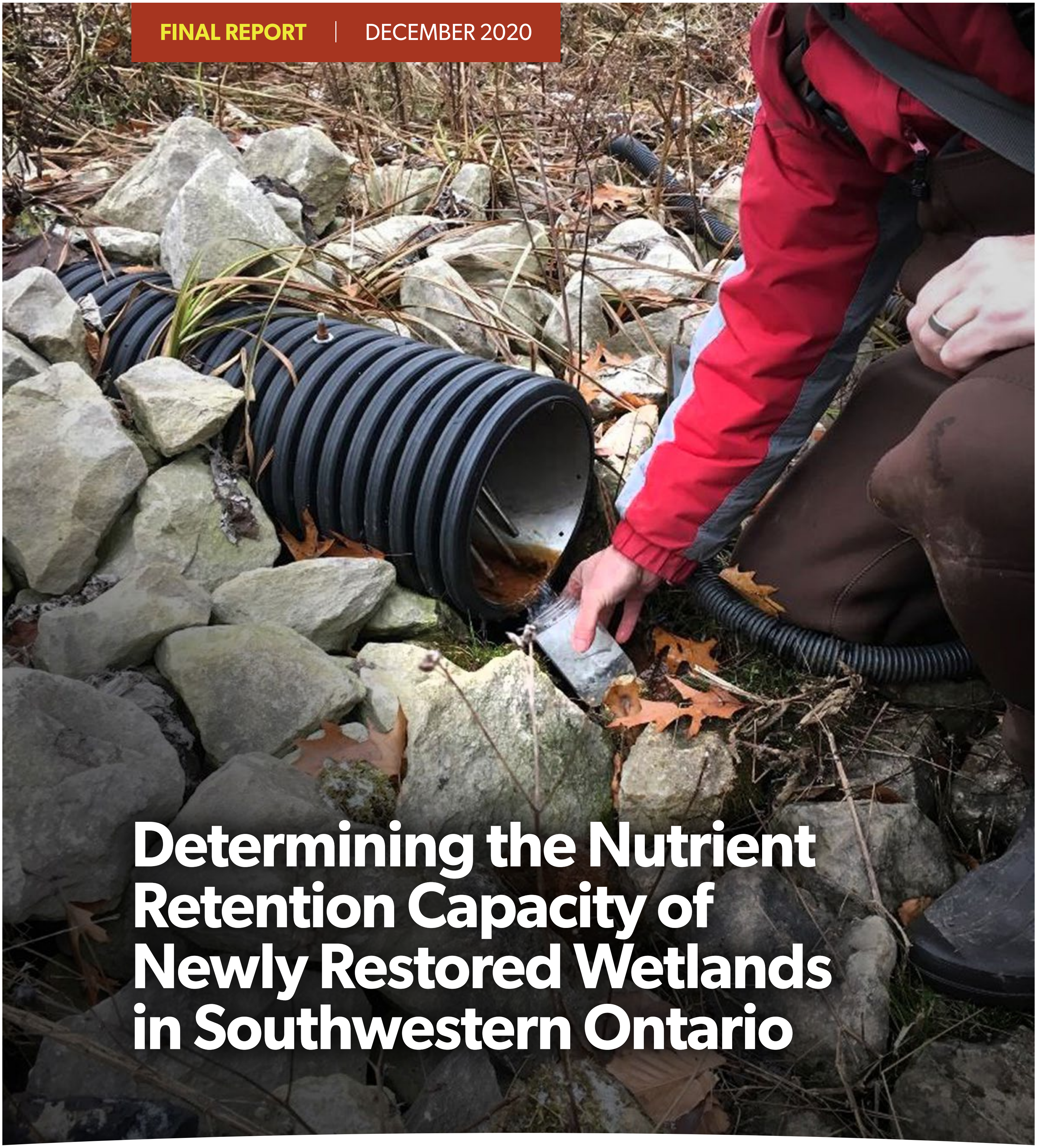
FINAL REPORT | DECEMBER 2020



Determining the Nutrient Retention Capacity of Newly Restored Wetlands in Southwestern Ontario

Ducks Unlimited Canada

Institute for Wetland and Waterfowl Research

Determining the Nutrient Retention Capacity of Newly Restored Wetlands in Southwestern Ontario.

AUTHORS
Bryan Page, Research Biologist, Institute for Wetland and Waterfowl Research, Ducks Unlimited Canada.
Parsa Aminian, Conservation Programs Engineer, Ducks Unlimited Canada.
Owen Steele, Head of Conservation Programs – Ontario, Ducks Unlimited Canada

ACKNOWLEDGEMENTS
We would like to sincerely thank all landowners who allowed their wetland restoration projects to be monitored as part of this project. The kindness and trust that was shown to allow DUC's staff and partners to access their private land at a weekly, and sometimes biweekly, rate was truly gracious. From many meetings in the field, it is clear they are all passionate about their wetland projects and are concerned for Lake Erie's water quality.

This project was funded in partnership with the *North American Wetlands Conservation Act* of the U.S. Fish and Wildlife Service and the Ontario Ministry of Natural Resources and Forestry. We greatly appreciate the assistance of the St. Clair Region Conservation Authority in conducting field work over the course of this project.

COVER IMAGE:
Weekly site monitoring was conducted by staff from the St. Clair Region Conservation Authority. © DUC

AMENDMENT:
Amendment to the report, as of December 2020, includes updates to the 'Contributing Area' of the Method section (page 14), and two erroneously labeled sites on page 60 and 63, with revisions to the corresponding appendix (pages 46 and 47). For more information on the updates, please contact report author; Bryan Page at b_page@ducks.ca

Institute for Wetland and Waterfowl Research

Table of Contents

List of Tables

List of Figures

Executive Summary

Canada and the United States, as guided by the 2012 Great Lakes Water Quality Agreement, adopted phosphorus reduction targets for the western and central basins of Lake Erie in 2016 to minimize impacts from nuisance algae. Restored wetlands have been identified as natural infrastructure with the potential to reduce phosphorus loads entering streams and rivers across the working landscape of southwestern Ontario and ultimately reduce phosphorus loading to Lake Erie. Ducks Unlimited Canada monitored eight newly restored edge-of-field wetlands that received nonpoint source agricultural runoff for one water year (October 1, 2018 to September 30, 2019) to determine the nutrient retention capacity and the nutrient reduction efficiency of these restored systems. Wetland nutrient removal rates were found to be positively correlated with nutrient loading rates. TP and TN mean wetland retention capacity were determined to be 7.2 and 378 kg ha^{-} $year^{-}$, respectively. TP and TN mean reduction efficiency were determined to be 39 % and 44 %, respectively. All eight wetland basins retained SRP with an overall net SRP retention capacity of 5.7 kg ha^{-} $year^{-}$ and a mean 67 % reduction efficiency. Restored wetlands were found to function in a nutrient retention role in all four seasons. These results indicate that restored wetlands can be effective to reduce nonpoint source nutrients from entering Lake Erie.

Prepared by:
Bryan Page
Research Biologist
Institute for Wetland and Waterfowl Research
Ducks Unlimited Canada
January 17, 2020

Project Overview

In 2012, the Great Lakes Water Quality Agreement (GLWQA) was signed between Canada and the United States (U.S.) demonstrating an international commitment to restore and protect the waters of the Great Lakes (GLWQA 2012). The GLWQA binational team has recommended a 40% reduction in phosphorus loading relative to the year 2008 to bring the western and central basins of Lake Erie back to a mesotrophic state, and the eastern basin of Lake Erie back to an oligotrophic state (Team 2015). Additionally, the GLWQA requested the Lake Erie basin governments develop a Domestic Action Plan to guide the achievement of the phosphorus reduction targets. In February 2018, the Canada-Ontario Lake Erie Action Plan (LEAP) was released highlighting the importance of wetland restoration as a recommended strategy to help reduce phosphorus loads entering Lake Erie (Canada-Ontario 2018). Based on this recommendation, a detailed standardized wetland monitoring protocol to assess the nutrient retention capacity of newly restored wetlands (ages 2 to 6 years old) was developed in July of 2018 (DUC 2018). This standardized protocol, produced by Ducks Unlimited Canada (DUC), was designed to be applied to the major types of wetland restoration projects implemented in southwestern Ontario and has been peer reviewed by federal and provincial government personnel, various local conservation authorities, and academics with an expertise in wetland monitoring.

On October 1, 2018, DUC's Institute for Wetland and Waterfowl Research (IWWR) began implementing the standardized wetland monitoring protocol as part of a research project aimed at assessing the ability of newly restored wetlands to retain nutrients on the landscape in southwestern Ontario. This report presents the final data from this project for the period covering October 1, 2018 to September 30, 2019 representing one full water year of monitoring.

Project goals and objectives

The overall goal of this project is to quantify the mass of nutrients retained in newly restored wetlands in southwestern Ontario to determine if such natural infrastructure can effectively mitigate nutrient export in this agricultural landscape. This information is required to help quantify how wetland restoration can help the LEAP reach the phosphorus reduction targets set for Lake Erie.

The specific objectives of this project are:

- Determine the wetland nutrient retention capacity (kg ha^{-} yr^{-}) of newly restored wetlands in southwestern Ontario.
- Determine the nutrient reduction efficiency (%) of newly restored wetlands in southwestern Ontario.
- Explore relationships between wetland basin characteristics and nutrient retention capacity.

Introduction

Over the past two decades, Lake Erie has once again entered into a state of eutrophication. Land use change, climate change, and efficient drainage of agricultural landscapes through surface and subsurface drainage are among the main reasons for the recent increased phosphorus loads to Lake Erie (IJC 2014). Phosphorus enters Lake Erie via point sources (wastewater discharge) and non-point sources (agricultural runoff, urban runoff). A recent report demonstrated that the majority of phosphorus entering Lake Erie is from non-point sources (Maccoux et al. 2016). The form of phosphorus delivered to Lake Erie has also shifted with soluble reactive phosphorus (SRP) comprising a larger proportion of the overall phosphorus load, resulting in more bioavailable phosphorus for algal growth (Jarvie et al. 2017). With wetland loss rates in excess of 85% in many counties of southwestern Ontario (DUC 2010), it has been proposed that wetland restoration can play an important role in retaining non-point source phosphorus on the landscape. However, there has been no attempt to quantify specific nutrient retention rates for phosphorus and/or other nutrients in newly restored wetlands within this geographic area of Canada.

Wetlands are widely acknowledged for their capacity to intercept and retain non-point source phosphorus, acting as buffers to reduce the load of phosphorus to downstream lakes (Zedler 2003, Hansson et al. 2005, Dunne et al. 2015). Wetlands retain phosphorus via biotic and abiotic processes. Micro-organisms can assimilate phosphorus from the water column (Richardson 1985), periphyton and other algae can retain phosphorus from the water column (Wetzel 2001) and macrophytes have been reported to accumulate phosphorus during growth periods (Fisher and Acreman 2004). While these biotic processes assimilate phosphorus during growth phases, they can also release phosphorus back to the water column at times of senescence. Abiotic processes that contribute to phosphorus retention include the sorption of dissolved phosphorus to cations such as iron, calcium and aluminum and the physical sedimentation of particulate phosphorus (Wetzel 2001). However, sorption processes are often governed by dissolved oxygen levels, and phosphorus can be released under anoxic conditions to the water column (Hogan et al. 2004) while increased water flow through a wetland can cause resuspension of sediment bound phosphorus and other particulate phosphorus thereby increasing the phosphorus load out of the wetland (Fan et al. 2012). Physical characteristics such as wetland area, depth and position on the landscape can further influence the ability of wetlands to retain or release phosphorus at various points in time (Fan et al. 2012, Land et al. 2016).

With numerous complex processes and physical factors involved in governing phosphorus cycling within a wetland basin, researchers quantify phosphorus retention in a wetland by measuring the total inputs and outputs of phosphorus to calculate a net phosphorus retention value. This metric which can be reported as a phosphorus retention capacity (kg ha^{-} yr^{-}) or as phosphorus reduction efficiency (%) is used as an indicator of a specific wetlands function to reduce (or release) phosphorus to downstream rivers and lakes. Phosphorus reduction efficiency reported in the literature can vary widely. Kovacic et al. (2000) monitored three constructed wetlands in Illinois for three years that received agricultural runoff with phosphorus reduction efficiencies ranging from a net loss of 54% to a net retention of 80% with an overall 2% phosphorus removal rate. A two year study on seven newly constructed wetlands in Sweden that received agricultural runoff were found to have a total phosphorus (TP) retention capacity ranging from 11 to 175 kg ha^{-} yr^{-} (Johannesson et al. 2015). Fisher and Acreman (2004) conducted a review of the literature and found that 41 of 48 wetlands retained phosphorus, 5 of 41 wetlands released phosphorus and 2 of 48 wetland showed no net change. (Mitsch and Gosselink 2000) summarized total phosphorus retention capacities from constructed wetlands that receive nonpoint source pollution in a cold climate ranging from 4.0 to 29.0 kg ha^{-} yr^{-}. Based on the variability in these research results, it is evident that the variety of biotic and abiotic processes within a wetland along with the physical characteristics of the wetland basin can influence phosphorus retention.

The phosphorus retention capacities of newly restored wetlands located at the 'edge of field' location in southwestern Ontario are unknown. Our study aims to determine these retention capacities for phosphorus and nitrogen species in newly restored wetlands across the agricultural landscape of southwestern Ontario. DUC's interest in this research is to guide and better understand the potential of its wetland and waterfowl conservation activities to contribute natural infrastructure that captures and reduces phosphorus flowing downstream.

Study sites

Between November 2017 and August 2018, we visited a series of 37 newly restored wetlands that had been implemented specifically as wildlife habitat by DUC and its conservation partners to select the study sites. The vast majority of restored wetlands in southwestern Ontario can be described as 'edge of field' sites where the wetland is located in a low-lying area of the landscape that receives runoff from agricultural landscapes. We focused our monitoring on newly restored edge of field wetlands that were >0.1 ha in area as these represent the bulk of wetland restoration occurring in this landscape. With data requirements, logistical requirements and financial considerations, eight newly restored wetlands were selected within the Lake Erie drainage basin. These included sites in the Thames River watershed, the Syndenham River watershed, Kettle Creek watershed and Catfish Creek Watershed were selected to test the standardized wetland monitoring protocol for assessing nutrient retention.

The locations of the eight newly restored wetland research sites, hereafter referred to as 'sites', are shown in Figure 1. The eight restored wetlands range in age from 2 to 6 years and range in area from 0.14 ha to 0.74 ha. All sites are located at the lower edge of an agricultural field and all receive runoff from upland agricultural landscapes. This agricultural runoff originates from overland sheet flow and/or from buried agricultural drainage tile (hereafter referred to as "tile") that outlets directly into the wetland. Site FE has an upland comprised of both hay and row crop production, while the other seven sites receive runoff strictly from row crop production with corn and soybean being the dominant crop types (Table 1). Pictures of each site are provided in Appendix A.

Four sites (LL, BL, FE, DY) have no defined inflow channel. Six of eight sites had outflow culverts as part of their final wetland restoration project design (FE, DY, OH, MO, KE, MA) while site LL had an outflow culvert installed on October 11, 2018 and BL had an outflow culvert installed on February 1, 2019 before the basins reached spill elevation. Sites OH and KE both have two tile inlets that contribute directly into the wetland basin while site DY has one tile inlet. Sites MO and MA have tile inlets that produce inflow into a gully which leads to the main inflow of the wetland. At these sites, a culvert was present (site MA) and installed (site MO) to provide one main inflow site directly above the wetland. Sites OH and KE are the only two sites that have defined channels that strictly deliver overland flow into the wetland basin. Site BL is the only site where the upland tile drainage system discharges the tile water away from the basin into a separate drainage ditch.

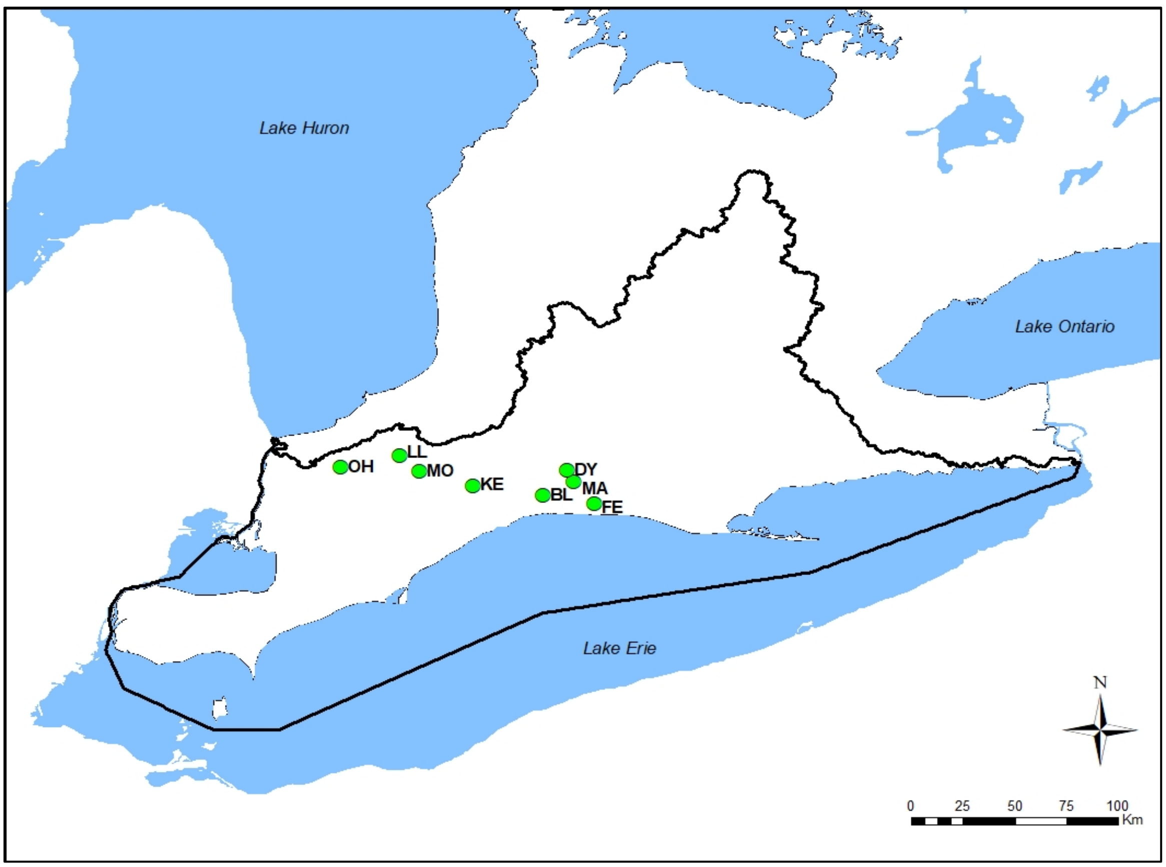


Figure 1. Locations of eight restored wetland research sites across southwestern Ontario within the Lake Erie watershed.

Table 1. Site information.

Site ID	Basin Age (years)	Basin Area (ha)	Basin Volume (m^3)	Contributing Area (ha)	Contributing Area: Wetland Area	2018 Crop	2019 Crop
OH	2	0.74	6,253	18.3	25	Soybeans	Soybeans
LL	5	0.48	3,720	3.0	6	Corn	Soybeans & Corn
MO	5	0.14	1,013	30.0	219	Soybeans	Soybeans
KE	2	0.19	827	63.6	334	Corn	Soybeans
FE	6	0.53	4,231	3.5	7	Hay & Soybeans	Hay & Soybeans
MA	5	0.18	927	8.0	43	Soybeans	Corn
DY	3	0.21	1,880	2.2	10	Soybeans	Winter Wheat
BL	2	0.17	1,247	2.7	16	Corn	Soybeans

Methods

To measure inflow and outflow at all inlets and outflow channels, low profile area velocity sensors with an accompanying data logger (Teledyne 2150 or Teledyne 4150) were used. These flow sensors contain a pressure transducer that allows for continuous depth measurement (limited to 25 mm water depth) and utilize Doppler technology to measure continuous flow velocity (range of -1.5 m s^- to 6.1 m s^-). Prior to deploying these systems in the field, 16 flow sensors and loggers were brought to the Hydraulics Research and Testing Facility at the University of Manitoba where they were calibrated in a controlled flume. Once the flume was set to a specific flow rate (mean flow rate of 22 L min^-), all 16 flow probes attached to the data loggers were deployed in the flume to assess the calibration of each. All 16 flow probes and loggers showed good recorded flow rates when compared to the control flow rate of the flume and were deemed fit for field deployment (Appendix A).

Field equipment was installed at the eight sites between September 19^{th} to the 26^{th}. Twelve low profile area velocity sensors and data loggers were deployed. All eight outflow culverts were equipped with a continuous flow logger while sites OH and KE each had a tile inflow with a diameter large enough to have a continuous flow probe installed. Low profile velocity sensors were attached to a spring ring which was inserted inside the culvert to hold the flow sensor in place. Culvert diameters at each site were entered into the Flowlink software and the flow loggers were programed to measure water level and velocity every 15 minutes. From the culvert diameter, water depth and water velocity, flow rates were calculated and logged every 15 minutes.

Water level was recorded every six hours during the ice-off season (October 1 to November 31, 2018 and April 1 to September 30, 2019) using Ecotone water level recorders that were installed in each wetland basin. On the last week of November, the ecotone water level recorders were replaced with AssetPack3 (AP3s) equipped with a laser level that records distance from the laser head down to the water surface. Water level using the AP3s were logged up to four times a day during the off-ice season from April 1 to September 30, 2019.

