H2Ohio Wetland Monitoring Program 2024 Annual Report

Volume 1, Executive Summary; Program-wide Results

The Maumee River, adjacent to the H2Ohio Forder Bridge Floodplain Reconnection Project.
Photo credit: Genna Hunt

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The present volume (Volume 1) of the 2024 Annual Report describes the key H2Ohio Wetland Monitoring Program results from the Water Year 2024 (October 1, 2023–September 30, 2024).

Note: The data and management summaries contained in this report are provisional. Every effort has been made to ensure their correctness. The H2Ohio Wetland Monitoring Program is supported by the Ohio Department of Natural Resources, the Ohio Water Development Authority, the U.S. Environmental Protection Agency's Great Lakes Restoration Initiative, and the Ohio Department of Higher Education's Harmful Algal Bloom Research Initiative Program. The information, findings, and conclusions in this report are those of the authors and do not necessarily represent the views of the funding organizations. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the State of Ohio or the U.S. Government. Contact the H2Ohio Wetland Monitoring Program prior to using these data and before citing research and management findings.

Authors

Coordination Team

Lauren Kinsman-Costello, Principal Research Lead, Kent State University
Olivia Schloegel, Research Coordinator, Kent State University
Raíssa Mendonça, Chief Data Manager, Kent State University
Kenneth J. Anderson, Postdoctoral Scholar, Kent State University
Siena Larrick, Outreach & Engagement Coordinator, Kent State University
Lauren Brown, Vegetation Research Coordinator, Bowling Green State University

Research Team Leads

Richard Becker, University of Toledo
Thomas Bridgeman, University of Toledo
Kennedy Doro, University of Toledo
Stephen J. Jacquemin, Wright State University
Nathan Manning, Heidelberg University
Ganming Liu, Bowling Green State University
Kevin McCluney, Bowling Green State University
Helen Michaels, Bowling Green State University
W. Robert Midden, Bowling Green State University
Silvia Newell, University of Michigan

Technical Co-Authors

Ahzegbobor P. Aizebeokhai, University of Toledo
Jakob Boehler, Heidelberg University
David Dean, University of Toledo
Ethan Glassman, Bowling Green State University
Connor Gluck, Kent State University
Haley Hoehn, Wright State University
Genna Hunt, Bowling Green State University
Ewan Isherwood, Bowling Green State University
Morgan Jutte, Wright State University
Corbin Kohart, Bowling Green State University
Hannah LaPoint, University of Toledo
Sang Suk Lee, Bowling Green State University
Austin Nainiger, Heidelberg University
Ishfaq Rahman, University of Toledo
Leticia Sandoval, University of Toledo
Zach Swan, University of Toledo

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Executive Summary

H2Ohio Wetland Projects Continue to Retain Nutrients

In 2024, the H2Ohio Wetland Monitoring Program (WMP) monitored 45 restoration, enhancement, and construction projects (hereafter Projects), eight of which were intensively monitored Focal Projects. Ten projects had sufficient data to estimate annual net nutrient retention, and all ten projects retained nitrogen (N) and phosphorus (P; Table 1). Conversion of agriculture to wetland prevented up to 1.1 lbs. of P loss per acre (average 0.5 lbs./acre). Monitored Projects filtered up to 495 lbs./acre of new incoming P with only one monitored site releasing nutrients (3 lbs. of P; 0.1 lbs./acre). However, the conversion of agriculture to wetland meant that even the Project which released P supported a net reduction in P loading. Monitored Projects filtered up to 5961 lbs. of new incoming N (0–970 lbs./acre). Although most Projects retained nutrients, **nutrient retention within Projects in 2023 and 2024 was lower than expected compared to long-term averages due to dry or drought conditions.** With lower stream flows, less flooding, and less runoff, the nutrient retention potential of wetland Projects was not fully met due to decreased delivery of nutrient-laden water.

Table 1. Estimated retention of phosphorus (P) and nitrogen (N) in H2Ohio wetland Projects with sufficient data. Positive values indicate net retention (including both filtration of incoming nutrients, and P runoff prevention from conversion of agriculture to wetland) of nutrients during the 2024 water year (October 1–September 30). Lbs./acre = pounds per acre of restored wetland.

