLC database by default, the use of these datasets together is entirely reasonable. However, the polygons within the SLC database are extremely coarse as compared to detailed data, which may be available at the municipal level. Figure 32 shows the contrast in polygon resolution between the SLC and AAFC

(2019) Agricultural Interpretation Database by municipality. In this application of the PTMApp, a version of the more detailed municipal soil data was used with the needed input data sets defined, using the same methods as Cordeiro et al. (2018). This data is currently unpublished but may become available at a later date from AAFC.

As was already described in Section 2.2.1, errors may be present within land-use datasets, which can result in erroneous quantities of nutrients being exported within a watershed modelled with the PTMApp. However, incorrect land-use assignments can also have other effects within a PTMApp model, like the incorrect assignment of certain BMP types, such as those that require the existing land use to be cultivated crops. For this reason, it is important to select land-use data that is not only high resolution but also accurate and up to date. In this application of the PTMApp, the 2018 AAFC (2023) annual crop inventory was used, which has a spatial resolution of 30 m and is generally updated annually. However, even in later annual AAFC crop inventories, the erroneous barren land at the location explored in Sections 2.2.1 and 2.3.1 exists. This finding emphasizes the importance of modellers reviewing nutrient hotspots in their PTMApp models for accuracy, even if they are using the most up-to-date data.

2.4.4 BMP Performance Statistics and Functions

Section 2.1.3.2 described how reduction ratios are calculated for individual BMPs in the PTMApp and how those ratios are used with a five-number summary of performance statistics to calculate final reduction rates. The default median phosphorus removal and decay coefficients for each of the water storage BMP types in the PTMApp are provided in Table 4. Section 2.1.3.2 also described how the default methodology was modified to account for the exceedingly low decay coefficient for farm ponds/wetlands, which limits model accuracy in determining water quality benefits for events greater than a 10-year, 24-hour storm event. However, although an effort was made to improve the representation of conservative water storage BMPs for events like spring runoff, additional considerations and variables could still be explored to improve model accuracy.

Table 4. Default median PTMApp Storage BMP performance statistics and decay factors

BMP type	Median phosphorus removal coefficient, Q2	Decay coefficient, k
Farm pond/wetland	0.72	0.01
DWM	0.55	0.26
Water and sediment control basin	0.76	0.05
Regional pond/wetland	0.53	1.22
Large wetland restoration	0.50	2.00

Source: based on Houston Engineering, Inc., 2021.

The first consideration to improve the accuracy of BMP evaluations within the PTMApp is to assess the default reduction rates and performance statistics of monitoring data collected in the Canadian Prairies. This assessment was intended within this application of the PTMApp model; however, the COVID-19 pandemic in 2020 and drought conditions in 2021 limited substantial hydrometric data collection over the duration of this effort. In light of these circumstances, it is worth considering that the default annual PTMApp values do align with recent research in this area, for example, with unpublished research by Vanrobaeys et al. (n.d., as cited by Mulla & Whetter, 2020) showing total annual load reductions of TP for an enhanced ditch and pond in Morden, Manitoba, being 93% and 71% in 2016 and 2017, respectively.

While it may be adequate to modify phosphorus removal coefficients using reduction ratios and decay coefficients at the scale of this model application, it is also possible that more sophisticated methods may be integrated to better evaluate water storage BMPs. For instance, Simoes et al. (2022) demonstrated the use of treatment wetland models (Kadlec & Wallace, 2009) for the evaluation of water retention practices that relate phosphorus reduction rates to retention time, free water depth, and incoming load concentration. The PTMApp already generates the data that would be needed to consider water depth and incoming load concentration in a wetland treatment model; therefore, only some estimation or generalization of retention time would be required to potentially develop a more sophisticated nutrient reduction model. Integration of these variables into the assessment could also have the added benefit of making the distinction between “regional pond/wetland,” “large wetland restoration,” and “farm pond/wetland” performance redundant. The implementation of simplified treatment wetland models, or other similar methods, would facilitate better estimates of nutrient reduction performance and enable BMPs that provide a greater return on investment to stand out in output evaluation.

2.4.5 BMP Unit Costs and Cost Functions

The cost analysis function within the PTMApp primarily estimates total BMP cost through linear relationships with physical dimensions, though the WASCoB practice is an exception that uses a fixed per-practice cost. For farm ponds/wetlands, as previously discussed, the unit cost is based on BMP area, as are most others within the PTMApp, but an estimate based on volume is used instead in the case of denitrifying bioreactors. These unit costs are defined within the PTMApp in USD by default, as shown in Table 5, and may not translate perfectly to the Canadian Prairie economic context. Furthermore, these unit costs are static and do not consider potential cost advantages associated with the economies of scale or unique land replacement costs, such as whether cropland is marginal or highly productive, as was mentioned in Section 2.2.4. However, despite these limitations of the default PTMApp methodology, the cost analysis function can be modified or circumvented by the user to improve the usefulness of BMP cost-effectiveness calculations, as was previously reviewed in Section 2.2.4.

Table 5. Default PTMApp BMP unit costs

BMP type	Cost (USD)
Farm pond/wetland	$812.05/acre
DWM	$5.54/acre
WASCoB	$4,500/each
Regional wetland/pond	$20,439.57/acre
Large wetland restoration	$20,439.57/acre
Riparian buffer	$1,065.87/acre
Filtration strip	$496.08/acre
Saturated buffer	$1,367.78/acre
Denitrifying bioreactor	$38.02/yd^3
Infiltration trench/small infiltration basin	$36.45/yd^2
Multi-stage ditch (open channel)	$4,036.56/acre
Critical area planting	$293.77/acre
Grade stabilization	$53.10/yd^2
Grassed waterway	$1,062.86/acre
Lake and wetland shoreline restoration	$37.98/yd^2
Perennial crops	$480.80/acre
No-till	$11.03/acre
Cover crops	$33.52/acre
Reduced tillage	$11.03/acre
Forage/biomass planting	$44.84/acre
Prescribed grazing	$6.34/acre
Nutrient management of groundwater	$6.84/acre
Nutrient management – Phosphorus	$6.84/acre
Nutrient management – Nitrogen	$6.84/acre

Source: based on Houston Engineering, Inc., 2021.

If a user wishes to modify the default unit costs for BMPs within the PTMApp, the unit costs are easily user defined within the PTMApp interface within ArcGIS Pro. The challenge may lie instead with respect to aligning these costs with the expectations of watershed managers who may be using PTMApp spatial targeting outputs to evaluate BMPs. If an inventory of existing BMP implementations is available from within a Canadian Prairie watershed, it is possible to test and adjust the default unit costs against historical data. It is also the case that the full cost of BMP implementation must be considered during evaluation. For example, the per-acreage cost for the DWM practice is relatively low but does not consider the original cost of excavation and installation of tile drainage that this practice assumes to have already been incurred by the landowner. Therefore, if it is preferred that the particular costs be built into or neglected from these unit costs, this may be completed by modifying the default values in the PTMApp.

