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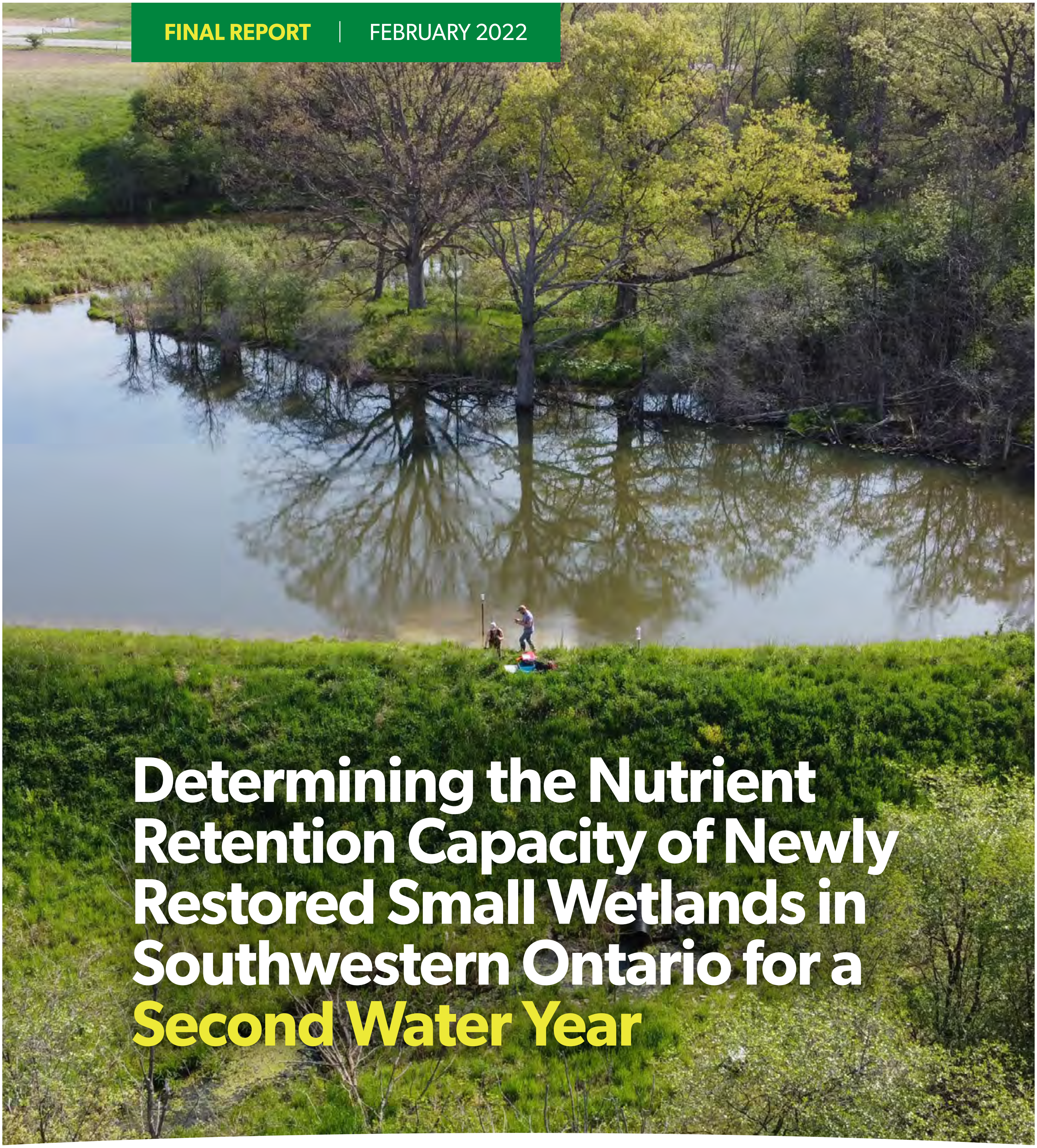

Determining the Nutrient Retention Capacity of Newly Restored Small Wetlands in Southwestern Ontario for a Second Water Year

Ducks Unlimited Canada

Institute for Wetland and Waterfowl Research

Determining the Nutrient Retention Capacity of Newly Restored Small Wetlands in Southwestern Ontario for a Second Water Year.

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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 that can reduce phosphorus loads entering streams and rivers across the working landscape of southwestern Ontario and can therefore assist in reducing phosphorus loads to Lake Erie. Ducks Unlimited Canada continued to assess nutrient retention in eight newly restored edge-of-field wetlands for a second water year (October 1, 2020 to September 30, 2021) to expand on and validate results from the first year of monitoring. Precipitation varied across seasons in year 2 compared to year 1 by -63 mm in the fall, -67 mm in the winter, -140 mm in the spring and +142 mm in the summer. In this second year of monitoring we measured mean TP and TN retention of 16.1 and 144.8 kg ha^{-1} year^{-1}, respectively. TP and TN mean reduction efficiency were 54% and 52%, respectively. Two year mean TP and TN wetland retention capacity were 11.7 and 261.2 kg ha^{-1} year^{-1}, respectively. SRP retention capacity and reduction efficiency in this second year of monitoring was 3.4 kg ha^{-1} year^{-1} and 59%, respectively. The mean SRP retention capacity and reduction efficiency over the two year monitoring period was 4.8 kg ha^{-1} year^{-1} and 60%, respectively. These results demonstrate that restored wetlands can effectively reduce nonpoint source nutrients from entering Lake Erie spanning a range of hydrological conditions.

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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 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 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 expertise in wetland monitoring.

On October 1, 2018, DUC's Institute for Wetland and Waterfowl Research (IWWR) implemented the standardized wetland monitoring protocol for one water year beginning October 1, 2018 as part of a research project aimed at assessing the ability of newly restored wetlands to retain nutrients and reduce non-point source nutrient pollution in southwestern Ontario. The results from this one year project demonstrated that newly restored small wetlands are effective sinks of both total and dissolved forms of phosphorus and nitrogen, including soluble reactive phosphorus (DUC 2020).

After the initial year of monitoring, it was decided that a second year of monitoring would be beneficial to provide nutrient retention estimates for newly restored wetlands under different moisture conditions. This data will provide the sound science needed to validate the year one results allowing DUC and all conservation partners completing similar work to accurately calculate the nutrient reduction value of their restored wetlands. This report presents both the first year of data collected from October 1, 2018 to September 30, 2019 and year two data collected from October 1, 2020 to September 30, 2021.

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 under different hydrological conditions 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 phosphorus reduction targets set for Lake Erie.

The specific objectives of this project are:

- Determine the wetland nutrient retention capacity (kg ha^{-1} $year^{-1}$) of newly restored wetlands in southwestern Ontario for a second water year.
- Determine the nutrient reduction efficiency (%) of newly restored wetlands in southwestern Ontario for a second water year.
- Explore relationships between wetland basin characteristics and nutrient retention capacity.
- Compare data generated in year 1 and year 2 to assess what is driving the differences in nutrient retention (or release) amongst the eight study sites.
- Determine if the second year of data validates the results from year 1 which concluded that restored wetlands can act as effective nutrient sinks in the Lake Erie watershed.

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 found 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 or other nutrients in newly restored wetlands within this region 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, and phosphorus can be released under anoxic conditions to the water column (Hogan et al. 2004). Additionally, 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).

Researchers quantify phosphorus retention in a wetland by measuring the total inputs and outputs of phosphorus from the system. Phosphorus retention capacity (kg ha^{-1} year^{-1}) and phosphorus reduction efficiency (%) are two metrics commonly used to indicate if a specific wetland can 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, who were receiving agricultural runoff, over a three year period and measured 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 of seven newly constructed wetlands receiving agricultural runoff in Sweden found total phosphorus (TP) retention capacities ranging from 11 to 175 kg ha^{-1} year^{-1} (Johannesson et al. 2015). Fisher and Acreman (2004) conducted a literature review 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) found total phosphorus retention capacities of constructed wetlands that receive nonpoint source pollution in a cold climate to range from 4.0 to 29.0 kg ha^{-1} year^{-1}. A recent literature review of restored wetlands located in Europe and North America report for multiyear studies a median TP and TN retention capacity of 6.3 and 430 kg ha^{-1} year^{-1}, respectively (Land et al. 2016). 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.

A recent study by Cheng and Basu (2017) modeled wetland size and retention time and reported wetland nutrient retention efficiency for TP and TN of 49.0 and 49.4 %, respectively. These authors also found that small wetlands between 0.03 and 0.32 ha provided the greatest nutrient removal potential. These small wetlands are referred to as “Biogeochemical Hotspots” and outcompete large wetlands in terms of nutrient retention efficiency. Crumpton et al. (2020) studied 26 wetlands in the corn belt of Iowa and reported a wide nitrate removal efficiency ranging from 9 to 92% and concluded that wetlands have a substantial capacity to reduce non-point source nitrogen loads. On a national scale in the continental United States, recent modeling suggests that with specially targeted wetland restoration to “hotspots”, an increase in wetland area of 10% will double the wetland nitrogen removal capacity provided by all remaining wetlands (Cheng et al. 2020).

The need for monitoring data such as nutrient loads in and out of wetlands and daily water level data has routinely been reported as a data gap within the literature (Whigham and Jordan 2003). While the availability of empirical data is increasing there is still significant data gaps which need to be addressed to effectively quantify wetland nutrient retention at the daily, monthly and yearly scales (Golden et al. 2019).

Study Sites

Between November 2017 and August 2018, we visited a series of 37 newly restored wetlands that were designed specifically as wildlife habitat. The 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 projects in this region of southern Ontario. For our study eight newly restored wetlands were selected within the Lake Erie drainage basin with sites located in the Thames River, Syndenham River, Kettle Creek and Catfish Creek watersheds where we implemented a 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 at the start of year 1 and range in area from 0.14 ha to 0.78 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 crops with corn and soybean being the dominant crop types (Table 1). Pictures of each site from year 1 and year 2 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. Sites BL and LL are two sites where the upland tile drainage system discharges the tile water away from the basins into a separate drainage ditch.

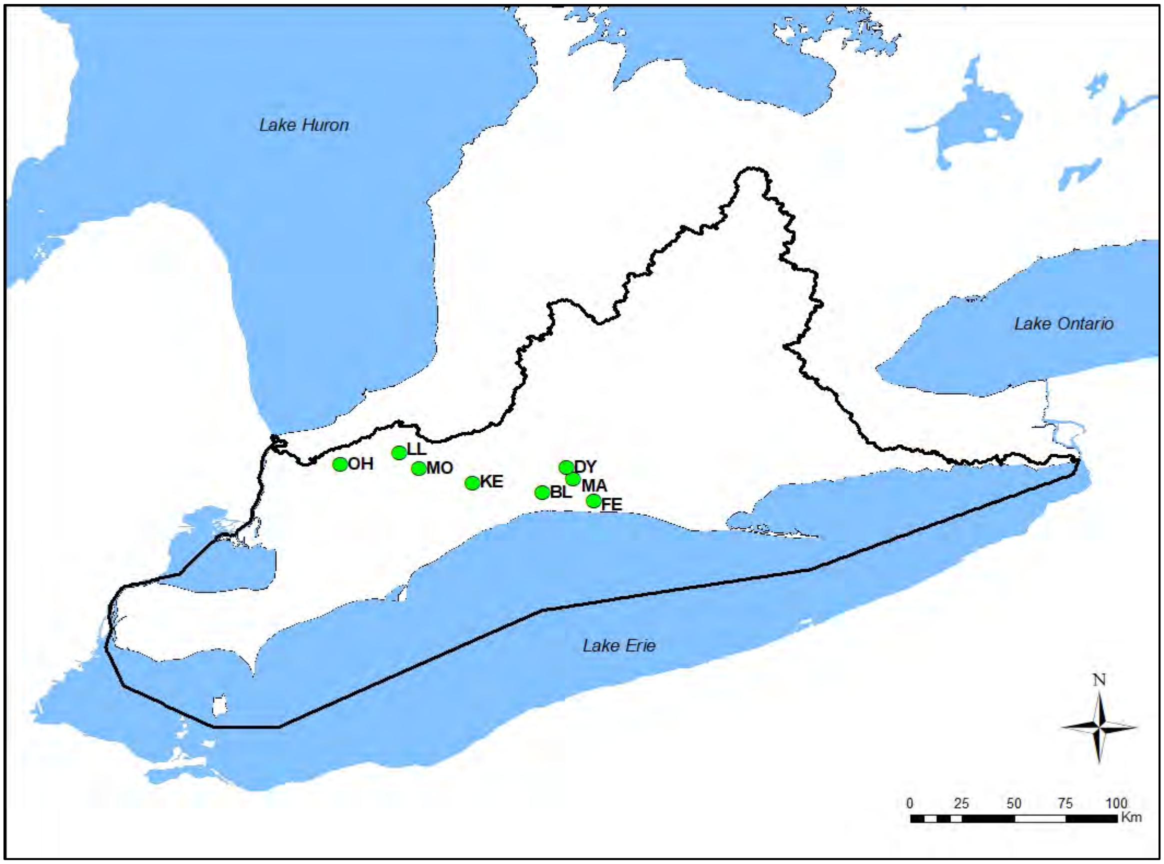

Figure 1. Locations of eight restored wetland research sites across southwestern Ontario within the Canadian portion of the Lake Erie watershed.

Table 1. Site information.

Site ID	Basin Age (years)	Basin Area (ha)	Basin Volume (m^3)	Contributing Area (ha)	Contributing Area : Wetland Area	Fall Crop	Spring/Summer Crop
				Year 1			
OH	2	0.78	5,365	18.3	24	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
				Year 2			
OH	4	0.78	5,365	18.3	24	Corn	Soybean
LL	7	0.48	3,720	3.0	6	Soybeans	Corn
MO	7	0.14	1,013	30.0	219	Soybeans	Corn
KE	4	0.19	827	63.6	334	Corn	Corn & Soybeans
FE	8	0.53	4,231	3.5	7	Hay & Soybeans	Hay and Soybean
MA	7	0.18	927	8.0	43	Corn	Winter Wheat
DY	5	0.21	1,880	2.2	10	Corn	Soybeans
BL	4	0.17	1,247	2.7	16	Winter Wheat	Corn

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^{-1} to 6.1 m s^{-1}). Prior to deploying these systems in the field in both year 1 and year 2, the 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, all flow probes (attached to the data loggers) were deployed in the flume to assess the calibration of each. All flow probes and loggers showed good recorded flow rates both years 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 in the last two weeks of September in year 1 and the last two weeks of August in year 2. 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 (Teledyne ISCO) 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.

Year 1 water level was recorded every six hours during the ice-off season (October 1 to November 31, 2018) 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 every six hours from December 1, 2018 to September 30, 2019. Year 2 water level was recorded every six hours using AP3s. As a QA/QC precaution in year 2, two meter sticks were deployed above one another attached to a post in each wetland basin to collect weekly manual water level data in case of water level logger failure.

Runoff trays were deployed at four sites both years that have no defined inflow point (LL, FE, DY, BL) to collect runoff contributed to the wetland basins during precipitation events. Apparent dry conditions at the time of equipment setup in year 2 resulted in the deployment of two runoff trays at site KE. 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

DUC contracted the St. Clair Region Conservation Authority (SCRCA) to collect field data in year 1 while in year 2 DUC staff and a general contractor (Elise Gabrielli, B.Sc. M.Sc) collected field data. 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 handheld 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 handheld 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. During year 1, water quality samples were collected once at baseflow and once during a rain event in the fall and once at baseflow and once during a snow/rain event in the winter at each site. Water quality samples were collected nearly every week when flow occurred from the start of the spring freshet to the end of the spring (February 1 to May 30 for both years) 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 (if flow was present). A total of 258 water quality samples from all inflows and outflows were collected in year 1. Year 2 followed the same water quality sampling schedule, however, due to the wet water year experienced during year 1, the year 2 water quality budget was increased in preparation for a wet water year. A total of 325 water quality samples from all inflows and outflows were collected in year 2.

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

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
	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 using a swing sampler in both years. 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), particulate phosphorus (PP) and particulate nitrogen (PN) were calculated.

A handheld 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 obtained from Environment and Climate Change Canada (ECCC) Climate ID station # 6144478 located in London, Ontario. Precipitation nutrient chemistry was obtained from ECCC Station # STC for year 1. ECCC did not collect precipitation nutrient chemistry during year 2 due to the global pandemic. Therefore, year 2 precipitation water chemistry was calculated as the mean from monthly samples collected over 2017 to 2019. Stratus Precision Rain Gauge made to the specifications of the United States Weather Bureau were deployed at 1 meter height beside each wetland in year 2 and monitored weekly from October 1 to November 30 and May 1 to September 30.

Sediment samples were collected from each basin in September of year 1. 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. A surveyed wetland water surface elevation of all eight sites was again collected in October of 2020.

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.

Contributing Area

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 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.

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 to March 31 for year 1 and December 1 to March 22 for year 2).

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 mass of nutrients retained by the total mass of inflow nutrients divided by 100 to obtain a percentage.

Reported seasonal break downs correspond to the months of October and November for fall, December through February for Winter, March through May for spring 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 19 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. In Year 1 precipitation was above average with the bulk of precipitation falling during the spring period (March to May). The abnormally wet spring was followed by a warm summer that quickly dried upland fields adjacent to the study wetlands and resulted in lower water levels within the study wetlands for the summer period. In Year 2 precipitation was similar to the long-term average, but with much lower precipitation in the fall, winter and spring with a very high amount of precipitation occurring in late summer. A widespread major rain event at the end of the water year (September 22 and 23) delivered most of the summer precipitation and was 43% greater than the 19-year seasonal mean. In the absence of this major event, summer precipitation would have been below average precipitation. Daily precipitation, cumulative precipitation and daily snow on ground depths are reported in Appendix A.

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

Time Period	Year 1 Precipitation (mm)	Year 2 Precipitation (mm)	Year 1 Precipitation Compared to 19 Year Mean (%)	Year 2 Precipitation Compared to 19 Year Mean (%)	2003 to 2021 Mean Precipitation (mm)
Oct. 1 to Sept. 30	1,053	924	+11	-3	951
Oct. 1 to Nov. 30	200	137	+21	-17	165
Dec. 1 to Feb. 28	221	154	+2	-29	217
Mar.1 to May. 30	299	159	+26	-33	238
June 1 to Sept. 30	332	474	+1	+43	330

Basin nutrient chemistry

Concentrations of all phosphorus species showed similar trends over both years. TP concentrations ranged widely across the study wetland basins (Figures 2 and 3), with trophic status ranging from mesotrophic to hyper-eutrophic (CCME 2004). With respect to basin nutrient concentrations, site MA appears to be an outlier with a mean basin TP concentration more than double that of the next site when ranking in decreasing order of mean basin TP concentrations. Median TP concentrations across the study basins were similar across years. The median fraction of SRP as a proportion of TDP decreased from approximately 50% to 33% from year 1 to year 2. Slightly more than 50% the total phosphorus was present in particulate form during both study years.

Concentrations of nitrogen species showed similar trends over both years with most of the nitrogen in the dissolved form (Figures 4 and 5). The majority of dissolved nitrogen was present as nitrate in both years. The interquartile range of TN, TDN and NO_3^{-1} mean concentrations are larger for year 2 due to higher nitrogen concentrations reported in sites KE and OH. NH_3 comprises only a small fraction of the nitrogen present in both years.

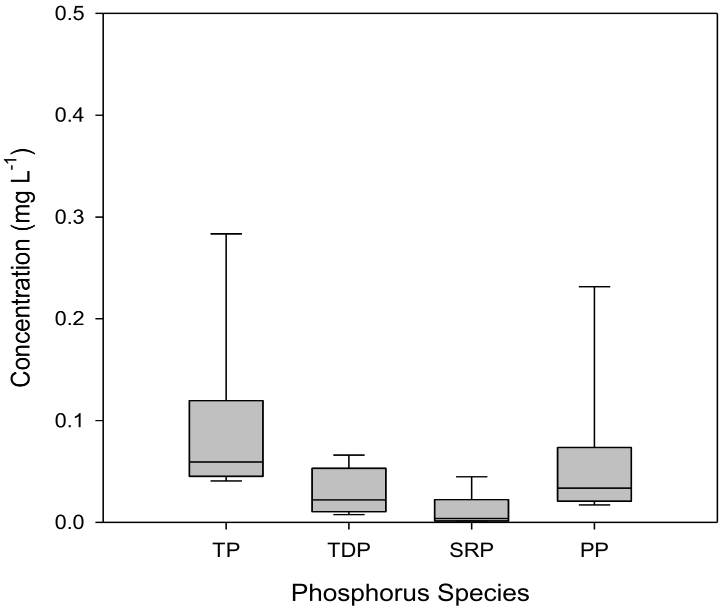

Figure 2. Box plot of the mean concentrations of four phosphorus species measured in eight restored wetland basins in year 1.