		Total P		Total N	
Project	**Description**	**lbs.**	**lbs./ acre**	**lbs.**	**lbs./ acre**
Oakwoods	Isolated pools, one floodplain pool	117	1.1	0	0
Forder Bridge	Tile-drain catchment-fed treatment train	43	2.2	34	6.8
St. Joe Restoration	Tile-drain catchment-fed treatment train	49	0.5	410	12.4
Redhorse Bend	Floodplain	42	0.9	98	3.9
Magee Marsh	Reconnected diked coastal marsh	43	0.2	689	4
Springcreek	Side-channel wetland	87	2.5	1052	42
Tipp City	Side-channel wetland	50	4.4	1121	112
Burntwood	Pumped flow-through wetland	297	9.5	5961	221
Brooks Park	Flow-through wetland	57	11	4316	863
Walnut Creek	Side-channel wetland	534	29	4701	270
MEDIAN		**54**	**2**	**871**	**27**

Balancing Connection and Water Residence Time Maximizes Nutrient Retention

Connecting wetland Projects to water sources with elevated nutrient concentrations maximizes nutrient retention. Projects that receive drainage from large areas that export nutrients (e.g., agricultural land) and hold that water for extended periods (days or more), retain the most nutrients. However, when conditions are dry, as in the drought experienced by most of Ohio in

2024, fewer nutrients are transported in the Lake Erie watershed, including to wetland Projects[1]. A successful but resource-intensive strategy to maximize nutrient retention in dry years is to actively move water (e.g., pump water) from high-nutrient rivers, streams, and other water bodies into treatment systems. The Burntwood-Langenkamp Wetland Conservation Area in Mercer County provides an example. Here, an actively managed pump moves water from the high-nutrient Burntwood Creek into the wetland when flow is too low to passively flood.

Wetland designs must account for a range of possible weather conditions and should aim to capture nutrients in runoff and floodwater but also to hold water long enough for biological and chemical processes to retain nutrients. This requires accurate knowledge of drainage and consideration of the shape, size, and landscape position of the as-built wetland. For example, floodplain and side-channel wetlands are designed to fill from adjacent rivers. If pumps are not used, these wetlands passively fill when the water level of the river exceeds the elevation of its connection with the wetland. If the elevation at this connection is too high, the wetland will rarely, if ever, flood and will not be able to process nutrients in the river that bypasses it. If the elevation of the connection is too low, water may flow into the wetland and right back out. Pumps and water level control structures may have costs but can improve connectivity and residence time. Therefore, H2Ohio projects should consider hydrological design choices relative to the location within the watershed that optimize its nutrient reduction potential. **Wetland design reports should provide supporting technical details including (but not limited to):**

- characteristics of the wetland's source water including, as relevant, the expected drainage area of the Project, its dominant land use(s), and the degree to which engineered drainage systems like agricultural drainage tiles and/or storm drain networks contribute,
- the expected frequency of inundation for specific locations or inlet structure elevations,
- the expected residence times within pools and along flow paths,
- the location and elevation of outlet structure(s), and
- if drainage infrastructure like water level control structures and/or pumps will be installed, information about how these will be used to manage Project hydrology.

Vegetative Communities Feature High Nutrient Storage Capacity

In new wetland projects in which existing vegetation was removed and seeding occurred, wetland vegetation nutrient stocks (measurements of total vegetation nutrient within a Project at a point in time) quickly increased following construction (1–3 years). Nutrients absorbed by plants can be a mix of existing nutrients and "new" nutrient inputs. Nutrient retention by plants increases as vegetation establish and grows. Conversely, in Projects where restoration doesn't disturb existing vegetation (e.g., coastal diked wetland enhancements), vegetation nutrient stock can start high, exceeding total annual nutrient inputs. These high initial plant nutrient stocks are not equivalent to new nutrient filtration but do reduce nutrient losses from the wetland. Additionally, increases in vegetation nutrient stock over time following restoration likely include

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[1] Hounshell, A., L. Johnson, and R. Stumpf. 2024. Nutrient and environmental factors regulating western Lake Erie cyanobacterial blooms. Aquatic Ecosystem Health & Management 26:63–75.

some capture of new nutrients. When conditions limit plant growth, such as the drought seasons in 2023 and 2024, new nutrient retention in plants is diminished but not eliminated.