In addition to modifying unit costs for BMPs using the default methodology of the PTMApp, users can also implement non-linear cost functions that consider economies of scale or other factors if desirable. However, this type of modification requires that a user be comfortable with creating and calculating fields within attribute tables of BMP polygons within ArcGIS, as it is not a built-in capability of the PTMApp interface. For example, a user may create a new field within the attribute table for their BMP polygons and implement a function for farm ponds/wetlands whose effective unit cost decreases as their area increases. A modified cost function could also consider other variables, like existing land use and soils, if they are known to impact the cost of their construction. The modified total cost of BMPs using a manually defined field can then be divided by nutrient or sediment reductions to develop more representative cost-effectiveness calculations that can provide even more accurate spatial targeting.

3.0 Modelling Applications: Insights and options

This section provides insights on applications of BMP spatial targeting using the PTMApp from the perspectives of the Government of Manitoba, Watershed District managers, and First Nations involved with the LLEP. It also provides insights on how these applications may be relevant to the rest of the national Living Labs program, its larger hydrologic modelling working group, and across Canada more generally.

3.1 Manitoba Provincial Government, Watershed District Managers, and First Nations

To facilitate documenting insights from Manitoba's provincial government, watershed managers, and First Nations, representatives from each group participated in LLEP working group discussions over the course of the initiative. Following the complete development of the PTMApp model described in Section 2, applications of the model were tested with feedback from these groups. These discussions included live demonstrations of model outputs rendered and explored in different formats and the facilitation of an in-person tour of recommended BMPs for the Swan Lake study area, informed by those model results. In all cases, attributes available within PTMApp polygonal outputs helped to predict the performance of feasible BMPs to deliver on desired watershed outcomes. Furthermore, because of the awareness-building exercise of the in-person tour, some of the identified BMPs have the potential to undergo an investigation into their actual viability, a detailed assessment, and potential construction in the future.

The following sub-sections share insights for spatial targeting models across several topic areas, including

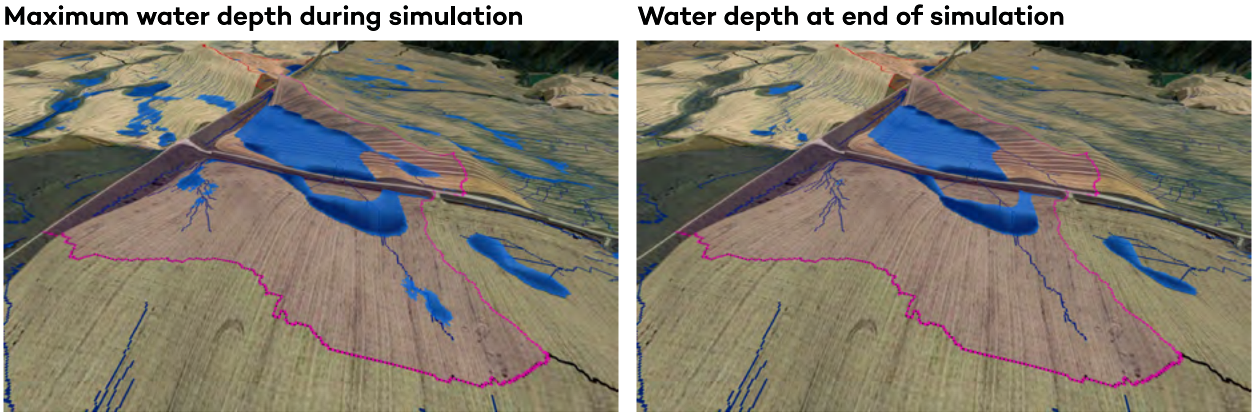
- communication of model outputs
- BMP site selection methods and validation
- landowner priorities, concerns, and willingness
- the value of local knowledge in hydrologic modelling
- watershed-specific concerns
- alternative site selection methodologies

Communication of Model Outputs

The methods used to communicate complex model development strategies to stakeholders often influence the confidence associated with recommendations derived from these exercises. For example, the use of 3-dimensional (3D) mapping for topographic data and overlaying outputs from hydrologic simulation helped to communicate both the challenges and opportunities of hydraulic simulation to address non-contributing areas. This style of model output presentation can help encourage managers of watersheds to better understand the importance of detailed hydrologic input datasets like culvert inventories and the value they bring to improving model functionality and accuracy. As this type of dataset is usually unavailable across much of the Canadian Prairies, this type of visual communication strategy may be helpful to accelerate buy-in from those watershed managers who often lead these data collection efforts.

Figures 33 and 34, for example, show satellite imagery projected onto the PTMApp model's hydro-conditioned DEM, flow accumulation pathways, and the maximum and end-of-simulation HEC-RAS water depths. Both figures illustrate the natural undulations of the Prairie pothole landscape and how water may become trapped in the upstream headwaters of a watershed and not contribute to discharge at its outlet. However, while the non-contributing area could be simulated in Figure 33 as it is primarily a consequence of the landscape topography, the non-contributing area in Figure 34 could not. This inability to estimate the non-contributing area was due to the upstream culvert elevation not being known, and the burn line height was therefore set to the bottom of the ditch elevation from the DEM. That is, the pond on the upstream side of the road would have a greater area and volume in the end, and maximum simulation results had the culvert elevations not been assumed to have the same elevation as the bottom of the ditch. As another example of the benefit of presenting visualizations like these, the description of a "burn line" used in hydro-conditioning methods may be lost by the layman; however, a 3D image of a road with a cut through it makes the concept almost self-explanatory.

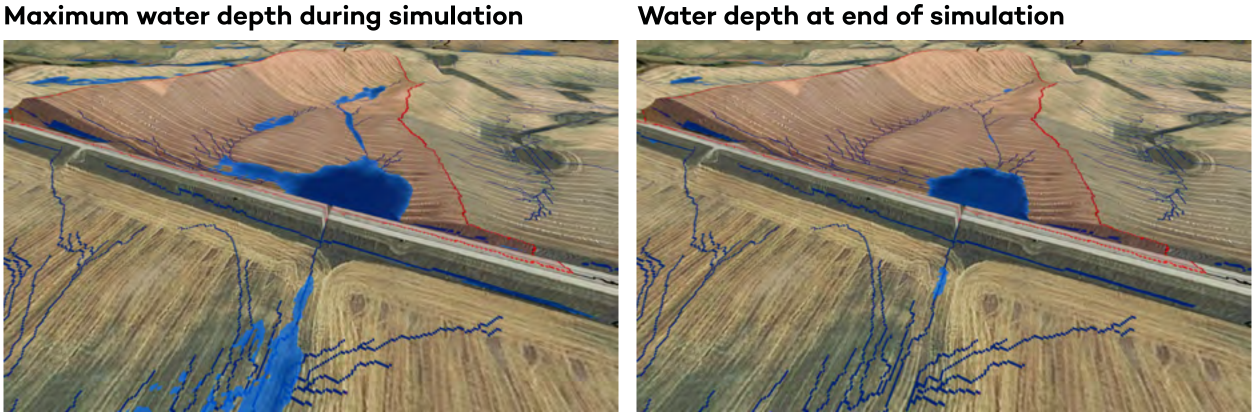
Figure 33. 3D visualization of successful non-contributing area analysis


Maximum water depth during simulation

Water depth at end of simulation

Source: Author render.

Figure 34. 3D visualization of unsuccessful non-contributing area analysis



Source: Author render.