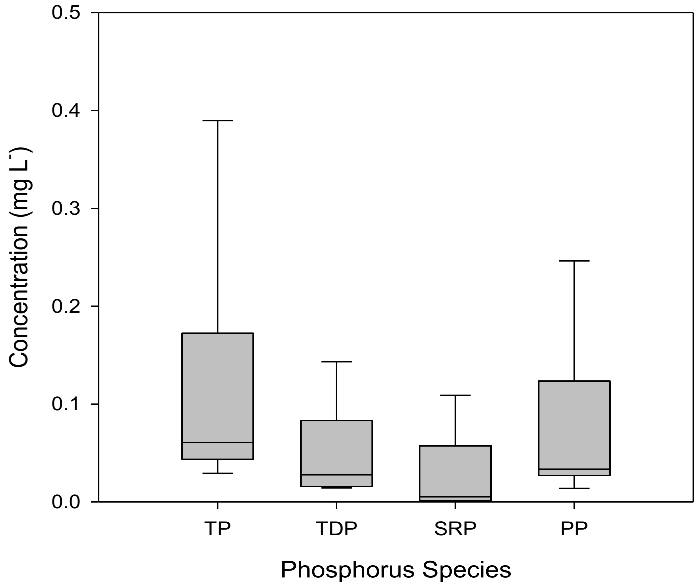

Figure 3. Box plot of the mean concentrations of four phosphorus species measured in eight restored wetland basins in year 2.

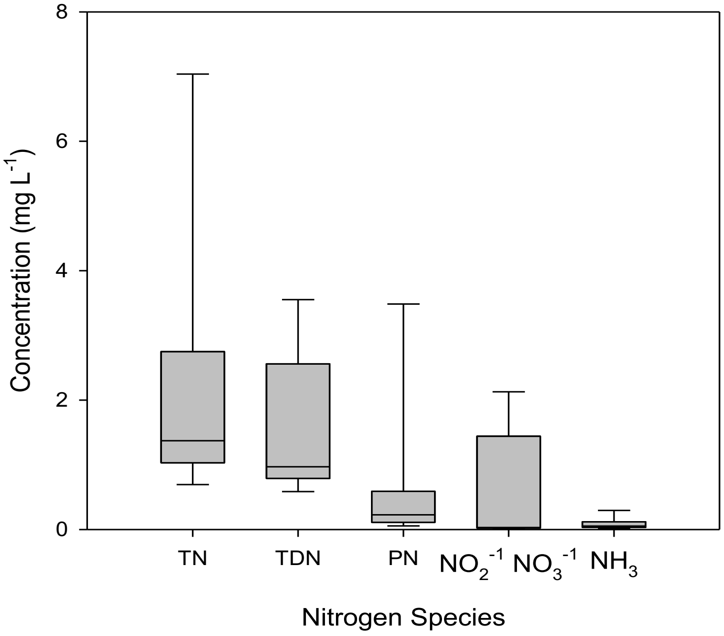

Figure 4. Box plot of the mean concentrations of five nitrogen species measured in eight restored wetland basins in year 1.

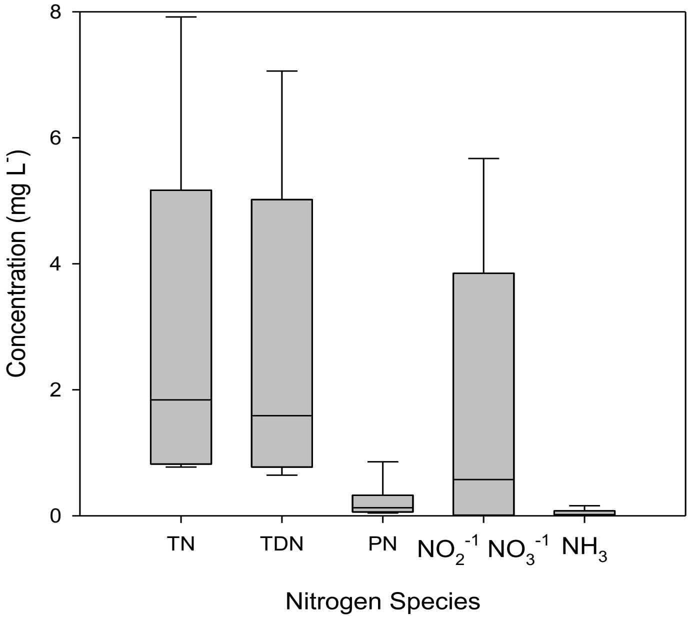

Figure 5. Box plot of the mean concentrations of four phosphorus species measured in eight restored wetland basins in year 2.

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 from year 2 is presented in Table 4. Mean specific conductance ranged from 0.04 to 1.10 mS cm^{-1} . pH of inflows and outflows were neutral to slightly alkaline with DY outflow having the highest pH. Dissolved oxygen ranged from 6.50 mg L^{-1} to 14.03 mg L^{-1} with no consistent difference between inflows and outflows. Year 1 YSI data is presented in Appendix A40 for reference.

Table 4. Year 2 water quality data collected with a handheld YSI unit at inflows and outflows of eight restored wetland basins.

Site	Inflow or Outflow	Water Temp (°C)	Specific Conductance (mS cm^{-1})	Total Dissolved Solids (g L^{-1})	pH	Dissolved Oxygen (mg L^{-1})
OH	Tile #1 inflow	9.86 ± 1.02	1.10 ± 0.15	0.71 ± 0.09	6.98 ± 0.04	8.84 ± 0.53
	Surface inflow	9.90 ± 2.42	0.77 ± 0.36	0.50 ± 0.24	7.32 ± 0.09	11.49 ± 1.66
	Outflow	10.51 ± 1.65	0.48 ± 0.03	0.31 ± 0.01	7.31 ± 0.09	9.96 ± 0.70
LL	Surface inflow	7.29 ± 1.94	0.16 ± 0.05	0.1 ± 0.03	7.26 ± 0.17	12.83 ± 1.56
	Outflow	9.75 ± 1.65	0.28 ± 0.00	0.18 ± 0.00	7.54 ± 0.07	12.79 ± 0.35
MO	Surface and tile inflow	10.67 ± 1.47	0.75 ± 0.05	0.50 ± 0.03	7.31 ± 0.06	11.03 ± 0.86
	Outflow	10.46 ± 1.85	0.60 ± 0.04	0.41 ± 0.03	7.28 ± 0.09	10.51 ± 0.98
KE	Tile #1 inflow	10.24 ± 1.27	1.12 ± 0.1	0.71 ± 0.06	7.38 ± 0.07	11.09 ± 0.80
	Surface inflow	9.20 ± 2.84	0.17 ± 0.03	0.12 ± 0.02	7.29 ± 0.18	9.90 ± 1.23
	Outflow	11.20 ± 1.78	0.91 ± 0.09	0.59 ± 0.06	7.71 ± 0.16	12.08 ± 1.15
FE	Surface inflow	6.02 ± 2.66	0.04 ± 0.00	0.02 ± 0.00	7.28 ± 0.24	12.40 ± 4.71
	Outflow	8.06 ± 1.46	0.45 ± 0.02	0.29 ± 0.01	7.13 ± 0.06	11.46 ± 1.00
BL	Surface inflow	18.58 ± 2.28	0.10 ± 0.01	0.06 ± 0.00	7.14 ± 0.11	6.50 ± 2.49
	Outflow	NS	NS	NS	NS	NS
MA	Surface and tile inflow	9.38 ± 1.60	0.71 ± 0.06	0.46 ± 0.04	7.16 ± 0.04	10.69 ± 0.86
	Outflow	10.27 ± 1.31	0.58 ± 0.04	0.37 ± 0.03	6.97 ± 0.04	7.46 ± 0.82
DY	Surface inflow	5.18 ± 1.04	0.15 ± 0.02	0.10 ± 0.01	7.30 ± 0.16	12.41 ± 1.09
	Outflow	8.20 ± 1.95	0.50 ± 0.08	0.32 ± 0.05	7.81 ± 0.19	14.03 ± 2.51

NS = no sample

Hydrology

Total and seasonal flow volumes from inflows and outflows of the eight restored wetland basins from year 1 and year 2 are presented in Table 5 and Table 6, respectively. Detailed seasonal flow percentages from all inflows and outflows for year 1 and year 2 are reported in Appendices A. Total inflows in year 1 ranged from 3,195 m^3 to 190,427 m^3 while total inflows in year 2 ranged from 2,587 m^3 to 101,234 m^3. Inflow volumes of all sites in year 1 were greater than year 2 with the larger volume differences being reported at sites with larger contributing area:wetland area ratios (KE, OH, MO, MA) compared to sites with smaller contributing area:wetland area ratios (LL, FE, DY, BL) (Figure 6). At sites with tile drains (OH, KE, DY), discharge from tile accounted for 24% to 50% of total inflows in year 1, and 13% to 62% in year 2. Direct precipitation in year 1 was overall a minor contributor of volume to all eight wetlands. Separating the eight sites into two groups based on contributing area, sites with contributing areas <3.6 ha had a higher proportion of rain input as a percentage of total inflow (range 12% - 17%), relative to sites with larger contributing areas >7.9 ha (range 1% - 3%). Precipitation was lower in year 2 resulting in decreased runoff volume to all sites. This resulted in direct precipitation accounting for a greater proportion of the overall water volume contributed to the basins during year 2. Similarly, in Year 2, direct precipitation percentage of total inflow volume for the four sites with contributing areas <3.6 ha ranged from 20% to 47%, while sites with larger contributing areas >7.9 ha ranged from 1% to 8%.

The mean percentage of inflow volumes broken down by season for both years is presented in Figure 7. The percentage of inflow volume delivered to the basins in the fall and winter seasons was similar between year 1 and year 2, with the fall season in year 1 delivering a slightly higher percentage of volume relative to year 2. Vast contrasts are seen among inflow volume percentages in the spring and summer between years 1 and 2. Spring inflow volumes in year 1 were more than double the inflow volumes delivered to the wetland basins in year 2. Conversely, summer inflow volumes were four times higher in year 2 compared to year 1.

Table 5. Year 1 total and seasonal breakdown of inflow and outflow volumes.

Site	Inflow or Outflow	Total Flow	Fall Flow	Winter Flow	Spring Flow	Summer Flow
			m^3			
OH	Tile Inflow	36,140	9,141	11,727	8,793	6,479
	Overland Inflow	93,209	9,371	35,444	40,862	7,533
	Rain Inflow	4,215	1,083	0	1,380	1,752
	Total Inflow	133,564	19,595	47,171	51,035	15,764
	Outflow	131,834	19,234	47,095	50,755	14,749
MO	Overland & Tile Inflow	116,734	22,574	35,186	51,080	7,893
	Rain Inflow	831	214	0	272	345
	Total Inflow	117,565	22,788	35,186	51,352	8,239
	Outflow	118,265	23,145	35,949	51,481	7,691
MA	Overland & Tile Inflow	40,020	7,522	17,214	14,996	287
	Rain Inflow	1,009	284	0	373	352
	Total Inflow	41,029	7,806	17,214	15,369	639
	Outflow	40,008	6,366	17,648	15,691	302
KE	Tile Inflow	94,405	24,474	26,747	40,824	2,359
	Overland Inflow	94,749	20,184	29,369	39,905	5,290
	Rain Inflow	1,273	371	0	458	444
	Total Inflow	190,427	45,029	56,117	81,187	8,093
	Outflow	189,617	45,558	56,491	80,010	7,558
BL	Overland Inflow	2,767	343	664	1,673	86
	Rain Inflow	428	117	0	214	97
	Total Inflow	3,195	460	664	1,888	183
	Outflow	2,050	0	188	1,862	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	838	2,917	7
FE	Overland Inflow	12,030	249	2,617	7,664	1,500
	Rain Inflow	2,388	719	0	427	1,243
	Total Inflow	14,418	968	2,617	8,091	2,743
	Outflow	10,943	249	2,617	7,664	413
LL	Overland Inflow	17,158	2,801	6,273	6,754	1,331
	Rain Inflow	2,231	661	0	431	1,138
	Total Inflow	19,389	3,462	6,273	7,185	2,469
	Outflow	16,689	2,919	6,273	7,108	389

Table 6. Year 2 total and seasonal breakdown of inflow and outflow volumes.

Site	Inflow or Outflow	Total Flow	Fall Flows	Winter Flows	Spring Flows	Summer Flow
			m^3			
OH	Tile Inflow	24,604	4,917	10,500	4,594	4,593
	Overland Inflow	25,670	7,208	8,633	2,304	7,526
	Rain Inflow	4,255	686	0	722	2,847
	Total Inflow	54,529	12,810	19,133	7,620	14,966
	Outflow	47,415	11,665	17,911	6,381	11,458
MO	Overland & Tile Inflow	31,211	56	5,387	7,791	17,977
	Rain Inflow	686	63	0	174	449
	Total Inflow	31,897	119	5,387	7,966	18,426
	Outflow	31,498	0	5,144	7,938	18,416
MA	Overland & Tile Inflow	14,840	691	5,722	4,478	3,949
	Rain Inflow	956	84	0	254	618
	Total Inflow	15,795	775	5,722	4,733	4,566
	Outflow	13,013	232	5,572	3,112	4,096
KE	Tile Inflow	62,714	8,225	21,779	11,337	21,373
	Overland Inflow	37,103	3,028	18,221	3,439	12,416
	Rain Inflow	1,417	230	0	308	878
	Total Inflow	101,234	11,483	40,000	15,084	34,667
	Outflow	95,184	11,116	38,912	13,102	32,054
BL	Overland Inflow	1,823	98	657	271	797
	Rain Inflow	763	45	0	184	534
	Total Inflow	2,587	143	657	455	1,332
	Outflow	0	0	0	0	0
DY	Tile Inflow	474	0	0	68	406
	Overland Inflow	2,354	664	131	801	758
	Rain Inflow	688	124	0	98	466
	Total Inflow	3,516	788	131	967	1,630
	Outflow	1,569	0	1	702	867
FE	Overland Inflow	3,173	153	1,812	645	563
	Rain Inflow	2,847	436	0	795	1,616
	Total Inflow	6,020	589	1,812	1,440	2,179
	Outflow	728	98	193	49	388
LL	Overland Inflow	4,720	40	1,606	1,064	2,009
	Rain Inflow	2,501	504	111	307	1,579
	Total Inflow	7,221	545	1,717	1,371	3,588
	Outflow	976	0	66	910	0

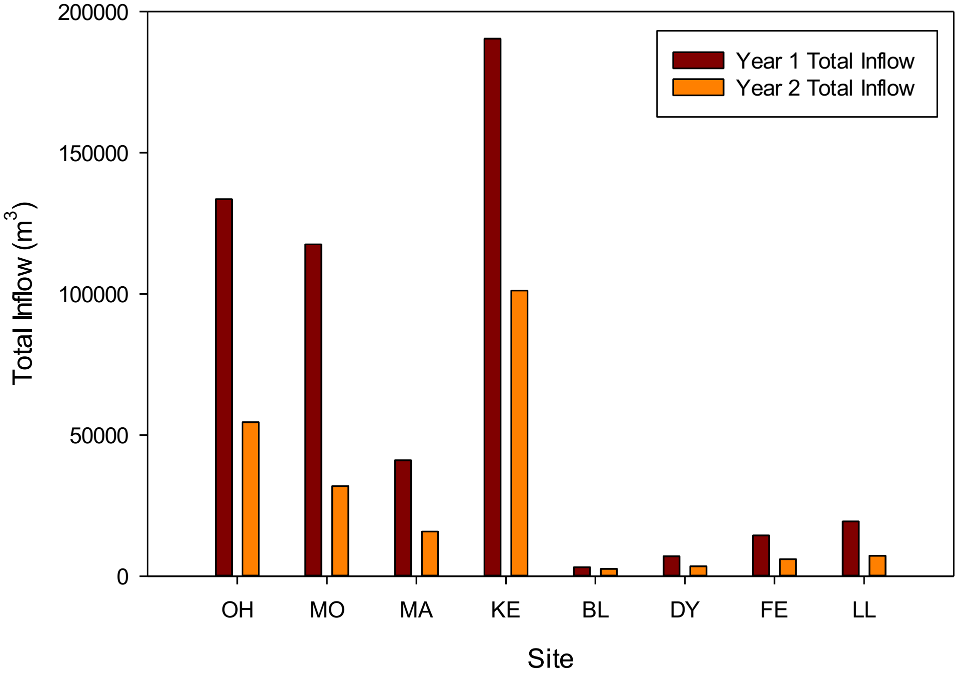

Figure 6. Total inflow volume to the eight restored wetland basins in year 1 and year 2.

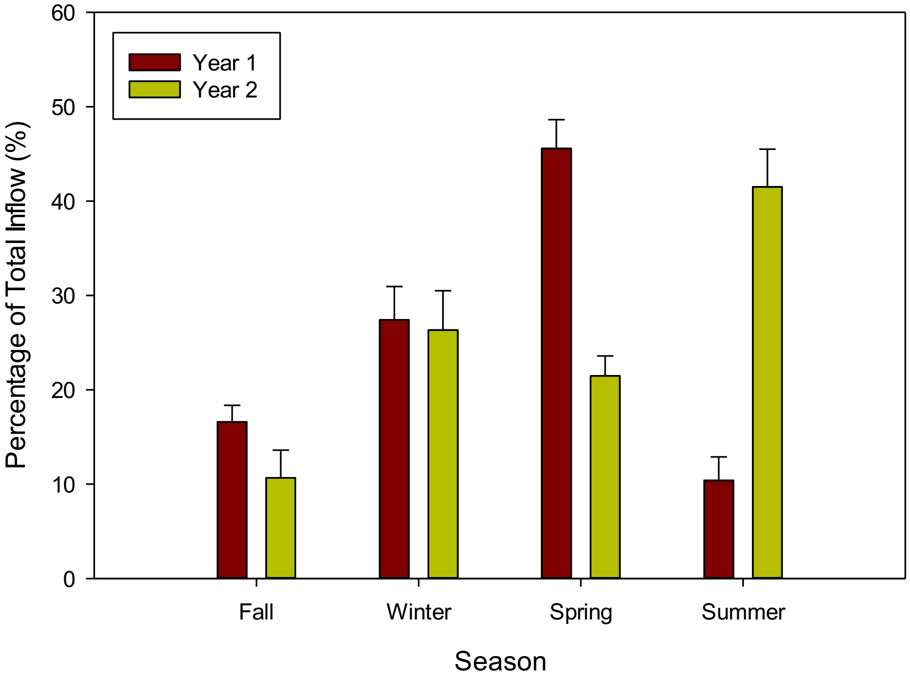

Figure 7. Seasonal breakdown of the mean percentage of total inflow delivered to eight restored wetland basins in year 1 and year 2.

Detention Time

Detention time for the eight newly restored wetland basins are presented in Table 7. Detention times were calculated using the mean daily inflow rates to provide an indicator of the overall detention time for the restored wetlands over the course of the entire year. Detention times ranged from 1.6 days to 173.6 days in year 1 and from 3.1 days to 457.7 days in year 2. Detention 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 detention time based on mean inflow rates at our eight sites over two years is 119 days. The overall high mean detention time, for each year individually and both years overall, demonstrates that these restored wetland basins exhibit a trait which is desirable if the goal is to mimic (to some degree) detention times that are designed for treatment wetlands.

Table 7. Detention times of eight restored wetland basins.

Site	Basin Volume (m^3)	Year 1 Detention Time at Mean Daily Flow (days)	Year 2 Detention Time at Mean Daily Flow (days)	Mean Detention Time at Mean Daily Flow (days)
OH	5,365	14.8	39.8	27.3
MO	1,013	3.1	11.7	7.4
MA	927	8.4	22.2	15.3
KE	827	1.6	3.1	2.3
BL	1,247	173.6	284.9	229.2
DY	1,880	97.1	264.9	181.0
FE	4,231	121.8	457.7	289.7
LL	3,720	75.3	331.6	203.4
Mean ± Std Error		61.9 ± 23	176.9 ± 63	119.4 ± 41.7

Wetland nutrient loads, retention capacity and reduction efficiency

Net mass of nutrients retained in the newly restored wetlands are presented in Table 8. Nutrient reduction capacity of restored wetlands defined as the mass of nutrients retained by the area of a wetland over one year is presented in Table 9. Nutrient reduction efficiency of restored wetlands for the study period are reported in Table 10. Total nutrient loads for all inflows and outflows of the eight restored wetlands basins for both years are presented for reference in Appendix A.

During our study, a net positive TP retention occurred at seven basins in year 1 and at six basins in year 2 (Table 8). Across the eight sites net TP retention ranged from -6.5 to 15.6 kg year^{-1} in year 1 and -1.7 to 16.1 kg year^{-1} in year 2. Retention of dissolved fractions of phosphorus (TDP and SRP) were positive in seven of eight basins during both years. TN retention was positive at all eight basins in year 1 and at seven of the eight basins in year 2. Across all sites net TN retention ranged from 1.3 to 235.9 kg $year^{-1}$ in year 1 and -110.4 to 235.1 kg $year^{-1}$ in year 2. Retention for the main dissolved fractions of nitrogen (TDN and NO_3^-) was positive in all eight basins in year 1, with only one basin having negative retention in year 2. Retention of the suspended fraction of nitrogen (PN) was positive in six basins in each of the two years. Overall, mean retention was positive for all major fractions of phosphorus and nitrogen across the eight wetland basins over the two study years.