The longevity of plant nutrient storage ranges from less than one year to multiple years. Durations of plant nutrient storage, the rate of plant decay and release of nutrients, and other methods of nutrient capture by plants (e.g., sedimentation) are currently under investigation through supplemental funding (Harmful Algal Bloom Research Initiative). In many Projects, Cattails (Typha spp.) contributed the most to nutrients in plant biomass. However, Cattails tend to outcompete other species, lowering biodiversity and habitat value. Using data from H2Ohio Projects with more diverse plant communities, the WMP has identified specific wetland plant species that feature high nutrient storage capacity but also promote biodiversity, including Broadleaf arrowhead (*Sagittaria latifolia*), American water plantain (*Alisma subcordatum*), Soft rush (*Juncus effusus*), Woolgrass (*Scirpus cyperinus*), and Pickerelweed (*Pontederia cordata*).

Soil Conditions Within Wetlands that Promote Nutrient Retention

Most soils monitored in H2Ohio Projects have moderate to high capacity to retain additional phosphate. On average, soil phosphate sorption capacity (SPSC) values have increased, but additional analysis is required to affirm the cause of this increase. In many wetland Projects, soil is disrupted during construction due to earth-moving associated with pool excavation, flow path routing, berm construction, etc. The observed SPSC increases may thus be due to changes in soil chemistry, removal and/or placement of soils with greater sorption capacity, accumulation of new incoming sediment with capacity to sorb phosphorus, or some combination of these. Continued analysis of existing data and monitoring is being supported by a supplemental U.S. Environmental Protection Agency Great Lakes Restoration Initiative grant to evaluate the efficacy of SPSC to predict wetland nutrient removal effectiveness.

2024 Monitoring Program Benefits and Accomplishments

H2Ohio WMP Volunteered in Response to ODNR Request for Proposal Review- The Wetland Monitoring Program (WMP) volunteered to convene a panel of 12 experts to review 13 H2Ohio wetland proposals in response to an Ohio Department of Natural Resources (ODNR) request for assistance. As reviewers, WMP researchers noted which proposed projects would likely retain meaningful nutrient loads. These insights were directly used to improve selection criteria and design of funded Projects. In addition, researchers identified documentation needs to ensure relevant information was obtained for all future proposed Projects.

Leveraged Resources to Better Inform Design and Management Decisions- H2Ohio WMP funding (ODNR, Ohio Water Development Authority) supports data collection to assess the magnitude of nutrient load reduction. In other words, the primary goal is to answer the question: *Do* H2Ohio wetland Projects retain nutrients? However, to inform wetland design and management, understanding what promotes nutrient retention is needed. The WMP sought additional funding to address questions related to *how* wetlands retain nutrients. In 2024, this effort resulted in obtaining a second U.S. EPA GLRI award and two ODHE HABRI awards. Collectively, these efforts also support student training. In 2024 alone, the WMP partnered with at least five master's or doctoral students and provided monitoring experience to approximately 20 undergraduate students, many of whom have conducted independent research projects and presented their results at scientific and management meetings.

Shaping a Robust Monitoring Program for Science-Based Management- The H2Ohio WMP began as the first H2Ohio Projects were completed in 2020 and 2021. Similar coordinated programs often spend years developing protocols, but the WMP's adaptive approach embraced that early data collection, while not perfectly optimized, would generate valuable information and learning opportunities. Preliminary data in 2021 and 2022 established baseline conditions, informed protocols and data management infrastructure, and directed sampling designs[2]. In 2023, sufficient monitoring had been completed in select Projects to meaningfully estimate annual nutrient retention[3]. In 2024, the H2Ohio WMP Framework was finalized to establish more comprehensive guidelines regarding how to select Projects for monitoring, parameters measured, and sampling frequency[4]. The updated Framework describes the Program's Guiding Principles: (1) a commitment to responsible, open, sound science, (2) cultivating a community of researchers, professionals, and partners, (3) learning by doing in an adaptive framework, (4) focus on wetland function, and (5) building a foundation for long-term monitoring.

Next Steps

The H2Ohio Wetland Monitoring Program fills a critical knowledge gap for Ohio and the nation by evaluating the nutrient retention function of diverse restored wetlands over time, not just immediately post-construction. Within the first years of a new wetland's construction, plant communities are still establishing, and soil conditions are still equilibrating. Abnormally dry or wet conditions can skew results towards over- or under-estimating longer-term function. Restored and constructed wetlands are rarely adequately monitored[5]. Data from one of the few systems with long-term monitoring (the Old Woman Creek Wetland, Huron, OH) demonstrates that a **minimum of three years of data** is needed to accurately assess trends. **Conclusions drawn from the few years of data collected may underestimate the long-term ability of H2Ohio wetlands to mitigate nutrient loading because of drier-than-average conditions in 2023 and 2024.** In addition, new technologies and approaches are constantly being developed and implemented.