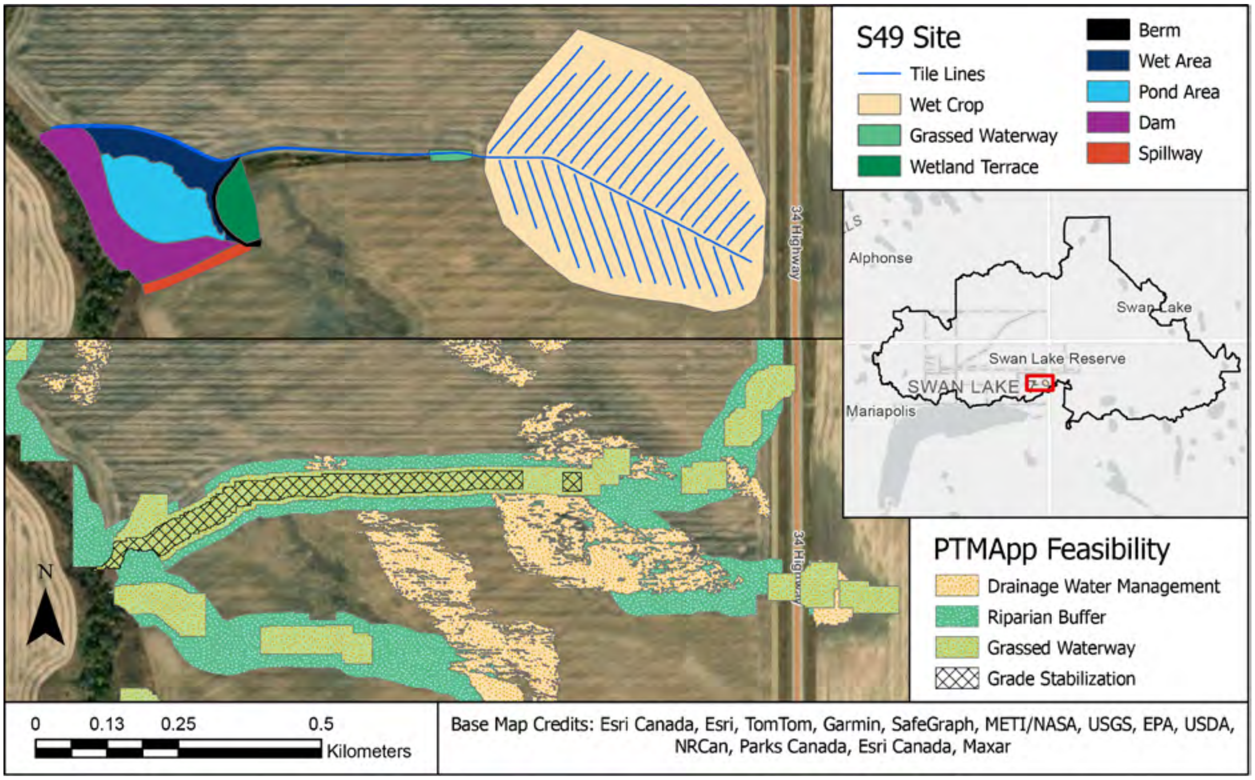
BMP Site Selection Methods and Validation

The number of BMPs assessed by the PTMApp, both in terms of the variety of classifications and the quantity deemed feasible from a single model run, can be intimidating to both the modeller and end user. For this reason, it is useful to reduce the quantity of BMPs produced by the PTMApp before presenting model outputs to project funders or developers. It is also possible to increase the confidence that end users have for model outputs by demonstrating the validity of predicted BMP feasibility. This process of BMP selection, filtration, and validation may be done in several ways; thus, it is important for the modeller to consider who they are preparing the data for and any targeted environmental outcomes.

In this application of the PTMApp model, the Government of Manitoba, the Pembina Valley Watershed District, and Swan Lake First Nation were the target audiences. Therefore, BMP selection and filtration were performed based on several criteria that these end users care most about, such as BMP intersection with non-contributing areas, TP removal, cost-effectiveness, and qualifying whether specific BMPs may be considered "non-starters," for which reasoning can vary between each group. BMPs that may be considered non-starters, for example, include farm ponds/wetlands that may be recommended by the PTMApp in the middle of—rather than the edge of—high-value cropland, where it generally may not be desirable by the landowner. While there is a built-in BMP screening function within the PTMApp, it only accounts for BMP efficiency above the 50th percentile in each output data set. Thus, other more sophisticated considerations may be required to better distill BMP outputs.

A validation of estimated BMP feasibility was completed for the S49 study site within the Swan Lake study area watershed. The S49 site consists of a set of controlled tile drains that feed into a downstream reservoir that is actively managed with stop logs and with upland surface runoff passing through a vegetated channel before entering the reservoir. Figure 35 illustrates the components of the S49 site as well as the feasibility of several overlapping BMP types estimated by the PTMApp. As can be noted, there is significant overlap between the as-built S49 site and the PTMApp recommendations for both the DWM practices and overland protection/filtration practices just downstream. However, unlike the S49 site, PTMApp did not recommend any downstream water retention practices as was decided for construction without the use of PTMApp. This is because the PTMApp does not provide estimations for water retention practices requiring the construction of small dams or other significant earthwork, which, in theory, could be built anywhere with enough streamflow and resources for construction (a limitation that will be revisited in the review of "alternative site selection methodologies").

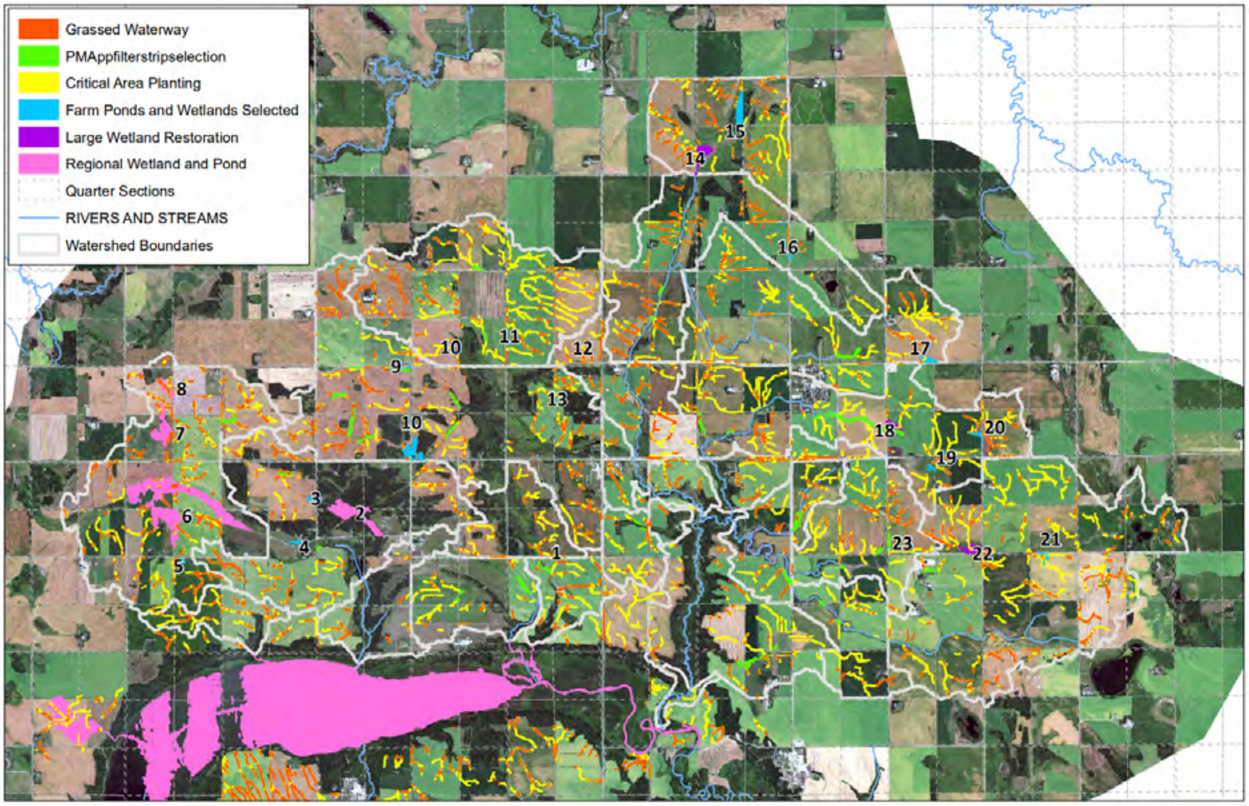
Figure 35. Validation of BMP feasibility at the S49 site