TP retention capacity varied considerably over the two years ranging from -35.2 to 84.4 kg ha^{-1} $year^{-1}$ with an average across all sites for both years of 11.7 kg ha^{-1} $year^{-1}$ indicating that overall, these restored wetlands act as phosphorus sinks. Site MO alternated from acting as a TP sink in year 1 to acting as a TP source for year 2. Overall TP retention capacity decreased over 6 of the sites in year 2 with MA behaving as less of a TP source in year 2, while site KE retained much more TP in year 2. This resulted in the mean TP retention capacity for year 2 being greater than that of year 1, albeit with a larger standard error. TDP retention capacity ranged from -5.6 to 38.3 kg ha^{-1} $year^{-1}$ with an average across all sites for both years of 6.2 kg ha^{-1} $year^{-1}$. A significant fraction of the TDP retained is the highly bioavailable SRP fraction with an average across all sites for both years of 4.8 kg ha^{-1} $year^{-1}$. For both years PP was slightly less than half of the TP retained. Over the two study years, TN retention capacity ranged from -806.2 to 1238.5 kg ha^{-1} $year^{-1}$ with a mean of 261.2 kg ha^{-1} $year^{-1}$ indicating that overall, these restored wetlands act as nitrogen sinks. The mass of TDN and NO_3^- retained ranged from -736.5 to 1071.6 kg ha^{-1} $year^{-1}$, and -665.6 to 1016.7 kg ha^{-1} $year^{-1}$, respectively. PN and NH_3 data were reported as either being retained or released in minor amounts.

Nutrient reduction efficiency of all major phosphorus and nitrogen species increased in year 2 across the eight restored wetlands. Overall, TP reduction efficiency ranged widely from -84 to 100% across both years with an average of 46%. In general, a little more than half of TDP entering the restored wetland basins was retained with a slightly higher overall efficiency for SRP at 60%. Site MA in both years and site MO in the second year acted as phosphorus sources and drove the phosphorus reduction efficiency range lower while the four sites with the smallest contributing area:wetland area ratios drove the range higher with site BL reporting a 100% retention efficiency in year 2 due to not spilling at all due to the dry year. TN reduction efficiency ranged across both years from -24 to 100% with an average of 47% over the two years. TDN and NO_3^{-1} two year mean reduction efficiencies of 44 and 50%, respectively, demonstrate that the majority of nitrogen retained within these wetland basins is in the form of NO_3^-.

Table 8. Net mass of nutrients retained in all newly restored wetlands over two water years.

Site	TP	TDP	SRP	PP	TN	TDN	PN	TKN	DKN	NO_3^{-1}	NH_3	DIN
kg year^{-1}												
Year 1												
OH	15.6	2.7	2.2	12.9	179.6	170.1	9.6	47.1	35.6	132.6	-4.8	127.8
LL	6.7	1.9	1.7	4.7	42.0	29.3	12.6	31.4	17.6	7.1	7.2	17.7
MO	2.0	0.6	0.8	1.4	75.0	76.8	-1.8	-28.2	-26.7	105.9	-0.5	102.7
KE	3.7	2.4	1.8	1.2	235.9	204.2	31.7	42.1	9.8	193.7	2.0	195.9
FE	2.1	0.8	0.5	1.3	21.3	14.1	7.2	17.8	9.4	3.4	6.0	9.5
MA	-6.5	-1.0	-1.4	-5.5	145.9	164.7	-18.8	-38.1	-26.7	184.6	-19.3	164.7
DY	3.4	2.1	1.9	1.2	16.8	12.5	4.2	6.9	2.1	9.8	2.7	12.6
BL	1.2	0.6	0.7	0.5	1.3	1.0	0.4	1.4	0.8	0.0	0.3	0.3
Mean ± S.E.	3.5 ± 2.1	1.2 ± 0.4	1 ± 0.4	2.2 ± 1.8	89.7 ± 30.7	84 ± 29.3	5.6 ± 5	10 ± 10.9	2.7 ± 7.4	79.6 ± 29.8	-0.7 ± 2.9	78.9 ± 27.7
Year 2												
OH	15.5	3.1	1.8	12.4	235.1	187.4	47.6	61.6	11.8	174.6	0.0	173.4
LL	4.6	4.3	4.5	0.3	172.7	171.8	1.0	155.7	153.4	17.0	44.9	62.0
MO	-0.6	0.2	0.1	-0.8	-110.4	-100.9	-9.6	-17.1	-7.9	-91.2	-2.3	-95.7
KE	16.1	7.3	4.8	8.8	83.9	50.0	33.9	50.2	15.6	35.4	14.2	47.9
FE	1.3	0.9	0.8	0.4	6.8	5.7	1.1	4.8	2.2	2.0	1.7	3.7
MA	-1.7	-0.8	-0.7	-0.9	132.2	127.3	4.9	-2.3	-7.7	137.2	-4.1	130.4
DY	2.8	1.2	1.1	1.5	6.0	7.0	-1.0	3.0	1.4	2.2	0.9	3.3
BL	2.0	1.5	1.5	0.5	15.5	13.8	1.7	13.7	11.6	1.5	3.8	5.6
Mean ± S.E.	5 ± 2.4	2.2 ± 0.9	1.7 ± 0.6	2.7 ± 1.7	67.7 ± 39	57.7 ± 34.6	9.9 ± 7	33.7 ± 19.8	22.5 ± 18.9	34.8 ± 29.7	7.3 ± 5.7	41.3 ± 29.5
Year 1 and Year 2												
Mean ± S.E.	4.2 ± 1.5	1.7 ± 0.5	1.3 ± 0.4	2.5 ± 1.2	78.7 ± 24.1	70.9 ± 22.1	7.8 ± 4.2	21.8 ± 11.3	12.6 ± 10.1	57.2 ± 21.1	3.3 ± 3.2	60.1 ± 20.1

Table 9. Nutrient retention capacity of eight restored wetland basins over two water years.

Site	TP	TDP	SRP	PP	TN	TDN	PN	TKN	DKN	NO_3^- [1]	NH_3	DIN
						kg ha^{-1} $year^{-1}$						
						Year 1						
OH	20.0	3.5	2.8	16.5	230.3	218.0	12.3	60.4	45.7	170.0	-6.1	163.8
LL	13.9	4.0	3.4	9.9	87.2	60.9	26.3	65.3	36.5	14.8	15.0	36.9
MO	14.6	4.4	5.6	10.2	547.7	560.7	-13.0	-205.6	-195.3	773.1	-3.7	749.6
KE	19.4	12.9	9.4	6.5	1238.5	1071.9	166.6	220.8	51.5	1016.7	10.8	1028.4
FE	3.9	1.5	0.9	2.5	40.1	26.5	13.6	33.6	17.7	6.4	11.3	17.8
MA	-35.2	-5.6	-7.6	-29.6	789.5	891.2	-101.7	-205.9	-144.4	998.8	-104.2	891.2
DY	15.9	10.0	9.2	5.9	79.5	59.4	20.0	32.5	10.1	46.4	12.9	59.9
BL	6.9	3.8	4.1	3.1	7.9	5.8	2.2	8.0	4.7	0.1	2.0	2.0
Mean ± S.E.	7.4 ± 6.4	4.3 ± 1.9	3.4 ± 1.9	3.1 ± 4.9	377.5 ± 157.2	361.8 ± 150.3	15.7 ± 25.9	1.1 ± 50.6	-21.6 ± 33.1	378.2 ± 164.5	-7.7 ± 14	368.6 ± 155.7
						Year 2						
OH	20.9	4.2	2.5	16.7	317.0	252.7	64.3	83.1	15.9	235.5	0.0	233.9
LL	9.6	9.0	9.4	0.6	359.1	357.1	2.1	323.7	318.9	35.3	93.4	128.9
MO	-4.2	1.5	0.7	-5.6	-806.2	-736.5	-69.7	-124.5	-57.4	-665.6	-16.9	-698.6
KE	84.4	38.3	25.2	46.1	440.6	262.5	178.1	263.7	81.8	186.0	74.7	251.6
FE	2.5	1.7	1.4	0.8	12.8	10.7	2.1	9.1	4.2	3.8	3.2	6.9
MA	-9.2	-4.4	-3.9	-4.8	715.4	689.0	26.4	-12.6	-41.6	742.6	-22.1	705.8
DY	13.3	5.9	5.3	7.3	28.7	33.3	-4.6	14.3	6.8	10.2	4.2	15.7
BL	11.9	9.0	8.7	2.9	91.2	81.4	9.8	80.6	68.4	8.7	22.3	33.0
Mean ± S.E.	16.1 ± 10.3	8.1 ± 4.5	6.1 ± 3.1	7.9 ± 5.9	144.8 ± 159.6	118.7 ± 144.6	26 ± 25.3	79.6 ± 52.2	49.6 ± 41.9	69.5 ± 136.7	19.8 ± 14.9	84.6 ± 137.8
						Year 1 and Year 2						
Mean ± S.E.	11.7 ± 5.9	6.2 ± 2.4	4.8 ± 1.7	5.5 ± 3.8	261.2 ± 112.3	240.2 ± 105.5	20.9 ± 17.5	40.4 ± 36.5	13.9 ± 27.4	223.9 ± 110.7	6 ± 10.5	226.6 ± 106.9

Table 10. Nutrient reduction efficiency of eight restored wetland basins for two water years.

Site	TP	TDP	SRP	PP	TN	TDN	PN	TKN	DKN	NO_3^{-1}	NH_3	DIN
%												
Year 1												
OH	38	40	66	38	42	53	9	19	26	73	-23	62
LL	81	85	99	79	61	61	60	60	58	56	68	66
MO	17	17	38	17	8	8	-8	-27	-34	13	-3	12
KE	6	19	22	2	26	25	29	14	5	32	11	31
FE	86	87	96	85	77	74	82	76	69	82	84	83
MA	-84	-18	-27	-277	40	47	-162	-97	-99	57	-197	49
DY	90	92	93	87	56	53	65	56	42	55	92	60
BL	74	74	82	73	32	37	24	38	44	3	49	25
Mean ± S.E.	38 ± 20	49 ± 14	58 ± 15	12 ± 43	42 ± 7	44 ± 7	12 ± 27	17 ± 19	14 ± 19	46 ± 9	9 ± 32	48 ± 8
Year 2												
OH	71	68	74.9	71	48	44	74	44	16	49	-1	49
LL	99	100	100.0	90	99	100	77	99	100	100	100	100
MO	-20	16	17.1	-50	-24	-22	-263	-50	-26	-22	-86	-23
KE	38	32	28.1	44	14	9	58	21	8	10	25	11
FE	92	100	99.8	80	92	95	79	90	90	100	98	98
MA	-37	-23	-22.4	-93	37	37	60	-13	-78	41	-376	39
DY	92	98	99.7	88	53	83	-33	56	53	43	91	52
BL	100	100	100.0	100	100	100	100	100	100	100	100	100
Mean ± S.E.	54 ± 19	61 ± 16	62 ± 16	41 ± 25	52 ± 15	55 ± 16	19 ± 42	43 ± 19	32 ± 22	52 ± 15	-6 ± 57	53 ± 15
Year 1 and Year 2												
Mean ± S.E.	46 ± 13	55 ± 10	60 ± 11	27 ± 24	47 ± 8	50 ± 8	15 ± 24	30 ± 13	23 ± 14	49 ± 9	1 ± 32	50 ± 8

Exploratory Analysis

In general, the contributing area of the restored wetland basins is positively correlated with the TP inflow load in both years (Figure 8). TP inflow load is found to be correlated with net TP retention capacity (Figure 9-A) with year 2 having a steeper slope. There are two possible outlying points in Figure 9-A, site MA in year 1 with a large negative net TP retention capacity and site KE in year 2 with a large positive net TP retention capacity. To investigate this relationship further, both data points were removed, and the remaining seven sites for each year were re-plotted (Figure 9–B). With these sites removed in their respective year, the correlation remains positive and the best-fit-lines are similar. Net TP retention capacity is positively correlated in year 1 and negatively correlated in year 2 with basin area, basin volume and detention time (Figure 10). When contributing area and contributing area: wetland area ratio is plotted against net TP retention capacity, a neutral relationship is demonstrated in year 1 while a positive relationship in demonstrated in year 2. This may indicate that upland area and the size of the wetland basin in relation to the upland area may be influential in retaining phosphorus during a dry year (Figure 11). Basin age is negatively correlated with net TP retention capacity during both years (Figure 12). Basin age is negatively correlated with TP inflow load as that the older restorations received less TP load than the recent restored wetland (Figure 13). It is critical to outline that TP inflow load drives TP retention capacity (Figure 9).

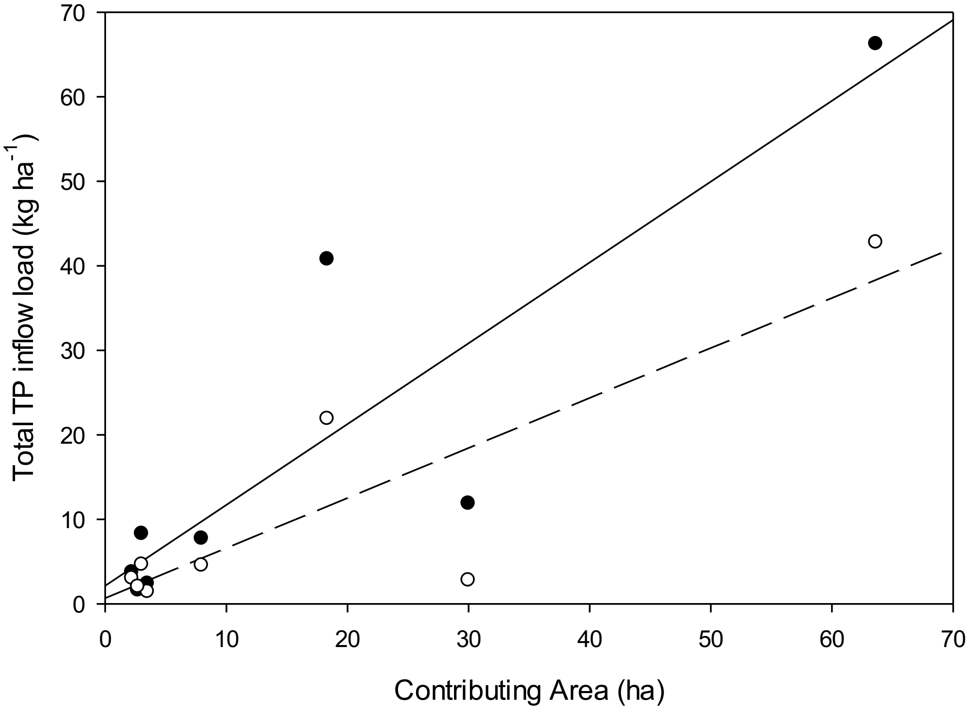

Figure 8. Linear relationship between contributing area and inflow TP loads for one year, black dots and solid line is year 1 data while white dots and dashed line is year 2 data.

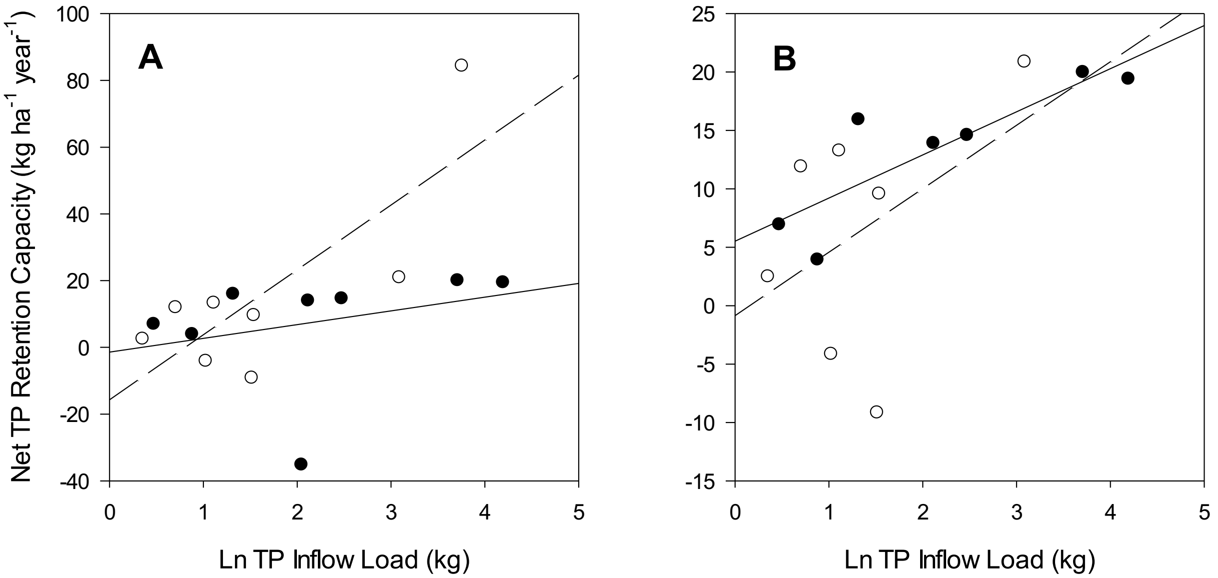

Figure 9. Linear relationship between Ln TP inflow load and net TP retention capacity including all sites (A) and excluding site MA in year 1 and site KE in year 2 (B), black dots and solid line is year 1 data while white dots and dashed line is year 2 data.

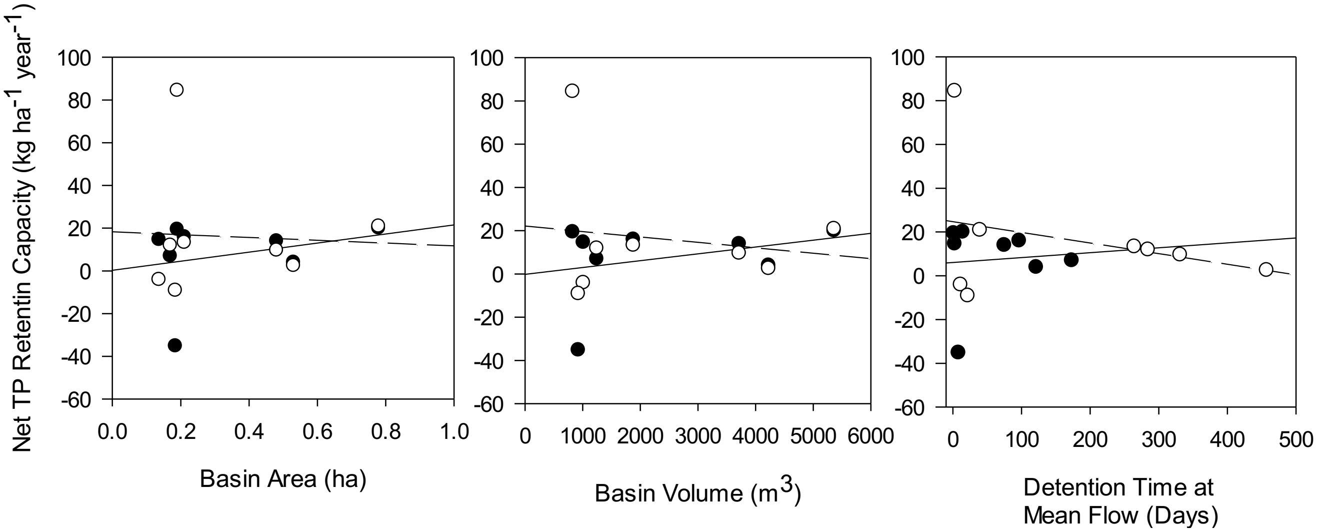

Figure 10. Linear relationships between basin area, basin volume and retention time with net TP retention capacity, black dots and solid line is year 1 data while white dots and dashed line is year 2 data.

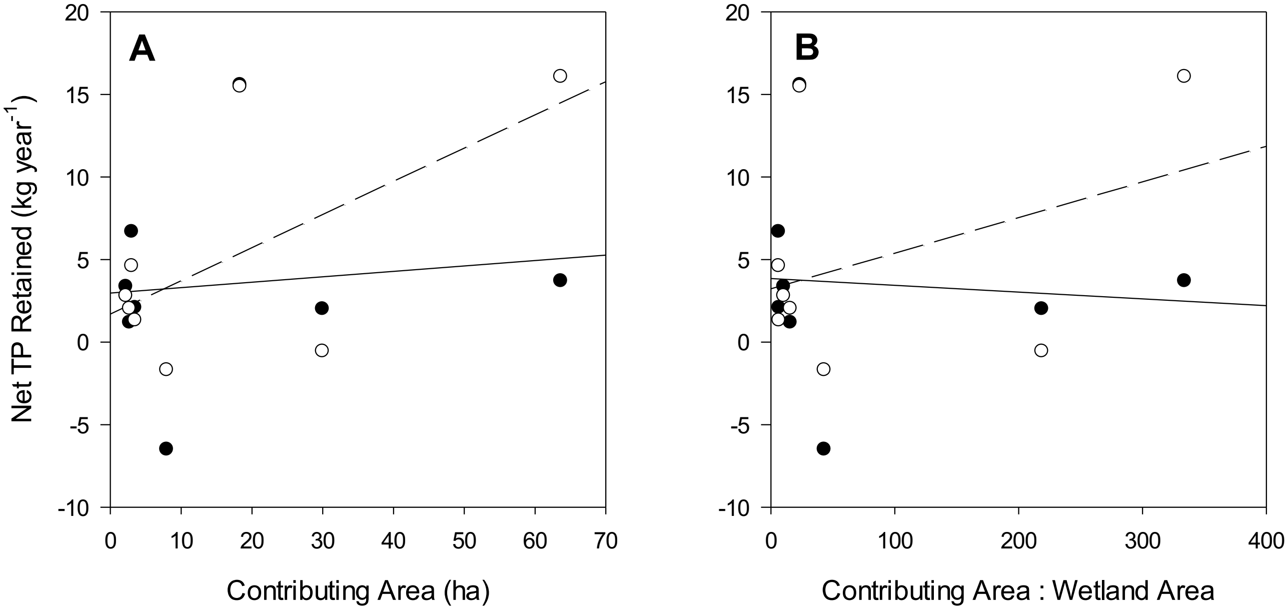

Figure 11. Linear relationship between contributing area (A) and contributing area: wetland area (B) with net TP retained, black dots and solid line is year 1 data while white dots and dashed line is year 2 data.