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[2] H2Ohio Wetland Monitoring Program. 2022. H2Ohio Wetland Monitoring Program: 2022 Annual Progress Report. Ohio Department of Natural Resources, Office of Coastal Management. https://doi.org/10.17605/OSF.IO/CVBSX
[3] Lake Erie and Aquatic Research Network, Wetlands and Water Quality Group. 2023. H2Ohio Wetland Monitoring Program: 2023 Annual Progress Report, Vol. 1. Ohio Department of Natural Resources, Office of Coastal Management. https://osf.io/gef6d/
[4] H2Ohio Wetland Monitoring Program, 2024. *H2Ohio Wetland Monitoring Program: Monitoring Framework.* Kinsman-Costello, L.E., K. Fussell, C. Winslow, J. Kerns, O.F. Schloegel, R. Mendonça, R. Becker, T. Bridgeman, K. Doro, S. J. Jacquemin, L. Johnson, G. Liu, K. McCluney, H. Michaels, W.R. Midden, S. Newell, M. Back, L. Brown, I. Rahman, and Z. Swan. Lake Erie and Aquatic Research Network (LEARN) for the Ohio Department of Natural Resources (ODNR). Columbus, OH, USA.
[5] Anderson, K.J., B. Adhikari, O.F. Schloegel, R. M. Mendonca, M.P. Back*, N. Brocato*, J.A. Cianci-Gaskill, S.E. McMurray, C. Bahlai, D.M. Costello, L.E. Kinsman-Costello. 2024. We know less about phosphorus retention in constructed wetlands than we think we do: A quantitative literature synthesis. Ecological Indicators. 169.

Table of Contents

About This Report

In the H2Ohio Wetland Monitoring Program 2024 Annual Report, Program researchers have built upon the foundation laid in the 2023 Annual Report by more clearly defining the intended audience for distinct portions of the report and integrating feedback from the intended audience where possible. For example, feedback from partners invited to the 2025 H2Ohio Wetland Monitoring Program Workshop directly informed improvements to results-based Management Considerations for specific Projects. Additionally, while most of the data are presented in the scientific standard of metric units, researchers have used units that are relevant to the intended audience or original management use (e.g., cubic feet per second for streamflow, lbs./acre for wetland parcel nutrient retention) where needed. Program researchers adopted a set of operational definitions to ensure precision in scientific communication of Monitoring Program Results. Finally, in order to better address the questions asked by diverse stakeholders (e.g., state agency staff, property managers, other applied science researchers) amidst inevitable resource constraints, this report includes results that are informed by supplementally funded data collection.

2024 Annual Report Structure and Intended Audiences

The present volume (Volume 1) is the first of four volumes of the H2Ohio Wetland Monitoring Program 2024 Annual Report. The components of the 2024 Annual Report are described below, along with their intended primary audience.

Volume 1: Executive Summary and Program-Wide Results

The first volume is intended for policy makers and managers who are interested in Monitoring Program findings relating to how wetlands retain nutrients across the H2Ohio Program, rather than in details of specific H2Ohio Projects.

- Executive Summary: Summary of key takeaways from all content. This section is intended for high-level policy makers.
- About this Report: Definitions of important terminology including water year and nutrient retention. Overview of report structure and intended audiences. This section is intended for all readers of the report.
- Program-Wide Results Overview: A more in-depth summary of broad lessons learned by the Monitoring Program than what is presented in the Executive Summary. This section is intended for policy makers and managers who are interested in Monitoring Program conclusions about how different wetlands are retaining nutrients. This section is broken down into six subsections:
    - Nutrient Budget Results: a full accounting of nutrient retention by monitored H2Ohio Projects.
    - Climatic Drivers of Nutrient Loading and Wetland Function: a summary of the climatic context under which the monitoring program has been working, with a strong focus on how recent drought conditions shape results.