Runoff trays were deployed at four sites that have no defined inflow point (LL, FE, DY, BL) to collect runoff contributed to the wetland basins during precipitation events. Runoff trays were positioned near the riparian/field interface to collect runoff that was generated in the upland field and not water that was generated or influenced by any part of the wetland basin (i.e. riparian area). Specific locations of the runoff trays were selected based on the area that contained an adequate slope to increase the chance of collecting enough runoff water to represent the major land use within the contributing area of the restored wetland basins. Runoff trays were placed on the ground in areas that were lightly excavated so the lip of the runoff tray was flush with the upland soil/vegetation interface then secured with four anchor pegs to prevent the trays from shifting over time. Runoff trays were then covered with a large board to prevent the trays from receiving atmospheric contamination. Thermo Scientific Storm Water Samples Bottles (1 liter) were deployed in holes beneath the runoff trays. These bottles contain a dome cover to keep the bottle clean while deployed along with a coarse filter which keeps any large debris from entering the bottle. The protective dome likewise acts to fill the bottle up slow over the course of a runoff event so the water collected is not solely from the immediate first flush of the runoff event. Runoff trays were cleaned during each site visit with distilled water to remove any dirt and dust that may have accumulated on the tray surface while the runoff bottles were replaced with a clean bottle. Pictures of the deployed field equipment are provided in Appendix A.

Data Collection: October 1, 2018 to September 30, 2019

DUC contracted the St. Clair Region Conservation Authority (SCRCA) to help collect field data over the course of the project. In general, field sites were visited once every week with sites visited twice during periods of high flows and not visited on weeks when flow either stopped or was at stable base flow conditions in mid-winter. On each visit, inflows and outflows with flow loggers were downloaded and the water level sensor of the flow probes was recalibrated. Manual flow measurements were taken with a Hach hand held flow probe when flows were high. When flows were low, a container was filled up with water for a set amount of time and the volume collected was measured using a graduated cylinder. This was done in triplicate. When surface flow occurred into the wetland, manual flow measurements were collected with the Hach hand held flow probe. Table 2 lists the methodologies used to measure flow at each site.

The water quality sampling schedule for sampling the inflows and outflows was designed to collect samples intensively during the spring freshet when most of the flow was anticipated to occur and less frequently during the fall, winter and summer to obtain confident bulk estimates of nutrient loads in and out of each wetland. Water quality samples were collected once at baseflow and once during a rain event in the fall (October 1, 2018 to November 30, 2018) at each site. Water quality samples were collected once at baseflow and once during a snow/rain event in the winter (December 1, 2018 to January 31, 2019) at each site. Water quality samples were collected every week when flow occurred from the start of the spring freshet to the end of the spring (February 1, 2019 to May 30, 2019), at times twice a week. Two water quality samples at each site were collected during the summer months to account for a rain event and baseflow (June 1,2019 to September 30, 2019).

Table 2. Methods of flow measurement used at each site.

Site	Inflow or Outflow	Continuous Flow Logger	Hand Held Hach Flow Probe	Bucket and Stop Watch at Low Flows	Inflow Measured from Daily Difference in Water Level
OH	Tile Inflow #1	x	x	x	
	Tile Inflow #2			x	
	Overland Inflow		x		
	Outflow	x	x	x	
MO	Inflow	x	x	x	
	Outflow	x	x	x	
MA	Inflow	x	x	x	
	Outflow	x	x	x	
KE	Tile Inflow #1	x	x	x	
	Tile Inflow #2			x	
	Overland Inflow		x		
	Outflow	x	x	x	
BL	Surface Inflow				x
	Outflow	x	x	x	
DY	Surface Inflow				x
	Tile Inflow		x	x	
	Outflow	x	x	x	
FE	Surface Inflow				x
	Outflow	x	x	x	
LL	Surface Inflow				x
	Outflow	x	x	x	

Water quality samples were collected from the wetland basins twice (fall and summer) using a swing sampler. Once wading into the wetland up to a depth of one meter, the swing sampler bottle was rinsed three times with wetland water. Then with the sampler extended, a sample was collected and used to rinse the sampled bottle followed by filling up one third of the bottle. Two other samples were collected at two other locations within the wetland to obtain a composite water sample representing the water quality of the wetland basin.

Once water quality samples were collected, they were placed in a cooler with ice packs. Water quality samples were submitted to ALS Environmental laboratories in London, Ontario for the chemical analysis of total phosphorus (TP), total dissolved phosphorus (TDP), soluble reactive phosphorus (SRP), total kjeldahl nitrogen (TKN), dissolved kjeldahl nitrogen (DKN), nitrate and nitrite (NO_3^- and NO_2^-) and ammonia (NH_3). Total nitrogen (TN) and total dissolved nitrogen (TDN) were calculated.

A hand held YSI water quality meter was used to collect *in situ* measurements of water temperature, pH, specific conductance, salinity, and dissolved oxygen when water quality samples were collected. The YSI probes were calibrated prior to each sampling event. In the field, a designated sample bottle was rinsed three times and filled up. The YSI probe was placed into the bottle and once the readings stabilized, the data was recorded.

Precipitation data used for this project was taken from Environment and Climate Change Canada (ECCC) Climate ID station # 6144478 located in London, Ontario. Precipitation nutrient chemistry was obtained from ECCC Station # STC.

Soil samples were collected with an Oakfield soil core at the end of September 2019. At each site, soil samples were collected in triplicate at three points along a 10 meter transect. The top 15 cm of each soil core were combined to form one composite samples. Sediment samples were collected at the same time near the basin outflow. Two sediment samples were collected with a handheld Watermark universal sediment corer. The top 5 cm of each core were combined to form one composite sample. All soil and sediment samples were stored in a dark cooler at field moisture and analyzed within 7 days from the sampling date for Olsen phosphorus at A & L Labs in London, Ontario.

Basin bathymetry and storage curves

Elevation-storage curves were created for each of the eight restored wetlands based on a field survey and GIS analysis conducted in the fall of 2018. A land surveying contractor (Callon Dietz; London, ON) was retained to perform topographic (over land) and bathymetric (wetland bed) surveying using real-time kinematic GPS surveying tools. Surveys were delivered in the UTM NAD 1983 CSRS horizontal coordinate system, and the CGVD28 (HT_2.0) vertical coordinate system. The contractor collected survey points to build a surface that extended at least 20 cm above the spill point of the wetland, ensuring that adequate storage volumes could be estimated during wet periods. The contractor delivered survey points to DUC, including information on: the horizontal and vertical coordinates of each survey point, a description of the point collected, date and approximate time of the survey, and a surveyed wetland water surface elevation.

ArcGIS was used to develop elevation-storage curves for each restored wetland basin. First, the survey points were filtered to exclude non-topographic points, such as tree boundaries and infrastructure (note that while these points are useful in orienting the site and determining flow paths, they are not useful in determining storage areas). The remaining topographic and bathymetric points were used to generate Triangular Irregular Networks (TINs). These TINs describe the surfaces created between adjacent survey points, and therefore describe the basin shape of each of the eight wetlands. Similarly, an artificial flat TIN surface can be created to represent any potential water surface elevation intersecting the topographic TIN. For each wetland, the Surface Difference tool was used in ArcGIS to determine the volume in between the survey-generated TIN and artificial flat-water TINs at incremental depths above the bottom of the wetland basin.

Since time-stamped water surface elevations were surveyed, these points were used to perform a datum-shift for the level dataloggers deployed at each site. Once data were retrieved from the loggers and shifted to match the time-stamped surveyed elevations, daily storage time series from the measured elevations at each site were calculated based on the elevation-storage curves. Storage curves (and surface area curves) generated for each site are included in Appendix A. Daily mean surface water elevation, wetland area and wetland volume generated from the storage curves and the water level recorders for the off-ice season are also presented in Appendix A.

Contributing areas

Automated watershed delineation was performed using LiDAR data collected from Land Information Ontario (LIO) using the Green Kenue software platform (CHC 2010). Raw LiDAR survey files were resampled 10 m x 10 m resolution raster tiles in ArcMap. These tiles were imported to Green Kenue, and the A^t search algorithm was used to determine watershed boundaries at each of the eight wetland outlets. Watershed boundaries were ground-truthed in several ways. First, they were overlain on imagery to check for obvious errors, such as boundaries crossing water bodies. Next, several watershed boundaries bordered roads or other elevated rights-of-way. In these cases, site inspection was performed to determine if culverts existed, which would result in larger watersheds. Ultimately, five of seven watersheds were acceptable after the first round of delineation. Three sites required further investigation.

The KE watershed delineation was confounded by the powerline right-of-way; the LiDAR DEM included a high band of data along the right-of-way which split the KE watershed in two. Artificial flowpaths were added as a polyline shapefile directly into Green Kenue. This allowed Green Kenue to correctly route flowpaths from the northeast tract of land toward site KE.

For all sites, DEMs were generated from the point cloud. While this was successful for 6 of 8 sites, this was unsuccessful at site DY and MA. The resampling method erroneously represented the tree canopy as solid ground at these sites, which represented an unrealistic ground slope. The Ontario Flow Assessment Tool (OFAT) is an online watershed delineation tool developed by the Ontario Ministry of Natural Resources and Forestry (MNRF) which allows a user to delineate a watershed by selecting a point on a map. The resulting watershed polygon from this tool was ground-truthed and found to delineate the contributing area of site MA to our satisfaction. The DY wetland is situated west of a developed agricultural field and drains west into a treed ravine, and the DEM resampling method resulted in a calculated watershed slope that was in the opposite direction of the actual slope. The first attempts at watershed delineation resulted in reverse flow direction, and thus a watershed that was, in reality, downslope from the basin. A more realistic watershed for site DY was approximated by subtracting the watershed area falsely flowing into the wetland (82.00 ha) from the total (incorrect) watershed flowing out of the wetland (84.05 ha). This left behind only the land to the east, totalling 2.2 ha. This area was confirmed by ground-truthing inspections. Site maps demonstrating the contributing areas with the wetland basin digital elevation model in coloured slices are shown in Appendix A.

Hydrologic calculations

Daily mean flow rates were calculated for inflows and outflows equipped with continuous flow loggers when water depth was above 25mm. When the flow depth was below 25mm at these sites, the manual flow data was used to calculate daily flow rates. For sites with no direct inflow, when water was levels were below spill elevation the daily mean water elevation was used with the depth volume curve to calculate daily inflow rates by subtracting the volume of the previous day from the current day with a net positive volume indicating a gain of volume that day. When these basins with no defined inflows were above spill elevation, the mean daily outflow rate was used as the mean daily inflow rate.

Sites OH, KE and DY had defined tile inflows flowing directly into the wetland basin that were clearly separated from the remaining surface inflow. At these sites, daily surface inflow was calculated from subtracting daily tile inflow from daily outflow.

Nutrient load calculations

Nutrient loads at each inflow and outflow site were calculated by multiplying the daily mean flow volume by the corresponding daily nutrient concentration. In the fall period, nutrient concentrations collected at baseflow were used on days when baseflow occurred and nutrient concentration collected during a rain event were used on days when flow was elevated due to a rain event. This was also done in the winter when baseflow and elevated flows were sampled from precipitation events. With the frequent weekly to bi-weekly water quality sampling during the spring freshet, daily nutrient concentrations were extrapolated between days when sites were sampled. Daily nutrient concentrations in the summer were selected based on the nearest day that the site was sampled due to the nature of intermittent flow that occurred over the summer months.

Daily rain concentrations from the day the water chemistry sample was collected were used for the previous and following 15 days. Precipitation input volume was calculated by multiplying the daily surface area of the wetland basin by the daily rain depth. Daily rain loads were calculated by multiplying the daily rain nutrient concentration by the daily basin volume. Snow input to these wetland basins is difficult to account for as most snowfall appeared to redistribute to the edges and uplands of all wetland basins after it fell but before it melted. Direct snowfall was therefore not accounted for during the four months that snow fell (December 1, 2018 to March 31, 2019).

Wetland nutrient retention capacity calculations

Wetland nutrient retention capacity was calculated by summing all daily input loads and subtracting the daily output loads. Input loads include (where applicable) surface inflow, tile inflow and precipitation inputs. The daily loads were then added together to obtain the net nutrient mass retained per wetland. This value was divided by the wetland area at spill elevation to obtain the wetland nutrient retention capacity per area. Nutrient reduction efficiency was calculated by dividing the total input mass of nutrients by the total mass of outflow nutrients divided by 100 to obtain a percentage.

Reported seasonal break downs correspond to the months of October and November for fall, December and January for Winter, February through May for spring freshet and June through September for Summer. This report with focus on phosphorus species in all its discussions but will include nitrogen species data in tables and figures.

Results

Precipitation

A summary of precipitation for the past 17 water years (October 1 to September 30) from the Environment and Climate Change Canada (ECCC) weather station in London, Ontario (ID 6144478), including a breakdown of seasonal precipitation is presented in Table 3. Mean annual precipitation recorded during our study was 11% above average across this period. While precipitation for the fall and summer seasons were normal, precipitation recorded between February 1, 2019 and May 31, 2019 was responsible for the higher precipitation recorded during our study. This coincides with the start of the spring freshet (February 1) to the end of the spring season (May 31). The abnormally wet spring was quickly followed by a warm/dry summer that quickly dried upland fields adjacent to the study wetlands and resulted in decreased water levels within the study wetlands.

Table 3. Precipitation summary from ECCC station Climate ID 6144478 located in London, Ontario.

Time Period of Water Year	2019 Water Year Total Precipitation (mm)	2003 to 2019 Water Year Mean Total Precipitation (mm)	2019 Water Year Total Precipitation Compared to 17 Year Mean (% difference)
Oct. 1 to Sept. 30	1,053	951	111
Oct. 1 to Jan. 31	329	317	104
Feb. 1 to Apr. 30	276	222	124
May 1 to May 31	115	91	127
June 1 to Sept. 30	332	321	103

Basin nutrient chemistry

TP concentrations ranged widely across the study wetland basins (Figure 2), with trophic status ranging from mesotrophic to hyper-eutrophic (CCME 2004). More than half the total phosphorus was typically present in particulate form with the remainder comprised of dissolved phosphorus. While SRP is generally a small fraction of TP for most basins, sites OH and KE had elevated mean SRP concentrations comprising 22 and 40 % of TP respectively.

TN concentrations in the study wetlands ranged from 0.6 mg L^- to 8.32 mg L^- with a median of approximately 1.5 mg L^- (Figure 3). Site MA is responsible for skew seen in Figure 3 as it has a mean TN concentration of 7.0 mg L^- while the other sites mean range from 0.7 to 3.2 mg L^-. Nearly all nitrogen is in the dissolved form dominated by NO_3^- and NO_2^-, while NH_3 is found to comprise only a small fraction of the nitrogen present.

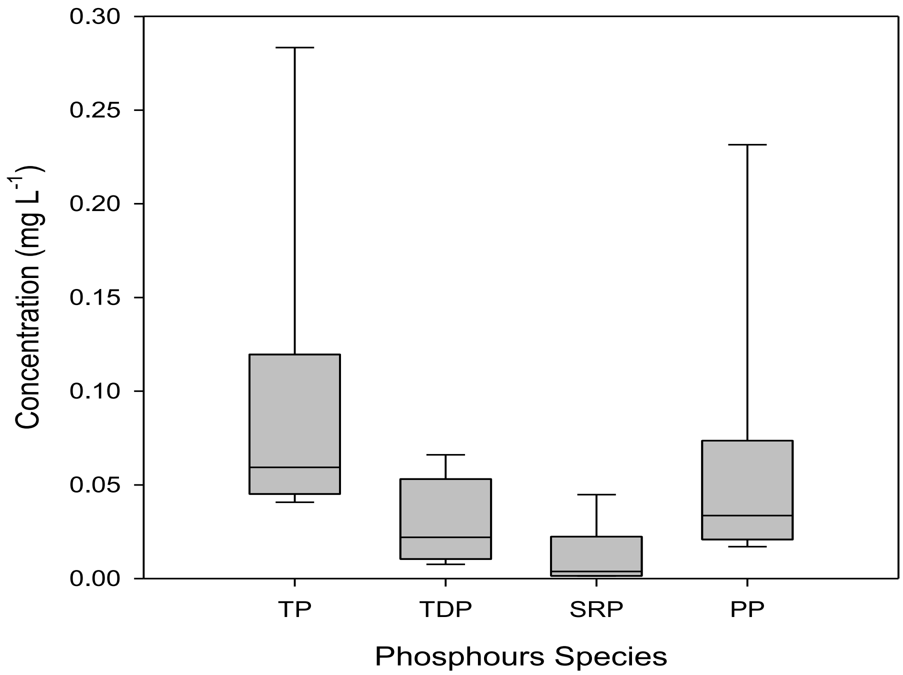


Figure 2. Concentrations of the four phosphorus species measured in restored wetland basins (n=8) between October 2018 and August 2019.

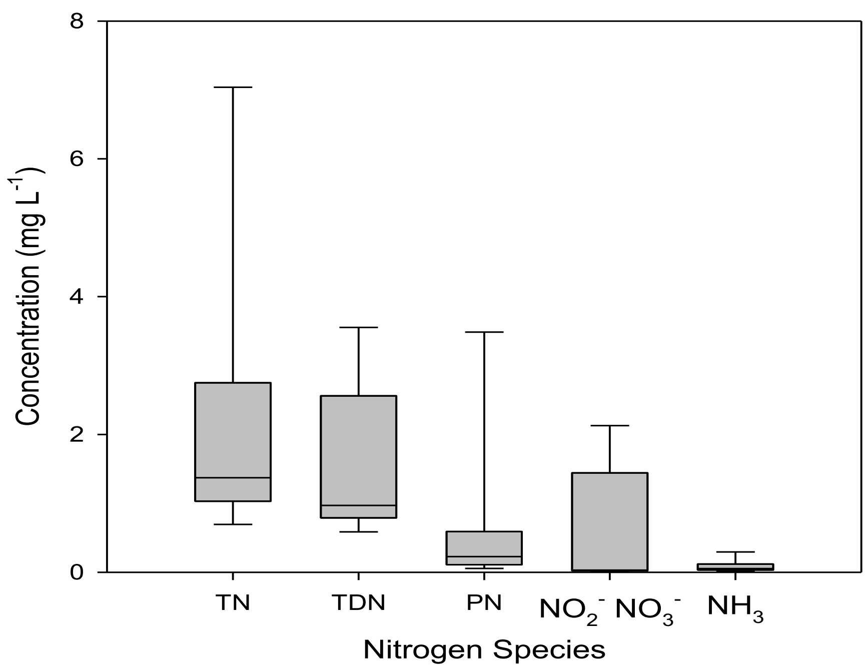


Figure 3. Concentrations of the five nitrogen species measured in restored wetland basins (n=8) between October 2018 and August 2019.

YSI water quality data

A summary of water quality parameters measured in situ with a handheld YSI unit at the inflows and outflows of all wetland basins is presented in Table 4. Mean specific conductance ranged from 0.10 mS cm^{-} to 0.91 mS cm^{-}. pH of the inflows and outflows were neutral to slightly alkaline with inflow and outflow pH of each basin remaining fairly consistent throughout the monitoring period. Dissolved oxygen at the inflows and outflows ranged from 6.75 mg L^{-} to 11.11 mg L^{-} with no consistent difference between inflows and outflows.

Table 4. Water quality data collected with a hand held YSI unit at inflows and outflows of eight restored wetland basins.

Site	Inflow or Outflow	Water Temp (°C)	Specific Conductance (mS cm^{-})	Total Dissolved Solids (g L^{-})	pH	Dissolved Oxygen (mg L^{-})
OH	Tile #1 inflow	6.03 ± 1.58	0.49 ± 0.12	0.39 ± 0.09	7.84 ± 0.12	11.11 ± 1.10
	Surface inflow	10.12 ± 2.44	0.28 ± 0.02	0.18 ± 0.01	8.01 ± 0.07	8.08 ± 0.88
	Outflow	8.65 ± 2.34	0.63 ± 0.34	0.41 ± 0.22	7.82 ± 0.19	7.88 ± 0.05
LL	Surface inflow	10.91 ± 2.55	0.37 ± 0.08	0.24 ± 0.05	8.11 ± 0.11	10.38 ± 1.23
	Outflow	6.69 ± 2.38	0.25 ± 0.01	0.16 ± 0.01	8.20 ± 0.17	11.14 ± 0.92
MO	Surface & tile inflow	9.58 ± 2.30	0.67 ± 0.06	0.43 ± 0.04	7.75 ± 0.04	8.41 ± 0.87
	Outflow	9.48 ± 2.28	0.52 ± 0.04	0.34 ± 0.03	7.80 ± 0.04	8.14 ± 0.77
KE	Tile #1 inflow	6.42 ± 1.61	0.91 ± 0.14	0.59 ± 0.09	8.11 ± 0.07	9.51 ± 0.64
	Surface inflow	5.42 ± 1.43	0.20 ± 0.14	0.13 ± 0.09	8.20 ± 0.63	11.45 ± 1.21
	Outflow	10.08 ± 2.69	0.68 ± 0.11	0.44 ± 0.07	8.24 ± 0.14	9.15 ± 1.26
FE	Surface inflow	7.95 ± 3.27	0.18 ± 0.05	0.12 ± 0.03	7.99 ± 0.21	8.39 ± 2.04
	Outflow	10.30 ± 2.64	0.24 ± 0.02	0.16 ± 0.01	8.00 ± 0.13	8.55 ± 0.97
BL	Surface inflow	14.58 ± 3.28	0.10 ± 0.02	0.07 ± 0.01	8.43 ± 0.30	7.33 ± 1.18
	Outflow	9.20 ± 4.22	0.13 ± 0.03	0.08 ± 0.02	8.31 ± 0.26	9.02 ± 1.08
MA	Surface & tile inflow	6.58 ± 1.67	0.51 ± 0.04	0.33 ± 0.03	7.87 ± 0.05	9.59 ± 0.93
	Outflow	10.13 ± 2.58	0.41 ± 0.04	0.26 ± 0.03	7.88 ± 0.05	8.11 ± 0.64
DY	Surface inflow	11.75 ± 3.40	0.27 ± 0.08	0.66 ± 0.52	8.30 ± 0.28	6.75 ± 0.21
	Outflow	12.41 ± 4.34	0.29 ± 0.03	0.20 ± 0.03	8.25 ± 0.16	6.97 ± 1.09

Hydrology

Total flow volumes from inflows and outflows, as well as seasonal flows from all eight sites are presented in Table 5. Percent flows from all inflows with seasonal breakdown from all eight sites are presented in Table 6. Total outflows varied by one order of magnitude among the eight wetland basins over the course of the water year. Seven of eight sites had slightly higher inflow volumes relative to outflow volumes due to those basins generating storage volume mainly in the summer season. One site (MO) had a slightly higher outflow volume compared to inflow volume, which may indicate potential contributions from groundwater seepage into the basin that was unaccounted for. At sites with tile drains (OH, KE, DY), discharge from tile accounted for 24 % to 50 % of total flows to the wetlands. Precipitations was a minor contributor of volume to the four sites with contributing areas <3.6 ha ranging from 12 % to 17 %, while sites with larger contributing areas >7.9 ha rain volume was negligible at providing 1 % to 3 % of total volume.