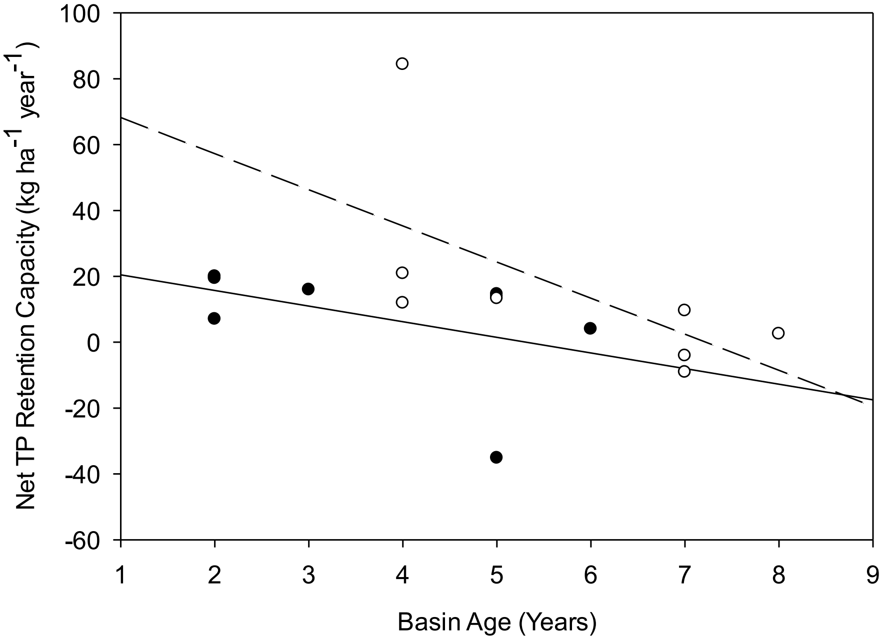

Figure 12. Linear relationship between basin age and net TP retention capacity, black dots and solid line is year 1 data while white dots and dashed line is year 2 data.

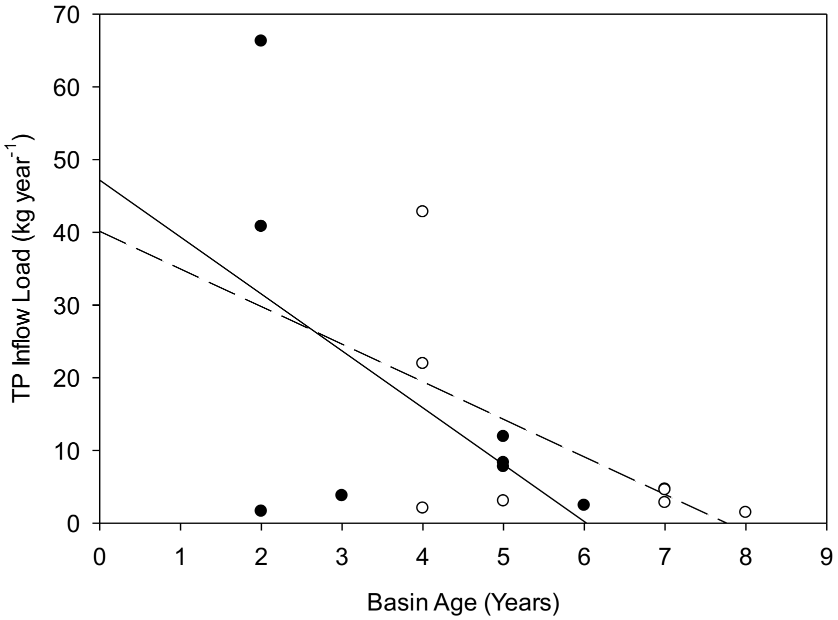

Figure 13. Linear relationship between basin age and TP inflow load,black dots and solid line is year 1 data while white dots and dashed line is year 2 data.

Discussion

Variable water years

Southwestern Ontario experienced a variety of precipitation inputs over the two year period of this study. This resulted in the eight restored wetland basins and their contributing areas experiencing a wet spring resulting in flows through some wetlands from March to May (year 1) and a dry spring with limited flow during this period in year 2. To demonstrate this difference, Site OH outflow produced flow above 0.006 m^3 sec^{-1} for 74 days in the spring of year 1 compared to only 19 days in year 2. The contrasting water years further provided both a dry summer (year 1) and a year with a significant summer rainfall event > 100mm (year 2). This difference in timing of precipitation inputs over both years influences nutrient loading and retention which is discussed further in this section.

Restored wetland site details

Removal of phosphorus varied across wetlands for both water years. Site OH was found to have the highest retention capacity of TP in year 1 and the second highest in year 2 among all sites with PP acting as a major fraction of TP being retained in both years. This site was unique in that the above average amount of precipitation that occurred during the spring and into the month of May in year 1 resulted in the surface runoff eroding a gully from the uplands into 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 year 1. This is reflected in PP comprising a major fraction of TP for net mass retained in both years (Table 8).

Site MA exhibited lower inflow loads than outflow loads for TP, TDP, SRP and PP over both years resulting in the site MA acting as a net source of phosphorus with a high negative net retention capacity for those four phosphorus species (Table 9). Seventeen of 19 grab samples collected from the inflow over the course of year 1 had lower TP concentrations than did the corresponding outflow TP concentration. In year 2, 18 of 24 grab samples collected when both inflow and outflow were active resulted in the inflow having lower phosphorus concentrations than the outflow. One potential explanation for why this site behaved differently compared to the others for both water years is related to sediment chemistry (Figure 14). Elevated soil test phosphorus concentrations were found in the wetland sediments at site MA relative to the other restored wetland sites we monitored. Phosphorus concentration in runoff is related to soil test phosphorus (STP) of the upland where it originates (Pote et al. 1996). This may indicate the upland contributing area may have contained higher soil test phosphorus concentrations in the past (and/or present), potentially resulting in site MA accumulating phosphorus over time. These findings are preliminary and require further study but suggest that the high STP recorded in the site MA sediments may be one reason why site MA acted as a phosphorus source over both years.

Site BL had the lowest net TP mass retained of all seven basins which exhibited a net positive retention capacity in year 1 (Table 9). While the upland of site BL is tiled, the tile outlet does not spill into site BL. 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 limits 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, sparse surface flow entered the basin of site BL. As the lower hydrological inflow resulted in site BL having a higher 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. Higher surface inflow nutrient concentrations were reported entering the basin in year 2 relative to year 1, as well the lower precipitation in year 2 resulted in site BL not spilling in year 2. This resulted in site BL having higher nutrient retention values in year 2 compared to year 1.

Site KE had one of the highest TP retention capacity in year 1 and the highest TP retention capacity in year 2, however its TP reduction efficiency is the lowest for both years when referring to sites that acted as TP sinks. This is due to site KE having the largest contributing area and one of the smallest basin areas resulting in the largest contributing area to wetland area ratio (Table 1). This resulted in site KE receiving the most runoff volume and highest TP loads of all sites for both years. Even with the lowest residence time of all sites, this site behaved as a sink for phosphorus and nitrogen (Table 8).

Site FE had the lowest TP wetland retention capacity that is positive among all sites for both years (Table 9) while at the same time reporting higher than average TP reduction efficiency both years (Table 10). Site FE is large with the second highest surface area of all study basins but has a relatively small contributing area. The outflow of site FE was continuously discharged during Year 1, with flow only ceasing in the summer. In year 2 baseflow was intermittent. When inquiring with the landowner in May in year 1 about the continuous baseflow, 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 (K. Fergusson, personal communication). This altered the behaviour of this wetland by releasing the volume of water slowly over time instead of pulses of outflow water that would otherwise occur. 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 over both years.

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. This is the only basin in the study that reversed from being an overall nutrient sink in year 1 to an overall nutrient source in year 2. The small basin, albeit located below this large upland area, retained a net positive mass of TP over year 1. 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 during the first year of the study. In year 2, 19 of the 24 water samples collected when the basin was spilling revealed the outflow to have higher TP concentrations than the inflow which resulted in the site being a TP source. Alternatively, only 6 of 17 samples collected when the basin was spilling revealed the outflow to have higher nitrate concentrations than the inflow. Specifically, one single large rain event at the end of June in year 2 resulted in inflow and outflow nitrate concentrations of 56.1 and 77.9 mg L^{-1}, respectively. The loads associated with this rain event were significant in converting site MO to a source of nitrogen in year 2. Conversely, these elevated nitrate concentrations were not reported during the significant precipitation event at the end of September in year 2, indicating a potential flushing of built up nitrogen may have been released during the June rain event.

Sites DY and LL both report similar TP retention capacities with above average TP reduction efficiencies in year 1. 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: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 in year 1. While phosphorus retention capacity was similar in year 2 among these two sites, nitrogen retention while positive, was lower at site DY than LL. Inflow volume at site DY was dominated by surface runoff during the dry conditions of year 2. This resulted in the lower surface runoff nitrate concentrations influencing the inflow loads while the outflow nitrate loads were elevated. The fact that discharge through site DY occurred over a limited period as well as the high retention associated with the significant flow event at the end of September resulted in this site acting as a nitrogen sink in year 2.

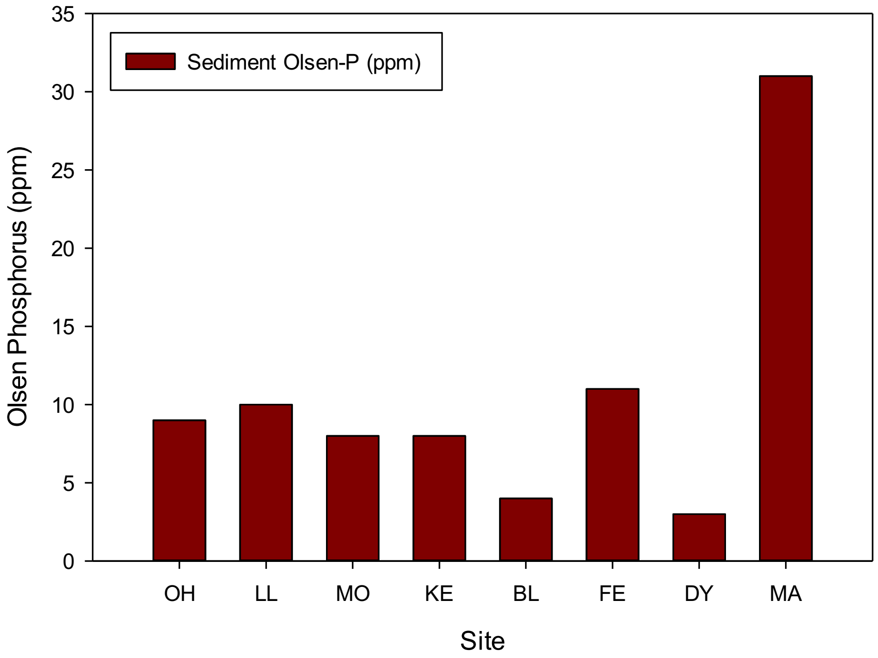

Figure 14. Sediment soil test phosphorus data from eight restored wetland basins sampled at the end of year 1.

Seasonal data

Retention capacity for phosphorus varied across seasons for both years (Figures 15 and 16). Year 1 TP retention capacity shows positive retention capacities in the fall and winter, a negative retention capacity in the spring period, followed by the highest positive retention in the summer season (Figure 15). 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 peaking in the fall and consistently low across all other seasons. A large variation of PP retention capacities is reported across all seasons with PP being a minor component of phosphorus retained in the fall and with nearly 50% the phosphorus being retained in the particulate form in the winter. The spring and summer seasons show large contrasts in PP retention with a high negative retention capacity in the spring. PP resulted as the dominant form of phosphorus retained in the summer with the highest net retention capacity of PP reported in year 1. If site MA is considered an outlier, the mean TP retention capacity in the spring season flips from negative to positive indicating that site MA is solely responsible for the spring negative TP retention capacity value.

Year 2 TP retention capacity was positive in all seasons and increased from fall to summer (Figure 16). We measured slightly negative retention capacities for dissolved fractions of phosphorus in the fall of year 2. This is due to site KE releasing an elevated mass of dissolved phosphorus during one rain event in the fall. Winter and spring show similar dissolved phosphorus retention due to both seasons having overall low flows. Summer dissolved phosphorus retention is reported to be very high driven by high retention capacities during the major rain event at the end of September. Monthly mean TP retention capacity for both years 1 and 2 are plotted in Appendix A40 to provide further detail on the timing and quantity of TP nutrient retention.

Retention capacity for nitrogen varied across seasons for both years (Figures 17 and 18). Spring of year 1 retained the most nitrogen across all seasons driven by the increased flows during this period. Fall, winter and summer all retained nitrogen in decreasing order with the vast majority of nitrogen present as nitrate. Year 2 reported much lower nitrogen retention across all seasons compared to year 1. Nitrogen retention capacity remains steady over the fall, winter and spring. Nitrogen retention in the summer season in year 2 resulted in the basins acting as a nitrate source due solely to site MO releasing nitrate during a large rain event that produced elevated inflow and outflow nitrate concentrations of 56 and 78 mg L^{-1}, respectively. While elevated nitrate concentrations were not reported often over the course of this project, nitrate concentrations this high are often reported from inflows and outflow of wetlands (Crumpton et al. 2020). Monthly mean TN retention capacity for both years 1 and 2 are plotted in Appendix A to provide further detail on the timing and quantity of TN nutrient retention.

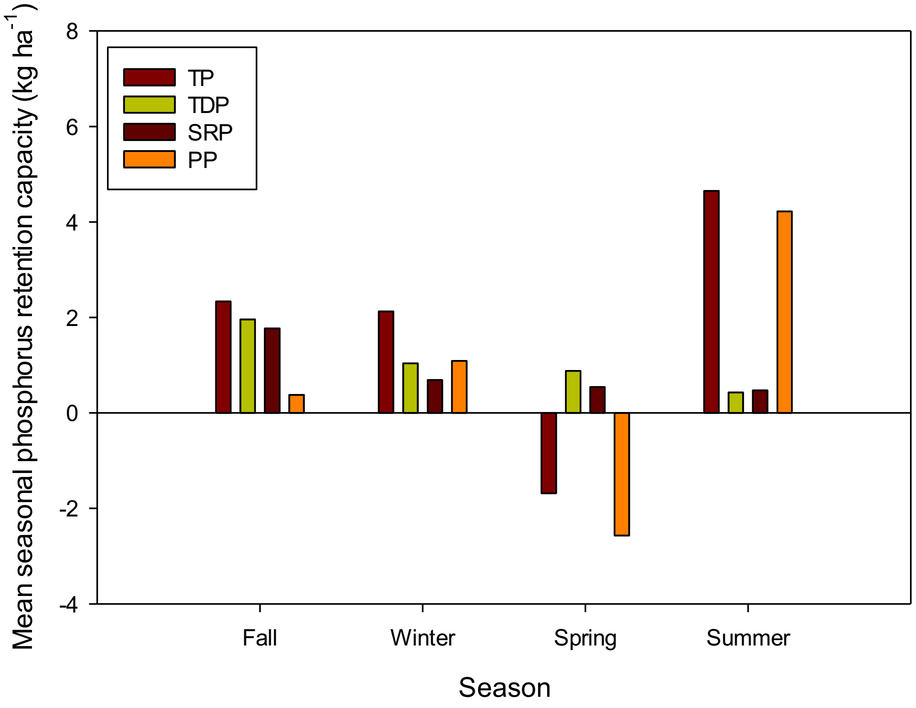

Figure 15. Year 1 mean retention capacity for TP, TDP, SRP and PP across four seasons.

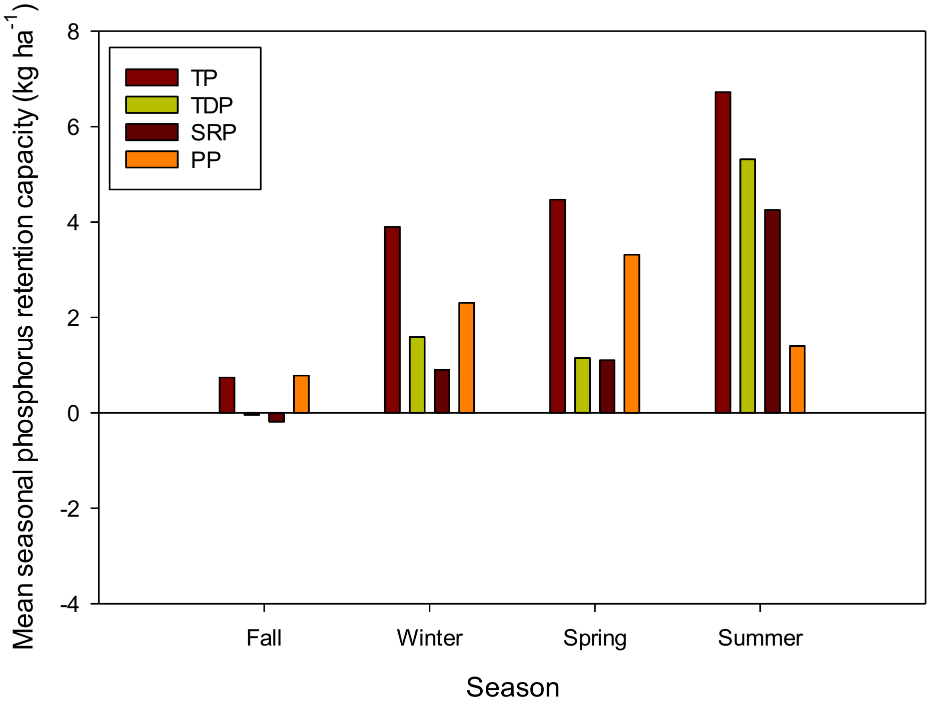

Figure 16. Year 2 mean retention capacity for TP, TDP, SRP and PP across four seasons.

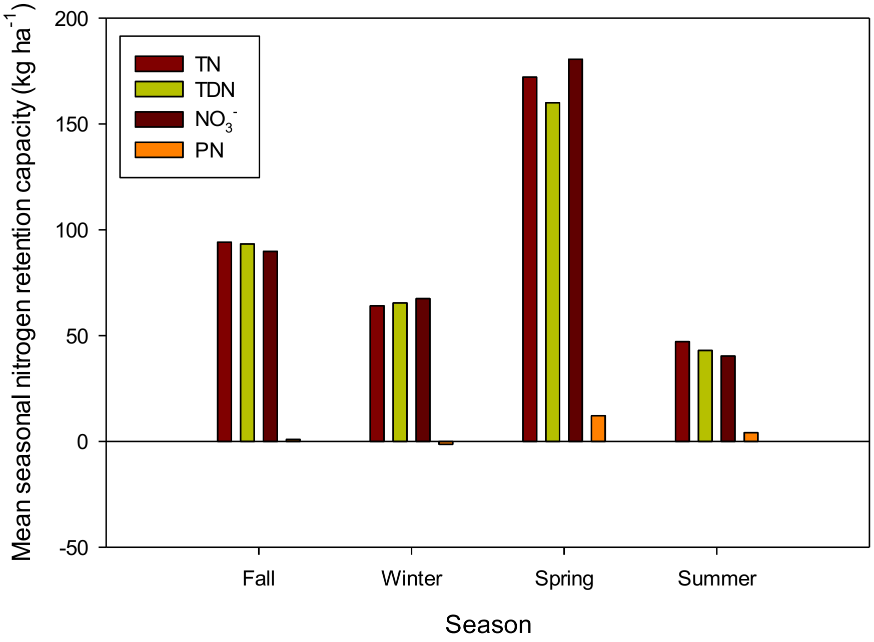

Figure 17. Year 1 mean retention capacity for TN, TDN, NO$_3^-$ and PN across four seasons.