  - Connectivity and Residence Time: a comparison across Projects illustrating the effect of wetland connectivity to both water and nutrient sources on their ability to retain nutrients.
  - Wetland Vegetation Monitoring Results Across Focal Projects: a summary of results highlighting the nutrient storage capacity of vegetation communities at wetland Projects.
  - Soil Drivers of Wetland Phosphorus Retention Across H2Ohio Projects: a summary of results highlighting features of wetlands that drive variability in phosphorus storage in soil.
  - Predicting and Assessing Nutrient Function: a summary of how Monitoring Program results could inform ODNR methods for predicting nutrient retention in pre-construction Projects, or unmonitored Projects.

Volume 2: Detailed Results

The second volume is intended for ODNR Project Leads, Project Partners, and any managers who are interested in the function of individual wetland Projects. Collaborating researchers will also find useful information in Volume 2.

- Comparing Monitored Projects: a summary of the data collected across the program for comparing detailed results among Projects. This section is intended for ODNR Project Leads and Project Partners who are interested in the scope and magnitude of data collected across Projects.
- Project by Project Summaries: eight Focal Project and 27 Non-Focal Project summaries that include Project description, management considerations, nutrient budget takeaways, surface water hydrology and nutrients, soil nutrient status and processes, and next steps to strengthen understanding.
- Appendices with additional results, sampling approaches, and calculation methods.

Volume 3: Program Accomplishments

The third volume is intended for other researchers who may want to learn more about communication efforts, monitoring development, and team science accomplishments. Additionally, this section may be relevant to on-the-ground agency staff or restoration professionals interested in learning more about how the Monitoring Program dialogues with partners. It includes:

- Outreach and Engagement: Description of the Monitoring Program's annual workshop, webinar, case studies, and advisory group.
- Monitoring Protocol Development: Examples of the Monitoring Program commitment to science-based protocols and knowledge-building.
- Professional Development: Synopsis of collaborative culture in the Monitoring Program.

Volume 4: Supplemental Information

The fourth volume contains a variety of figures that may be of interest to specific readers. Some of the figures in this volume are referenced in the text of previous volumes where relevant.

Timeframe of Data Analysis: Water Year

While many of the figures in this present report contain data collected across multiple years at each wetland Project, the scope of inference for nutrient budget related values and other trends is documented based on **water year**. The water year refers to the period between October 1st for a given calendar year through September 30th of the next year. For example, Water Year 2024 refers to October 1, 2023 to September 30, 2024. Water years more appropriately capture typical hydrological cycles in temperate systems that experience seasonally varying precipitation (like Ohio's) than calendar years. Summarizing annual hydrology and water quality data by water year is standard practice in scientific monitoring and water management.[6] The H2Ohio Wetland Monitoring Program decided to summarize data by water year in 2024. The 2023 H2Ohio WMP Annual Report summarizes data using calendar years, but this report and future products of the H2Ohio WMP, unless otherwise noted, will summarize data by water year.

Defining Nutrient Retention

For the analysis of Water Year 2024 data, Monitoring Program researchers distinguished nutrient filtration from runoff prevention (definitions below) because these represent two separate methods through which wetlands retain nutrients. Separating out these two methods serves to better highlight how some wetland Projects function mainly through filtration of nutrients (i.e., off-channel wetlands), some function mainly through runoff prevention (i.e., isolated wetlands), and some may provide a combination of these two components.

The Monitoring Program presently (April 2025) adheres to a set of operational definitions (Table 2). Monitoring Program researchers consider **nutrient retention** as the net effect of any combination of processes that prevent nitrogen (N) or phosphorus (P) export to downstream aquatic ecosystems, including runoff prevention and nutrient filtration (definitions below). **Runoff prevention** is the net effect of any processes that prevent nutrient export, including the reduction of fertilizer inputs, and prevention of legacy P- and N-rich surface water runoff and subsurface drainage. **Nutrient filtration** is the net effect of any ecosystem-scale processes that remove N and P that enters the wetland from outside of the system. **Nutrient stock** refers to a measurement of the amount N or P present in a defined ecosystem component (e.g., vegetation, soil, etc.) at a point in time. **Nutrient storage**, on the other hand, is expressed as a rate—an amount of nutrients stored in the ecosystem over a specific period of time. An assessment of nutrient storage requires information about where and when nutrients entered the system. Nutrient stocks thus have units of mass, like pounds or pounds per acre, whereas storage values are expressed in time-defined rate units like lbs. per year. Phosphorus has no environmentally relevant gaseous form and thus wetland filtration and storage of P are essentially equivalent.