Inflow during the fall season accounted for 7 % to 24 % of total annual inflow volume. Two sites (BL and DY) showed no outflow during this period indicating that the basins were below spill elevation and storing all inflow volume. Sites FE and LL had higher inflow than outflow volume indicating that these sites also stored water in the fall. Sites OH, MO, MA and KE were essentially operating as flow though sites with inflow and outflow volumes nearly identical.

Inflow during the winter season accounted for 3 % to 29 % of total annual inflow volume. Two sites (BL and DY) remained below spill elevation over the winter months and therefore had no outflow. All other six sites remained at or near spill elevation over the winter months. Winter flows as a percentage of total flows decreased slightly compared to the fall season flows with the exception of site LL.

The spring freshet accounted for most of the total annual flow volume (between 40 % and 71 %) into and out of all eight wetlands. All basins reached spill elevation in the spring freshet and remained at spill elevation over most of this period. Precipitation inputs into the basins were minimal for restored wetlands with contributing areas <3.6 ha and was negligible for restored wetlands with contributing areas > 7.9 ha. During the spring freshet period tile inlets contributed between 19 % and 50 % of the water entering the restored basins. However, for basins MO and MA, it was not possible to separate the contribution of water from tile inlets and overland flow. The summer period was the smallest seasonal contribution to total annual inflows entering the restored basins with the exception of sites FE and DY.

Table 5. Total and seasonal breakdown of inflow and outflow volumes.

Site	Inflow or Outflow	Total Flow (m^3)	Fall Flows (m^3)	Winter Flows (m^3)	Freshet Flows (m^3)	Summer Flow (m^3)
OH	Tile Inflow	36,140	9,141	5,545	14,974	6,479
	Overland Inflow	93,209	9,371	13,629	62,677	7,533
	Rain Inflow	4,215	1,083	0	1,380	1,752
	Total Inflow	133,564	19,595	19,175	79,031	15,764
	Outflow	131,834	19,234	19,111	78,740	14,749
MO	Overland & Tile Inflow	116,734	22,574	15,783	70,483	7,893
	Rain Inflow	831	214	0	272	345
	Total Inflow	117,565	22,788	15,783	70,755	8,239
	Outflow	118,265	23,145	17,546	69,883	7,691
MA	Overland & Tile Inflow	40,020	7,522	5,577	26,633	287
	Rain Inflow	1,009	284	0	373	352
	Total Inflow	41,029	7,806	5,577	27,006	639
	Outflow	40,008	6,366	5,101	28,238	302
KE	Tile Inflow	94,405	24,474	12,275	55,296	2,359
	Overland Inflow	94,749	20,184	13,677	55,598	5,290
	Rain Inflow	1,273	371	0	458	444
	Total Inflow	190,427	45,029	25,952	111,352	8,093
	Outflow	189,617	45,558	25,550	110,951	7,558
BL	Overland Inflow	2,767	343	476	1,861	86
	Rain Inflow	428	117	0	214	97
	Total Inflow	3,195	460	476	2,075	183
	Outflow	2,050	0	0	2,050	0
DY	Tile Inflow	1,664	175	0	1,367	122
	Overland Inflow	4,246	747	809	1,785	905
	Rain Inflow	1,159	284	0	411	465
	Total Inflow	7,069	1,205	809	3,563	1,492
	Outflow	3,761	0	0	3,755	7
FE	Overland Inflow	12,030	249	399	9,882	1,500
	Rain Inflow	2,388	719	0	427	1,243
	Total Inflow	14,418	968	399	10,309	2,743
	Outflow	10,943	249	399	9,882	413
LL	Overland Inflow	17,157	2,801	5,670	7,356	1,330
	Rain Inflow	2,231	661	0	431	1,138
	Total Inflow	19,388	3,462	5,670	7,788	2,468
	Outflow	16,689	2,919	5,670	7,711	389

Table 6. Total and seasonal breakdown of flow percentage at all inflows and outflows.

Site	Inflow or Outflow	Total Flow (%)	Fall Flow (%)	Winter Flow (%)	Freshet Flow (%)	Summer Flow (%)
OH	Tile Inflow	27	47	29	19	41
	Overland Inflow	70	48	71	79	48
	Rain Inflow	3	6	0	2	11
	Total Inflow	100	15	14	59	12
MO	Overland & Tile Inflow	99	99	100	100	96
	Rain Inflow	1	1	0	0	4
	Total Inflow	100	19	13	60	7
MA	Overland & Tile Inflow	98	96	100	99	45
	Rain Inflow	2	4	0	1	55
	Total Inflow	100	19	14	66	2
KE	Tile Inflow	49	54	47	50	29
	Overland Inflow	50	45	53	50	65
	Rain Inflow	1	1	0	0	5
	Total Inflow	100	24	14	58	4
BL	Overland Inflow	87	75	100	90	47
	Rain Inflow	13	25	0	10	53
	Total Inflow	100	14	15	65	6
DY	Tile Inflow	24	14	0	38	8
	Overland Inflow	60	62	100	50	61
	Rain Inflow	16	24	0	12	31
	Total Inflow	100	17	11	50	21
FE	Overland Inflow	83	26	100	96	55
	Rain Inflow	17	74	0	4	45
	Total Inflow	100	7	3	71	19
LL	Overland Inflow	88	81	100	94	54
	Rain Inflow	12	19	0	6	46
	Total Inflow	100	18	29	40	13

Retention time

Retention time for the eight newly restored wetland basins are presented in Table 7. Retention times were calculated using the maximum daily inflow rate to determine the minimum retention time for the restored wetland basins. We also calculated the retention time using mean daily inflow rates to provide an indicator of the overall retention time for the restored wetlands over the course of the entire year. Retention time at maximum inflows range from 0.1 to 8.3 days and at mean flows from 1.6 to 173.6 days. Retention times at maximum inflow rate demonstrates that under these conditions the basins can fill relatively quickly resulting in flow through conditions where inflow and outflow are roughly equivalent. However, it is important to note that maximum daily flow rates did not persist for long periods of time and as a result retention time based on maximum daily inflow represent a worst-case scenario. The retention time calculated using mean inflow rates provides a better indicator to assess how these wetlands behave for retaining nutrients over the whole year. Retention times for constructed wetlands to treat municipal wastewater with phosphorus retention as one of the goals range from 5 to 15 days (Mitsch and Gosselink 2000). The mean retention time at mean inflow rates at our eight sites is 62 days. Site BL which only had outflow for a short period of the year and site FE which exhibited nearly constant but very slow outflow rates have higher retention times that are not typical of the average restored wetland basin. The overall higher mean retention rate found in these eight sites shows they exhibit a trait which is desirable if the goal is to retain nutrients within the wetland basin. The mean retention times for the basins generally falls within the recommended guidelines for constructed wetlands to treat waste water.

Table 7. Retention times of eight restored wetland basins.

Site	Inflow or Outflow	Max daily flow ($m^3 s^-$)	Mean daily flow ($m^3 s^-$)	Basin Volume (m^3)	Retention Time at Max Flow (days)	Retention Time at Mean Flow (days)
OH	Total Inflow	0.0537	0.0042	6,253	1.3	17.2
	Outflow	0.0537	0.0042			
MO	Total Inflow	0.0560	0.0037	1,013	0.2	3.1
	Outflow	0.0550	0.0038			
MA	Total Inflow	0.0227	0.0013	927	0.4	8.4
	Outflow	0.0311	0.0013			
KE	Total Inflow	0.0781	0.0060	827	0.1	1.6
	Outflow	0.0807	0.0060			
BL	Total Inflow	0.0040	0.0001	1,247	3.8	173.6
	Outflow	0.0036	0.0001			
DY	Total Inflow	0.0040	0.0002	1,880	6.2	97.1
	Outflow	0.0030	0.0002			
FE	Total Inflow	0.0059	0.0005	4,231	8.3	121.8
	Outflow	0.0059	0.0003			
LL	Total Inflow	0.0180	0.0006	3,720	2.4	75.3
	Outflow	0.0180	0.0005			
Mean ± Std Error					2.8 ± 1.1	62.2 ±23.0

Wetland nutrient loads, retention capacity and reduction efficiency

Net mass of nutrients retained in the newly restored wetlands we monitored are presented in Table 8. Total annual nutrient loads for all inflows and outflows of the eight restored wetlands basins are presented in Table 9. Nutrient reduction capacity of restored wetlands which is the mass of nutrients retained by area of wetland over one year is presented in Table 10. Nutrient reduction efficiency of restored wetlands for the study period are reported in Table 11. Additionally, the seasonal breakdown of the wetland nutrient retention capacity, nutrient reduction efficiency and percent mass of phosphorus retained per site for all four phosphorus species are provided in Appendix A.

During our study, a net positive TP retention occurred at seven of the restored wetland basins with one site having a net negative TP retention. Across the sites net TP retention ranged from -6.5 to 15.4 kg (Table 8). Individual wetland TP inflow loading rates ranged from 1.6 to 65.86 kg while TP outflow loading rates ranged from 0.34 to 62.58 kg (Table 9). Tile inlets range widely with respect to overall TP loading rates with site OH and KE accounting for 24 % and 43 % of total TP loads respectively, while the tile inlet at site DY accounted for only 2 % of total TP inflow load. TP loads from rain were minimal. The overall TP retention capacity for all eight restored wetlands is 7.2 kg ha^{-} $year^{-}$ (Table 10) with a mean TP reduction efficiency of 39 % (Table 11).

Overall, the net mass of TDP retained in all basins followed the same trend reported for TP with seven of the restored wetland basins having a net positive retention and one basin having a negative retention/release (Table 8). Individual wetland total TDP inflow and outflow loading rates were much lower than was reported for TP ranging from 0.87 to 12.98 kg, and from 0.11 to 10.98 kg, respectively (Table 9). Sites with tile inlets varied in terms of TDP loading rates ranging from a low of 2 % (site DY) to 50 % (site KE) (Table 9) with rain input minimal for TDP loading inputs. The overall TDP retention capacity for all eight restored wetlands is 4.2 kg ha^{-} $year^{-}$ (Table 10) with a mean TDP reduction efficiency of 50 % (Table 11).

Net mass of SRP retained was positive in all eight wetland basins ranging from 0.5 to 2.1 kg for the year (Table 8). Annual loads delivered to the wetland basins via tile inlets ranged from <1 % to 61 % for sites DY and KE respectively while SRP outflow loads ranged from 0.02 to 6.27 kg (Table 9). SRP concentrations from grab samples at the outflow of sites DY and LL were always below detection limit while only two grab samples at the outflow of site FE were above detection limits. This contributed to the low outflow loads of SRP at these three sites. Site MA net SRP inflow loads were greater than the net SRP outflow loads leading to a high SRP retention capacity. This indicates that processes within this basin are initially contributing to the retention of SRP. However, site MA further reports both a high negative PP retention capacity demonstrating that a potential species shift from SRP to PP is occurring in the basin followed by the export of the newly bound SRP now bound in the particulate form. The high SRP retention capacity with the high negative retention capacity of PP in site MA demonstrates the high reactivity of SRP and with such high values, that site MA is behaving differently from the other 7 sites. The overall SRP retention capacity for all eight restored wetlands is 5.7 kg ha^{-} year^{-} (Table 10) with mean SRP reduction efficiency of 67 % (Table 11). If we were to consider site MA an outlier, the SRP retention capacity for the other seven restored wetlands is 5.0 kg ha^{-} year^{-} with a mean SRP reduction efficiency of 71 %. Rain contribution to SRP load was minimal for all sites.

Net PP retention was positive for seven of the eight restored wetland basins with one basin showing a net negative PP retention capacity which follows the same trend as TP and TDP retention capacities (Table 8). Individual wetland total PP inflow loads ranged from 0.73 to 52.89 kg. When compared to the TP input loads it is apparent that PP is a major fraction of the phosphorus entering these basins. PP loads entering the basins via tile inlets ranges from 0.04 to 52.89 kg (Table 9). Rain contribution for PP was minimal for all sites. The overall PP retention capacity for all eight restored wetlands is 3.0 kg ha^{-} year^{-} (Table 10) with a mean PP reduction efficiency of 13 % (Table 11).

Discussion

Restored wetland site details

Removal of phosphorus varied across wetlands. Site OH was found to have the highest net retention of TP with PP acting as a major fraction of TP being retained. This site was unique amongst all sites in that the higher above average amount of precipitation that occurred over the spring freshet and into the month of May resulted in the surface runoff eroding a gully from the uplands down towards the wetland basin where there is a substantial drop in elevation from the upland down to the wetland basin. This eroded gully acted as an efficient feature to drain the upland agricultural field of any surface water that was pooling and in doing so elevated the PP loading (and hence TP loading) to the wetland basin during this wet period of the year. This is reflected in PP comprising a major fraction of TP for net mass retained in Table 8.

Site MA showed lower inflow loads than outflow loads for TP, TDP and PP resulting in the site MA acting as a net source of phosphorus with a high negative net retention capacity for those three phosphorus species. 17 of 19 grab samples collected from the inflow over the course of the year had lower TP concentrations than did the corresponding outflow TP concentration. These elevated phosphorus concentrations resulted in this basin being an outlier when compared to the other restored wetlands we monitored. One potential explanation for why this site behaved differently compared to the others is related to differences in soil phosphorus concentrations. Elevated levels of soil test phosphorus (STP) were found in both the upland soils and wetland sediment at site MA relative to the other restored wetland sites we monitored (Figure 5). While the relationship varies for different soil types, phosphorus concentration in runoff is related to STP of the upland it originates (Pote et al. 1996). These findings are preliminary and require further study but suggest that the high STP recorded at site MA may be one of several reasons that contribute to this site releasing P instead of retaining P.

Site BL had the lowest net TP mass retained of all seven basins which exhibited a net positive retention capacity (Table 8). While the upland of site BL is tiled, the tile outlet does not spill into site BL making this site unique among all sites where the upland is tiled. Instead, the tile drainage at site BL is directed away from the basin leaving only the surface runoff to provide inflow to this basin. Due to this design which limited the inflow volume, BL never reached spill elevation in the fall season, and the basin only slowly reached spill elevation in March. Once the spring freshet ended, very little surface flow entered the basin of site BL. As the lower hydrological inflow resulted in site BL having a high nutrient reduction efficiency (Table 11), the overall nutrient retention capacity for site BL for all phosphorus species was low but positive compared to the other sites due to the limited hydrological inflow.

Site KE is shown to have a higher TP retention capacity compared to the other sites however its TP reduction efficiency is one of the lowest at 5 %. This is due to site KE having the largest contributing areas and one of the smallest basin areas resulting in the largest contributing area to wetland area ratios (Table 1). This resulted in site KE receiving the highest hydrologic flows and TP loading rates of all sites. Even with the lowest residence time of all sites, a site designed such as this does act as an efficient sink for phosphorus as its nutrient retention capacity is reported as the second highest amongst all sites (Table 8).

Site FE reports the lowest TP wetland retention capacity that is positive among all sites (Table 10) at the same time reporting the second highest TP reduction efficiency at 86 % (Table 11). Site KE is large in area with the second highest surface area with a smaller contributing area. The outflow of site KE was continuously at baseflow over the year only having the flow cease in the summer. When inquiring with the landowner in May about this, we were informed that the control structure was damaged during installation. The downward flow pipe from the spill grate which leads to the lower horizontal spill pipe cracked 1 meter (estimated) below the spill elevation of the horizontal surface grate. This resulted in providing baseflow to continually seep down for the basin of the wetland into the cracked pipe and out of the control structure outflow pipe (pers comm landowner). This altered the behaviour of this wetland by releasing the volume of water slow over time instead of pulses of outflow water that would otherwise of occur at increased frequency from flow exiting the top grate of the control structure during runoff events. This slow release of water likely promotes settling of phosphorus in the basin and along with the increased size of the basin would contribute to the elevated TP reduction efficiency seen at this site.

Site MO was unique among all sites in that it has the smallest basin area with the second largest contributing area resulting in a large contributing area to wetland area ratio. The small basin, albeit located below this large upland area, retained a net positive mass of TP over the water year. Even with the second lowest TP reduction efficiency amongst all sites at 17 %, this smaller basin demonstrated the ability to retain phosphorus within its basin even after being exposed to higher inflows, which is similar to site KE.

Sites DY and LL both report similar TP retention capacities with above average TP reduction efficiencies. These sites behaved similar in that their water levels were often below spill elevation thus increasing the number of days when nutrient reduction efficiency would be at 100 %. The lower contributing area to wetland area ratios results in less volume of inflow into these basins compared to the wetland basins size and available storage. This contributed to the increased retention capacity and retention efficiency of these two sites.

Table 8. Net mass of nutrients retained in all newly restored wetlands over one water year.

Site	Net TP	Net TDP	Net SRP	Net PP	Net TN	Net TDN	Net PN	Net NO_3^-	Net NO_2^-	Net NH_3	Net DIN
						kg yr-					
OH	15.4	2.6	2.1	12.8	177.3	168.8	8.5	132.6	-1.7	26.8	127.7
LL	6.7	1.9	1.7	4.7	42.0	29.3	12.6	7.1	3.4	7.2	17.4
MO	2.0	0.5	0.8	1.5	74.9	76.7	-1.8	105.8	-2.7	-0.5	102.6
KE	3.3	2.4	1.7	0.9	232.6	201.4	31.2	192.0	0.2	2.0	194.1
FE	2.1	0.8	0.5	1.3	21.3	14.0	7.2	3.4	0.1	6.0	9.5
MA	-6.5	-1.0	1.7	-5.5	145.8	164.0	-18.9	184.5	-0.6	-19.3	164.6
DY	3.4	2.1	1.9	1.2	16.3	12.5	3.7	9.8	-2.0	79.5	9.3
BL	1.3	0.7	0.7	0.6	1.7	1.2	0.5	0.1	0.0	0.4	0.5
	3.4 ± 2.2	1.2 ± 0.4	1.4 ± 0.2	2.2 ± 1.8	89.0 ± 30.3	83.5 ± 29.1	5.4 ± 5.0	79.4 ± 29.7	-0.4 ± 0.7	12.8 ± 10.5	78.2 ± 27.8

Table 9. Total nutrient loads for one water year for all inflows and outflows of eight restored wetlands basins.

Site	Location	TP (kg)	TDP (kg)	SRP (kg)	PP (kg)	TN (kg)	TDN (kg)	PN (kg)	NO_3^- (kg)	NO_2^- (kg)	NH_3 (kg)	DIN (kg)
OH	Surface	32.76	4.91	2.23	27.85	332.55	249.12	83.43	145.30	1.04	15.69	162.03
	Rain	0.028	0.014	0.007	0.014	3.410	2.932	0.477	1.068	0.000	1.903	2.97
	Tile Inlet	7.80	1.72	0.97	6.08	88.75	66.97	21.79	36.06	0.16	3.17	39.39
	Total Inflow	40.59	6.64	3.21	33.94	424.71	319.02	105.70	182.42	1.20	20.76	204.38
	Outflow	25.20	4.02	1.09	21.19	247.37	150.18	97.19	49.81	1.29	25.59	76.69
MO	Surface	11.86	3.45	2.00	8.41	947.37	924.41	22.96	843.39	1.24	14.40	859.03
	Rain	0.01	0.00	0.00	0.00	0.67	0.58	0.09	0.21	0.00	0.38	0.59
	Total Inflow	11.87	3.45	2.00	8.42	948.04	924.99	23.06	843.60	1.24	14.77	859.62
	Outflow	9.87	2.92	1.24	6.94	873.10	848.26	24.84	737.77	3.96	15.28	757.01
LL	Surface	8.28	2.27	1.69	6.01	66.57	45.91	20.66	12.12	3.58	9.40	24.62
	Rain	0.02	0.01	0.00	0.01	2.22	1.91	0.31	0.69	0.00	1.24	1.94
	Total Inflow	8.30	2.28	1.69	6.02	68.79	47.82	20.97	12.82	3.58	10.64	26.55
	Outflow	1.61	0.34	0.02	1.27	26.83	18.51	8.32	5.70	0.17	3.42	9.17
KE	Surface	37.27	6.39	3.16	30.89	408.57	333.04	75.53	220.10	2.01	11.19	233.30
	Rain	0.01	0.00	0.00	0.00	0.96	0.83	0.13	0.30	0.00	0.54	0.84
	Tile Inlet	28.58	6.59	4.84	22.00	502.61	467.90	34.71	386.26	0.80	6.54	393.61
	Total Inflow	65.86	12.98	8.00	52.89	912.15	801.77	110.37	606.66	2.81	18.27	627.75
	Outflow	62.58	10.63	6.29	51.95	679.58	600.37	79.21	414.66	2.66	16.30	433.62
FE	Surface	2.39	0.88	0.51	1.52	25.52	17.02	8.49	3.44	0.11	5.93	9.48
	Rain	0.02	0.01	0.00	0.01	2.27	1.95	0.32	0.71	0.00	1.26	1.97
	Total Inflow	2.41	0.89	0.51	1.53	27.79	18.98	8.81	4.15	0.11	7.19	11.45
	Outflow	0.34	0.11	0.02	0.22	6.50	4.93	1.59	0.75	0.05	1.17	1.98
MA	Surface	7.73	5.75	5.11	1.97	362.26	350.77	11.50	323.40	0.34	9.35	333.09
	Rain	0.01	0.00	0.00	0.00	0.79	0.00	0.00	0.25	0.00	0.44	0.69
	Total Inflow	7.73	5.76	5.11	1.97	363.05	350.77	11.50	323.65	0.34	9.79	333.78
	Outflow	14.24	6.79	3.39	7.45	217.21	186.80	30.41	139.12	0.97	29.05	169.15
DY	Surface	3.67	2.27	2.08	1.39	12.08	6.88	5.20	2.37	0.19	2.30	4.85
	Rain	0.01	0.00	0.00	0.00	0.93	0.80	0.13	0.29	0.00	0.52	0.81
	Tile Inlet	0.06	0.03	0.01	0.04	16.57	15.88	0.69	15.08	0.03	0.16	9.88
	Total Inflow	3.74	2.30	2.09	1.43	29.59	23.56	6.03	17.73	0.22	2.98	15.55
	Outflow	0.38	0.19	0.15	0.19	13.33	11.03	2.31	7.96	0.09	0.25	6.29
BL	Surface	1.66	0.88	0.82	0.78	3.83	2.34	1.49	0.50	0.02	0.51	1.03
	Rain	0.00	0.00	0.00	0.00	0.34	0.29	0.05	0.11	0.00	0.19	0.30
	Total Inflow	1.66	0.88	0.82	0.78	4.16	2.63	1.54	0.61	0.02	0.70	1.33
	Outflow	0.38	0.19	0.13	0.19	2.45	1.42	1.03	0.50	0.03	0.31	0.84

Table 10. Nutrient retention capacity of eight restored wetland basins for one water year.