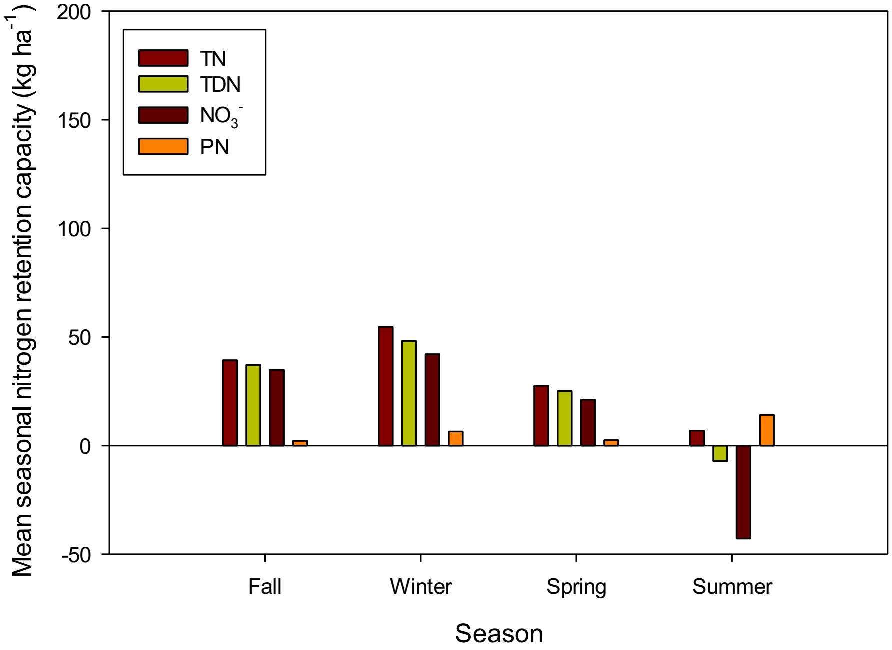

Figure 18. Year 2 mean retention capacity for TN, TDN, NO$_3^-$ and PN across four seasons.

The phosphorus retention capacity we measured in restored/created wetlands of 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 mean retention capacity from our two year study are lower for TP, the overall reduction efficiency we report is similar for TP (46%) and higher for TDP (55%). 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 sites KE and MO.

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 those included in our study with contributing area to surface area ratios ranging from 17 to 32. Two year mean TP reduction efficiency from our sites were higher and less variable relative to those reported by Kovacic et al. (2000). 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^{-1} year^{-1} and 30 to 380 kg ha^{-1} year^{-1}, respectively (Mitsch and Gosselink 2000). Our results for mean TP and TN retention capacity are within those ranges (Table 9). The wetlands in the cited study are larger (2 to 3 ha) compared to the wetlands in our study (Table 1) indicating nutrient retention capacity in our study wetlands may not be limited by the small basin area that is typical of restored wetlands in southwestern Ontario (Cheng and Basu 2017).

A review by Land et al. (2016) of multiyear studies on constructed and restored wetlands in Europe and North America report a mean wetland TP retention capacity of 40 kg ha^{-1} year^{-1} and a mean TP reduction efficiency of 44% (median of 6.3 kg ha^{-1} year^{-1} 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 12.6 kg ha^{-1} year^{-1} with 19% of our basin years (3 basin years of 16) 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^{-1} year^{-1} which is more than triple the mean 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 of 47% at our sites. The results of our study are comparable to those published broadly in the literature and for wetlands in similar landscapes.

Richardson and Qian (1999) report the average phosphorus assimilative capacity of North American wetlands to be near 10 kg ha^{-1} year^{-1} where ecosystem integrity is maintained. They state that when wetland phosphorus retention rates rise above this level the internal structure and function to the wetland ecosystems may be negatively affected. The TP retention capacity of our wetlands ranged from -35.2 to 20.0 kg ha^{-1} $year^{-1}$ in year 1 and ranged from -9.2 to 84.4 kg ha^{-1} $year^{-1}$ in year 2. Our study captured both wet and dry conditions, highlighting the ability of these wetlands to act as sinks during different hydrological conditions. Our average TP retention capacity of 11.7 kg ha^{-1} $year^{-1}$ is similar to the average phosphorus assimilation capacity of North American wetlands as reported by Richardson and Qian (1999). Based on our results, we expect these restored wetlands to continue retaining phosphorus without jeopardizing wetland function. However, these systems should be re-evaluated periodically to verify continued nutrient retention and ecosystem function.

Recommendations

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

1. This two year study demonstrates that small wetlands retain nutrients on the landscape under a variety of hydrological conditions. As a result, these wetlands provide natural infrastructure contributing to the achievement of water quality objectives and more resilient communities. Based on our results, it is recommended that Lake Erie Basin governments consider the development of Domestic Action Plans (DAP) that create wetland protection and restoration programs and polices that support the Lake Erie Action Plan (LEAP) in achieving pollutant reduction targets to improve water quality in Lake Erie.
2. This data set can be used to develop or improve landscape scale nutrient processing models. It is recommended ecological modeling experts incorporate this data to advance nutrient processing models at the landscape scale to provide further information for watershed managers.
3. Natural wetlands as well as older restored wetlands across southwestern Ontario that receive direct agricultural runoff should be studied to provide insight on the degree of nutrient saturation within these systems and provide information that can drive adaptive management processes.
4. Dissolved and suspended phosphorus concentrations increase from the top of the water column to the bottom of a wetland. Therefore, it is recommended to incorporate passive surface drains at the spill point on the constructed dyke and to use this as the main outflow when managed for full volume. This will provide increased nutrient retention by only drawing water from the top layer of the wetland which will have the lowest phosphorus concentrations.

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 for a second water year. Year 2 results were to be compared to year 1 results to determine if a second year of data validates the original conclusion that newly restored wetlands act as effective nutrient sinks across the southwestern portion of the Lake Erie watershed.

Overall, the second year of data reports newly restored wetlands to have TP and TN retention capacities of 16.1 and 144.8 kg ha^{-1} $year^{-1}$, respectively. On average, these restored systems will retain nutrients and will reduce nutrient loads downstream. The TP and TN reduction efficiency was found to be 54% and 52%, respectively. Our second year of results are again similar to what is reported in the literature for restored wetlands that receive agricultural runoff.

The average of both water years reports newly restored wetlands to have TP and TN retention capacities of 11.7 and 261.2 kg ha^{-1} $year^{-1}$, respectively. The two year mean TP and TN reduction efficiency was found to be 46% and 47%, respectively.

Six of the eight wetlands had net positive retention capacity and reduction efficiency for TP while seven of eight wetlands had net positive retention capacity and reduction efficiency for TN.

SRP retention capacity was positive for seven of the eight restored wetland basins. The second year and two year mean SRP retention capacity are 6.1 and 4.8 kg ha^{-1} $year^{-1}$, respectively. This 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 during an overall dryer year 2 compared to year 1 continues to be TP load, with the higher TP load into the wetland increasing the net TP retention capacity.

Overall, the second year of data further supports the year 1 study findings that restored wetlands are important natural green infrastructure that can be effective for reducing nonpoint source nutrients pollution within the Lake Erie watershed.

Acknowledgements

Landowners

We would like to once again sincerely thank all landowners who allowed their wetland restoration projects to be monitored as part of this project. Without hesitation, each landowner granted us access to their land for a second year. 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 with our contractor to phone calls from DUC staff, it is clear they are all passionate about their wetland projects and are concerned for Lake Erie's water quality.

The second year of this project was funded by both Environment and Climate Change Canada via the Great Lakes Protection, and the *North American Wetlands Conservation Act* of the U.S. Fish and Wildlife Service.

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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 prior to year 1, August 2018.

Logger # or Flume	Level (m)	Velocity (m s^{-1})	Estimated flow rate (m^3 s^{-1})
1	0.139	0.128	0.023
2	0.13	0.118	0.020
3	0.13	0.119	0.020
7	0.13	0.122	0.021
8	0.128	0.119	0.020
9	0.131	0.116	0.020
10	0.131	0.123	0.021
11	0.127	0.121	0.020
12	0.13	0.128	0.022
13	0.13	0.119	0.020
14	0.131	0.125	0.022
15	0.131	0.122	0.021
16	0.131	0.133	0.023
17	0.127	0.119	0.020
18	0.13	0.119	0.020
19	0.134	0.128	0.022
20	0.132	0.127	0.022
Flume			0.022

Table A 2**.** Flow results when comparing the area velocity flow probes to the established flow rate of the controlled flume at the University of Manitoba prior to year 2, July 2020.

Logger # or Flume	Level (m)	Velocity (m s^{-1})	Estimated flow rate (m^3 s^{-1})
1	0.304	0.421	0.121
2	0.318	0.442	0.133
3	0.312	0.414	0.122
4	0.314	0.444	0.132
5	0.312	0.430	0.127
6	0.311	0.419	0.123
7	0.313	0.422	0.125
8	0.307	0.407	0.118
9	0.310	0.417	0.122
10	0.308	0.426	0.124
11	0.311	0.428	0.126
12	0.309	0.429	0.125
13	0.310	0.436	0.128
Flume	0.303	0.391	0.112

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Figure A 19**.** Close up of area velocity flow probe the outflow of site DY at period when site DY is not spilling.

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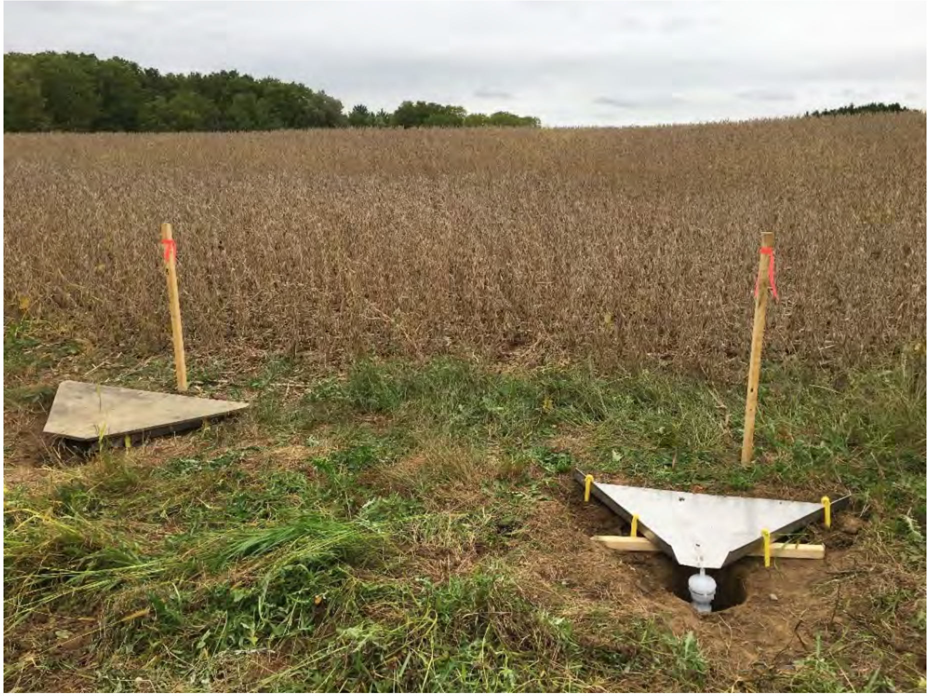


Figure A 21**.** Runoff trays at site DY with protective cover on (left) and off (right) with deployed sample bottle with cover designed to keep dust out of bottle when no flow occurs and to collect runoff water slowly to collect water sample over the runoff period.

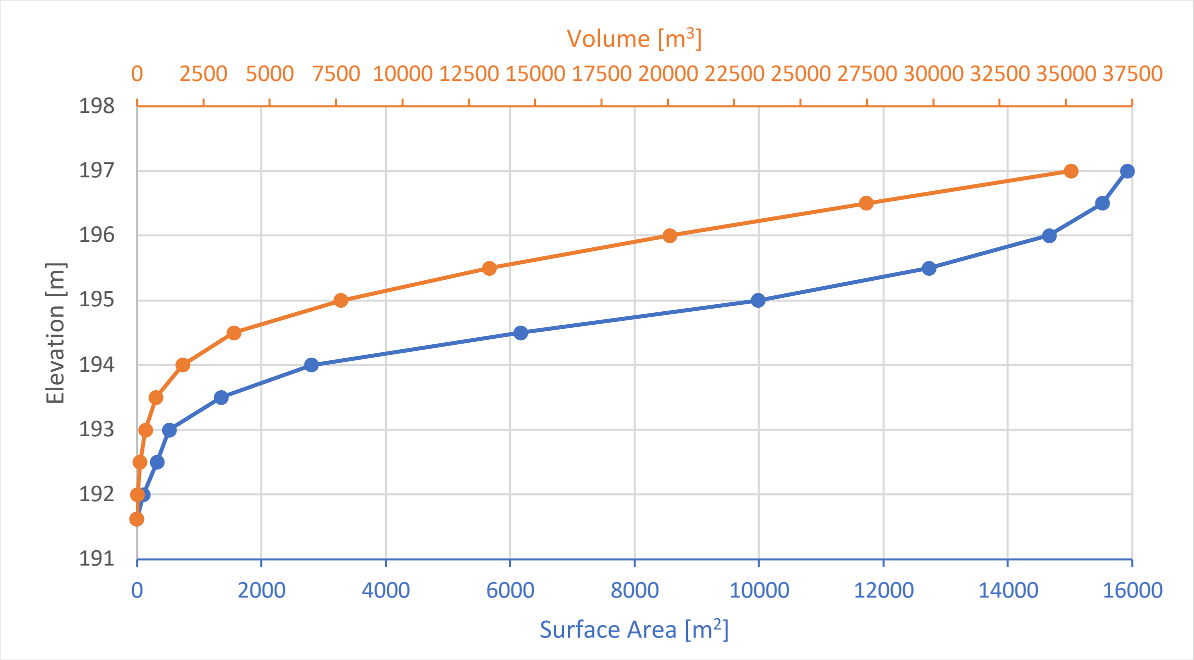


Figure A 22. OH storage curve.

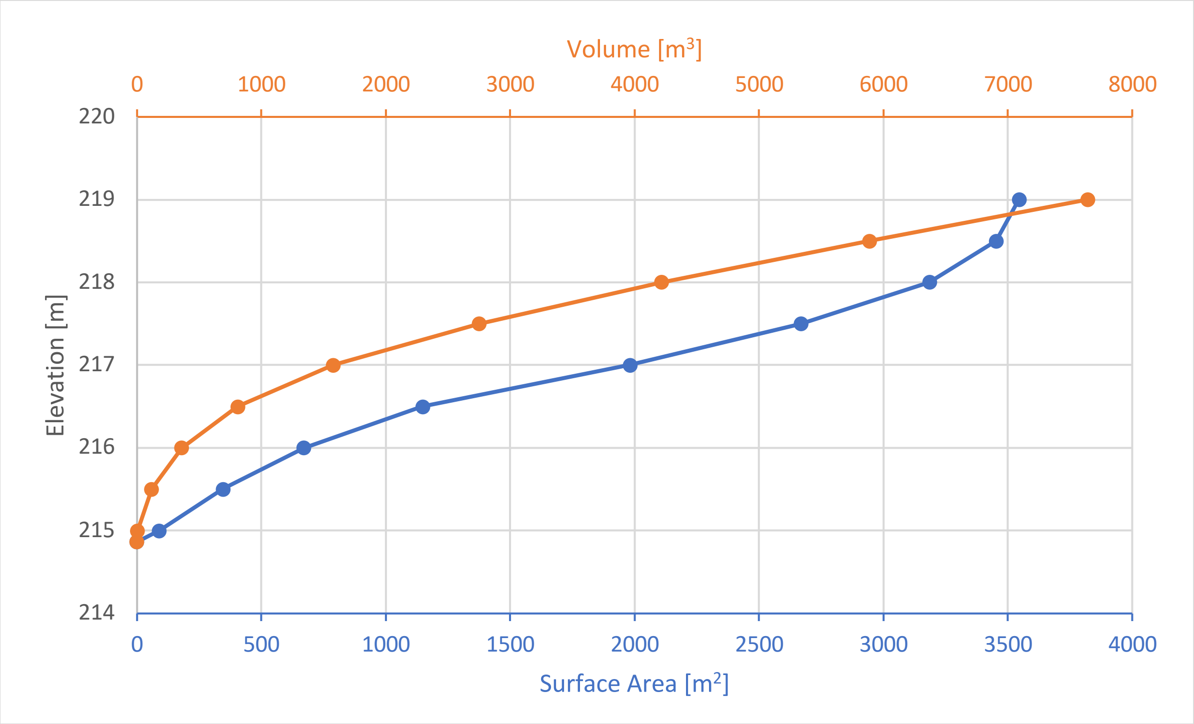


Figure A 23. MO storage curve.

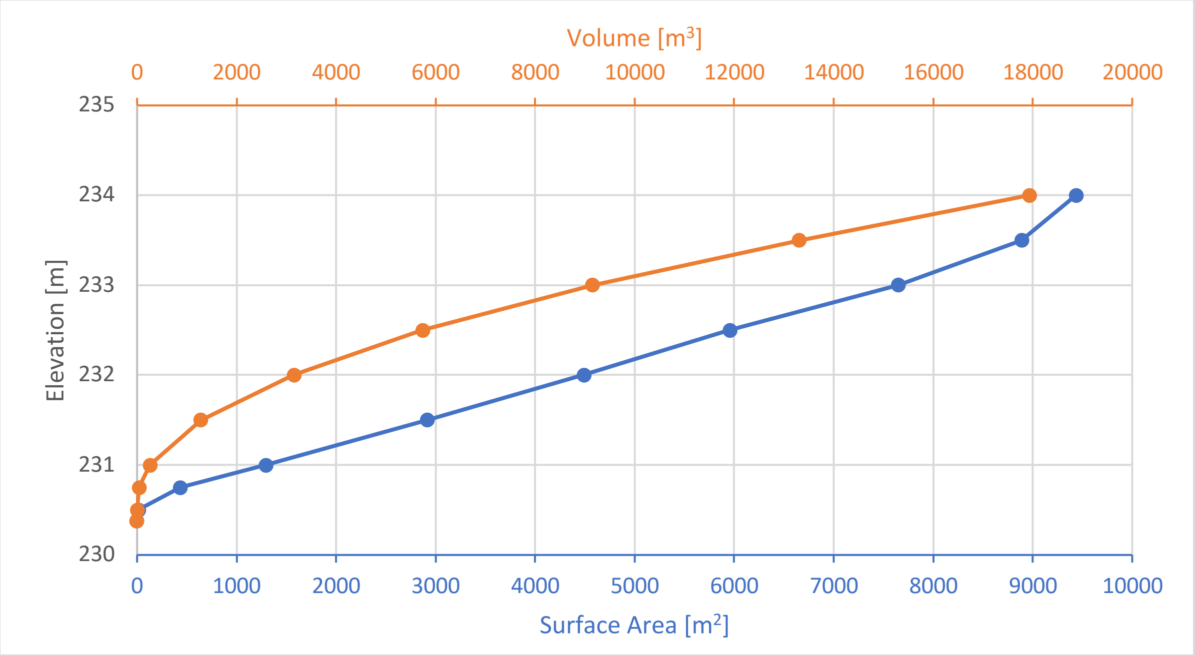


Figure A 24. LL storage curve.

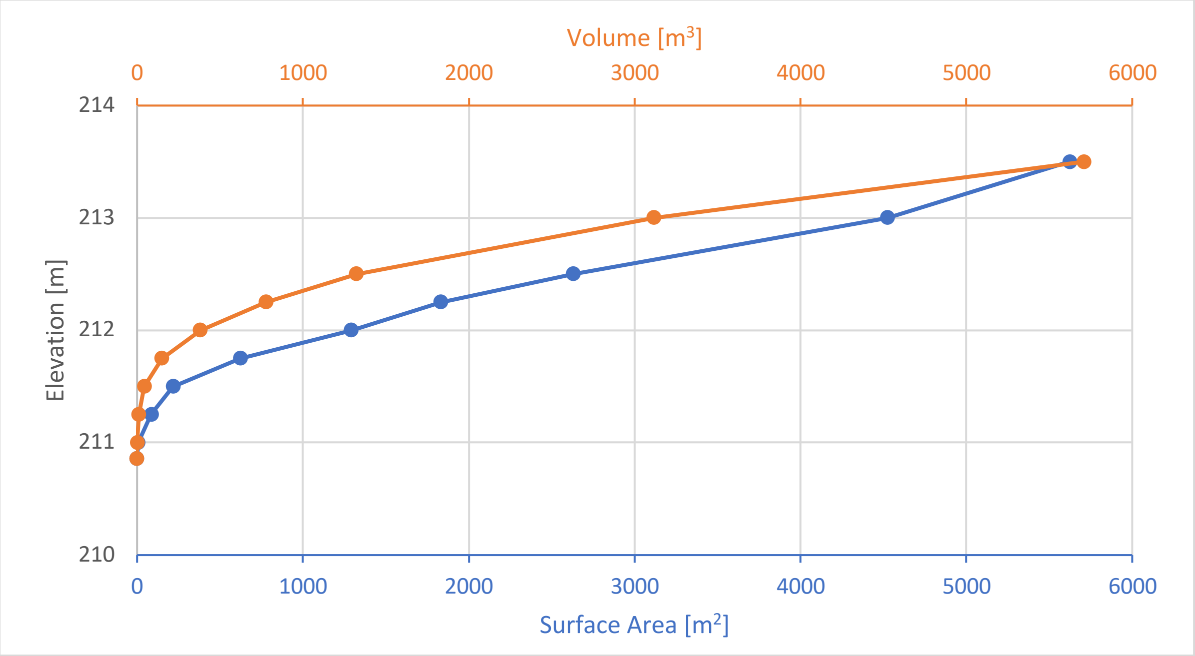


Figure A 25. KE storage curve.