Source: Author map.

Following a distillation of BMPs considering the criteria described previously, an in-person tour of recommended BMP sites within the Swan Lake study area was conducted on October 19, 2022. In attendance at the tour were personnel from IISD, AAFC, the Government of Manitoba, Swan Lake First Nation, and the Pembina Valley Watershed District. The tour was designed around 24 different stops with potential locations for several different BMP types, including farm ponds/wetlands, large wetland restoration, regional wetlands and ponds, grassed waterways, filter strips, and critical area planting. The map of sites printed and used to navigate during the tour is presented in Figure 36, and the insights shared herein are derived from discussions following these in-person site visits.

Figure 36. BMP tour map



Source: Author map.

The Value of Local Knowledge in Hydrologic Modelling

One of the points of discussion during the BMP site tour was with respect to the non-contributing area thresholds defined using the single ground truth site as identified in Section 2.1.2.2. For example, at two of the first farm pond/wetland sites that were visited, local knowledge from a member of the Swan Lake First Nation suggested these sites were within non-contributing areas, which differed from the model results. This insight implies that the criteria used to define average annual non-contributing areas using the single, previously known ground truth site may not have been strict enough and that these additional sites may be used to further refine the criteria used. It is also possible, however, that what can be qualified as an average annual non-contributing area can vary significantly between individuals and thus be difficult to quantify using mixed anecdotal evidence. It is understood that non-contributing areas are not static between years, as they depend on both antecedent and succeeding hydrologic conditions; therefore, it is reasonable to expect differences in interpretation of what is average by some observers and based on different modelling methods. However, this example demonstrates how engaging with and making local knowledge available early in the model development cycle has the potential to produce more useful outputs by aligning them more closely to the expectations of end users.

Landowner Needs and Willingness to Participate

Landowners' needs and willingness to participate are two of the most critical challenges in reviewing and recommending BMP using PTMApp models. In particular, with nutrient reduction being a priority in the Canadian Prairies, there is significant intersection between highly efficient BMPs and existing high-value agricultural land. For example, many of the farm ponds/wetlands identified to have the most cost-effective nutrient load reductions were also those that target high nutrient exporting catchments like cropland. As it is unreasonable to expect that agricultural producers would sacrifice large sources of income in cases like this, it is thought that compensation programs are needed to improve the viability of BMP targeting and implementation within nutrient hotspots like these. Conversely, spatial targeting could also be used to better establish eligibility for compensation by discouraging investment in BMPs that are considered ineffective for meeting program objectives. Maximizing benefits through priority targeting could also ultimately minimize the amount of cropland needed to be taken out of production to reach the same targets.

Another factor identified through BMP selection and prioritization exercises was the consideration of both upstream and downstream impacts of water resources on landowners. For example, one of the farm ponds/wetlands identified during the BMP tour was found likely to have flood-related benefits for the downstream landowner but may increase flooding for the upstream landowner. Although, in this specific case, the BMP may not be desirable for the upstream landowner, it should not be written off that a compensation agreement that is beneficial to both producers would be impossible, particularly if the overall impact of the project at the watershed scale is estimated to be net positive.

Alternative Model Output Interpretations

The BMP site tour also included feasible locations for alternative model outputs, such as grassed waterways, filter strips, and critical area planting. These sites were included as concerns about erosion are increasing within the Pembina Valley Watershed District, in that erosion is taking land out of production and creating dangerous landscapes for both landowners and livestock. While it was known in advance that significant gully erosion has occurred in the district, as evidenced within Figure 37, Watershed District managers do not know exactly where it would be likely to occur in the future, so that they can be proactive in their approach to the issue. For example, during the visitation of feasible critical area planting BMPs, incipient gully erosion could be observed just downstream of one of the tour stops, as shown in Figure 38.

This suggests that PTMApp outputs may be interpreted to identify problem areas before they become a concern and can be used to address localized and watershed-scale erosion issues without the specific need to measure their exact effectiveness.

Figure 37. Previously known and highly progressed gully erosion

Source: Author photo.

Figure 38. Newly discovered and incipient gully erosion downstream near a feasible critical area planting BMP site

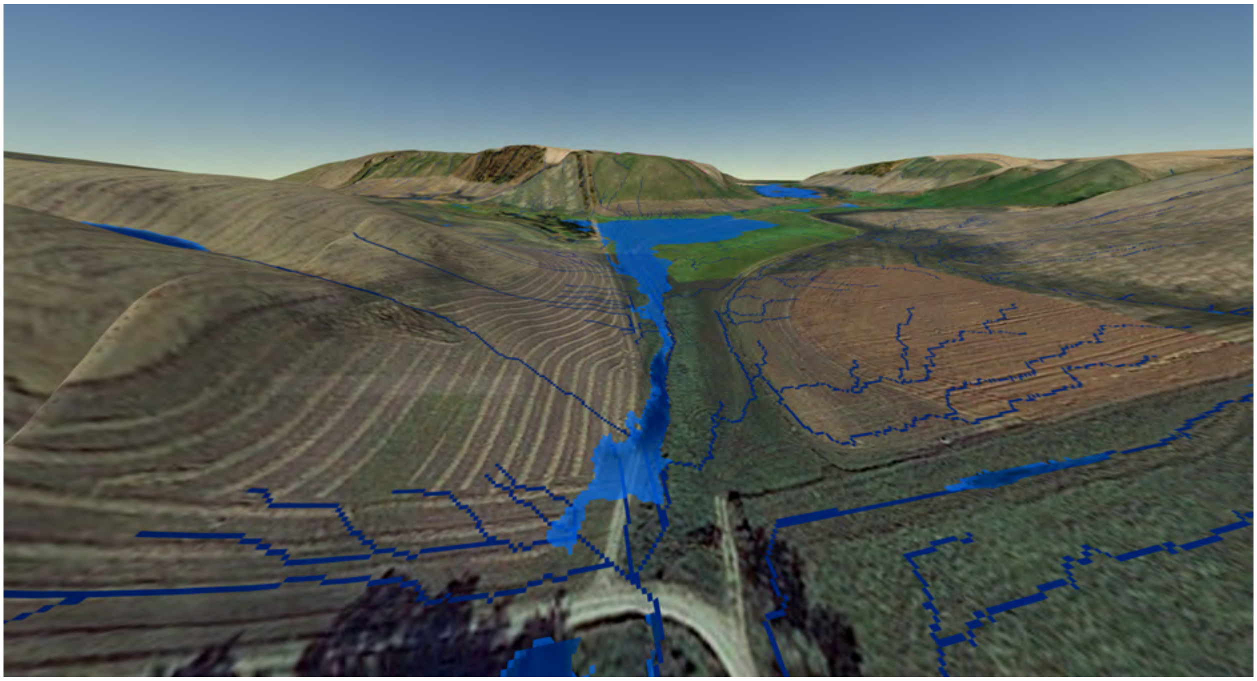
Source: Author photo.