Site	TP	TDP	SRP	PP	TN	TDN	PN	NO_3^-	NO_2^-	NH_3	DIN
					kg ha^- $year^-$						
OH	20.8	3.6	2.9	17.2	239.6	228.2	11.5	179.2	-2.3	36.2	172.6
LL	13.9	4.1	3.5	9.9	87.4	61.1	26.3	14.8	7.1	15.0	36.2
MO	14.3	3.7	5.4	10.5	535.3	548.1	-12.8	755.9	-19.4	-3.6	732.9
KE	17.3	12.4	9.0	4.9	1224.0	1060.0	164.0	1010.5	0.8	10.4	1021.7
FE	3.9	1.5	0.9	2.5	40.2	26.5	13.6	6.4	0.1	11.4	17.9
MA	-36.1	-5.7	9.5	-30.4	810.2	910.9	-105.1	1025.1	-3.5	-107.0	914.6
DY	16.0	10.0	9.3	5.9	77.4	59.7	17.7	46.5	-9.6	378.7	44.1
BL	7.6	4.1	4.1	3.5	10.1	7.1	3.0	0.6	-0.1	2.3	2.9
Mean ± Std Error	7.2 ± 6.5	4.2 ± 1.9	5.7 ± 1.2	3.0 ± 5.1	378.0 ± 156.5	362.7 ± 150.1	14.8 ± 25.9	379.9 ± 164.9	-3.4 ± 2.8	42.9 ± 50.3	367.9 ± 156.3

Table 11. Nutrient reduction efficiency of eight restored wetland basins for one water year.

Site	TP	TDP	SRP	PP	TN	TDN	PN	NO_3^-	NO_2^-	NH_3	DIN
					%						
OH	38	40	66	38	42	53	8	73	-7	-23	62
LL	81	85	99	79	61	61	60	56	95	68	65
MO	17	15	38	17	8	8	-8	13	-219	-3	12
KE	5	18	22	2	25	25	28	32	6	11	31
FE	86	87	96	85	77	74	82	82	50	84	83
MA	-84	-18	34	-277	40	47	-165	57	-184	-197	49
DY	90	92	93	87	55	53	62	55	59	92	60
BL	76	78	86	75	41	46	33	18	-82	56	37
Mean ± Std Error	39 ± 21	50 ± 15	67 ± 11	13 ± 43	44 ± 7	46 ± 7	13 ± 27	48 ± 9	-35 ± 41	11 ± 33	50 ± 8

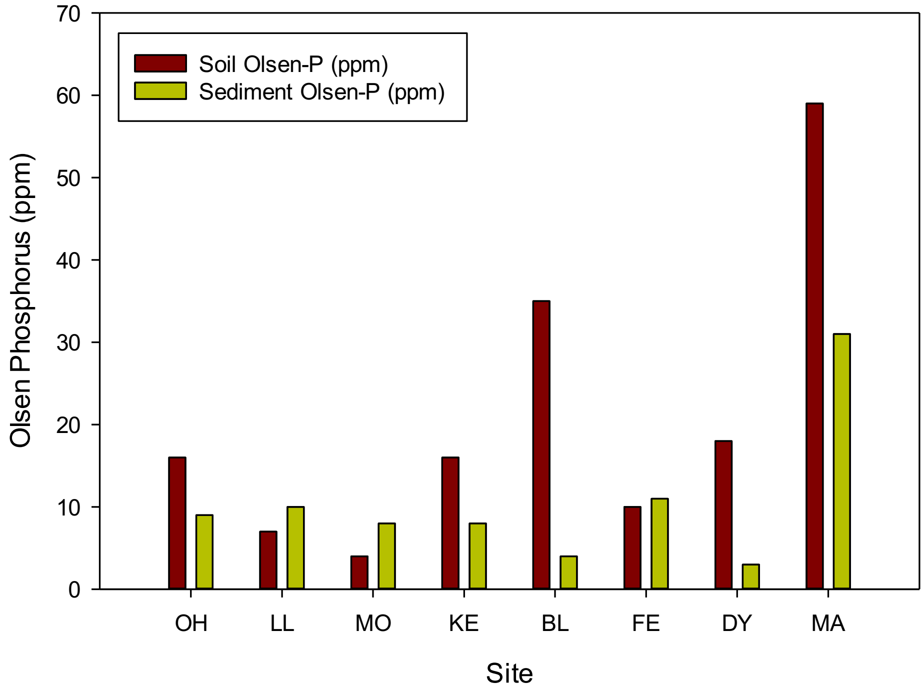


Figure 4. Upland and sediment soil test phosphorus from eight restored wetland basins.

Seasonal data

Mean wetland seasonal retention capacities and mean seasonal reduction efficiencies for TP, TDP, SRP and PP are reported in Figures 5 and 6, respectively. Seasons were defined as fall (October to November), winter (December to January), freshet (February to May), Summer (June to September).

Retention capacities for phosphorus species varies across all seasons. TP retention capacity peaks in the summer season, shows positive retention capacities in the fall and winter and shows a negative retention capacity in the freshet period. TDP retention capacity are positive for all seasons with a peak in the fall and the lowest retention capacity reported in the summer. SRP retention capacities are positive across all seasons with the fall and freshet season at similar peaks followed by a low, but positive retention capacity in the summer. A large variation of PP retention capacities is reported with a high net retention capacity of PP in the summer, a low positive retention capacity in the fall and winter seasons, and a high negative retention capacity in the freshet. The high summer PP retention capacity shows nearly all phosphorus retained in the summer months is in the particulate form. If site MA is considered an outlier, the TP retention capacity in the freshet season goes from a negative retention capacity to a positive retention capacity of 2.97 kg ha^{-}.

TP reduction efficiency gradually decreased from the fall season to the freshet season then increased to a peak reduction efficiency in the summer. The minimum in TP reduction efficiency in the freshet corresponds with the peak of hydrological flow through the wetland basins. TDP reduction efficiencies were similar across the fall and winter, they were lowest during the freshet and then are seen to increase in the summer months. The reduction efficiency of SRP was consistent across all four seasons with a slight decrease in the period of the freshet. PP reduction efficiency was variable across the seasons, decreasing from a positive reduction efficiency in the fall to a negative efficiency in the winter. PP reduction efficiency then increases nearing a net zero efficiency for the freshet and then shows a peak of PP reduction efficiency in the summer.

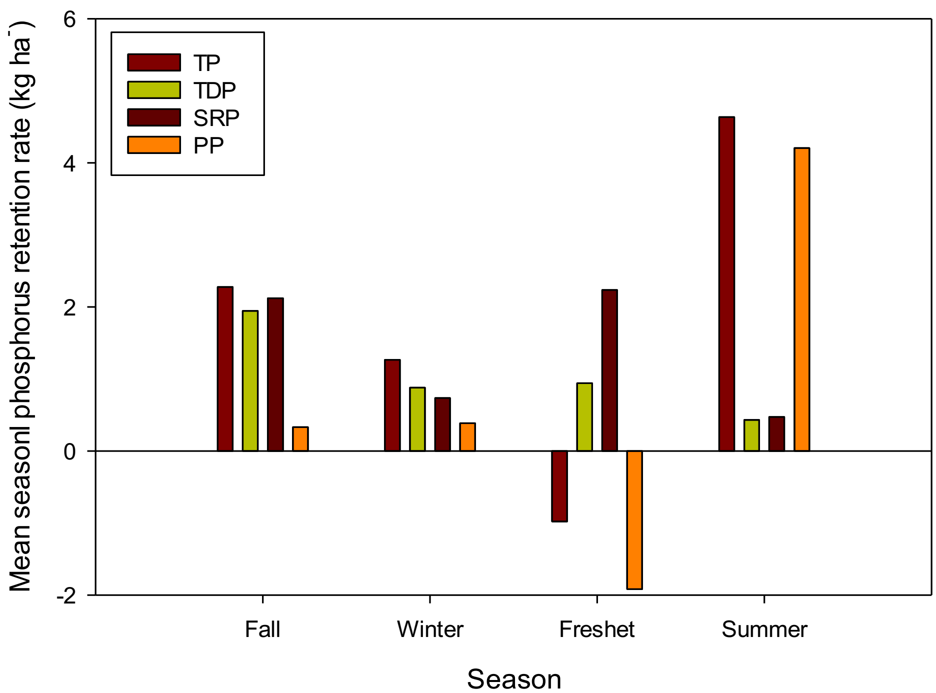


Figure 5. Mean retention capacity for TP, TDP, SRP and PP across four seasons.

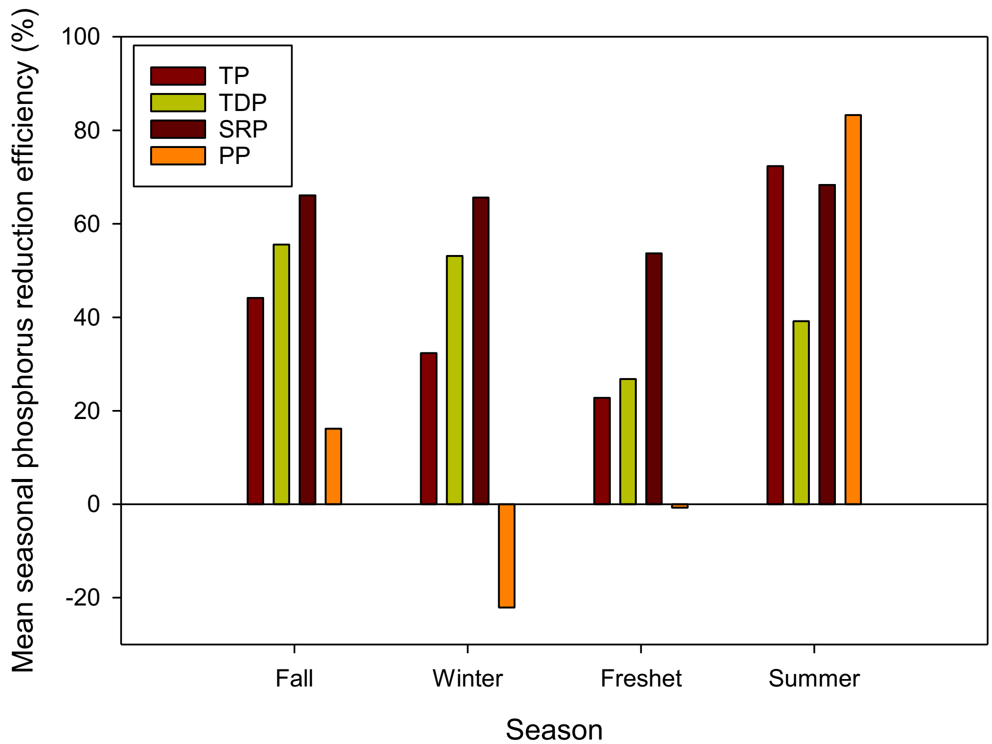


Figure 6. Mean percent reduction efficiency for TP, TDP, SRP and PP across four seasons.

Published data

The phosphorus retention capacity we measured in restored/created wetlands in southwestern Ontario are similar to those published in the literature. Phosphorus retention capacity in newly constructed wetland in Sweden receiving agricultural tile drainage had TP and TDP retention capacities of 69 and 17 kg ha^{-1} $year^{-1}$ with reduction efficiencies of 36 % and 9 % respectively (Kynkäänniemi et al. 2013). While the retention capacity from our study are lower for TP, the overall reduction efficiency we report is similar for TP (39 %) and higher for TDP (50 %). The wetland area in this study was 0.08 ha in area with a contributing area of 26 ha in sized for a CA:WA ration of 325 which is similar to site KE and MO. Results from these two individual sites (Table 10 and 11) indicate comparable results for sites with similar contributing and wetland areas.

Three constructed wetlands receiving agricultural tile drainage in central Illinois monitored over three years had mean TP and TN reduction efficiencies of 2 % and 37 % respectively (Kovacic et al. 2000). Individual basin TP and SRP reduction efficiencies for these wetlands varied tremendously over the study ranging from -27 to 90 % and -54 to 80 % respectively. Wetland area were similar to our study with contributing area to surface area ratios ranging from 17 to 32. Mean TP reduction efficiency from our sites were higher and less variable relative to those reported by Kovacic et al. (2000). Our study consisted of only one water year of monitoring while the study in Illinois was conducted over three years. This difference may be the reason reduction efficiencies were less variable in our study. The wetland TN reduction efficiency reported by Kovacic et al. (2000) is similar to our restored wetland basins.

Constructed wetlands in Illinois receiving high and low flows of nonpoint source pollution report a TP and TN retention capacity ranging from 4 to 29 kg ha^{-} year^{-} and 30 to 380 kg ha^{-} year^{-}, respectively (Mitsch and Gosselink 2000). Our results for mean TP and TN retention capacity are within those ranges (Table 10). The wetlands in the cited study are larger wetland (2 to 3 ha) compared to our study basins (Table 1) indicating nutrient retention capacity is not limited by the small basin area that is typical of restored wetlands in southwestern Ontario.

A review by Land et al. (2016) of constructed or restored wetlands in Europe and North America found a mean wetland TP retention capacity of 40 kg ha^{-} year^{-} with a mean TP reduction efficiency of 44 % (median of 6.3 kg ha^{-} year^{-} and 49 % respectively). They further report that 4 % of wetlands reviewed acted as net sources of phosphorus. The mean TP reduction capacity at our sites was lower while the median TP reduction capacity at our sites was higher at 14 kg ha^{-} year^{-} with 12 % of our sites (one site of eight) acting as a net source of phosphorus. The higher mean TP retention capacity reported by Land et al. (2016) is likely a result of much higher loading rates relative to our sites. Additionally, Land et al., (2016) reported mean wetland TN retention capacity of 850 kg ha^{-} year^{-} which is more than double the retention capacity we calculated for the restored wetlands we investigated. However, the mean TN reduction efficiency reported by Land et al., (2016) of 39 % was similar to the mean retention efficiency 44 % of our sites. The results of our study are comparable to this large review indicating that these eight restored wetlands function in a manner that can be considered typical of the average restored wetland in North America when comparing nutrient retention capacity and nutrient reduction efficiency.

Richardson and Qian (1999) report the mean phosphorus assimilative capacity of North American wetlands to be near 10 kg ha^{-} year^{-} where ecosystem integrity is maintained. They state that when wetland phosphorus loading rates rise above this level, there is risk to negatively affect the internal structure and function to the wetland ecosystem with increased TP export as a potential consequence. The TP loading rates to our wetlands ranged from 10 to 347 kg ha^{-} year^{-} with a median of 30 kg ha^{-} year^{-}. These TP loading rates reported in our study contributed to the mean TP retention capacity of 7.2 kg ha^{-} year^{-}. High loading rates on a yearly basis may result in a degraded wetland in a short period of time perhaps lowering the yearly TP reduction capacity of these restored wetlands. However, if the elevated loading rates are an outcome from an abnormally wet year, lower yearly loading rates could be typical of these systems resulting in less pressure and thus sustaining the ecological integrity of these basins.

Exploratory analysis

In general, the contributing area of the restored wetland basins is positively correlated with the TP inflow load (Figure 7). TP inflow load is found to be correlated with net TP retention capacity (Figure 8 - A). The outlying point in Figure 6 – A is site MA, the single site that had a large negative net TP retention capacity. To investigate this relationship further, site MA was removed and the remaining seven sites re-plotted (Figure 8 – B). With site MA removed, the correlation remains positive with an increase in the slope of the best-fit line. Net TP retention capacity is positively correlated with basin area, basin volume and retention time, however if site MA is removed, the three relationships produce a flat line (Figure 9). Site MA appears to be an outlier which strongly influences the slope of the relationship. This could be explained by the upland STP measured at site MA relative to all other sites or perhaps if the basin was not dredged as part of the initial restoration construction. When contributing area and contributing area: wetland area ratio are plotted against net TP retention, a neutral relationship is shown indicating that upland area and the size of the wetland basin in relation to the upland area may not be driving these restored wetland basins ability to retain TP (Figure 10). Basin age is negatively correlated with net TP retention capacity regardless of the inclusion or exclusion of site MA (Figure 11). Basin age is negatively correlated with TP inflow load as that the older restorations received less TP load than the recent restored wetland (Figure 12). It is critical to outline that TP inflow load drives TP retention capacity (Figure 8).

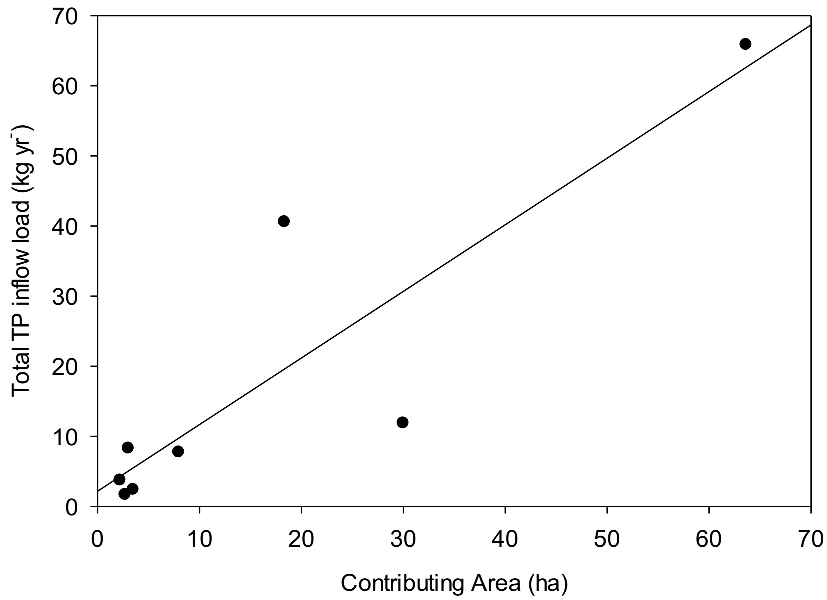


Figure 7. Linear relationship between contributing area and inflow TP loads for one year.

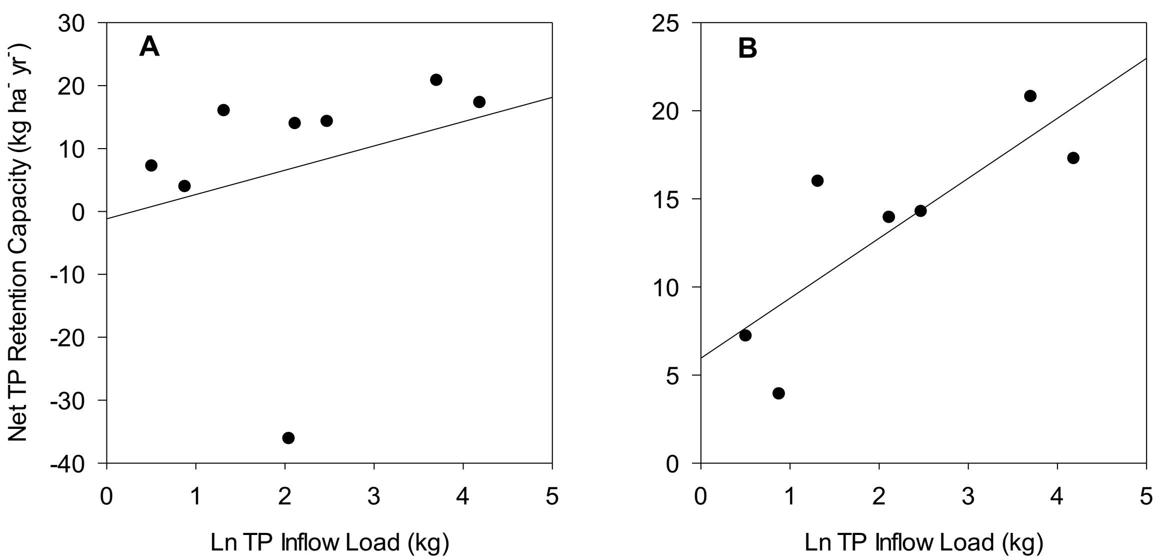


Figure 8. Linear relationship between Ln TP inflow load and net TP retention capacity including site MA (A) and excluding site MA (B).