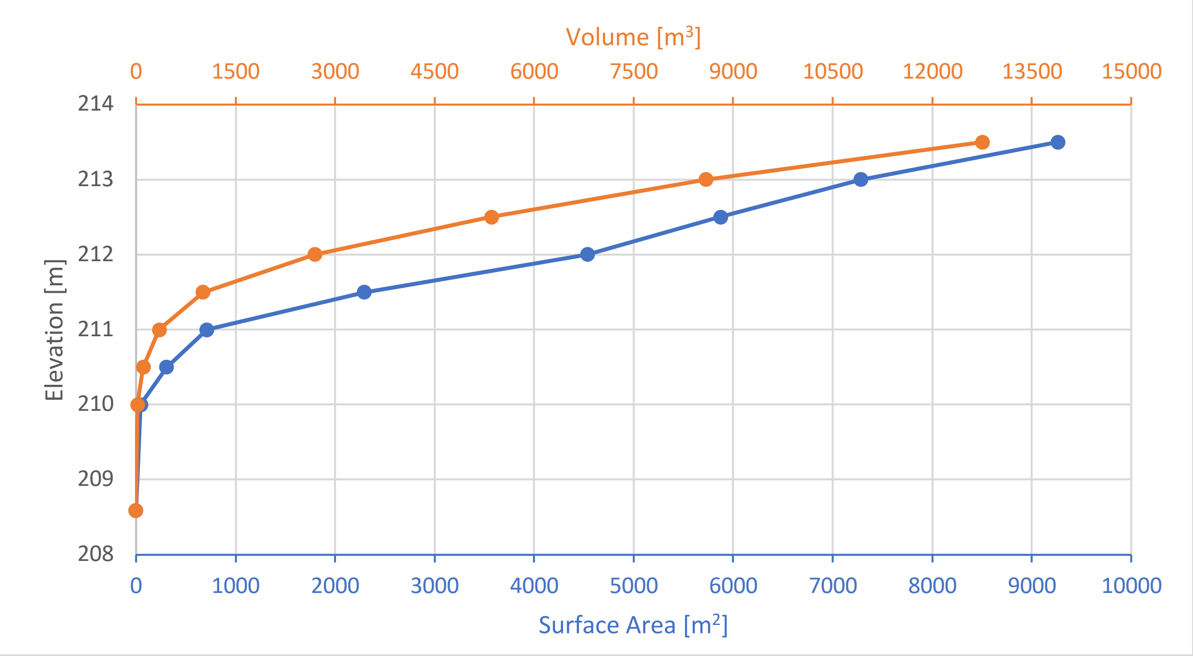


Figure A 26. FE storage curve.

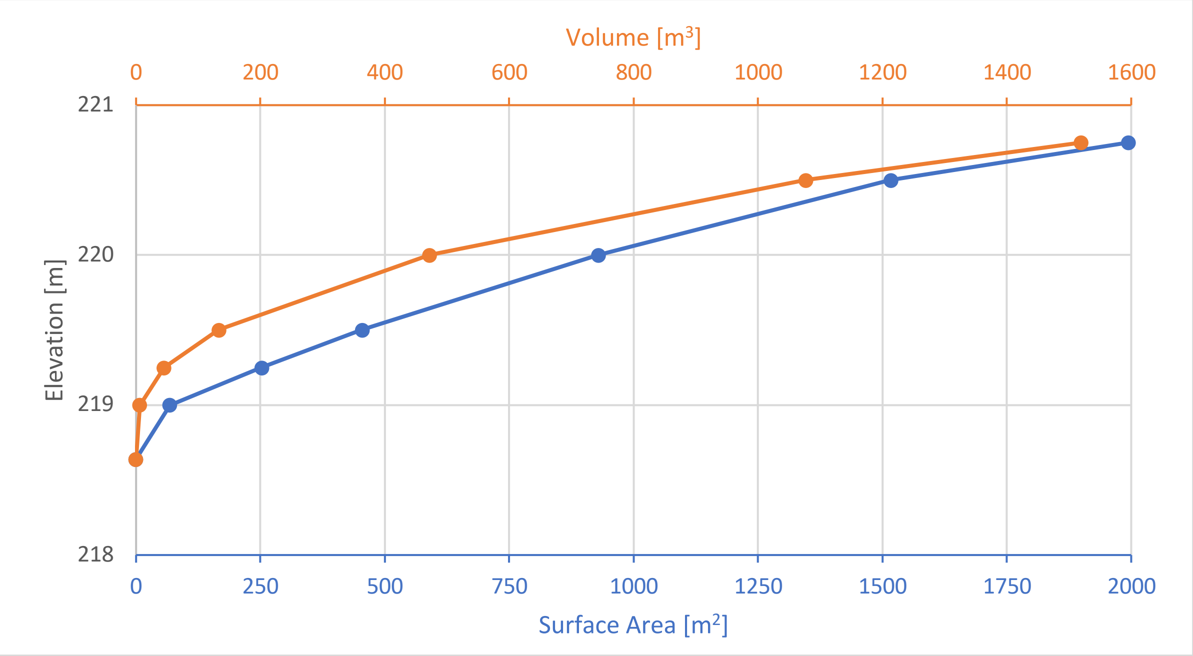


Figure A 27. BL storage curve.

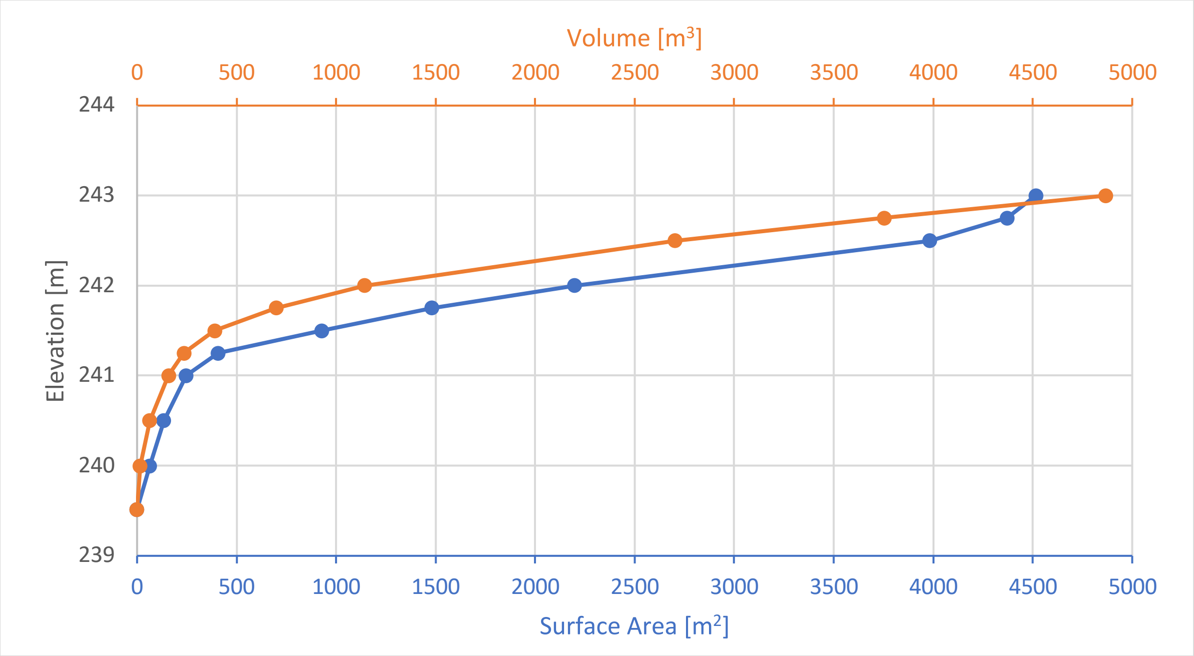
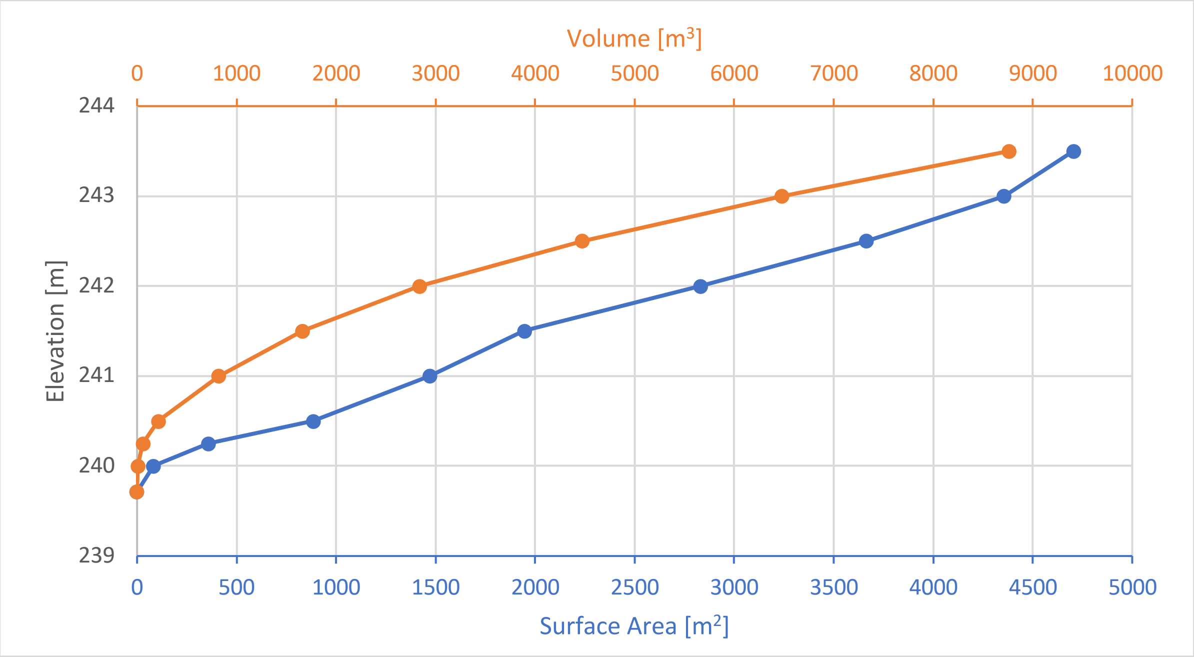


Figure A 28. MA storage curve.



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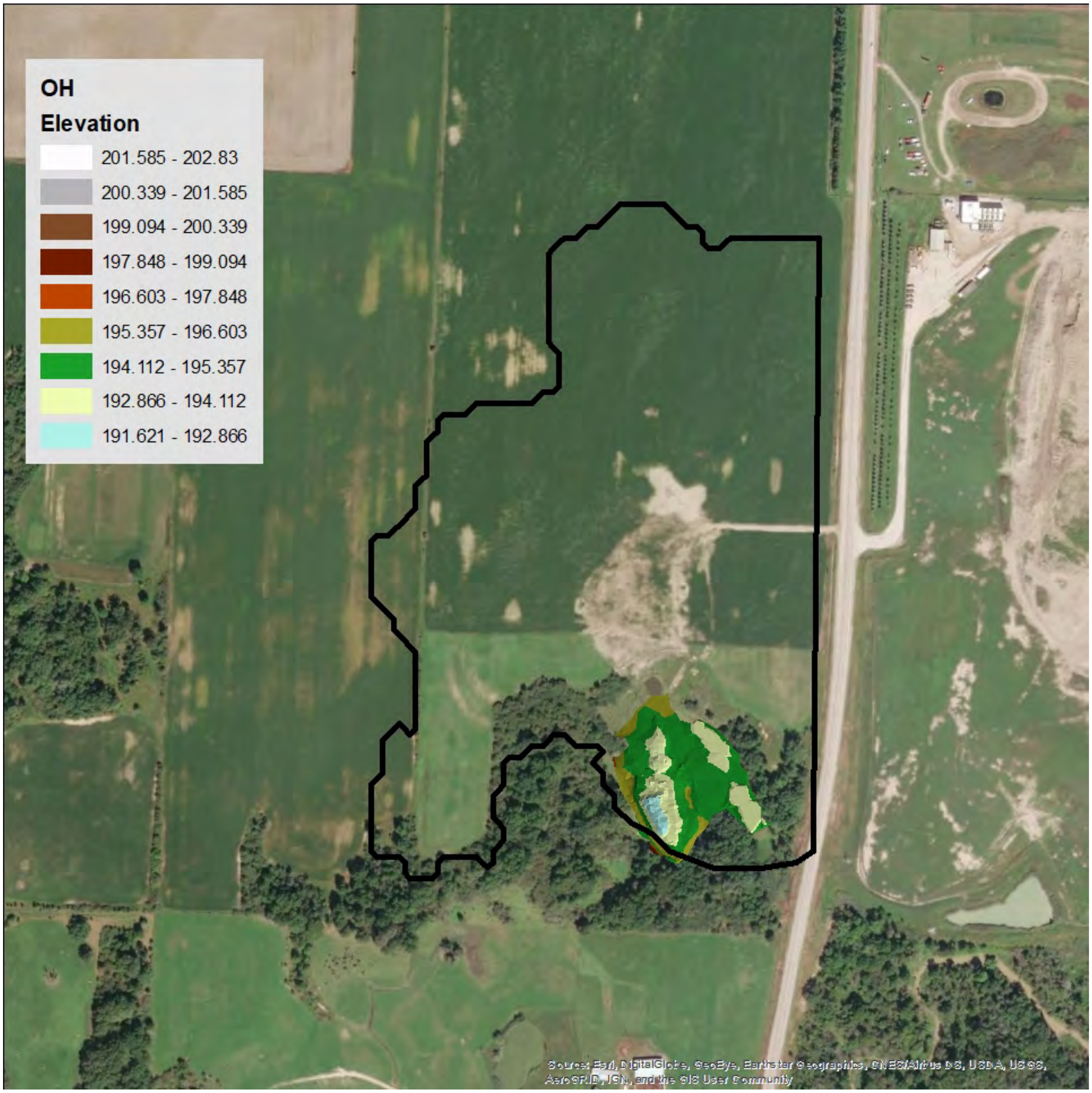
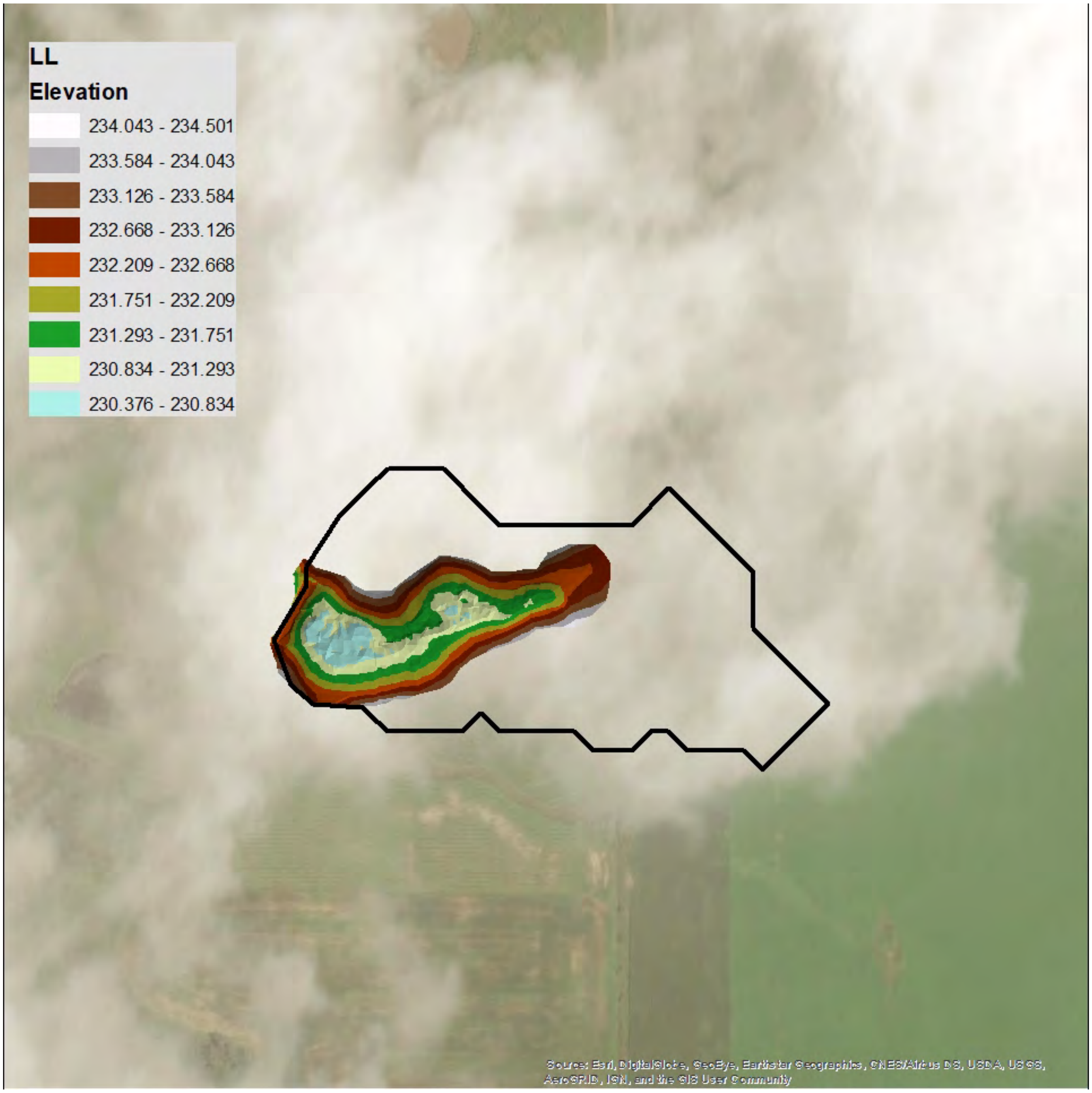


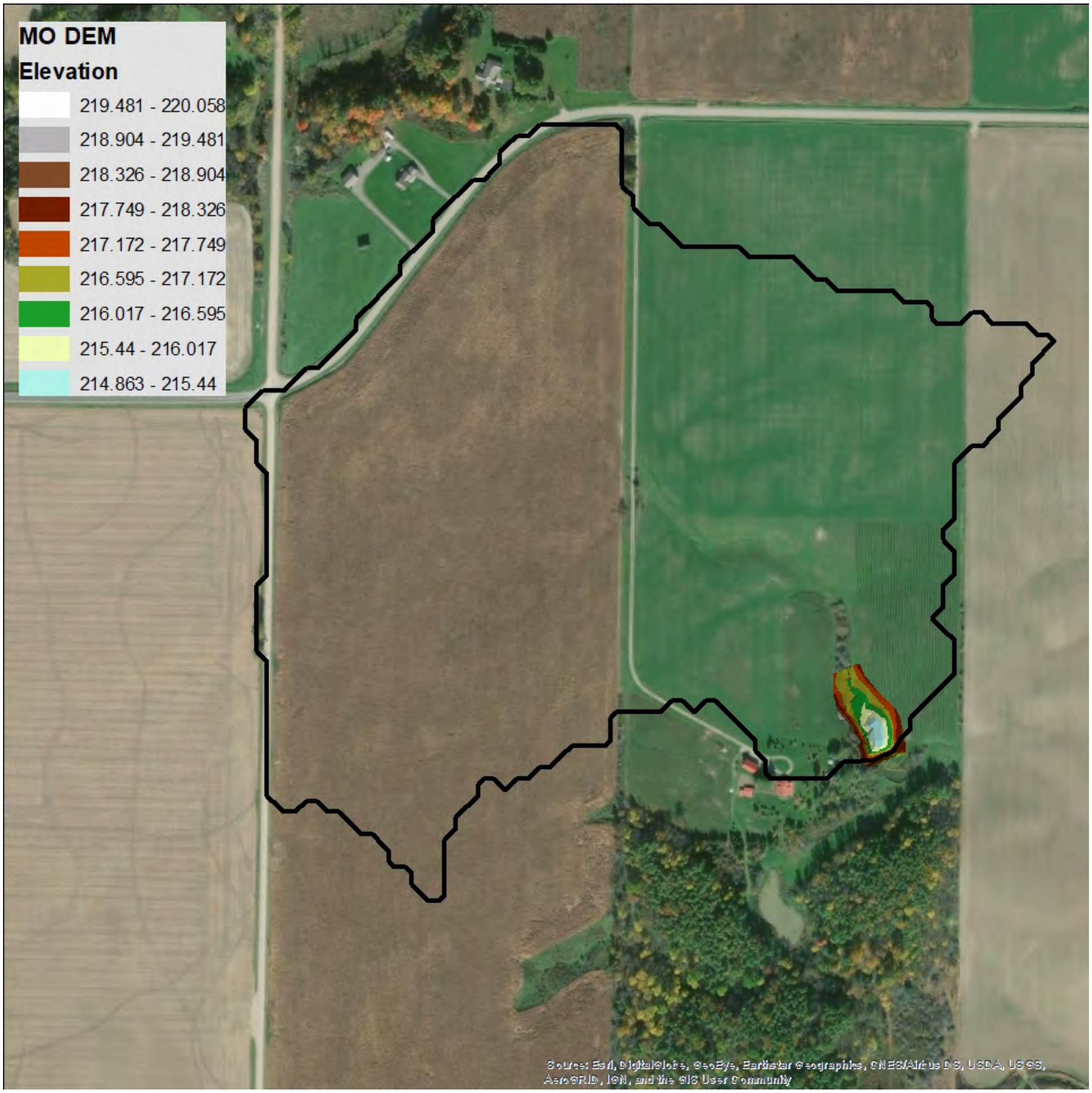
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure A 30**.** 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.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure A 31**.** 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.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure A 32**.** 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.