Alternative Site Selection Methodologies

One of the primary limitations of the PTMApp model for addressing targeted implementations of water retention projects across the Canadian Prairies is in its BMP feasibility methods. That is, the PTMApp is well suited to identifying water storage projects that utilize existing topography but is not capable of explicitly identifying or recommending adjustments to that topography, for example, through the construction of small dams. However, by default, the PTMApp produces several outputs that can help facilitate the manual process of small dam site identification and selection, such as flow accumulation rasters and feasible storage BMPs that rely solely on existing topography.

For example, one of the sites selected for the BMP tour was a potential water retention site that, when projected onto 3D maps and flow accumulation lines, revealed a larger natural bowl on the landscape that is evidently cropped around to a distance greater than the estimated permanent pond area, as illustrated in Figure 39. Upon visitation to the site, it was revealed through local knowledge that a culvert had been washed out downstream of this site recently, though flood mitigation strategies had not yet been investigated for the area. Using standard PTMApp outputs, the design of a small dam could be investigated at this location utilizing the permanent (retention) storage and estimated water quality benefits of the suggested ponded area as a baseline but expanded to provide additional temporary (detention) storage for improved flood mitigation benefits.

Figure 39. Overview of a proposed small dam within a natural bowl in the landscape and surrounding cropland



Source: Author render.

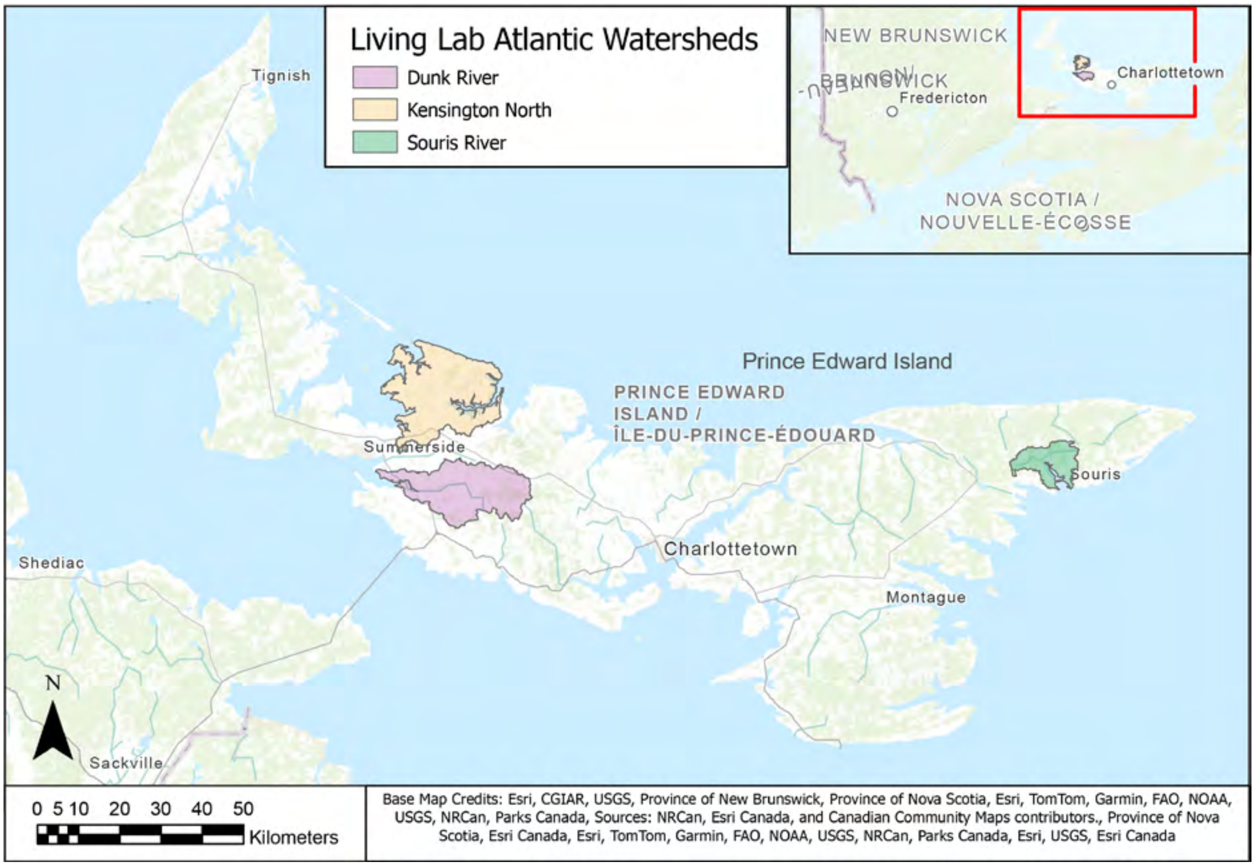
3.2 Options for PTMApp Models Within the Interprovincial Living Labs

In addition to the Canadian Prairies, challenges related to water quality and management are present in the other three Living Labs across the country. This section provides an overview of each Living Lab across Canada, existing modelling efforts, and the potential applicability of the PTMApp within each. An assessment of the resources required to develop further PTMApp models is not provided; however, it is assumed that data already prepared or the outputs of existing modelling efforts would streamline these options.

3.2.1 Living Lab Atlantic

The Living Lab Atlantic, located on Prince Edward Island, is facing water quality issues where the main source of contamination is the intensive application of fertilizers and pesticides to annual crops (potatoes, barley, and soybeans). Along with the accumulation of nutrients and sediments in surface water bodies, frequent rainfall contributes to the leaching of contaminants into the groundwater, affecting the quality of drinking water aquifers and leading to the eutrophication of marine estuaries.

Figure 40. Living Lab Atlantic study watersheds



Source: Author map.

In Prince Edward Island, intensive potato cultivation makes nitrate loss to the environment a significant issue. The modelling study area is the Dunk River watershed in the southern part of the province (Figure 40), where a SWAT model (Arnold et al., 1998) was used to simulate the movement of nitrate from cropped areas to the main outlet through intermediate points (water quantity and quality measurements). Similar to the LLEP Swan Lake study area, the objectives in this watershed are to identify major sources of nitrogen (N) export, predict the impacts of BMPs and land use on N loads, and provide N load estimates for crop rotation scenarios in order to mitigate eutrophication events.