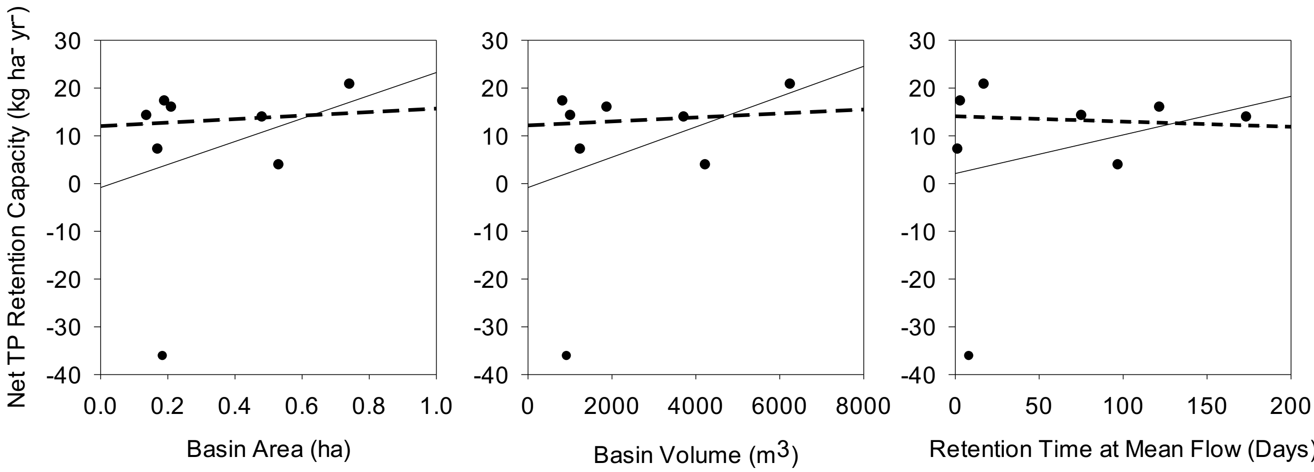


Figure 9. Linear relationships between basin area, basin volume and retention time with net TP retention capacity (solid line with all eight sites and dashed line with site MA removed).

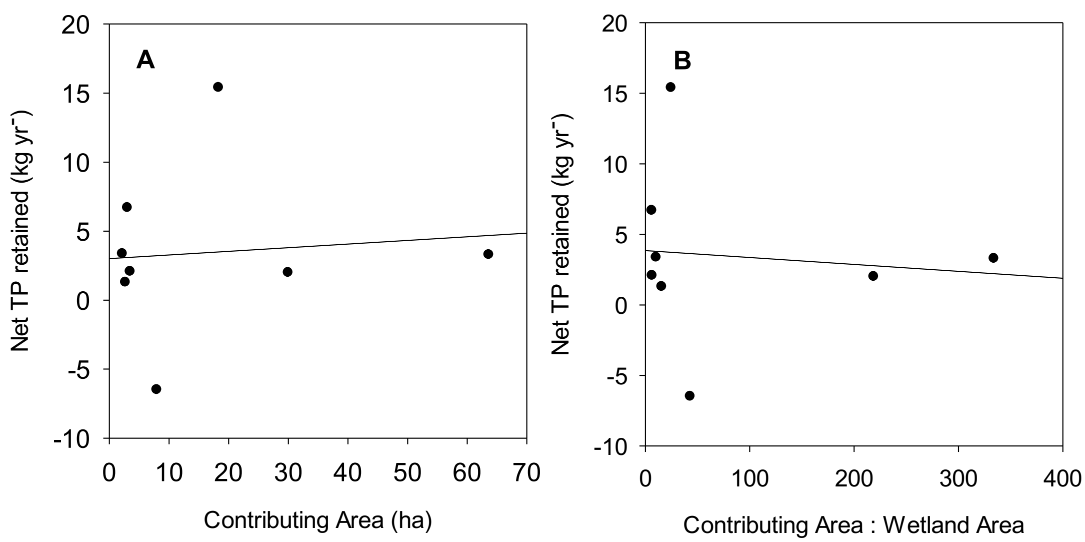


Figure 10. Linear relationship between contributing area (A) and contributing area: wetland area (B) with net TP retained.

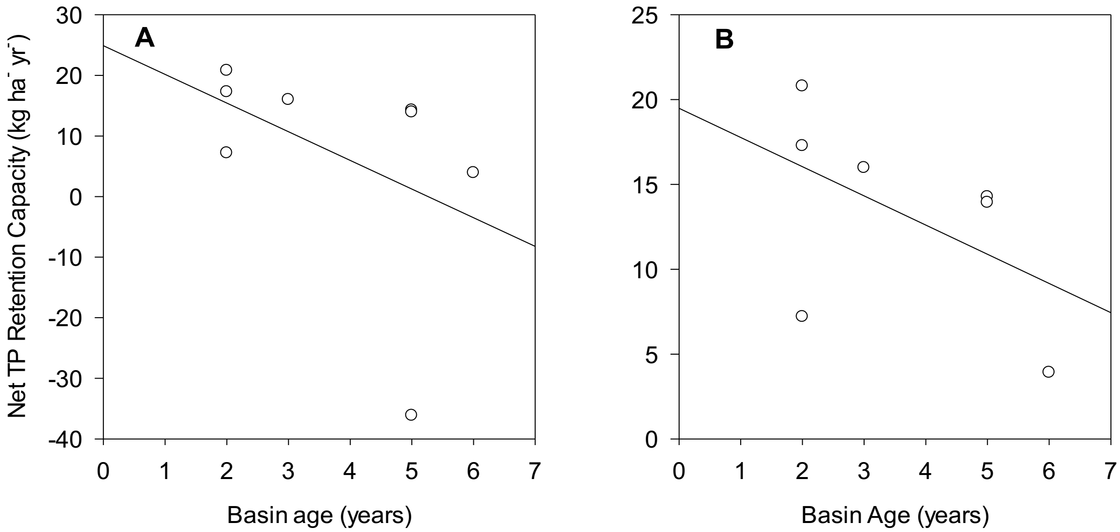


Figure 11. Linear relationship between basin age and net TP retention capacity including site MA (A) and excluding site MA (B).

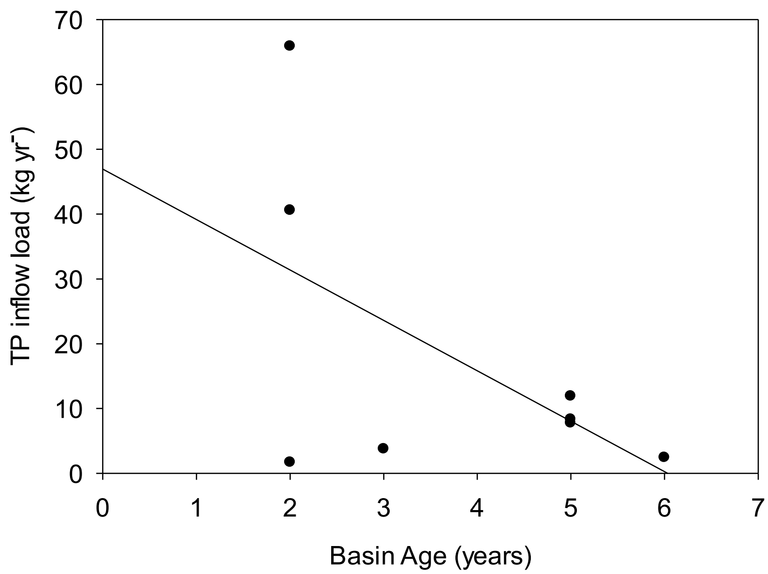


Figure 12. Linear relationship between basin age and TP inflow load.

Citizen Science

Citizen science is the engagement of the public (landowners, stakeholders, school children) in research projects to participate in the collection of scientific data. At times referred to as Public Participation in Scientific Research (PPSR), the involvement of the public in ecological investigations has proven to positively influence project outcomes based on the degree of public involvement in the research process (Shirk et al. 2012). Additionally, Church et al. (2019) found volunteers that were engaged in citizen science initiatives derived personal benefits from the participation that could be considered transformational and transcend into continued personal action to improve water quality, continued learning about local water issues, and BMP adoption.

For this project we engaged landowners to collect precipitation data at or near the restored wetland sites weekly, or more frequently if they were willing from May 1, 2019 to September 30, 2019. Imperial precision rain gauges made to the standards of the United States Weather Bureau were deployed beside the restored wetland basin at seven sites, with the rain gauge at site DY being located near the road which was 300 meters from the wetland basin. Rain gauges were secured to posts 1 meter above the ground in an area where trees would not influence the station. Field logbooks with a pencil were stored in a weather proof container attached to the post which secured the rain gauge. When field staff were on site for routine data collection, they would record the rain collected at the rain gauges to maintain a continuous record of rainfall.

Landowners were contacted via email and in person to inform and inquire if they would like to take part in this citizen science component of this project with several landowners agreeing to participate. Data collected from May 1, 2019 to September 30, 2019 is reported in Table 12 alongside rain data for the same period from the ECCC weather station in London and a local Cocorahs (www.cocorahs.org/Canada) precipitation station located within 20 km of the ECCC station.

The rainfall data collected at seven sites ranged from 216 to 489 mm over the five-month period. The rain gauge at site DY was damaged early in May so is reported as not available (NA). Sites MA and BL are two sites that appear to have large differences than the ECCC and Cocorahs stations. This is curious as site BL had the most data records collected by the landowner, often three times a week. This indicates that there is a strong possibility that this site did receive far less precipitation than what the ECCC and Cocorahs sites received. Site MA is also recorded lower rainfall than the other two stations indicating the possibility of less precipitation falling on this site. This demonstrates the importance of both local precipitation data and the value of a citizen science program which can provide detailed local data.

Table 12. Citizen science rain data collected from May 1, 2019 to September 30, 2019.

Site	Citizen Science Rain Gauge (mm)	Environment Canada Station - London - Climate ID 6144478 (mm)	Cocorahs Site ID: CAN-ON-31 (mm)
LL	393	447	420
OH	489		
MO	420		
KE	338		
BL	216		
FE	400		
MA	289		
DY	NA		

Recommendations

The following is a brief discussion on recommendations for future work based on the experience we have gained from collecting data over one water year while investigating the nutrient retention capacity of newly restored wetlands in southwestern Ontario.

1) We recommend investigating these eight restored wetlands for two additional water years to increase information on nutrient retention capacity for restored wetlands over multiple years.
2) Sediment accumulation should be measured to gain a better understanding of elevated phosphorus concentrations in wetland sediments.
3) Water quality samples could be collected on the rising limb and the falling limb of the hydrological event for one or two runoff events to determine the extent nutrient concentrations change at the inflows and outflow during these flow events.
4) We recommend using Spypoint Link EVO trail cameras to take three pictures daily of each outflow culvert to improve estimates when baseflow stops.
5) To obtain a data set of water/ice level over the winter month, meter sticks should be attached to a pole in the water with data collected by field staff using binoculars.
6) It is recommended that a detailed upland survey of soil test phosphorus (STP) takes place at all wetland sites.

Conclusion

The objectives of this research were to determine the wetland nutrient retention capacity and the nutrient reduction efficiency of newly restored wetlands in southwestern Ontario and to explore relationships between wetland basin characteristics and nutrient retention capacity. We studied eight newly restored wetland basins over one full water year (October 1, 2018 to September 30, 2019).

Overall, newly restored wetlands were found to have TP and TN retention capacities of 7.2 and 378 kg ha^{-} year^{-}, respectively. On average, these restored systems will retain nutrients and will reduce nutrient loads downstream. The TP an TN reduction efficiency was found to be 39 % and 44 %, respectively. Our results are similar to what is reported in the literature for restored wetlands that receive agricultural runoff.

Seven of the eight sites studied had consistent net positive retention capacity and reduction efficiency for all phosphorus and nitrogen species. One site was found to be a source of TP, TDP and PP while a sink of SRP. Investigations which study a wetlands ability to retain phosphorus often report a small percentage of study sites acting as sources of phosphorus (Land et al. 2016), and this study was no different. However, seven of our eight restored wetlands showed a positive water quality improvement.

SRP retention rates were higher than TDP retention rates in two of the restored wetlands indicating a chemical transformation of this highly reactive form of phosphorus upon entering the restored wetland basin. The SRP entering these basins may get bound to dissolved organic mater (or other ligands) or particulate matter which then is stored or exits these basins. The overall net SRP retention rate of 5.7 kg ha^{-} year^{-} demonstrates these restored wetland basins can play an important role in meeting the reduction of SRP loads set for Lake Erie.

The main driver of TP retention capacity in these wetlands was TP load, with the higher TP load into the wetland increasing the net TP retention capacity. Higher TP load into the wetlands was positively correlated with increasing contributing area. Of the seven sites that retained TP, there was no relationship between TP retention capacity and basin size, basin volume, or retention time. This indicates that, for most restored wetlands, regardless of the position on the landscape or the size of the basin, a restored wetland will act as a net sink for reducing nonpoint source phosphorus runoff to downstream water bodies.

Overall, our study results indicate that restored wetlands are important natural green infrastructure that can be effective for reducing nonpoint source nutrients from entering Lake Erie.

Acknowledgements

Landowners

We would like to sincerely thank all landowners who allowed their wetland restoration projects to be monitored as part of this project. The kindness and trust that was shown to allow DUC's staff and partners to access their private land at a weekly, and sometimes biweekly, rate was truly gracious. From many meetings in the field, it is clear they are all passionate about their wetland projects and are concerned for Lake Erie's water quality.

This project was funded in partnership with the *North American Wetlands Conservation Act* of the U.S. Fish and Wildlife Service and the Ontario Ministry of Natural Resources and Forestry. We greatly appreciate the assistance of the St. Clair Region Conservation Authority in conducting field work over the course of this project.

Cover image

Weekly site monitoring was conducted by staff from the St. Clair Region Conservation Authority. © DUC

References

Canada-Ontario. 2018. Canada-Ontario Lake Erie Action Plan.

CCME. 2004. Canadian water quality guidelines for the protection of aquatic life: Phosphorus: Canadian Guidance Framework for the Management of Freshwater Systems. In: Canadian environmental quality guidelines, 2004, Canadian Council of Ministers of the Environment, Winnipeg.

CHC. 2010. Green Kenue Reference Manual.

Church, S. P., L. B. Payne, S. Peel, and L. S. Prokopy. 2019. Beyond water data: benefits to volunteers and to local water from a citizen science program. Journal of Environmental Planning and Management **62**:306-326.

DUC. 2010. Southern Ontario Wetland Conversion Analysis.

DUC. 2018. A standardized wetland monitoring protocol to determine non-point source phosphorus mitigation associated with wetland restoration projects.

Dunne, E. J., M. F. Coveney, V. R. Hoge, R. Conrow, R. Naleway, E. F. Lowe, L. E. Battoe, and Y. Wang. 2015. Phosphorus removal performance of a large-scale constructed treatment wetland receiving eutrophic lake water. Ecological Engineering **79**:132-142.

Fan, X., B. Cui, Z. Zhang, and H. Zhang. 2012. Research for wetland network used to improve river water quality. Procedia Environmental Sciences **13**:2353-2361.

Fisher, J., and M. Acreman. 2004. Wetland nutrient removal: a review of the evidence. Hydrology and Earth System Sciences Discussions **8**:673-685.

GLWQA. 2012. Great Lakes Water Quality Agreement of 2012, Protocol Amending the Agreement Between Canda and the United States of America on Great Lakes Water Quality, 1978, As Ammended on October 16, 1983 and on November 18, 1987.

Hansson, L.-A., C. Brönmark, P. Anders Nilsson, and K. Åbjörnsson. 2005. Conflicting demands on wetland ecosystem services: nutrient retention, biodiversity or both? Freshwater Biology **50**:705-714.

Hogan, D. M., T. E. Jordan, and M. R. Walbridge. 2004. Phosphorus retention and soil organic carbon in restored and natural freshwater wetlands. Wetlands **24**:573-585.

IJC. 2014. A Balanced Diet for Lake Erie.

Jarvie, H. P., L. T. Johnson, A. N. Sharpley, D. R. Smith, D. B. Baker, T. W. Bruulsema, and R. Confesor. 2017. Increased soluble phosphorus loads to Lake Erie: unintended consequences of conservation practices? Journal of Environmental Quality **46**:123-132.

Johannesson, K. M., P. Kynkäänniemi, B. Ulén, S. Weisner, and K. S. Tonderski. 2015. Phosphorus and particle retention in constructed wetlands—A catchment comparison. Ecological Engineering **80**:20-31.

Kovacic, D. A., M. B. David, L. E. Gentry, K. M. Starks, and R. A. Cooke. 2000. Effectiveness of constructed wetlands in reducing nitrogen and phosphorus export from agricultural tile drainage. Journal of Environmental Quality **29**:1262-1274.

Kynkäänniemi, P., B. Ulén, G. Torstensson, and K. S. Tonderski. 2013. Phosphorus retention in a newly constructed wetland receiving agricultural tile drainage water. Journal of Environmental Quality **42**:596-605.

Land, M., W. Granéli, A. Grimvall, C. C. Hoffmann, W. J. Mitsch, K. S. Tonderski, and J. T. Verhoeven. 2016. How effective are created or restored freshwater wetlands for nitrogen and phosphorus removal? A systematic review. Environmental Evidence **5**:9.

Maccoux, M. J., A. Dove, S. M. Backus, and D. M. Dolan. 2016. Total and soluble reactive phosphorus loadings to Lake Erie: A detailed accounting by year, basin, country, and tributary. Journal of Great Lakes Research **42**:1151-1165.

Mitsch, W. J., and J. G. Gosselink. 2000. Wetlands (Third Edition). John Wiley & Sons.

Pote, D., T. Daniel, P. Moore, D. Nichols, A. Sharpley, and D. Edwards. 1996. Relating extractable soil phosphorus to phosphorus losses in runoff. Soil Science Society of America Journal **60**:855-859.

Richardson, C. J. 1985. Mechanisms controlling phosphorus retention capacity in freshwater wetlands. Science(Washington) **228**:1424-1426.

Richardson, C. J., and S. S. Qian. 1999. Long-term phosphorus assimilative capacity in freshwater wetlands: a new paradigm for sustaining ecosystem structure and function. Environmental science & technology **33**:1545-1551.

Shirk, J. L., H. L. Ballard, C. C. Wilderman, T. Phillips, A. Wiggins, R. Jordan, E. McCallie, M. Minarchek, B. V. Lewenstein, and M. E. Krasny. 2012. Public participation in scientific research: a framework for deliberate design. Ecology and Society **17**.

Team, T. 2015. Recommended phosphorus loading targets for Lake Erie. In Annex 4 Objectives and Targets Task Team.

Wetzel, R. G. 2001. Limnology: lake and river ecosystems. Gulf Professional Publishing.

Zedler, J. B. 2003. Wetlands at your service: reducing impacts of agriculture at the watershed scale. Frontiers in Ecology and the Environment **1**:65-72.

Appendix A

List of Tables

List of Figures

Figure A 1. Picture of site OH with ecotone water level recorder and AP3 water level recorder in the foreground.

Figure A 2. Picture of site MO.

Figure A 3. Picture of site KE.

Figure A 4 . Picture of site LL.

Figure A 5. Picture of site BL.

Figure A 6. Picture of site FE.

Figure A 7. Picture of site DY.

Figure A 8. Picture of site MA while basin bathymetry data being collected.

Figure A 9. Picture of an area velocity flow probe being tested for accurate calibration in a controlled flume at the Hydraulics Research and Testing Facility at the University of Manitoba prior to deployment in the field.

Table A 1. Flow results when comparing the area velocity flow probes to the established flow rate of the controlled flume at the University of Manitoba.

Logger # or Flume	Level (m)	Velocity (m s^{-1})	Estimated flow rate (L min^{-1})
1	0.139	0.128	23.0
2	0.130	0.118	20.2
3	0.130	0.119	20.3
7	0.130	0.122	20.9
8	0.128	0.119	20.1
9	0.131	0.116	19.9
10	0.131	0.123	21.1
11	0.127	0.121	20.3
12	0.130	0.128	21.9
13	0.130	0.119	20.3
14	0.131	0.125	21.5
15	0.131	0.122	21.0
16	0.131	0.133	22.9
17	0.127	0.119	20.0
18	0.13	0.119	20.3
19	0.134	0.128	22.4
20	0.132	0.127	22.0
Flume			22.0

Figure A 10. Deployed area velocity flow probe collecting flow data every 15 minutes at the outflow of site KE.

Figure A 11. Close up of area velocity flow probe the outflow of site DY at period when site DY is not spilling.

Figure A 12. Deployed ecotone water level at site FE.

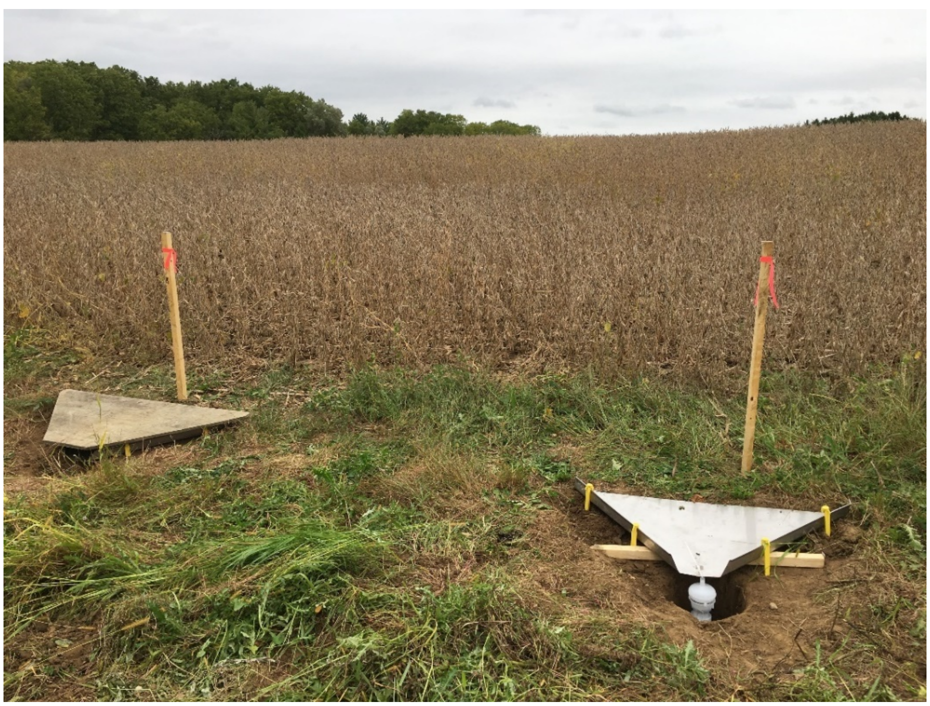


Figure A 13. Runoff trays at site DY with protective cover on (left) and off (right) with deployed sample bottle with cover designed to keep dust out of bottle when no flow occurs and to collect runoff water slowly to collect water sample over the runoff period.