[6] U.S. Geological Survey. (2022). *What is a water year?* U.S. Department of the Interior. https://www.usgs.gov/special-topics/water-science-school/science/water-year

However, N may be microbially transformed to gaseous forms that can be emitted from wetland systems into the atmosphere. Thus, only a portion of N retention by filtration is due to storage within the wetland, the rest is transformed into gaseous forms. For helpful background information about the processes in wetlands that store, move, and transform N and P see the H2Ohio Wetland Monitoring Program Framework[4].

Table 2. Operational definitions applied by the H2Ohio Wetland Monitoring Program in the 2024 Annual Report.

Word	Definition
Retention	Net effect of any processes that prevent nitrogen and phosphorus export to downstream aquatic ecosystems. Includes **filtration** and **runoff prevention**.
Storage	The net amount of nitrogen and phosphorus accumulated within a wetland ecosystem or defined ecosystem component (e.g., vegetation, soil, etc.) that remains within the wetland over a defined period of time (i.e., annual phosphorus **filtration** calculated by the Monitoring Program).
Stock	A measurement of nitrogen and phosphorus present in a defined ecosystem component (e.g., vegetation, soil, etc.) at a point in time.
Filtration	Net effect of any ecosystem scale processes that remove nitrogen and phosphorus that enter the wetland. Includes **storage** and transformation to gaseous forms of nitrogen.
Runoff Prevention	Net effect of any processes that prevent nitrogen and phosphorus export. Includes the reduction of fertilizer inputs, and prevention of legacy nitrogen and phosphorus surface water runoff and subsurface drainage.

Nutrient Budget Approach

The goal of the Wetland Monitoring Program is to understand the extent to which H2Ohio Projects retain nutrients. In practice this requires an accounting of wetland "budgets", the amount of nutrients that enter and leave a wetland. Researchers refer to the mass of nutrients entering or exiting wetlands over a given time period as nutrient loads. The loading to a wetland is the amount of nutrients it receives, while the difference between the load entering a wetland and the load leaving a wetland is the nutrient filtration by that wetland. Most budgets currently presented by the monitoring program are simple budgets calculated only with inputs and outputs, but as the program builds its database and its capacity to measure nutrients within different ecosystem compartments, the program is beginning to build more complex budgets that break down where in a wetland different portions of nutrients go, such as the proportion sorbed to soils, and the amount taken up by vegetation. Simple budgets provide an accounting for Projects, but the more complete budgets will contribute to a better understanding of why certain Projects perform better than others. For more details, refer to the "Intensive Monitoring: Nutrient Budget Measurements and Mechanistic Understanding in Select Focal Projects" section of the of the H2Ohio Wetland Monitoring Program Framework[4].

Release of Full Datasets

Data collected by the Monitoring Program is supported by a Data Management and Quality Control structure to provide data centralization and assure quality and consistency so that data can be used in a timely manner. The Program aims to publicly release data annually alongside or shortly following the publication of the H2Ohio Wetland Monitoring Program Annual Report, in a staggered timeframe that balances the urgency of the information need with the rigor of scientific assessment. In general, the annual report will provide extensive summarized data from the previous water year, and the publicly released datasets will contain raw data collected approximately two years prior via an embargoed data release (e.g., for the Annual Report containing summarized data for Water Year 2024, raw data up to Water Year 2022 will be released).

Funding Sources

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Program-Wide Results Overview

Nutrient Budgets

Estimating Phosphorus Runoff Prevention and Nutrient Filtration to Quantify Nutrient Retention in Select H2Ohio Projects

In select monitored Projects, H2Ohio Wetland Monitoring Program (WMP) researchers estimated two components of overall nutrient retention: phosphorus (P) runoff prevention and nutrient filtration. Researchers estimated annual P runoff prevention from the conversion of agricultural land to wetland for 33 H2Ohio Projects (Table 3). Nitrogen runoff prevention was not calculated, because edge of field nitrogen-loading data was unavailable. Estimating nutrient filtration requires additional data about hydrology and project landscape connectivity. Researchers collected sufficient data in Water Year (WY) 2023 and/or WY 2024 to calculate nutrient filtration in 11 H2Ohio Projects. In addition to Monitoring Program Projects, the Montpelier Project's water monitoring and subsequent nutrient budget calculation was performed by an affiliate research partner[9]. The Williamsburg Project was monitored entirely by an external partner during the 2024 water year[8]. Total nutrient retention was estimated for these 13 Projects using the total N filtration estimate and by adding together the P runoff prevention and total P filtration estimates.