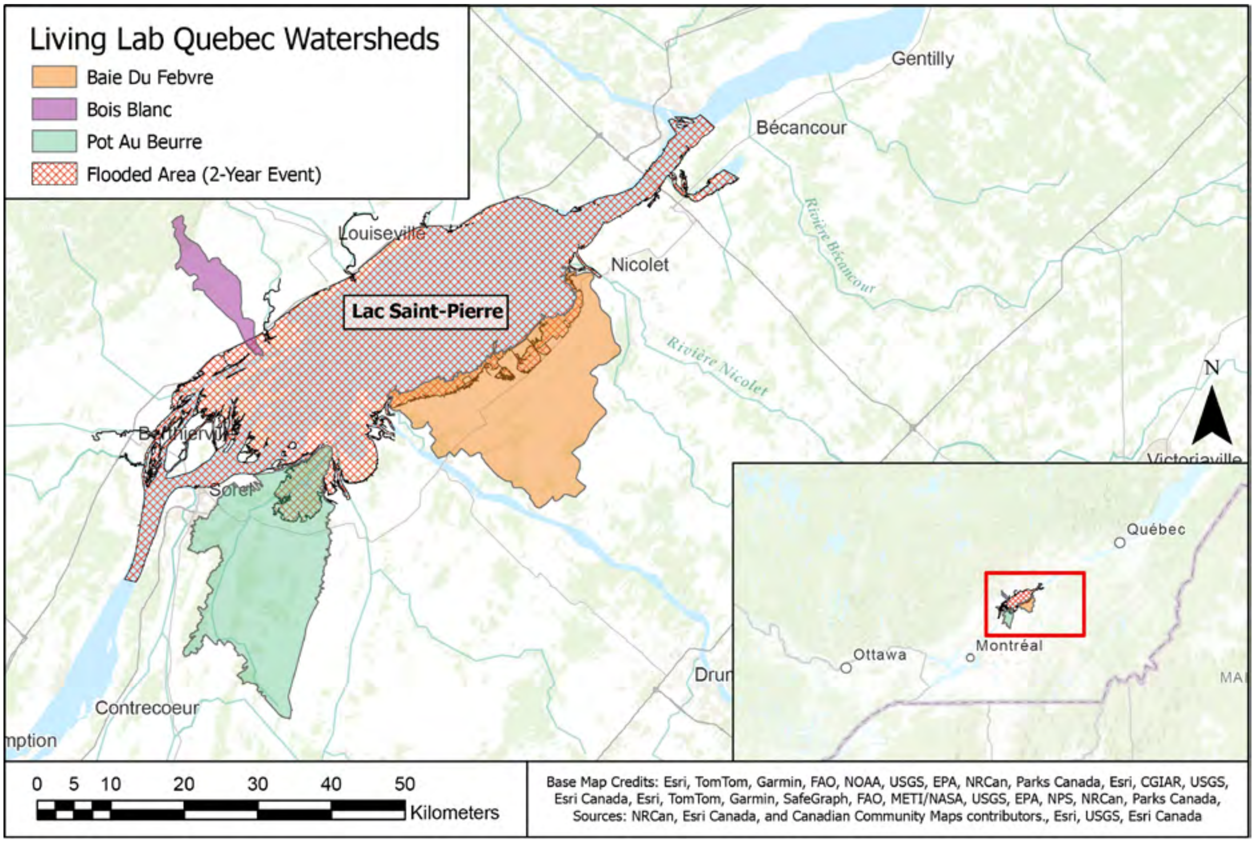
The Living Lab Atlantic project team leveraged SWAT models created a few years prior in the neighbouring Wilmot River watershed (Liang et al., 2020) to parameterize the base model. Preliminary results show that certain rotations, particularly with soybeans, significantly reduce N loads (Mohammad Amir Azimi, hydrological modeller, University of New Brunswick, personal communication, January 17, 2023). In this context, a model such as the PTMApp could open new opportunities for mitigating nutrient loads, including P reduction BMPs. Among other things, the PTMApp could identify alternative non-point sources of nutrient loading and propose complementary water management practices, including drainage control strategies and retention pond locations. Output from the PTMApp model could also contribute to estuarine model predictions. This type of companion modelling would be straightforward and not very resource intensive, as baseline data developed for SWAT is compatible with the PTMApp.

3.2.2 Living Lab Quebec

In Quebec, Living Lab activities take place within three different watersheds draining into Lake Saint-Pierre (a shallow widening of the St. Lawrence River). In recent decades, these low-relief watersheds have seen many perennial crops converted to annual crops (corn and soybeans). This trend has caused a significant increase in the transport of sediments and nutrients to Lake Saint-Pierre, in addition to the sediments transported during the spring floods around the lake. In addition to the degradation of water quality and the aquatic ecosystem, the accumulation of sediment deposits makes it difficult for shipping traffic in the narrow channel in the centre of the lake/river inlet and requires dredging.

In the Living Lab Quebec study areas, there is a history of modelling, including the SWAT-Qc model (Michaud et al., 2008) developed by the Institut de recherche et de développement en agroenvironnement. This SWAT-Qc model was developed specifically for the agricultural environment and simulates management practices and artificial drainage under Quebec conditions. In particular, the downstream areas of the Bois-Blanc, Pot-au-Beurre, and Baie-du-Febvre watersheds, near the shoreline of Lake Saint-Pierre (Figure 41) could benefit from the capabilities of the PTMApp, among others, because of the low-relief topography located in floodplains, which sometimes exhibits non-contributing areas (floodplain downstream of Baie-du-Febvre, also known as the South Shore orphan watersheds). In these regions, water contamination problems (sediment transport) occur mainly on an event basis and require solutions such as retention structures, flow control, and fertilizer management. The approach developed for the BMP feasibility study in the Swan Lake watershed could be adapted to this context.

Figure 41. Living Lab Quebec study watersheds, including Lac Saint-Pierre flooded area (2-year event, 1985–2020 reference scenario)



Source: Author map based on Ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs, 2023.