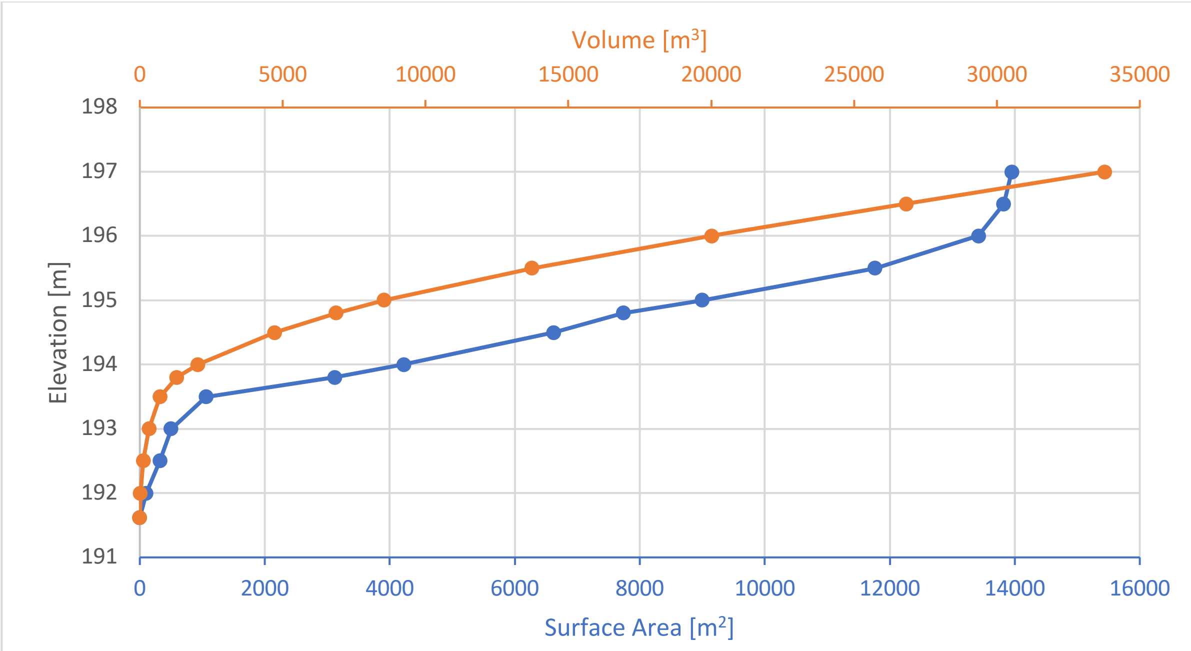


Figure A 14. OH storage curve.

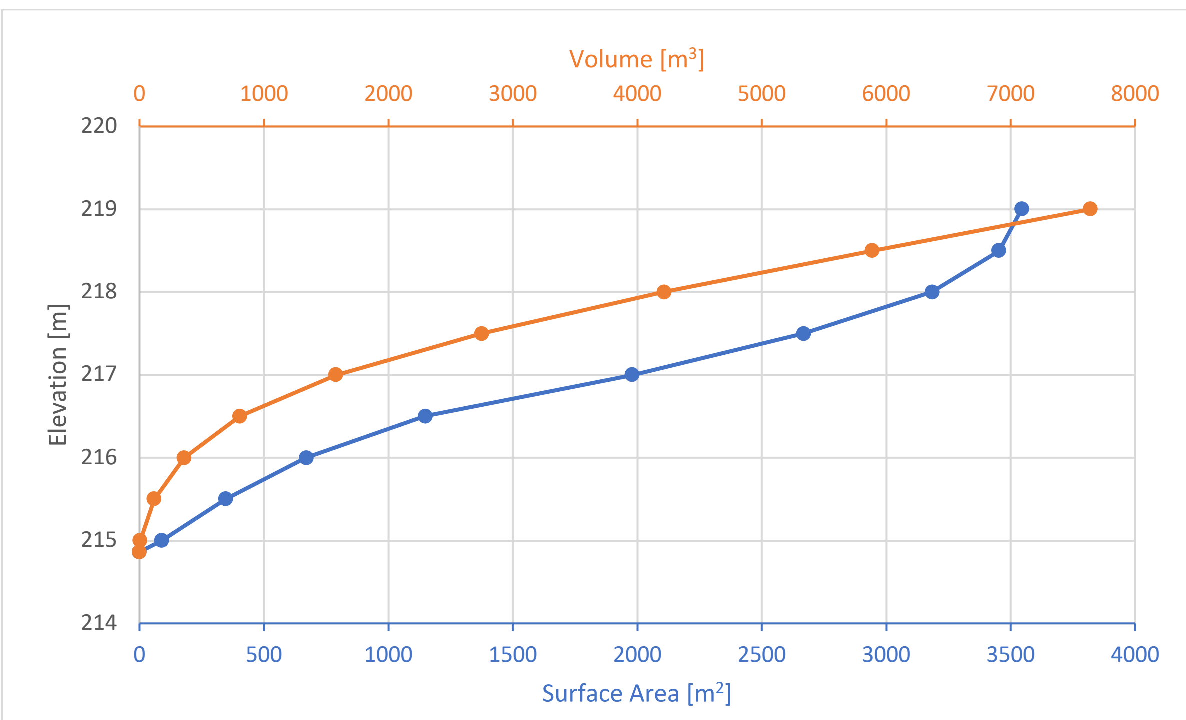


Figure A 15. MO storage curve.

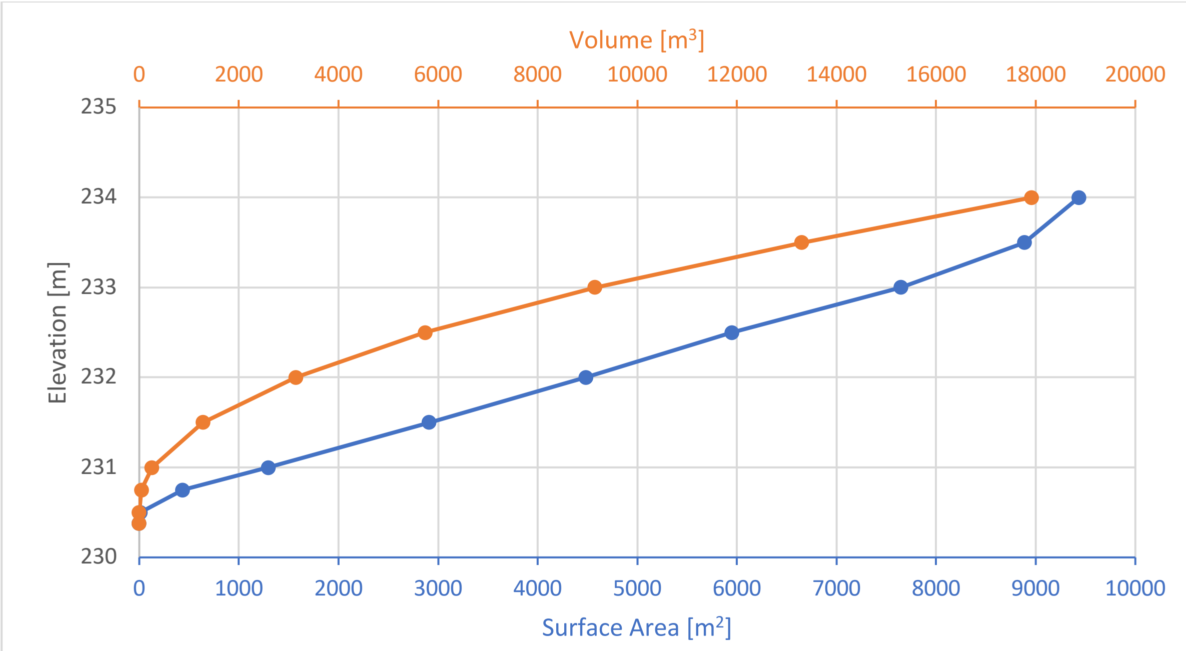


Figure A 16. LL storage curve.

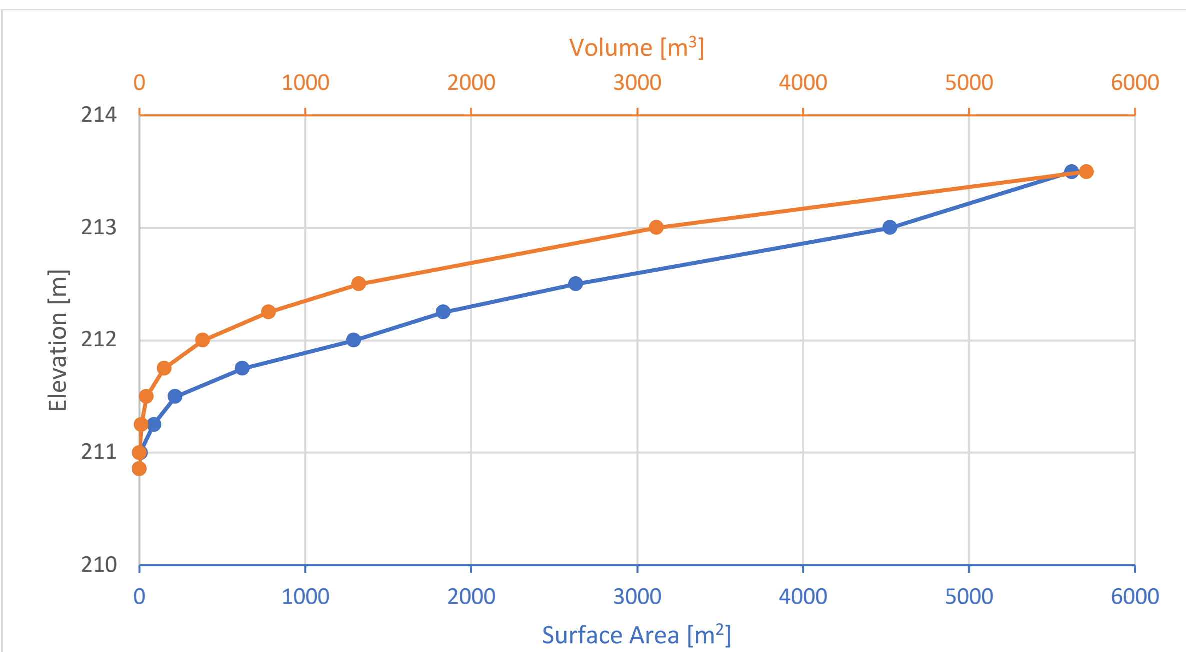


Figure A 17. KE storage curve.

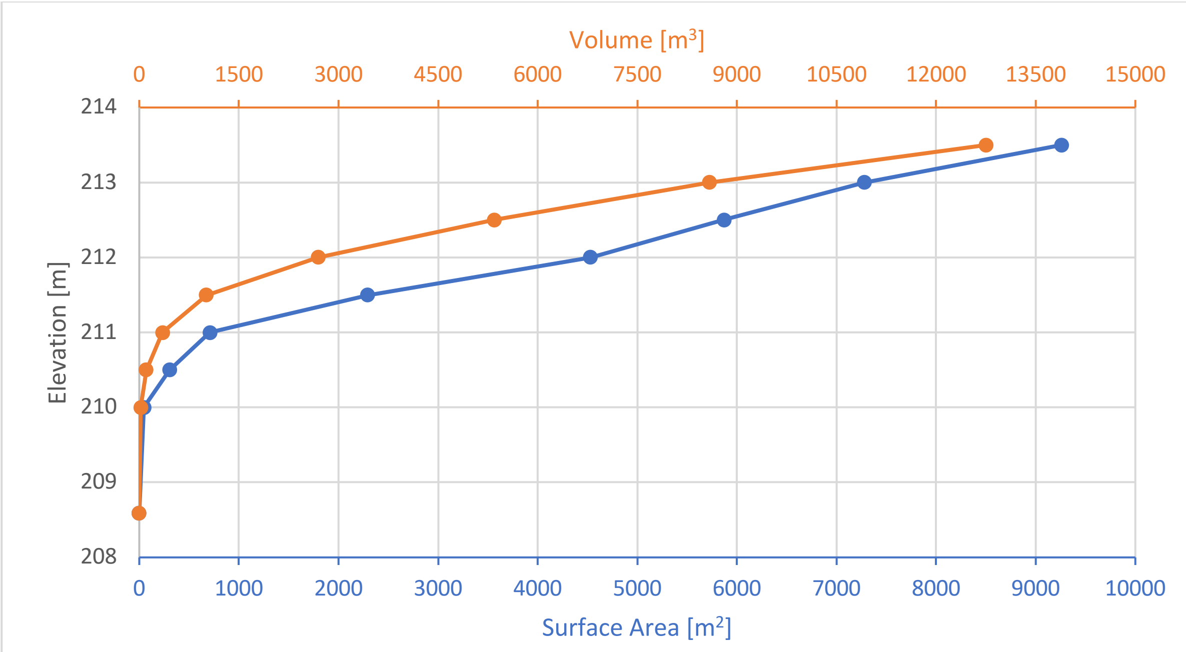


Figure A 18. FE storage curve.

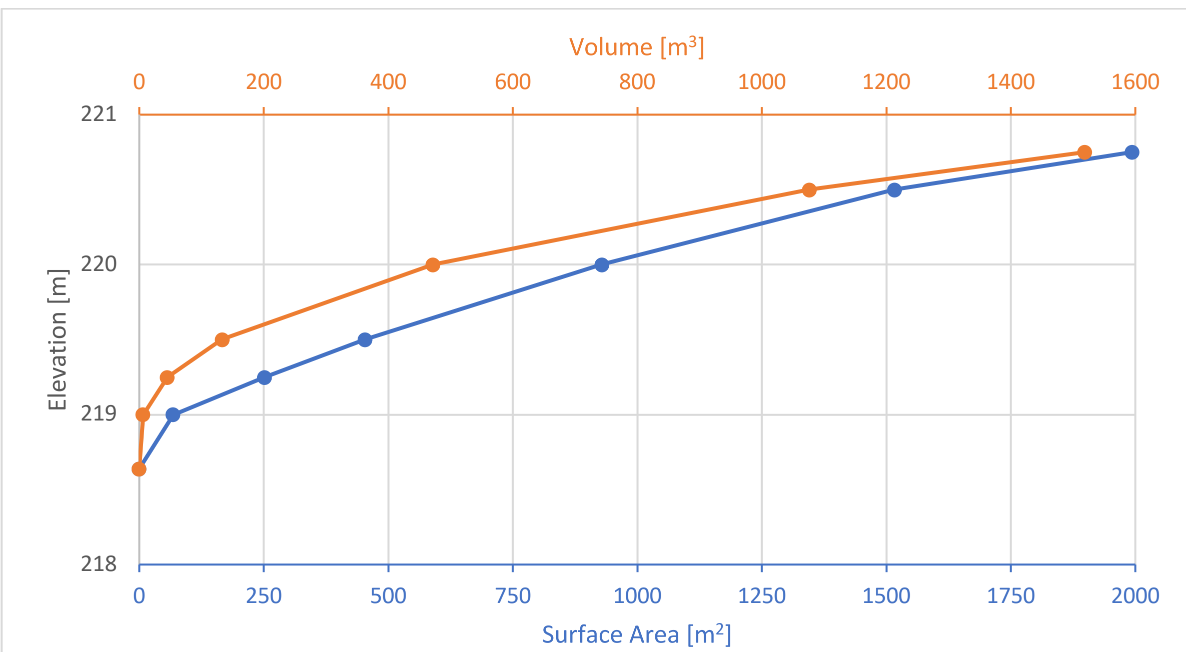


Figure A 19. BL storage curve.

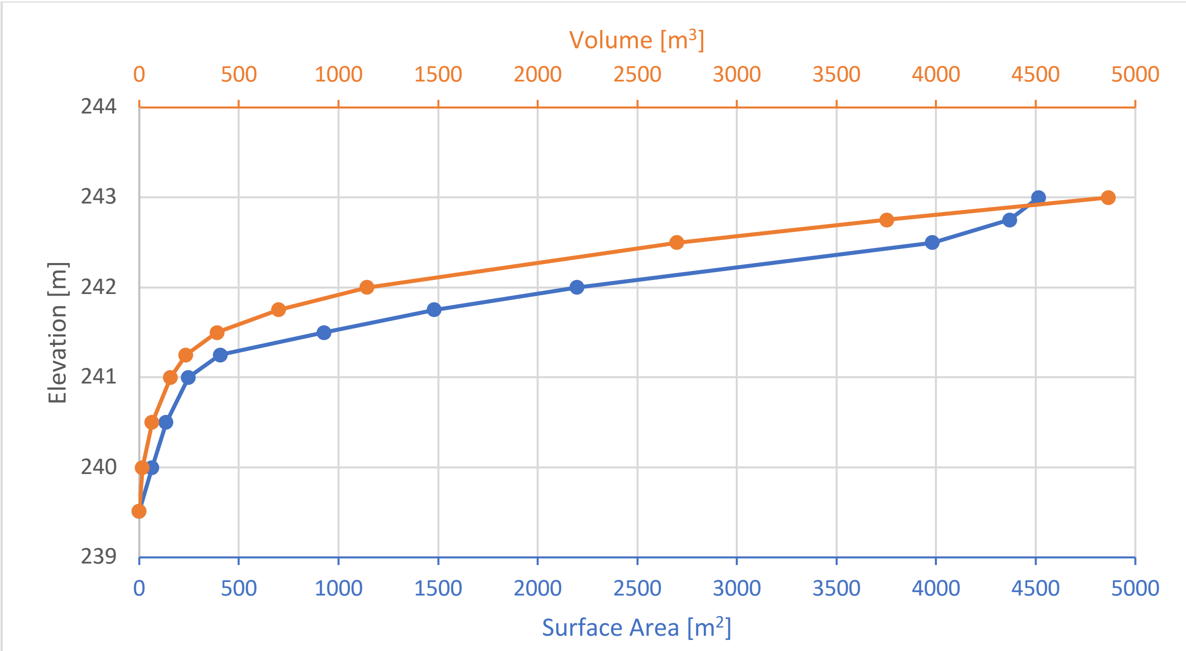


Figure A 20. MA storage curve.

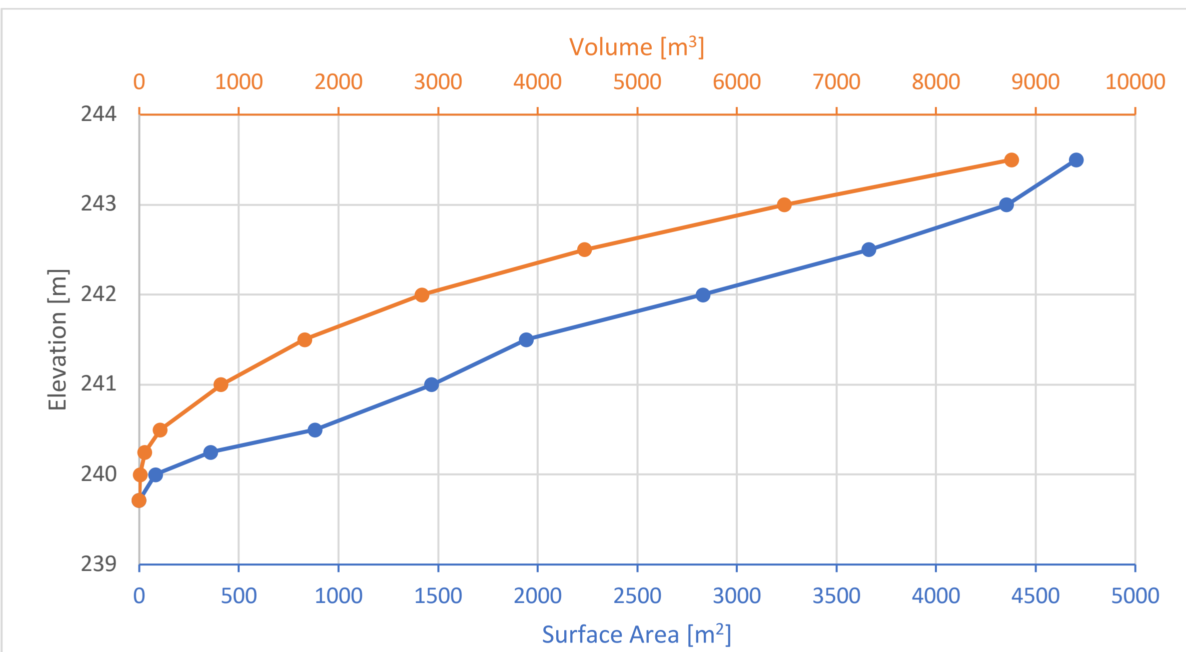


Figure A 21. DY storage curve.