Estimating nutrient filtration is easiest in flow-through and side-channel wetlands with constrained inflows and outflows. Monitored Projects in West and Central Ohio largely follow this structure. Projects with more complex hydrology (e.g., riparian floodplains, intermittent-flow tile drain-fed systems, and groundwater-fed or isolated Projects without conspicuous surface water connections) are challenging to monitor for nutrient budgets. These Projects often require more complicated sensor systems and longer monitoring time periods to effectively sample transient conditions, like brief storm events that may contribute the majority of the Project's annual nutrient retention. For coastal Projects and others in which actively managed water level control structures determine wetland inflows and outflows, nutrient budgeting is limited to Projects where management action details (e.g., the times and dates on which water level controls structures are raised or lowered) are accurately communicated to researchers. For details on the structure of Projects, and about how nutrient budgets were calculated, see Volume 2 of the H2Ohio Wetland Monitoring Program 2024 Annual Report.

Phosphorus Runoff Prevention

In projects where agricultural land was converted to wetlands, 11–117 lbs. of P runoff was prevented from being exported to downstream ecosystems from each Project, or **0.1–1.1 lbs. P per acre** (Table 4). P runoff prevention was calculated for portions of a Project that reduced P runoff due to the conversion from an agricultural field to wetlands based on edge-of-field monitoring in similar systems[7]. To convert P runoff prevention to lbs./acre, total P runoff prevention was divided by the area of the Project parcel that was converted from agricultural fields to wetlands, assuming that runoff from the entire property drains to the wetland. The Oakwoods Nature Preserve Wetland Restoration Project, East and West, with 111 combined parcel acres on which 50 acres of wetland were restored, prevented the most P runoff at 117 +/- 65 lbs. (about 1.1 lbs./acre). Seven monitored Projects did not involve transformation of agricultural land as part of the wetland restoration project and thus did not prevent P runoff. These Projects were implemented with the aim of filtering nutrients from upstream water sources.

[7] Pease, L. A., K. W. King, M. R. Williams, G. A. LaBarge, E. W. Duncan, and N. R. Fausey. 2018. Phosphorus export from artificially drained fields across the Eastern Corn Belt. Journal of Great Lakes Research 44:43–53.

Table 3. Characteristics of H2Ohio Projects with sufficient data and understanding to support estimate of nutrient retention components: prevention of P loss via runoff due to conversion of agricultural land to wetland ("P Runoff Prevention") and storage and/or transformation of new nutrients entering the wetland from upstream ("P & N Filt"). For each Project, the entire area of the Project parcel ("Total"), the area of agricultural land converted to wetland ("Ag to Wet"), and the area of wetland established ("Restore") are reported. †Indicates intensively monitored Focal Projects. Note the table continues onto the next page.

H2Ohio Project Information			Area (acres)			Nutrient Budgets	
MapID	Code	Full Name (Short Name)	Total	Ag to Wet	Restore	P Runoff Prevent	P & N Filt
		Northwest (Bowling Green State University Base Crew)					
17	FORB	†Forder Bridge Floodplain Reconnection (Forder Bridge)	54	5	5	x	x
11	SJRE	†St. Joseph's River Restoration Project (St. Joe Restoration)	94	33	33	x	x
20/21	OAKW/E	†Oakwoods Nature Preserve Wetland Restoration Project, West and East (Oakwoods)	111	50	50	x	x
31	MAUR	Rotary Riverside Preserve Restoration (Maumee River Floodplain/Huddle)	57	35	35	x	
13	OOPR	Oak Openings Preserve Wetland Restoration (Oak Openings)	48	22	22	x	
50	OTSS	Fox-Shank Living Laboratory (Otsego/Fox Shank)	16	6	13	x	
10	SJCO	St. Joseph Confluence Wetland Reconnection (St. Joe Confluence)	140	20	31	x	
25	VANO	Van Order Wetland & Forest Restoration (Van Order)	31	5	5	x	
33	WEIP	The Weisgerber-Pohlman Nature Preserve Restoration (Weisgerber-Pohlman)	75	7	70	x	
6	MONW	OSU Montpelier Wetland Restoration (Montpelier)	98	10	10	x	x
		North-central (Heidelberg University Base Crew)					
16	REDB	†Redhorse Bend Preserve Wetland Restoration (Redhorse Bend)	55	25	25	x	x
19	BLAR	Blanchard River Floodplain Restoration (Blanchard Floodplain)	50	27	27	x	
37	CBMC	Clary-Boulee-McDonald Nature Preserve (Clary-Boulee-McDonald)	162	45	45	x	
22	FRUW	Fruth Wetland Nature Preserve (Fruth)	18	10	10	x	
24	SRHE	Sandusky River Headwaters Preserve Wetland & Habitat Restoration (Sandusky Headwaters)	38	7	7	x	
47	SUGB	Sugarcamp 7 Blanchard Habitat Project (Sugarcamp)	20	9	9	x	
46	UPPB	Upper Blanchard River Watershed Project (Upper Blanchard)	30	30	30	x	
23	ANDW	Andreoff Wetland Restoration (Andreoff)	278	0	1.5	x	
32	BUEF	Buehler Farms Treatment Wetland (Bueler Farms)	45	0	40	x	