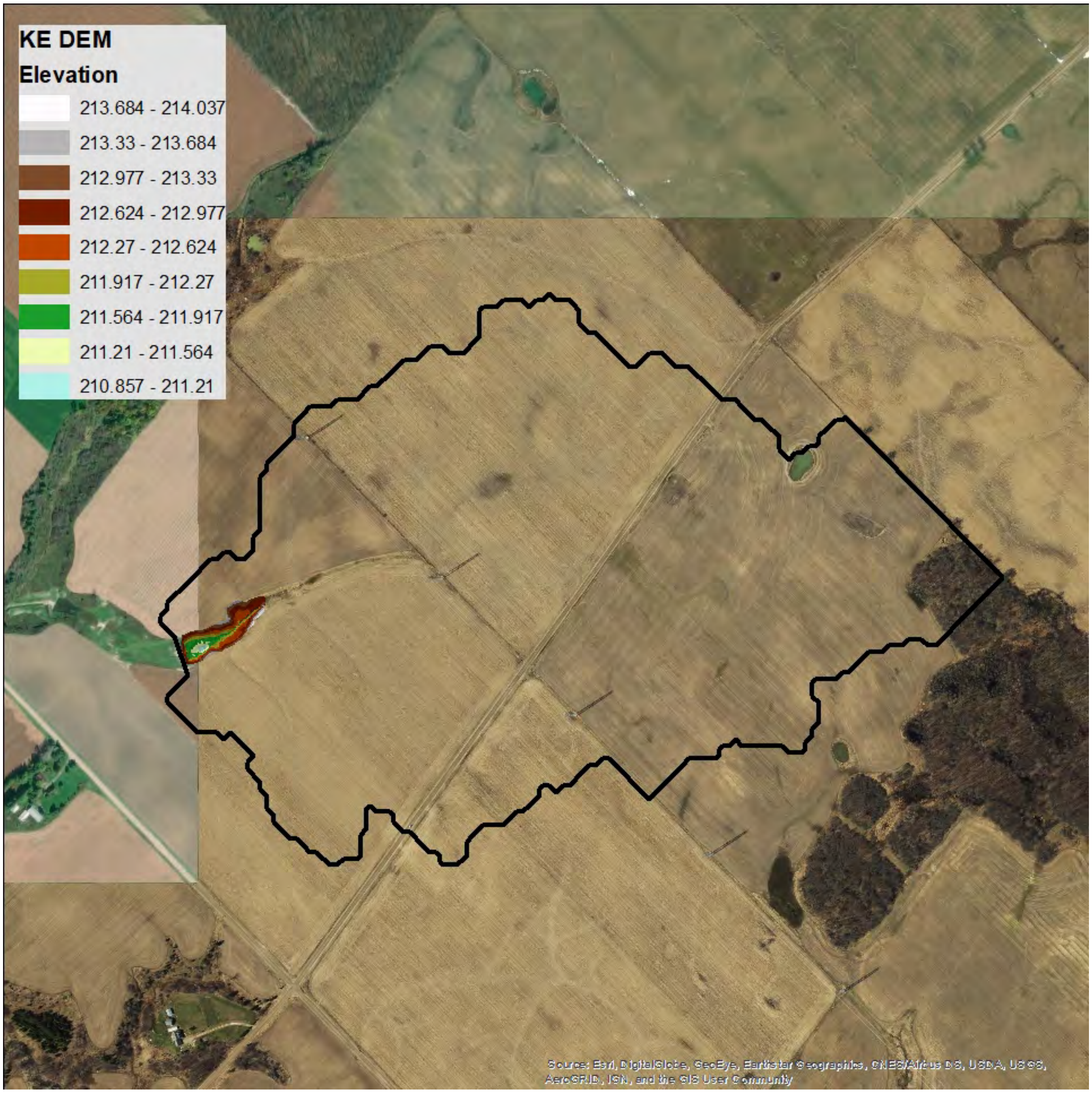
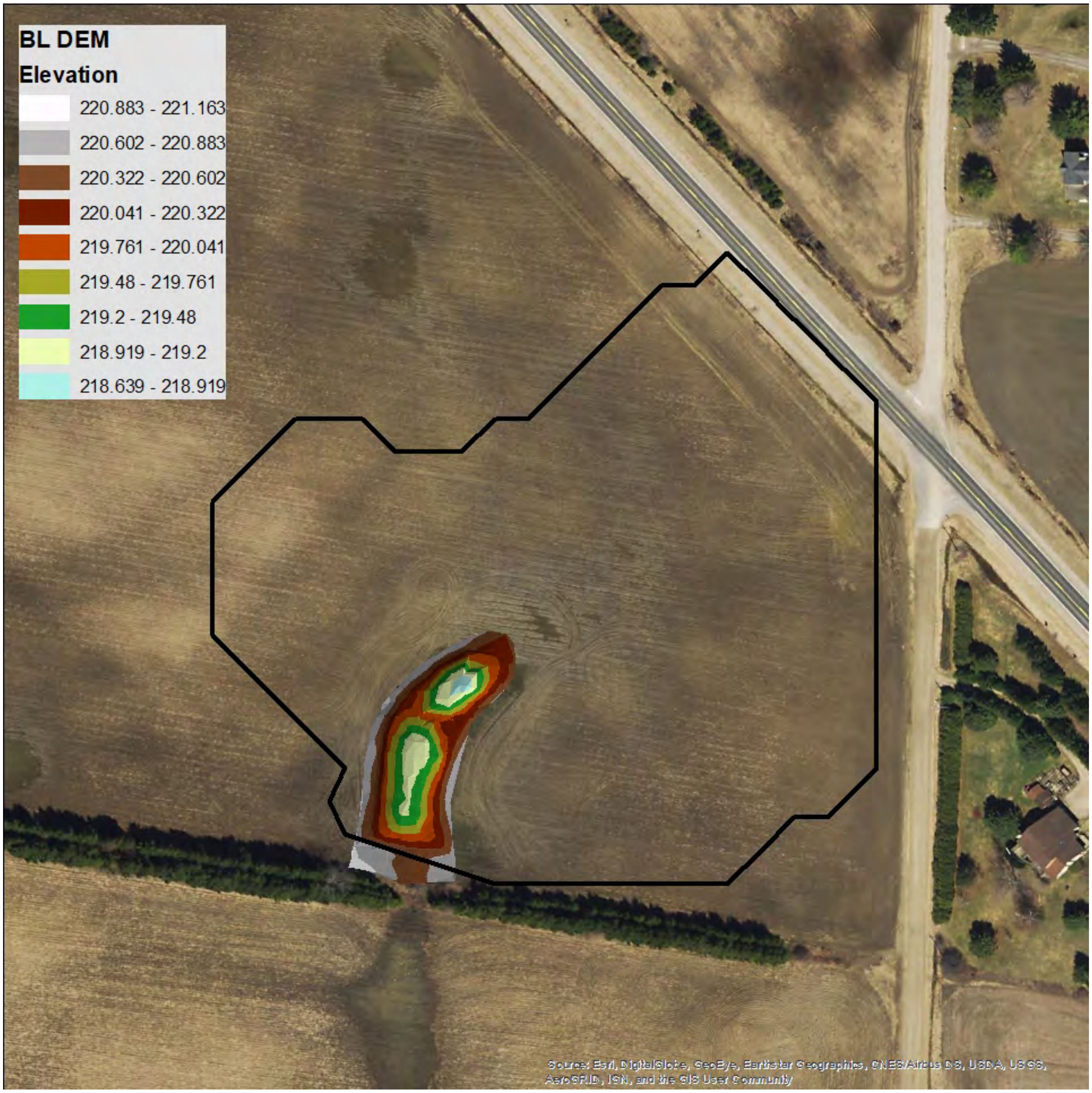
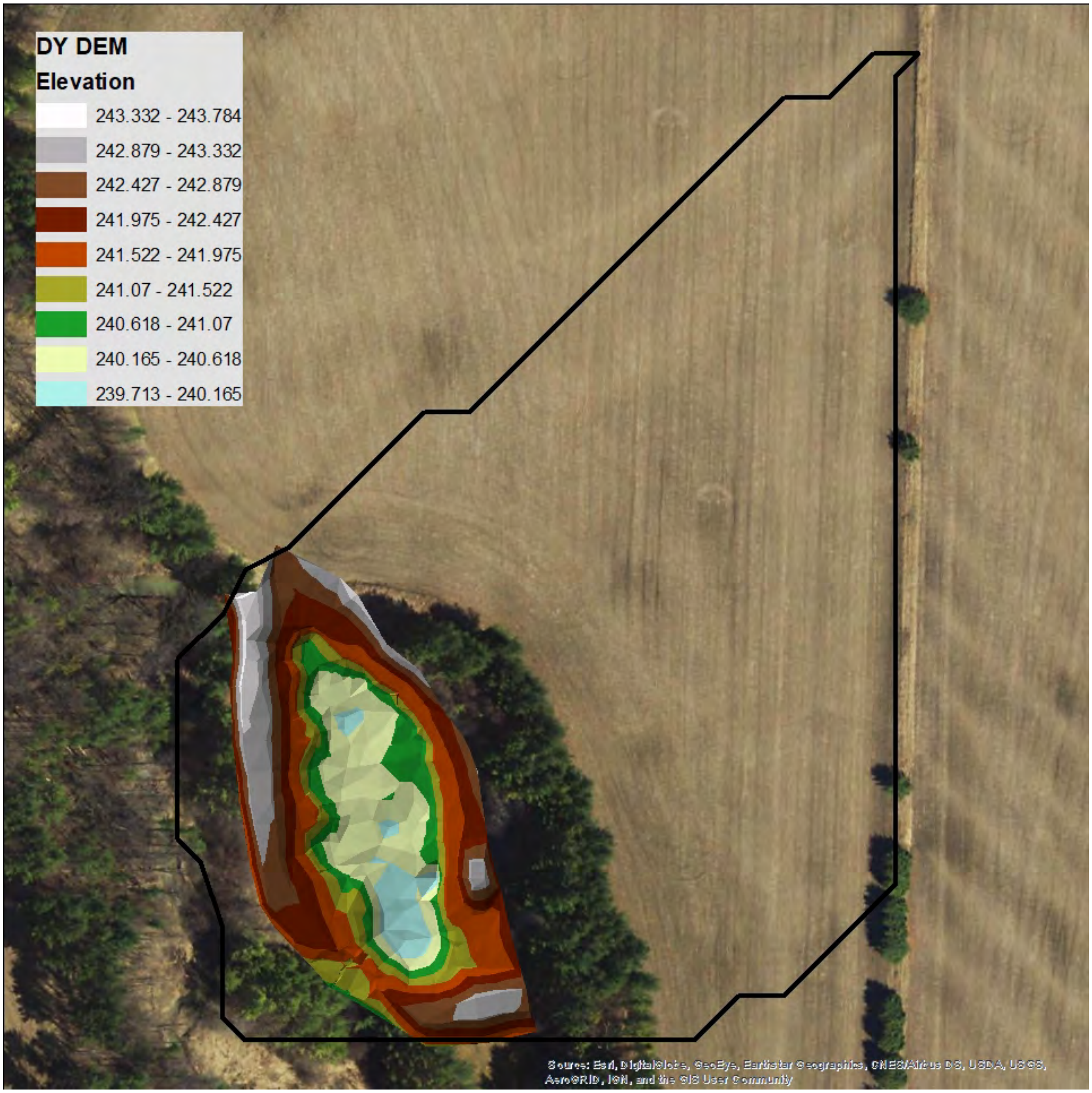


Figure A 33**.** Site KE with contributing area outline in bold and restored basin DEM with shaded slices displaying the elevation of the wetland basin up to a minimum of 1 meters above spill elevation.



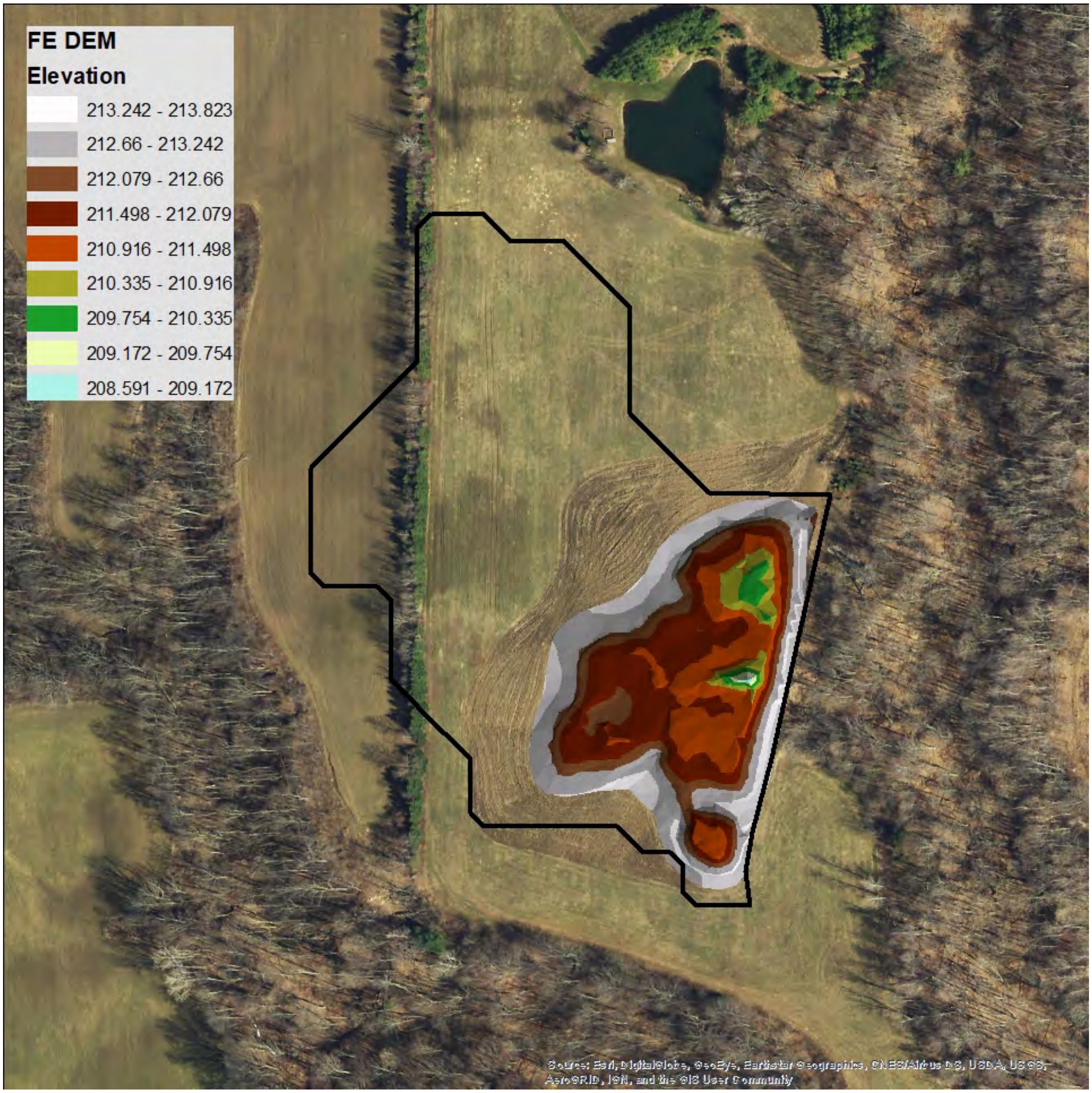
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure A 34**.** 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.



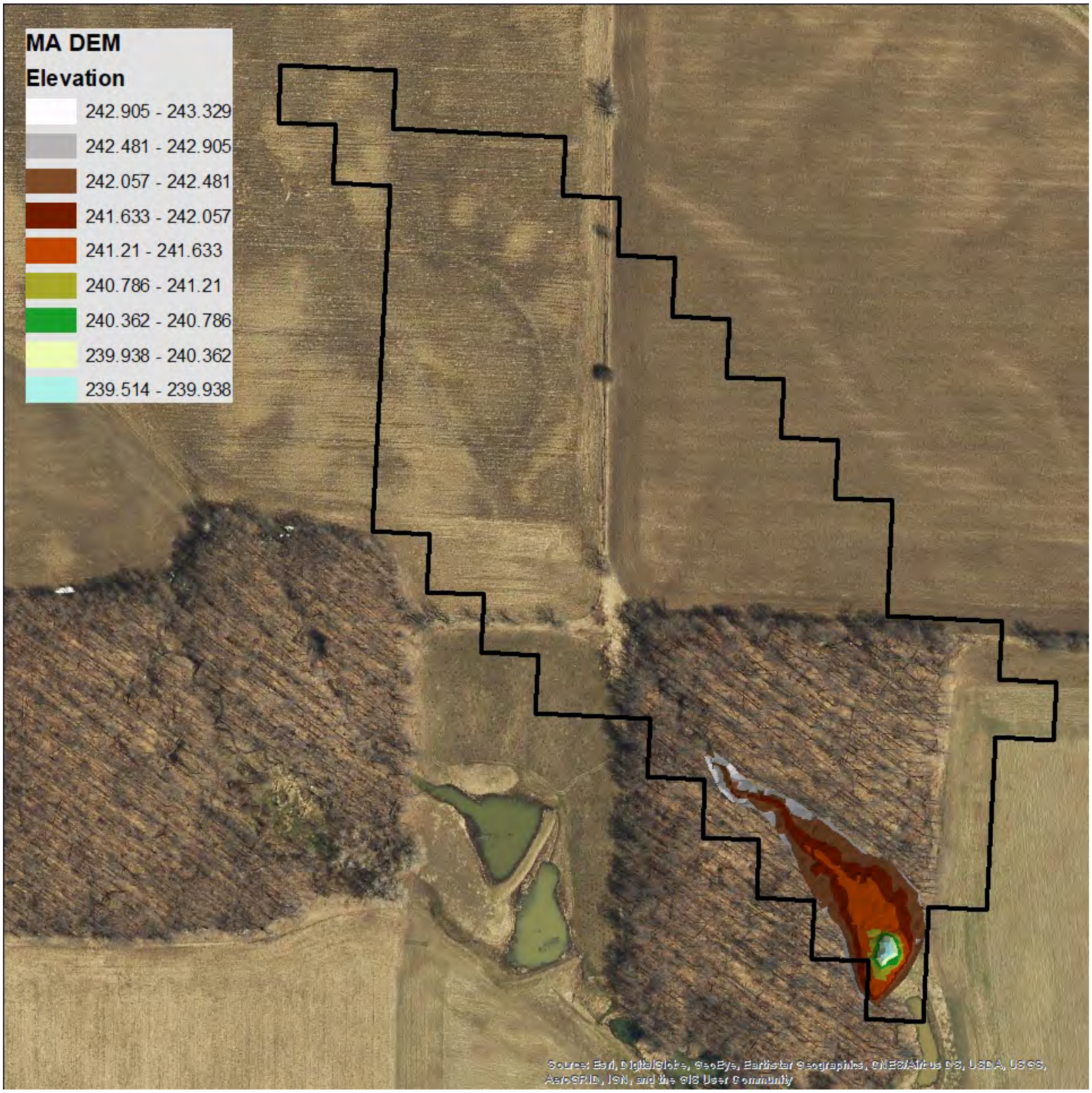
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure A 35**.** 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.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure A 36**.** 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.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure A 37**.** 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.