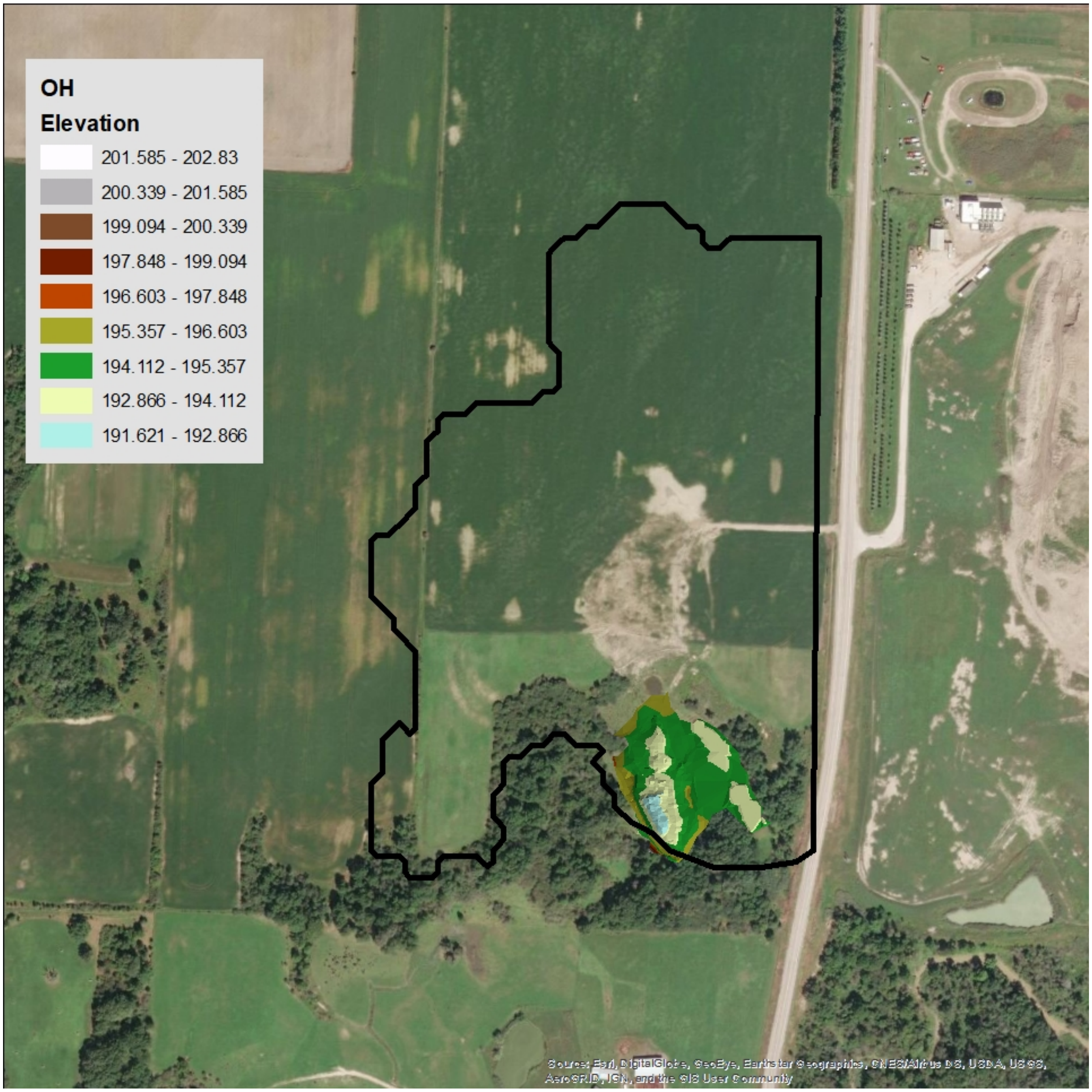


Figure A 22. Site OH with contributing area outline in bold and restored basin DEM with shaded slices displaying the elevation of the wetland basin up to a minimum of 1 meters above spill elevation.

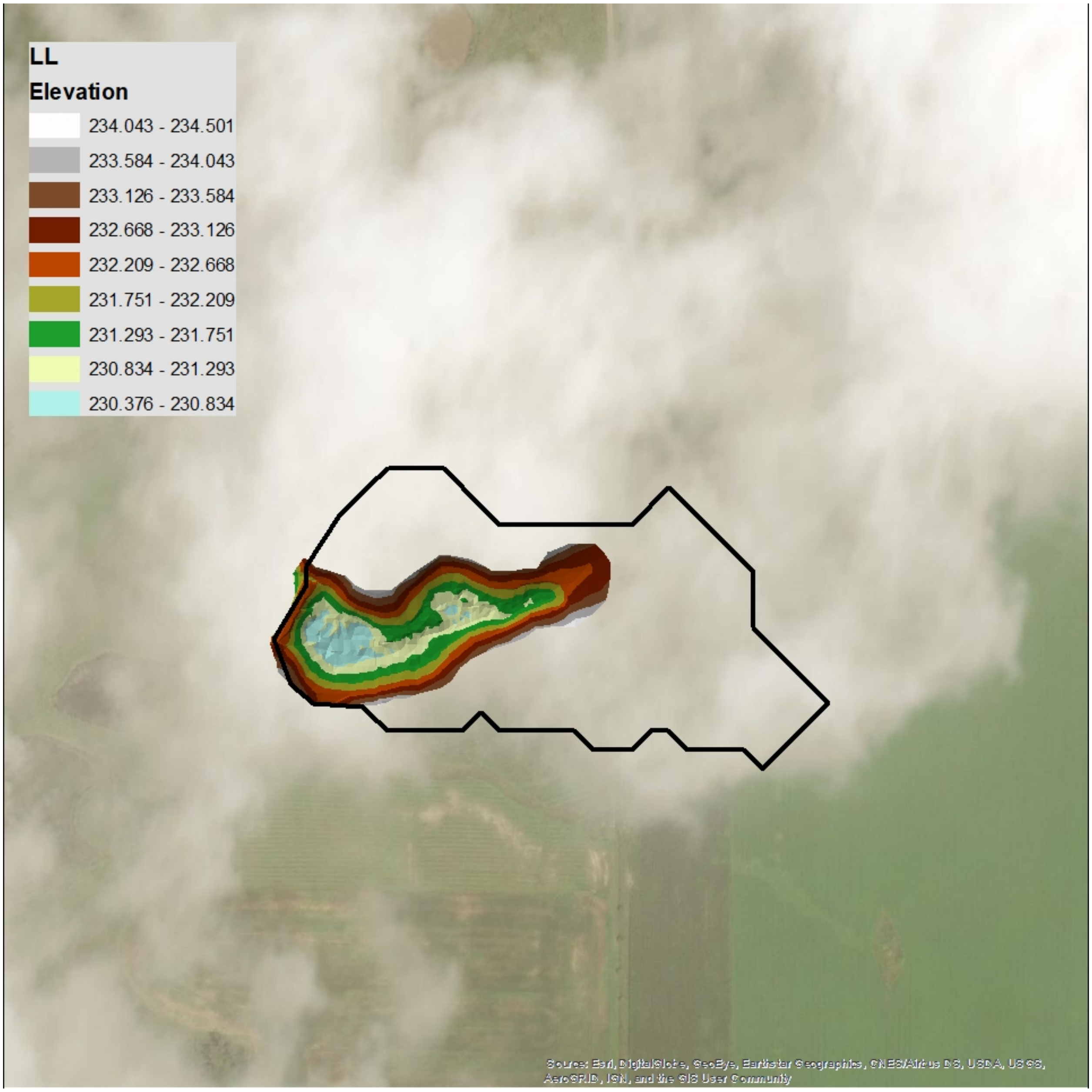


Figure A 23. Site LL with contributing area outline in bold and restored basin DEM with shaded slices displaying the elevation of the wetland basin up to a minimum of 1 meters above spill elevation.

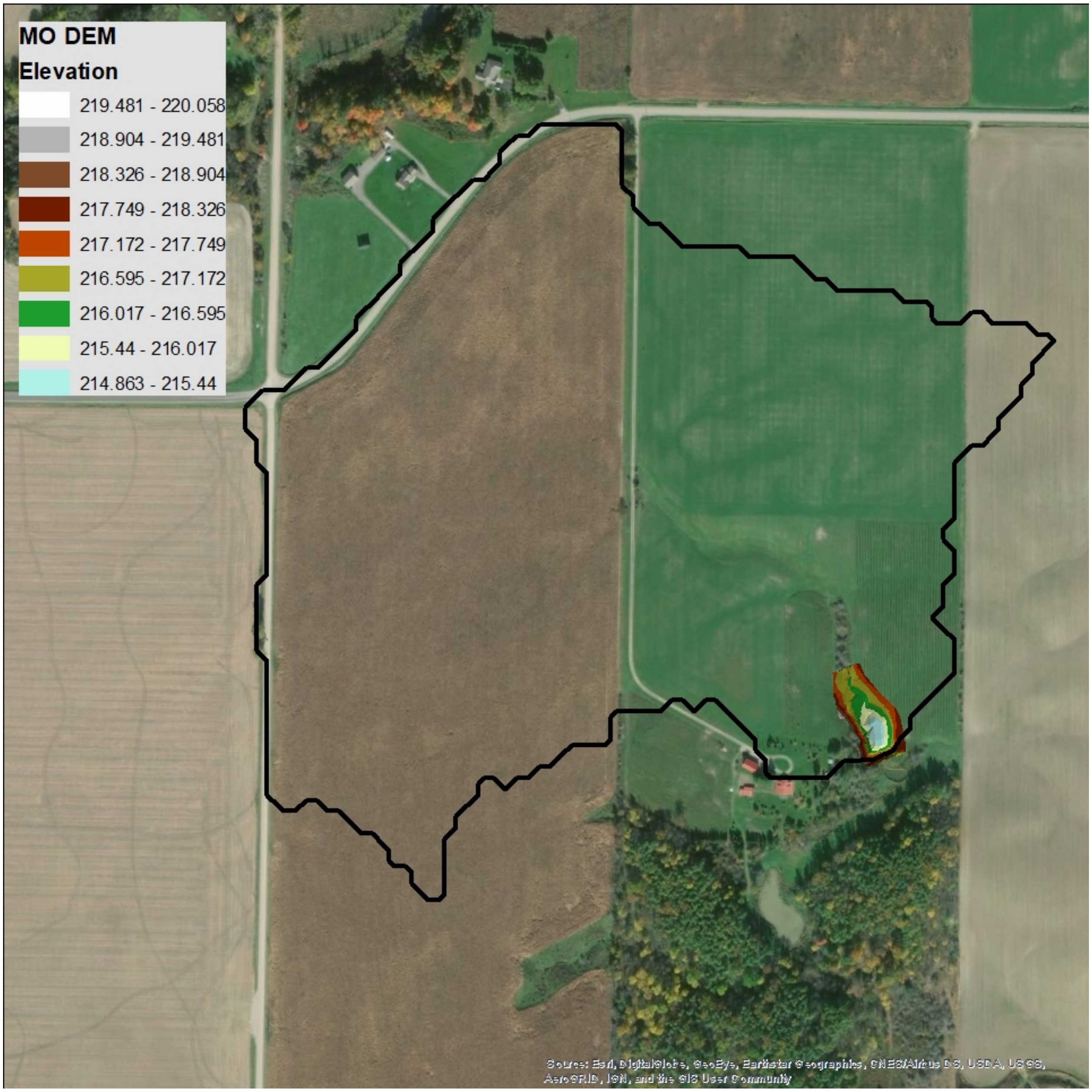


Figure A 24. Site MO with contributing area outline in bold and restored basin DEM with shaded slices displaying the elevation of the wetland basin up to a minimum of 1 meters above spill elevation.

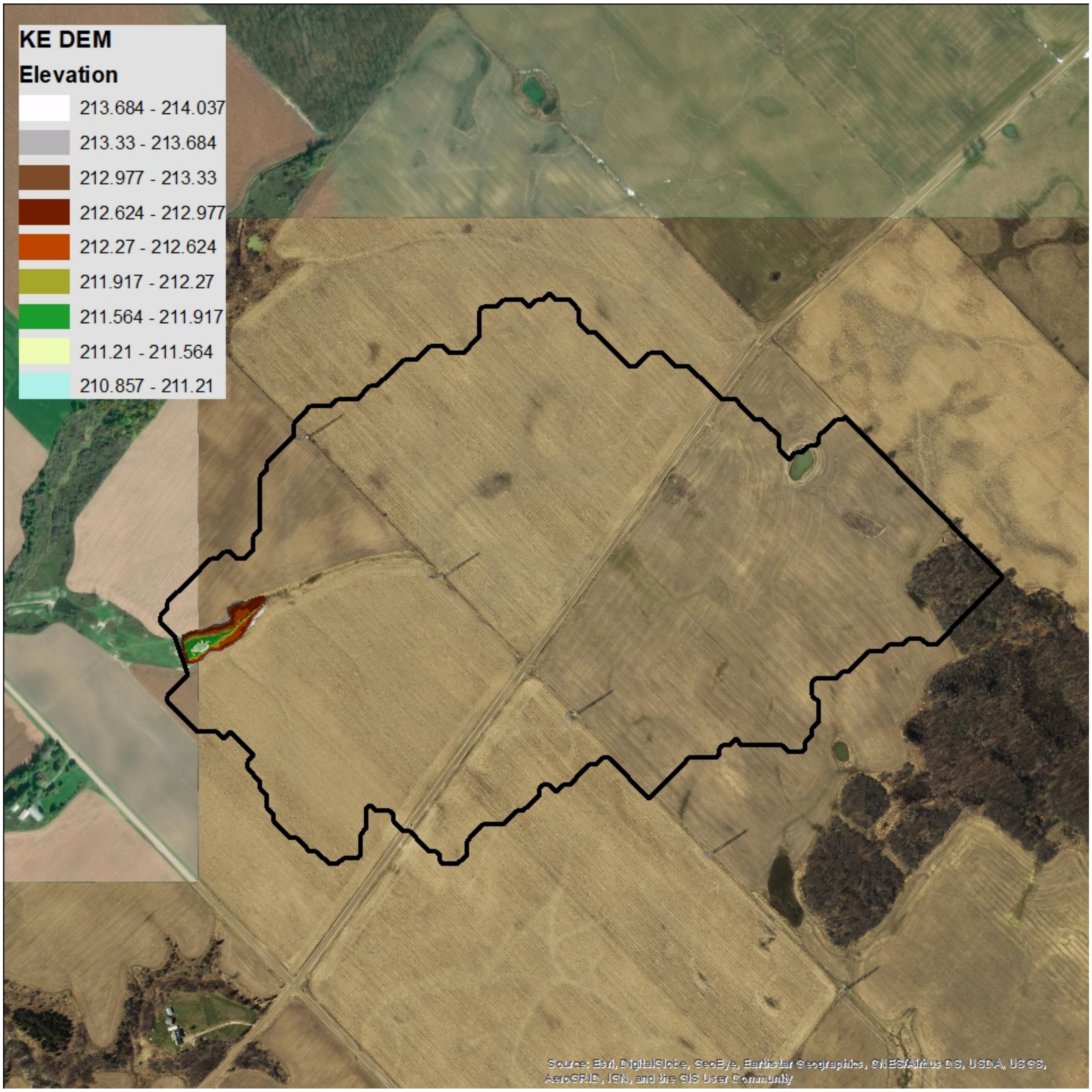


Figure A 25. Site KE with contributing area outline in bold and restored basin DEM with shaded slices displaying the elevation of the wetland basin up to a minimum of 1 meters above spill elevation.

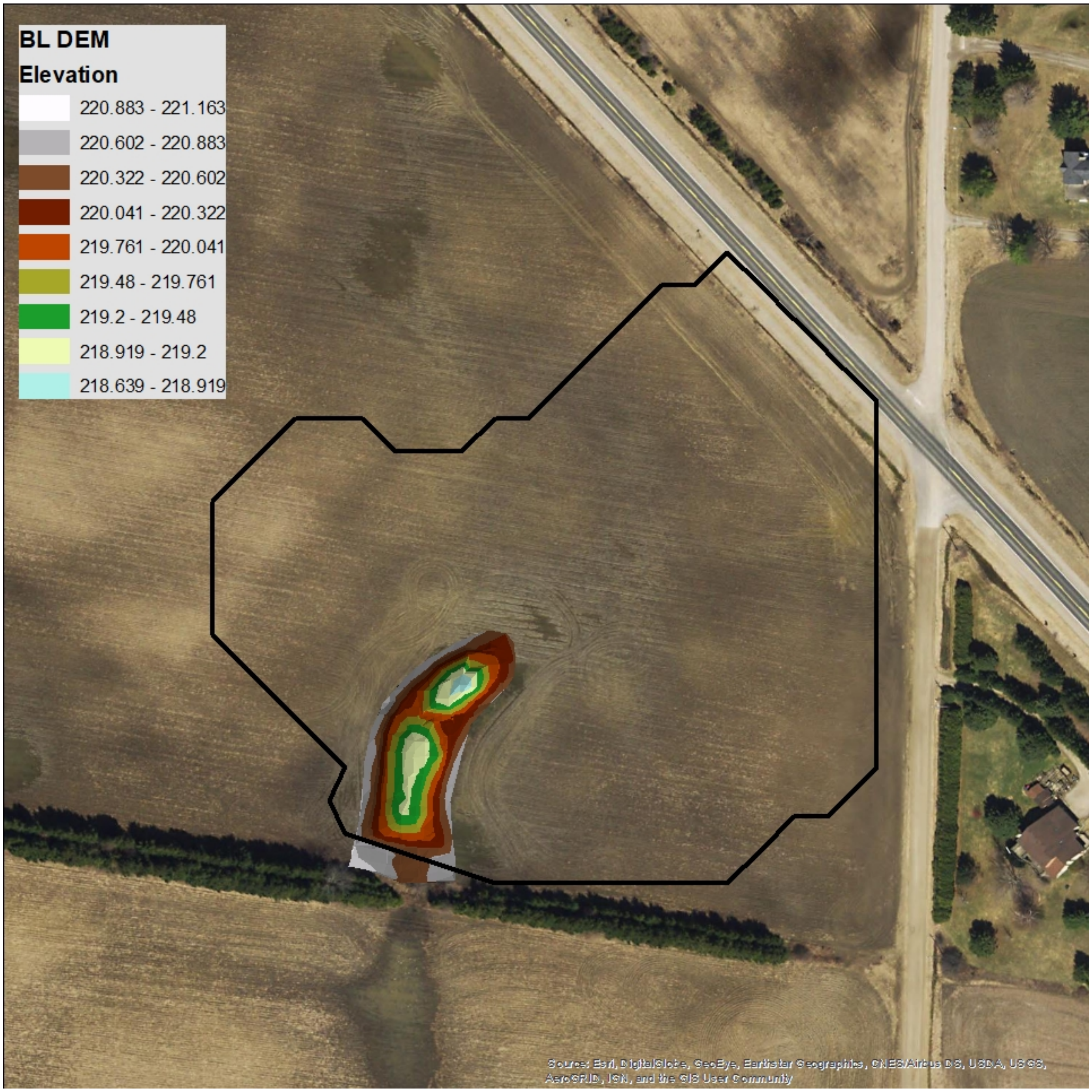


Figure A 26. Site BL with contributing area outline in bold and restored basin DEM with shaded slices displaying the elevation of the wetland basin up to a minimum of 1 meters above spill elevation.

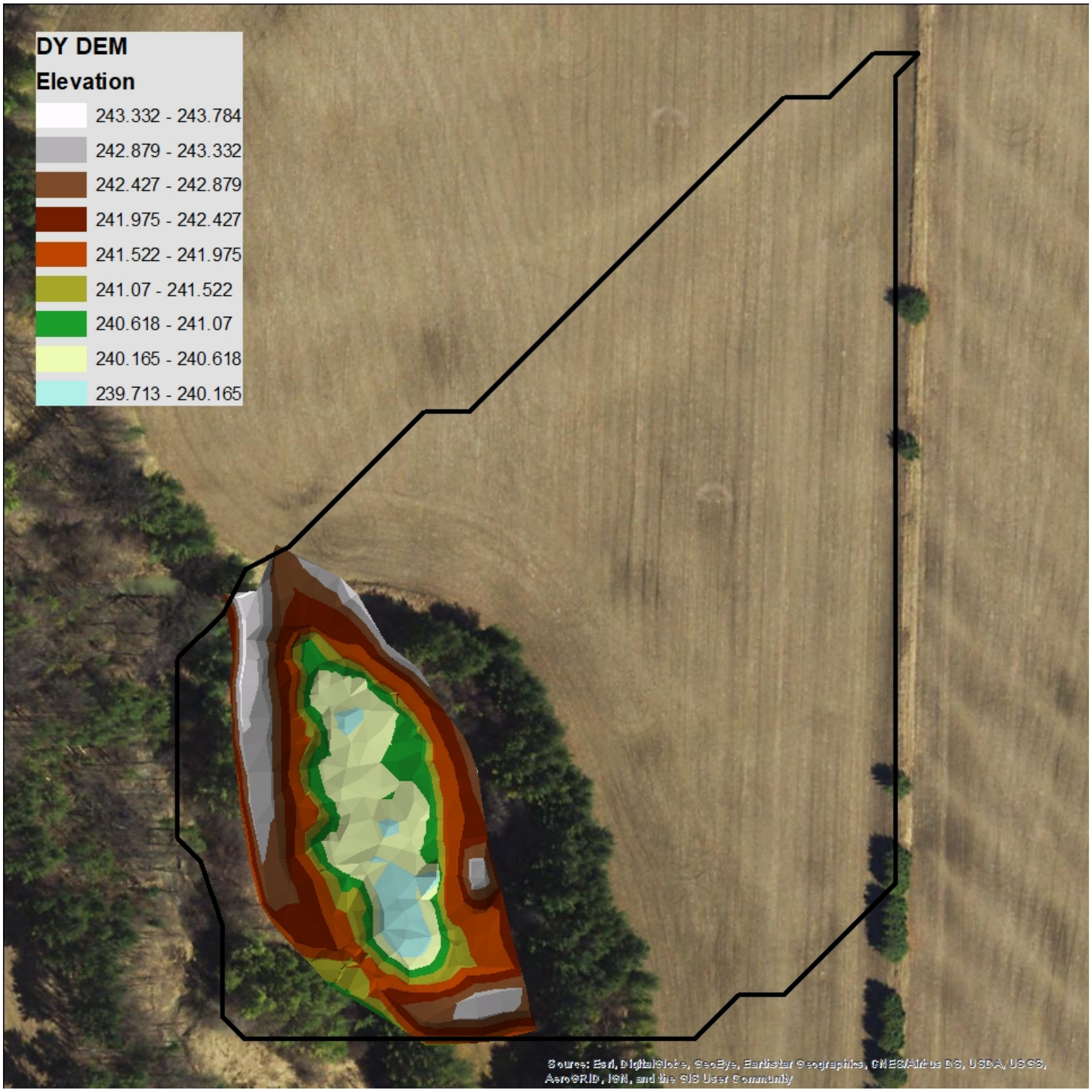


Figure A 27. Site DY with contributing area outline in bold and restored basin DEM with shaded slices displaying the elevation of the wetland basin up to a minimum of 1 meters above spill elevation.