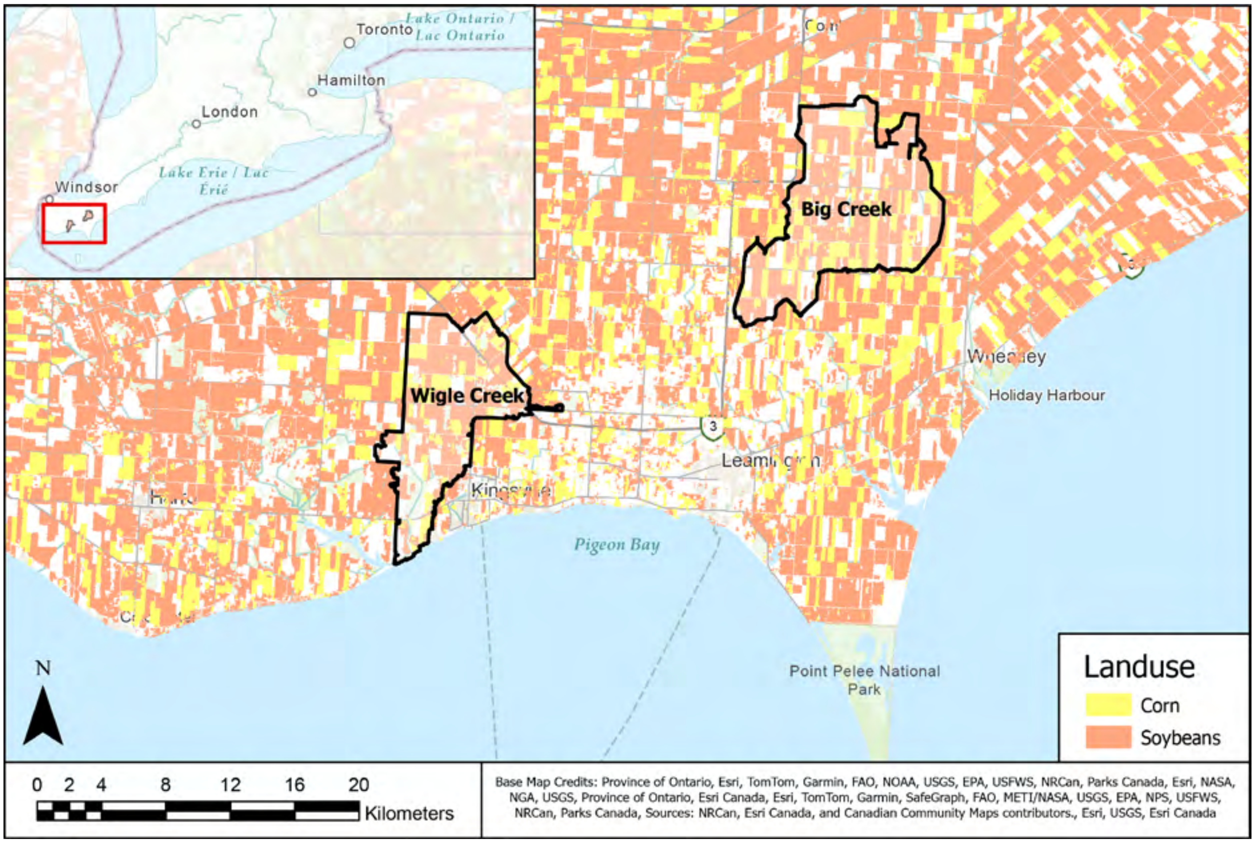
As part of this Living Lab, the field-scale HYDRUS 2D/3D finite element model (Šimůnek & Šejna, 2022) was also applied to evaluate the effectiveness of riparian buffers on solute (nutrient) transport from soils to streams. Water flow parameters developed at the field scale could help calibrate models such as SWAT or the PTMApp and potentially scale up the performance of riparian buffers to a larger scale (watershed) and promote the integration plan as a beneficial practice.

3.2.3 Living Lab Ontario

The Living Lab Ontario includes sites located in the Thames River watershed, whose outlet is Lake St. Clair, upstream of Lake Erie. Agriculture in southern Ontario is characterized by relatively flat, well-drained terrain and annual crops (corn and soybeans); extensive soil degradation is offset by high levels of fertilizer use, including phosphorus. The eutrophication issue in Lake Erie is a national priority, and several initiatives and programs are underway to improve practices to reduce nutrient losses from farmland.

In Ontario, the SNOWPACK model, previously developed for the Bay of Quinty (Richards et al., 2022), has been used to model ground snow accumulation and freeze-thaw dynamics in the Wigle Creek and Big Creek watersheds (Figure 42). In these two watersheds, agricultural land use, such as cropping corn and soybeans, is very prevalent. Eventually, data from the SNOWPACK model could be integrated into a model such as SWAT or the PTMApp to improve spring runoff event simulation and to better understand the impact of cover crops and fertilization practices on sediment/nutrient transport. SNOWPACK model input data can be adapted to the PTMApp and surrogate models like HEC-HMS (as explored in Section 2.4.1); field (soil moisture and temperature, snow water equivalent) and edge-of-field (water flow, water quality) data can also be used for calibration/validation.

Figure 42. Living Lab Ontario Wigle Creek and Big Creek study watersheds and 2021 AAFC crop inventory



Source: Author map based on AAFC, 2023.

Beyond the Living Labs, much hydrological modelling work has been done around Lake Erie, and the available data in this region offers an excellent opportunity to develop PTMApp models in the context of water management and BMP assessments during extreme events (e.g., the impact of water erosion on nutrient transport during heavy precipitation in a drought-affected region).

4.0 Summary and Conclusions

Section 1 of this report provided background on Canadian Prairie hydrology, including the impacts of climate change and extreme events on water quality and availability. The introduction also described a longstanding need for spatial targeting methods to be developed and tested, with specific considerations for the Canadian Prairie context. The Swan Lake study area, one of four LLEP watersheds, has facilitated this development and testing.

Building upon the PTMApp model (Houston Engineering Inc., 2016), Section 2 demonstrated that existing spatial targeting methods can be used as a foundation to consider high-frequency and severe nutrient-loading event scenarios, such as spring runoff in the Canadian Prairies. For example, Section 2.3.2 demonstrated how the consideration of inflow volume from a 2-year spring runoff for a farm pond/wetland BMP could only achieve 71% of its performance versus a 10-year, 24-hour rain event (i.e., a final TP reduction of 51% instead of 72%). BMP performance under spring runoff conditions is particularly relevant to the Swan Lake study area as 21.1% of farm pond/wetland BMPs (106 out of 503) saw performance reductions across the study area, with the lowest being just 57% of the median assessed value for the alternative 10-year 24-hour rain event (i.e., a final TP reduction of 41%). This section also suggested methods by which PTMApp inputs can be adapted to hydraulic models to assess non-contributing areas, which extends BMP evaluation to average flow conditions and their reduced effectiveness or non-effectiveness during these more typical events.

In the exploration of methods used to derive more conservative estimates for BMP performance under spring runoff conditions and to develop non-contributing areas, this report also provided numerous strategies and guidance for model development and output interpretation. Strategies included a description of the methods used for evaluating the hydrology and non-contributing areas of ungauged basins using HEC-HMS and HEC-RAS. Guidance included how a suite of outputs from the PTMApp model may be interpreted by decision-makers, as well as recommendations on the importance of reviewing large spatial input datasets for accuracy. For example, it was found that without a correction to the initial land-use input data in the PTMApp, the nutrient reduction estimated for a downstream farm pond/wetland BMP, in one case, could be 47.7% overestimated.

This report also reviewed several other inputs and methods that could be considered to obtain further improvements in PTMApp model accuracy; however, the list of inputs and methods was not exhaustive, and the impacts of each were not evaluated quantitatively. Some of these inputs and methods included

- sources of alternative hydrologic model inputs,
- recommendations for additional detail within hydro-conditioning inputs,
- recommendations for higher-resolution and detailed soil and land-use data,

- methods to improve BMP performance statistics and the implementation of more representative wetland treatment models, and
- methods to improve existing BMP unit costs and cost functions.