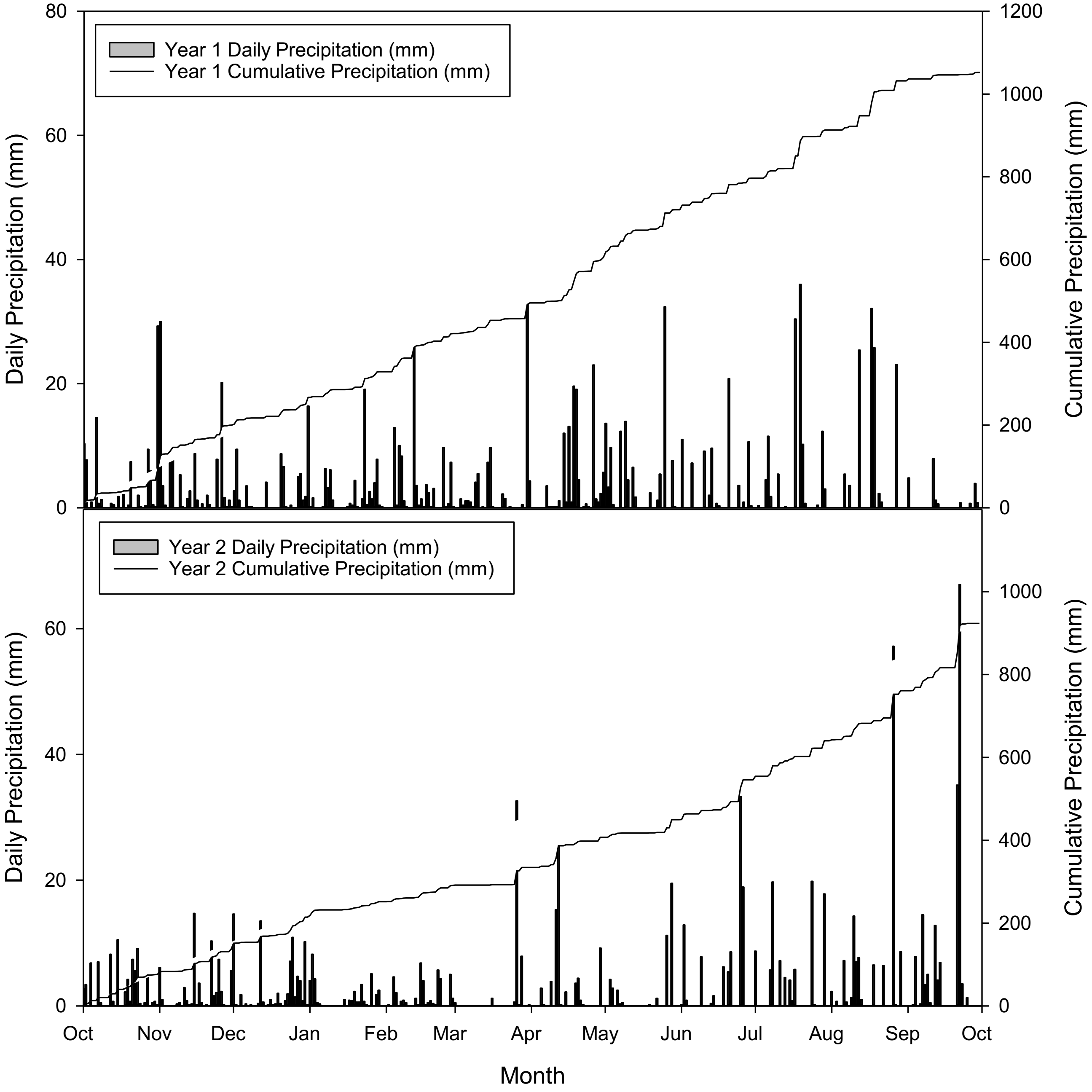


Figure A 38. Daily and cumulative precipitation at London, Ontario (ECCC Station Climate ID # 6144478) from October 1 to September 30 for year 1 and year 2.

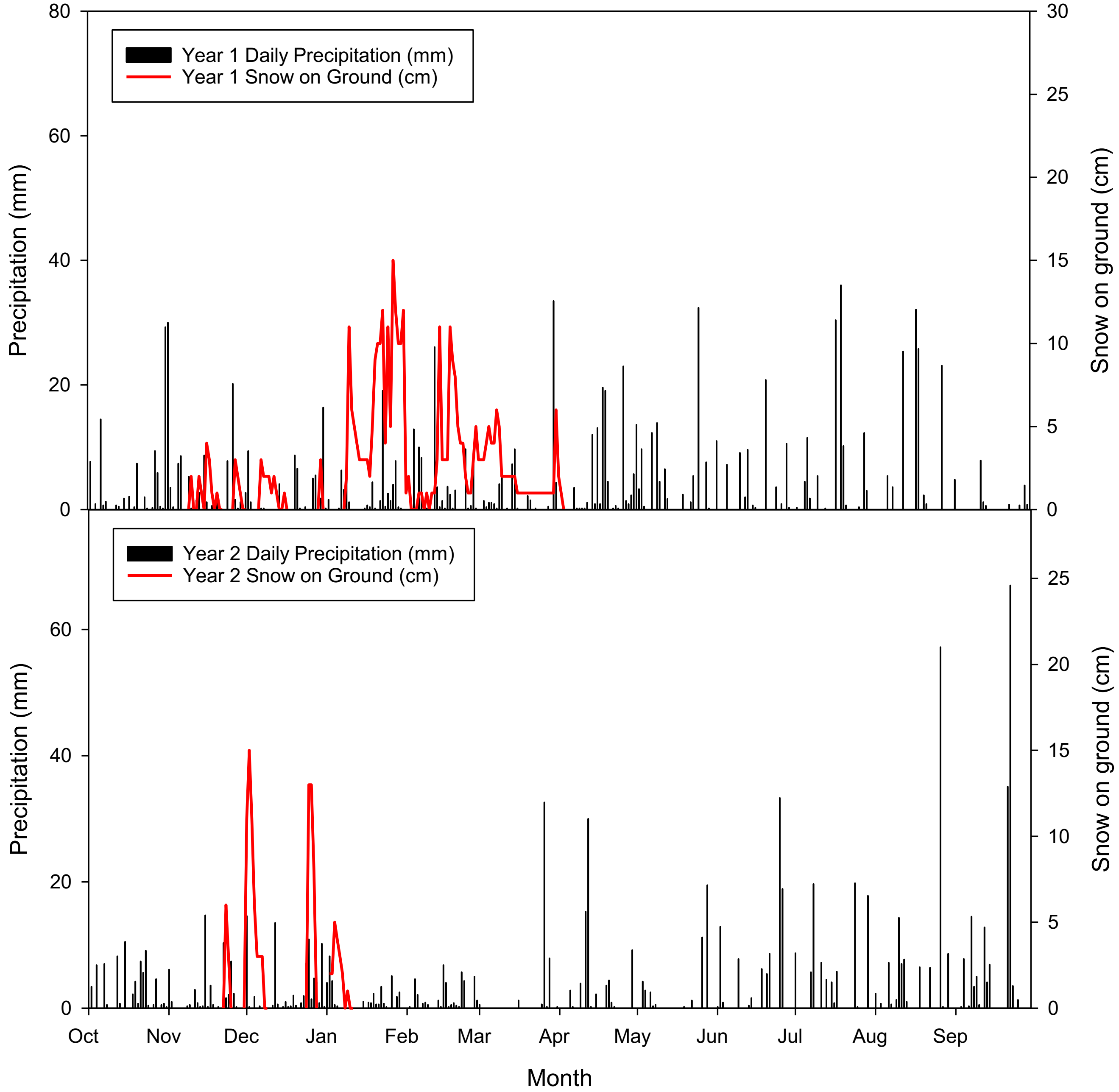


Figure A 39. Daily precipitation snow on ground at London, Ontario (ECCC Station Climate ID # 6144478) from October 1 to September 30 for year 1 and year 2.

Table A 3. Water quality data collected with a hand held YSI unit at inflows and outflows of eight restored wetland basins in year 1.

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

Table A 4. Year 1 total and seasonal breakdown of flow percentage at all inflows and outflows.

Site	Inflow or Outflow	Total Flow	Fall Flows	Winter Flows	Freshet Flows	Summer Flow
		%				
OH	Tile Inflow	27	47	25	17	41
	Overland Inflow	70	48	75	80	48
	Rain Inflow	3	6	0	3	11
	Total Inflow	100	15	35	38	12
MO	Overland & Tile Inflow	99	99	100	99	96
	Rain Inflow	1	1	0	1	4
	Total Inflow	100	19	30	44	7
MA	Overland & Tile Inflow	98	96	100	98	45
	Rain Inflow	2	4	0	2	55
	Total Inflow	100	19	42	37	2
KE	Tile Inflow	49	54	48	50	29
	Overland Inflow	50	45	52	49	65
	Rain Inflow	1	1	0	1	5
	Total Inflow	100	24	29	43	4
BL	Overland Inflow	87	75	100	89	47
	Rain Inflow	13	25	0	11	53
	Total Inflow	100	14	21	59	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	95	55
	Rain Inflow	17	74	0	5	45
	Total Inflow	100	7	18	56	19
LL	Overland Inflow	88	81	100	94	54
	Rain Inflow	12	19	0	6	46
	Total Inflow	100	18	32	37	13

Table A 5. Year 2 total and seasonal breakdown of flow percentage at all inflows and outflows.

Site	Inflow or Outflow	Total Flow	Fall Flows	Winter Flows	Spring Flows	Summer Flow
		%				
OH	Tile Inflow	45	38	55	60	31
	Overland Inflow	47	56	45	30	50
	Rain Inflow	8	5	0	9	19
	Total Inflow	100	23	35	14	27
MO	Overland & Tile Inflow	98	47	100	98	98
	Rain Inflow	2	53	0	2	2
	Total Inflow	100	0	17	25	58
MA	Overland & Tile Inflow	94	89	100	95	86
	Rain Inflow	6	11	0	5	14
	Total Inflow	100	5	36	30	29
KE	Tile Inflow	62	72	54	75	62
	Overland Inflow	37	26	46	23	36
	Rain Inflow	1	2	0	2	3
	Total Inflow	100	11	40	15	34
BL	Overland Inflow	70	68	100	60	60
	Rain Inflow	30	32	0	40	40
	Total Inflow	100	6	25	18	51
DY	Tile Inflow	13	0	0	7	25
	Overland Inflow	67	84	100	83	47
	Rain Inflow	20	16	0	10	29
	Total Inflow	100	22	4	28	46
FE	Overland Inflow	53	26	100	45	26
	Rain Inflow	47	74	0	55	74
	Total Inflow	100	10	30	24	36
LL	Overland Inflow	65	7	94	78	56
	Rain Inflow	35	93	6	22	44
	Total Inflow	100	8	24	19	50

Table A 6. Year 1 total nutrient loads 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^{-1} (kg)	TKN (kg)	DKN (kg)	NH_3 (kg)	DIN (kg)
OH	Surface	32.96	4.99	2.27	27.97	334.85	250.34	84.50	145.32	188.47	103.97	15.73	162.10
	Rain	0.028	0.014	0.007	0.014	3.410	2.932	0.477	1.068	2.342	0.000	1.903	2.97
	Tile Inlet	7.80	1.72	0.97	6.08	88.75	66.97	21.79	36.06	52.54	30.75	3.17	39.39
	Outflow	25.20	4.02	1.09	21.19	247.37	150.18	97.19	49.81	196.27	99.08	25.59	76.69
MO	Surface	11.86	3.45	2.01	8.41	947.44	924.48	22.96	843.46	102.75	79.78	14.40	859.09
	Rain	0.01	0.00	0.00	0.00	0.67	0.58	0.09	0.21	0.46	0.00	0.38	0.59
	Outflow	9.87	2.85	1.25	7.02	870.34	845.50	24.84	735.01	131.37	106.53	15.28	754.25
LL	Surface	8.28	2.27	1.67	6.01	66.57	45.92	20.66	12.12	50.87	30.21	9.40	25.11
	Rain Load	0.02	0.01	0.00	0.01	2.22	1.91	0.31	0.69	1.53	0.00	1.24	1.94
	Outflow	1.61	0.34	0.02	1.27	26.83	18.51	8.32	5.70	20.96	12.64	3.42	9.30
KE	Surface	37.68	6.48	3.21	31.20	411.94	335.83	76.11	221.77	188.13	112.02	11.27	235.08
	Rain Load	0.01	0.00	0.00	0.00	0.96	0.83	0.13	0.30	0.66	0.00	0.54	0.84
	Tile Inlet	28.58	6.59	4.84	22.00	502.61	467.90	34.71	386.26	115.55	80.84	6.54	393.61
	Outflow	62.58	10.63	6.27	51.95	679.58	600.37	79.21	414.66	262.27	183.06	16.30	433.62
FE	Surface	2.39	0.88	0.51	1.52	25.52	17.02	8.49	3.44	21.97	13.48	5.93	9.48
	Rain	0.02	0.01	0.00	0.01	2.27	1.95	0.32	0.71	1.56	0.00	1.26	1.97
	Outflow	0.34	0.11	0.02	0.22	6.51	4.92	1.59	0.75	5.71	4.11	1.17	1.98
MA	Surface	7.73	5.75	5.11	1.97	362.32	350.82	11.50	323.45	38.52	27.02	9.35	333.14
	Rain	0.01	0.00	0.00	0.00	0.79	0.68	0.11	0.25	0.54	0.00	0.44	0.69
	Outflow	14.24	6.79	6.52	7.45	217.21	186.80	30.41	139.12	77.12	53.71	29.05	169.15
DY	Surface	3.67	2.27	2.08	1.39	12.59	6.88	5.71	2.37	10.04	4.33	2.30	4.85
	Rain Load	0.01	0.00	0.00	0.00	0.93	0.80	0.13	0.29	0.64	0.00	0.52	0.81
	Tile Inlet	0.06	0.03	0.01	0.04	16.57	15.88	0.69	15.08	1.47	0.77	0.16	15.26
	Outflow	0.38	0.19	0.15	0.19	13.33	11.03	2.31	7.96	5.29	2.98	0.25	8.30
BL	Surface	1.60	0.87	0.85	0.73	3.83	2.34	1.49	0.50	3.31	1.82	0.51	1.03
	Rain	0.00	0.00	0.00	0.00	0.34	0.29	0.05	0.11	0.23	0.00	0.19	0.30
	Outflow	0.42	0.22	0.15	0.20	2.82	1.65	1.17	0.59	2.19	1.02	0.36	0.99

Table A 7. Year 2 total nutrient loads 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)	TKN (kg)	DKN (kg)	NH_3 (kg)	DIN (kg)
OH	Surface	16.31	2.86	1.52	13.44	256.44	203.44	53.00	159.32	96.50	43.49	0.97	160.92
	Rain	0.05	0.02	0.01	0.02	4.12	3.54	0.58	1.34	2.77	0.00	2.08	3.42
	Tile Inlet	5.56	1.70	0.93	3.86	232.28	221.09	11.19	192.21	39.94	28.75	0.87	193.21
	Outflow	6.44	1.49	0.62	4.95	257.79	240.66	17.13	178.27	77.61	60.48	3.95	184.13
MO	Surface	2.78	1.24	0.57	1.55	455.50	451.97	3.54	421.43	33.39	29.86	2.36	424.47
	Rain	0.01	0.00	0.00	0.00	0.66	0.57	0.09	0.22	0.45	0.00	0.34	0.55
	Outflow	3.36	1.04	0.47	2.32	566.59	553.42	13.18	512.82	50.89	37.71	5.01	520.72
LL	Surface	4.62	4.32	4.52	0.30	171.23	170.28	0.95	16.20	154.93	153.98	43.72	60.02
	Rain Load	0.03	0.01	0.01	0.01	2.42	2.08	0.34	0.79	1.63	0.00	1.22	2.01
	Outflow	0.05	0.02	0.00	0.03	0.91	0.61	0.30	0.03	0.87	0.57	0.01	0.05
KE	Surface	15.95	7.45	4.52	8.50	122.92	89.50	33.42	46.15	76.53	43.11	11.57	57.96
	Rain Load	0.02	0.01	0.00	0.01	1.37	1.18	0.19	0.45	0.92	0.00	0.69	1.14
	Tile Inlet	26.83	15.48	12.57	11.35	495.99	471.39	24.60	323.00	166.96	142.36	44.84	373.86
	Outflow	26.72	15.64	12.30	11.09	536.35	512.06	24.29	334.17	194.19	169.89	42.87	385.03
FE	Surface	1.39	0.86	0.76	0.53	4.62	3.58	1.04	1.11	3.49	2.45	0.33	1.46
	Rain	0.03	0.02	0.01	0.02	2.75	2.37	0.39	0.90	1.86	0.00	1.39	2.29
	Outflow	0.11	0.00	0.00	0.11	0.44	0.15	0.29	0.00	0.43	0.14	0.03	0.04
MA	Surface	4.55	3.61	3.23	0.93	354.03	346.04	7.99	335.72	17.88	9.89	0.62	336.77
	Rain	0.01	0.01	0.00	0.01	0.92	0.80	0.13	0.30	0.62	0.00	0.47	0.77
	Outflow	6.25	4.43	3.96	1.82	222.76	219.52	3.24	198.80	20.83	17.58	5.18	207.11
DY	Surface	2.96	1.26	1.11	1.70	6.03	3.61	2.42	0.93	4.20	2.38	0.58	1.81
	Rain Load	0.01	0.00	0.00	0.00	0.67	0.57	0.09	0.22	0.45	0.00	0.34	0.55
	Tile Inlet	0.07	0.01	0.01	0.06	4.69	4.25	0.44	3.88	0.80	0.36	0.05	3.94
	Outflow	0.24	0.03	0.00	0.22	5.33	1.41	3.92	2.88	2.42	1.30	0.08	3.00
BL	Surface	2.01	1.53	1.47	0.48	14.78	13.21	1.57	1.23	13.21	11.64	3.42	4.99
	Rain	0.01	0.00	0.00	0.00	0.74	0.64	0.10	0.24	0.50	0.00	0.37	0.61
	Outflow	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

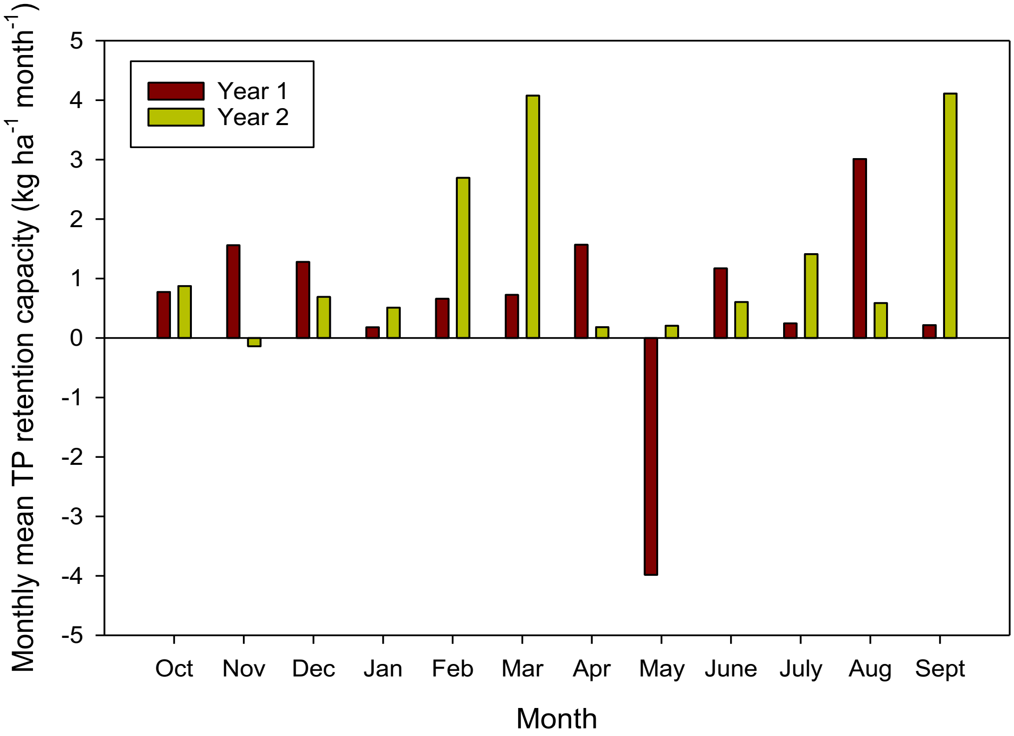


Figure A 40. Monthly mean TP retention capacity for years 1 and 2.

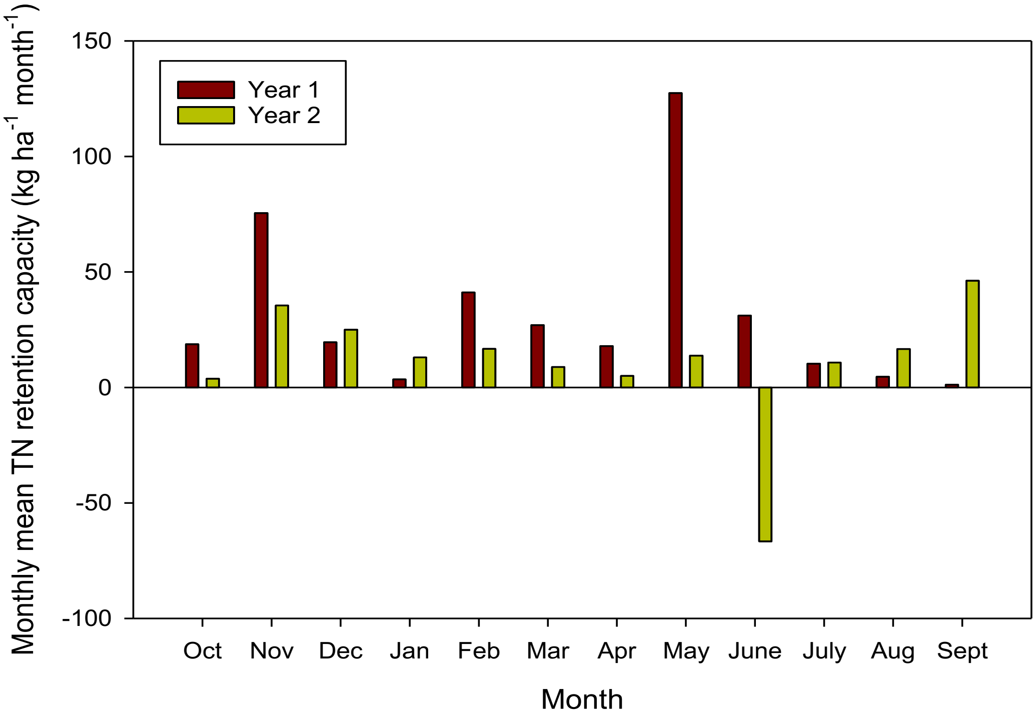


Figure A 41. Monthly mean TN retention capacity for years 1 and 2.

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