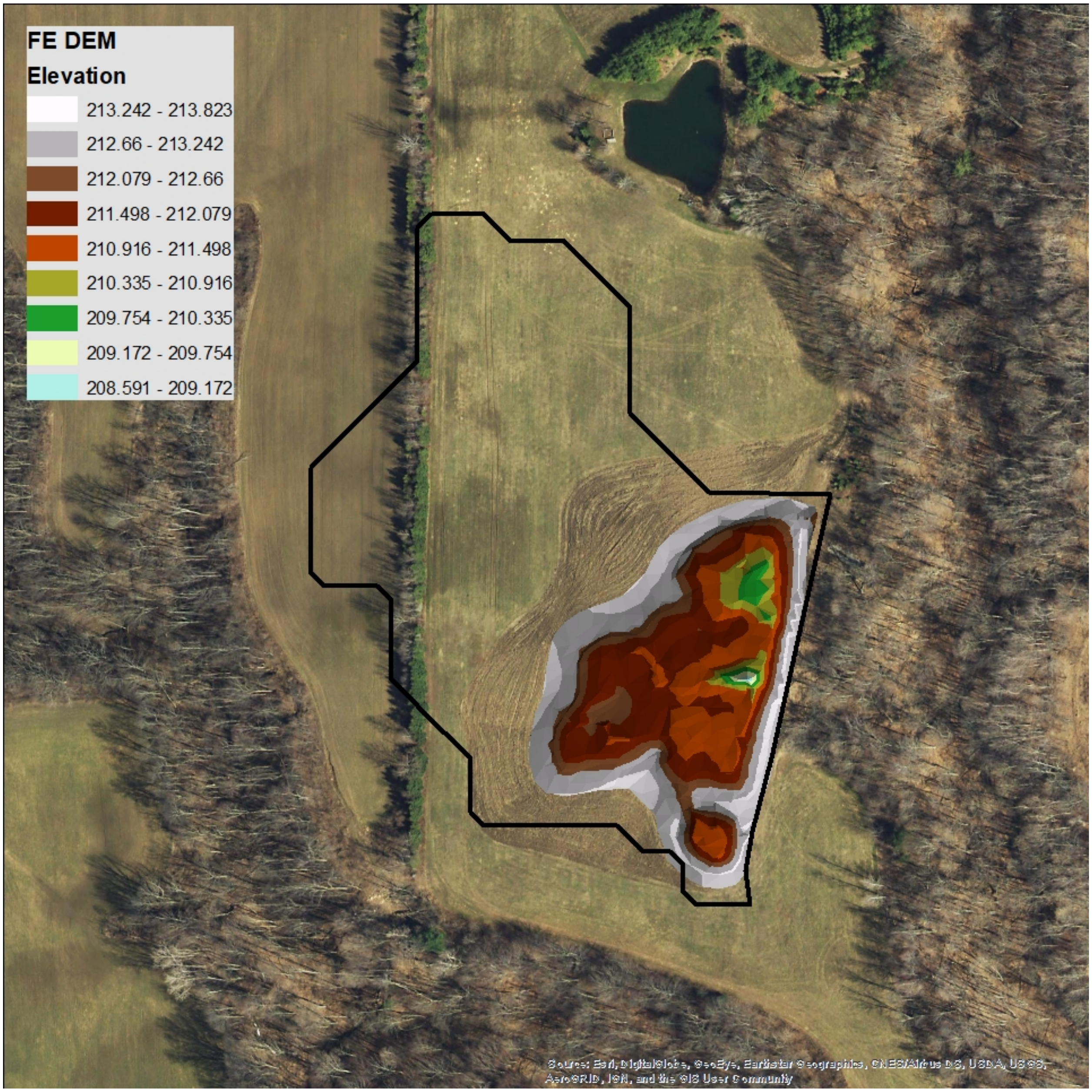


Figure A 28. Site FE with contributing area outline in bold and restored basin DEM with shaded slices displaying the elevation of the wetland basin up to a minimum of 1 meters above spill elevation.

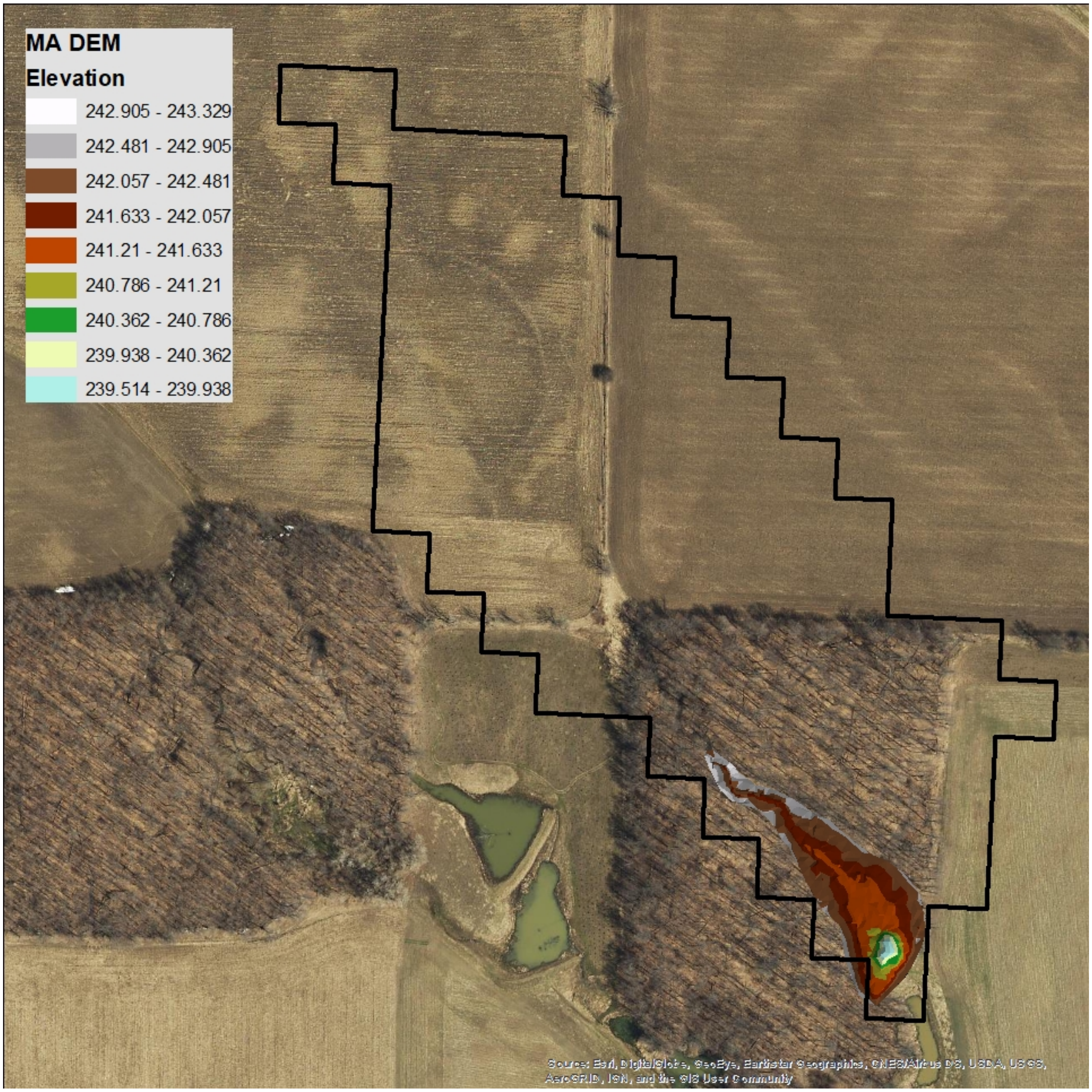


Figure A 29. Site MA with contributing area outline in bold and restored basin DEM with shaded slices displaying the elevation of the wetland basin up to a minimum of 1 meters above spill elevation.

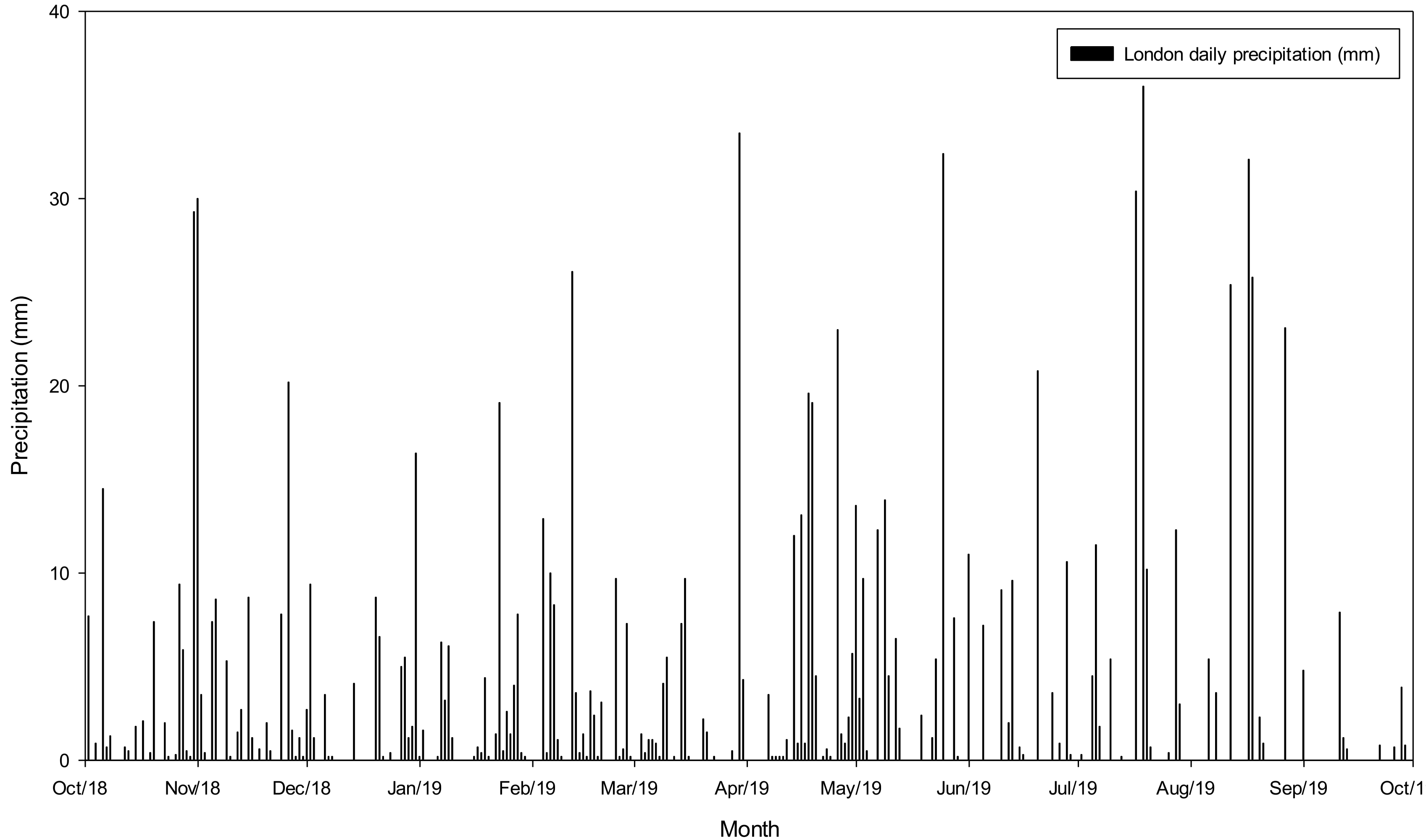


Figure A 30. Daily precipitation at London, Ontario (ECCC Station Climate ID # 6144478) from October 1, 2018 to September 30, 2019.

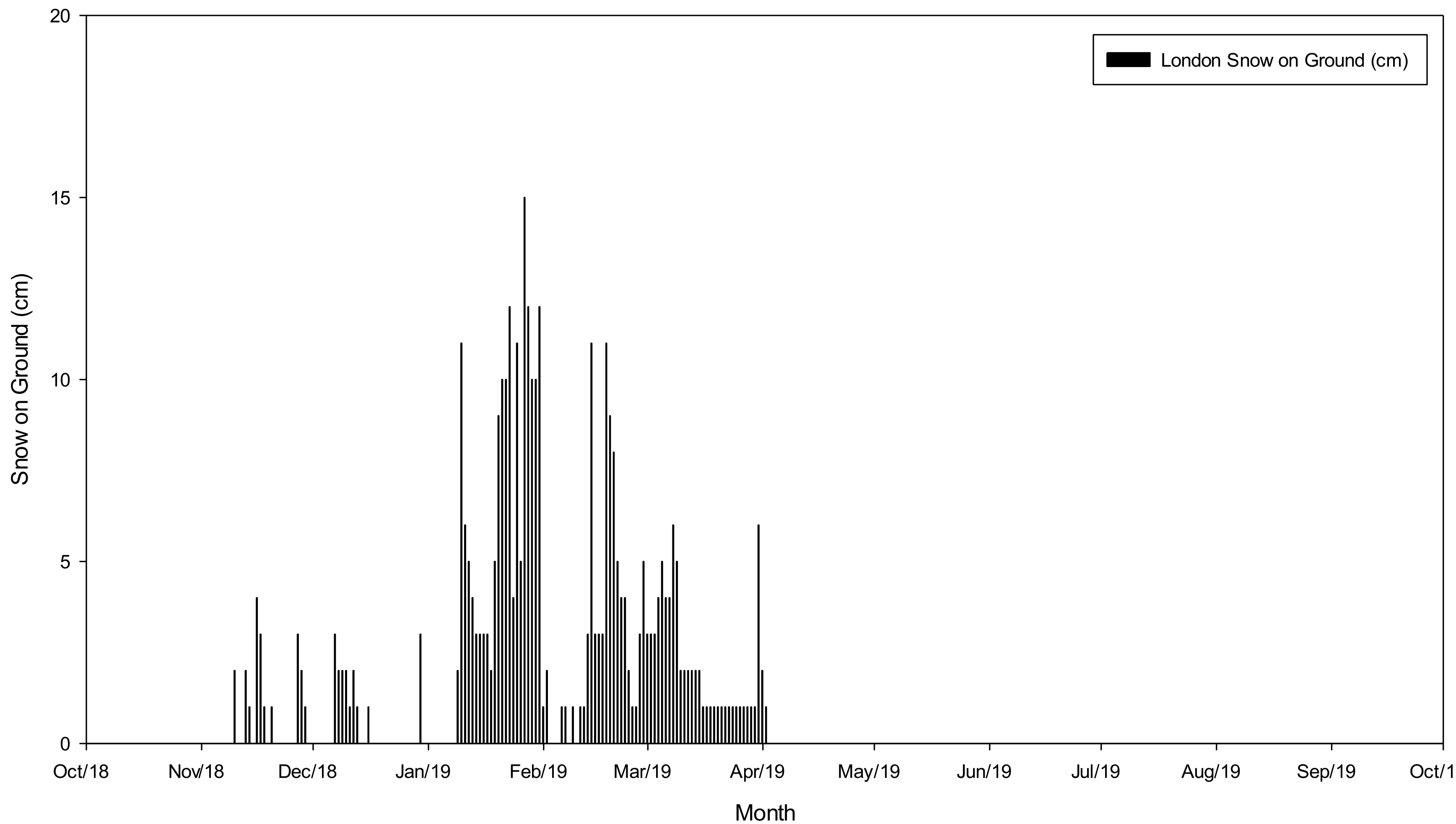


Figure A 31. Snow on ground at London, Ontario (ECCC Station Climate ID # 6144478) October 1, 2018 to September 30, 2019.

Table A 2. Net mass of four phosphorus species retained in eight restored wetlands across four seasons.

Site	Season	TP (kg)	TDP (kg)	SRP (kg)	PP (kg)
OH	Fall	2.81	0.60	0.41	2.21
	Winter	-0.31	0.57	0.50	-0.87
	Freshet	9.43	1.49	1.03	7.94
	Summer	3.45	-0.02	0.18	3.47
	Total	15.39	2.63	2.12	12.76
MO	Fall	0.21	0.14	0.09	0.06
	Winter	-0.29	-0.03	0.04	-0.27
	Freshet	-0.36	0.57	0.63	-0.92
	Summer	2.44	-0.16	-0.01	2.60
	Total	2.00	0.52	0.76	1.47
MA	Fall	-1.09	-0.23	0.29	-0.86
	Winter	-0.25	0.02	0.26	-0.27
	Freshet	-5.15	-0.80	1.20	-4.34
	Summer	-0.01	-0.01	0.00	0.00
	Total	-6.50	-1.03	1.74	-5.47
KE	Fall	-0.20	1.03	0.88	-1.23
	Winter	1.76	0.51	0.09	1.25
	Freshet	0.06	0.64	0.66	-0.58
	Summer	1.65	0.16	0.10	1.49
	Total	3.28	2.35	1.74	0.93
BL	Fall	0.96	0.57	0.57	0.38
	Winter	0.10	0.10	0.10	0.00
	Freshet	0.09	-0.05	0.05	0.14
	Summer	0.07	0.05	0.06	0.02
	Total	1.22	0.68	0.77	0.55
DY	Fall	1.85	1.21	1.20	0.64
	Winter	0.42	0.37	0.32	0.05
	Freshet	0.55	0.42	0.37	0.14
	Summer	0.53	0.11	0.05	0.42
	Total	3.36	2.11	1.94	1.25
FE	Fall	0.04	0.02	0.01	0.02
	Winter	0.01	0.01	0.01	0.00
	Freshet	1.41	0.27	0.12	1.14
	Summer	0.62	0.47	0.35	0.14
	Total	2.08	0.77	0.49	1.30
LL	Fall	15.64	1.28	1.24	14.36
	Winter	5.27	3.38	2.47	1.89
	Freshet	12.14	0.87	0.67	11.27
	Summer	6.30	5.92	5.35	0.38
	Total	39.35	11.44	9.73	27.90

Table A 3. Net nutrient retention capacity of four phosphorus species in eight restored wetlands across four seasons.

Site	Season	TP (kg ha^{-})	TDP (kg ha^{-})	SRP (kg ha^{-})	PP (kg ha^{-})
	Fall	3.80	0.81	0.55	2.99
	Winter	-0.41	0.76	0.67	-1.18
OH	Freshet	12.74	2.01	1.39	10.73
	Summer	4.67	-0.03	0.25	4.69
	Total	20.79	3.55	2.86	17.24
	Fall	1.47	1.01	0.68	0.46
	Winter	-2.11	-0.18	0.30	-1.93
MO	Freshet	-2.54	4.05	4.52	-6.59
	Summer	17.44	-1.13	-0.05	18.58
	Total	14.27	3.75	5.44	10.52
	Fall	-6.08	-1.30	1.58	-4.78
	Winter	-1.40	0.11	1.42	-1.51
MA	Freshet	-28.60	-4.47	6.69	-24.13
	Summer	-0.06	-0.06	-0.01	0.00
	Total	-36.14	-5.72	9.68	-30.41
	Fall	-1.03	5.43	4.62	-6.46
	Winter	9.29	2.71	0.46	6.58
KE	Freshet	0.32	3.39	3.50	-3.07
	Summer	8.70	0.85	0.55	7.86
	Total	17.28	12.38	9.13	4.90
	Fall	5.64	3.38	3.35	2.26
	Winter	0.60	0.58	0.59	0.02
BL	Freshet	0.54	-0.29	0.27	0.83
	Summer	0.42	0.31	0.34	0.10
	Total	7.20	3.99	4.56	3.21
	Fall	8.81	5.77	5.73	3.04
	Winter	2.01	1.77	1.54	0.24
DY	Freshet	2.64	1.98	1.77	0.65
	Summer	2.53	0.52	0.22	2.01
	Total	15.99	10.04	9.25	5.95
	Fall	0.07	0.03	0.02	0.04
	Winter	0.02	0.02	0.01	0.00
FE	Freshet	2.66	0.52	0.23	2.15
	Summer	1.16	0.89	0.66	0.27
	Total	3.92	1.46	0.93	2.46
	Fall	5.54	0.45	0.44	5.09
	Winter	1.87	1.20	0.87	0.67
LL	Freshet	4.30	0.31	0.24	3.99
	Summer	2.23	2.10	1.89	0.13
	Total	13.93	4.05	3.44	9.88

Table A 4. Reduction efficiency of four phosphorus species in eight restored wetlands across four seasons.

Site	Season	TP (%)	TDP (%)	SRP (%)	PP (%)
OH	Fall	44	43	46	45
	Winter	-6	47	70	-22
	Freshet	39	43	74	38
	Summer	73	-3	86	85
MO	Fall	14	29	29	7
	Winter	-51	-6	19	-142
	Freshet	-5	24	46	-21
	Summer	78	-94	-8	88
MA	Fall	-91	-25	33	-301
	Winter	-32	3	43	-297
	Freshet	-90	-20	33	-272
	Summer	-51	-61	-20	30
KE	Fall	-1	23	26	-8
	Winter	20	20	6	20
	Freshet	0	11	21	-2
	Summer	85	73	89	86
BL	Fall	100	100	100	100
	Winter	100	100	100	100
	Freshet	20	-34	7	43
	Summer	100	100	100	100
DY	Fall	100	100	100	100
	Winter	100	100	100	100
	Freshet	59	68	71	43
	Summer	100	100	100	100
FE	Fall	95	95	97	95
	Winter	69	76	90	28
	Freshet	82	72	86	86
	Summer	95	99	100	84
LL	Fall	91	80	98	93
	Winter	58	85	98	37
	Freshet	74	46	91	78
	Summer	99	99	100	93
ALL	Fall	44	56	66	16
	Winter	32	53	66	-22
	Freshet	22	26	54	-1
	Summer	72	39	68	83

Notes:

Ducks Unlimited Canada

Ontario Office
740 Huronia Road, Unit 1
Barrie, Ontario
L4N 6C6

Tel: 1-705-721-4444
Email: du_barrie@ducks.ca

www.ducks.ca