With methods for BMP spatial targeting in the Canadian Prairies established and a pilot PTMApp model of the Swan Lake study area considering them developed, practical applications of its model outputs were tested. These applications were assessed by the provincial Government of Manitoba, Watershed District managers, and First Nations, who each provided insights about the usefulness or limitations of methods and outputs from their perspectives.

From the Government of Manitoba's perspective, one of the primary limitations of the PTMApp is that it is not capable of recommending explicit adjustments to topography within its BMP feasibility functions. For this reason, the model cannot provide recommendations for the construction of small dams by default. However, the PTMApp is still useful for the identification of smaller permanent storage sites with strong baseline water quality benefits that could be constructed with additional temporary storage for flood mitigation benefits through additional engineering and design. Sites identified and designed using this strategy could help reduce the number of water retention sites that are developed only opportunistically based on landowner willingness alone.

From the perspective of Watershed District managers, information derived from modelling tools like the PTMApp can help engage landowners and get "buy-in" from producers on potential projects because it shows them the benefits (Neil Zalluski, personal communication, 2023). Even if there is not a high degree of confidence in the predicted effects and there are gaps in the science, it helps to open a dialogue with producers. Many are interested and willing to participate and contribute to assessing the performance of these BMPs on their land and helping to address science gaps. These tools can improve current targeting efforts, which are mainly limited to finding a small number of potential large-scale projects (e.g., large water retention projects and dams) identified through consultation with local municipalities and the Government of Manitoba and included within Integrated Watershed Management Plans. Because projects in these plans are assessed mainly for flood reduction benefits, information on smaller-scale sites accompanied by predictions for other benefits, such as downstream water quality improvements, would expand the scope for BMP targeting efforts (Neil Zalluski, personal communication, 2023; Justin Reid, personal communication, 2023). Identifying potential locations for small wetlands, class 1 and 2, and their benefits in terms of water storage and downstream water quality improvements, such as reduced nutrient delivery, would also help Watershed Districts get more of these land features in strategic locations (Cliff Greenfield, personal communication, 2023).

There are also opportunities for information produced by these tools regarding erosion reduction and sites that need protection or remediation, such as those where gullies are forming, and valuable farmland or other property is being lost or degraded. Expanding the assessment of BMP types beyond those related to water storage would be a significant asset to Watershed Districts and land managers like Swan Lake First Nation to support their goals of more effectively directing their limited resources to the most effective projects and locations (Cliff Greenfield, personal communication, 2023).

The relevance of and insights on the methods and outputs for PTMApp applications within other Living Labs across Canada were also reviewed. This brief overview of the national network of Living Labs in Canada covered relevant water issues and the hydrologic modelling work that is being completed in each. Although the PTMApp applications shared in this report focused on phosphorus, the practices shared can be extended to nitrogen and sediment modelling, which would require greater emphasis in these other watersheds. Furthermore, the presence of existing development efforts using models such as SWAT, which has inputs similar to those of the PTMApp, suggests that model development in these regions could be expedited.

The insights provided by a comprehensive group of different end users suggest that there continues to be a strong desire to develop spatial targeting models across the Prairies and Canada for better return on investment from BMPs. This desire also extends principally to natural infrastructure, which many structural BMPs fall under the definition of and which is seeing a greater push for development in Canada (Government of Canada, 2022b). Although the needs and priorities of each potential user group vary, the specific variations identified in this report are thought to be reasonable and could be accommodated within similar development efforts in the future. The alignment of model development efforts with different users' needs is of the utmost importance and may only be well understood through proper engagement with those users. This process of co-development was fundamental in establishing the LLEP and is recommended for any similar future BMP spatial targeting efforts.

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Appendix A. Model Input Data Summary

Tables A1, A2, and A3 provide a summary of the input data used for the Prioritize, Target, and Measure Application (PTMApp), Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS), and Hydrologic Engineering Center – River Analysis System (HEC-RAS) models presented in this document. Included in the summary for each model is the type of input data, its purpose within model development, and its source. Clear guidelines on how to develop a PTMApp model using default methodologies and its assumptions are freely available on the Minnesota Board of Water and Soil Resources' (2022) website within the PTMApp Learning Center. Additional guidance on developing PTMApp inputs using Canadian rather than U.S. input datasets is also provided by Houston Engineering Inc. et al. (2019) in their application of the model on the Roseau River. Similar prerequisite knowledge would be necessary to duplicate the modelling strategies presented for both the HEC-HMS and HEC-RAS models; for these, guidance is provided by the U.S. Army Corps of Engineers (2022a, 2022b). A review of these suggested resources is considered necessary for a hydrologic modeller to replicate all or parts of the presented modelling strategy in this document if they are not already familiar with these models.

Table A1. PTMApp input data

Input Data	Purpose	Source
LiDAR Digital Elevation Model (DEM)	Model terrain	Manitoba Land Initiative (Government of Manitoba, 2022c), National Elevation Dataset (United States Geological Survey, 2023)
Culvert inventory	Hydrocondition terrain	Agriculture and Agri-Food Canada (AAFC), Pembina Valley Watershed District, Province of Manitoba, and Swan Lake First Nation
Intensity-Duration-Frequency (IDF) curves	2- and 10-year 24-hour rainfall	Environment and Climate Change Canada (ECCC), 2019
Soil	Soil Conservation Service (SCS) curve number and RUSLE parameters	Agricultural Interpretation Database by municipality (AAFC, 2019) and Cordeiro et al., 2018
Land use	SCS curve number and RUSLE parameters	AAFC (2023) 2018 Crop Inventory
Stream flow	2- and 10-year spring runoff	HEC-HMS model (Table 7)
Total phosphorus (TP) concentrations	Nutrient export calibration	Lake Winnipeg Foundation (2019) Community Based Monitoring Network

Source: Authors.

Table A2. HEC-HMS input data

Input Data	Purpose	Source
Precipitation	Climate model	Regional Deterministic Precipitation Analysis (Canadian Meteorological Centre, 2019)
Shortwave/longwave radiation and wind	Climate model	WATCH-Forcing-Data-ERA-Interim (WFDEI) Meteorological Forcing Data (Weedon et al., 2014)
Air and dew temperature	Climate model	NASA (2019) POWER | Data Access Viewer, Agroclimatology Data
Stream flow	Hydrologic model calibration/validation	Water Survey of Canada, 2020
LiDAR DEM	Sub-basin parameters	Manitoba Land Initiative (Government of Manitoba, 2022b)
Soil	Sub-basin parameters	Agricultural Interpretation Database by municipality (AAFC, 2019)
Land use	Sub-basin parameters	AAFC (2023) 2018 Crop Inventory

Source: Authors.

Table A3. HEC-RAS input data

Input Data	Purpose	Source
LiDAR DEM	Model terrain	Manitoba Land Initiative (Government of Manitoba, 2022b)
Culvert inventory	Hydro-condition terrain	Agriculture and Agri-Food Canada, Pembina Valley Watershed District, Province of Manitoba and Swan Lake First Nation
Road/rail network	Flow cell boundaries	Manitoba Land Initiative (Government of Manitoba, 2022b)
IDF curves	2-year 24-hour rainfall event	ECCC (2019)
Soil	SCS curve number	Agricultural Interpretation Database by municipality (AAFC, 2019)
Land use	SCS curve number	AAFC (2023) 2018 Crop Inventory

Source: Authors.

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