H2Ohio Project Information			Area (acres)			Nutrient Budgets	
MapID	Code	Full Name (Short Name)	Total	Ag to Wet	Restore	P Runoff Prevent	P & N Filt
30	SPRM	Springville Marsh Wetland Extension (Springville Marsh)	66	50	50	x	
1	BRIC	Bright Conservation Area Wetland Restoration Initiative (Bright)	11	0	11	x	
		Northeast (Kent State University Base Crew)					
61	CHIL	Chippewa Lake Wetland Restoration (Chippewa Lake)	50	30	30	x	
49	TRUC	Trumbull Creek H2Ohio (Trumbull Creek)	30	30	30	x	
		Coastal (University of Toledo Base Crew)					
5	MAGM	†Magee Marsh Turtle Creek Bay Wetland Reconnection (Magee Marsh)	173	0	173	x	x
14	NORR	North Ridge Hunt Club Wetland Restoration (North Ridge)	30	23	23	x	
4	OTTN	Ottawa National Wildlife Refuge Wetland Reconnection Projects (Ottawa)	586	0	586	x	
		Southwest and Central (Wright State University Base Crew)					
61	BROP	†Brooks Park Wetland Creation & Water Quality Initiative (Brooks Park)	5	0	5	x	x
60	BWLK	†Burntwood-Langenkamp Wetland Conservation Area (Burntwood)	90	27	27	x	x
64	SPRC	Springcreek Off-Channel Wetlands (Springcreek)	55	25	25	x	x
65	TIPC	Tipp City Off-Channel Wetland (Tipp City)	20	10	10	x	x
71	WALC	Walnut Creek Treatment Restoration (Walnut Creek)	72	17.4	17.4	x	x
63	EFLA	Williamsburg Wetland Treatment System (Williamsburg)	5	0	3.5	x	x

Table 4. Phosphorus runoff prevented by H2Ohio wetland Projects, sorted by total mass (lbs. P). For calculation methods, see Volume 2 of the H2Ohio Wetland Monitoring Program 2024 Annual Report.

Project	Area (Acres)		P Runoff Prevented	
	Entire Project Parcel	Agriculture to Wetland Conversion	lbs. P	lbs. P/ Acre
Oakwoods East & West	111	50	117 ± 65	1.1
Clary-Boulee-McDonald	162	45	103 ± 70	0.6
Burntwood	90	27	57 ± 39	0.6
St. Joe Restoration	94	33	52 ± 25	0.6
Maumee River Floodplain/Huddle	57	35	46 ± 26	0.8
Walnut Creek	72	17	46 ± 31	0.6
Springville Marsh	66	50	42 ± 29	0.6
Forder Bridge	54	5	36 ± 24	0.7
Redhorse Bend	55	25	35 ± 24	0.6
Springcreek	55	25	35 ± 24	0.8
Blanchard Floodplain	50	27	32 ± 22	0.6
Chippewa Lake	50	30	32 ± 22	0.6
St. Joe Confluence	140	20	27 ± 13	0.2
Oak Openings	48	22	26 ± 13	0.5
Montpelier*	98	10	25 ± 12	0.3
Sandusky Headwaters	38	7	24 ± 16	0.6
Upper Blanchard	30	30	20 ± 13	0.7
North Ridge	30	23	20 ± 13	0.7
Trumbull Creek	30	30	19 ± 13	0.6
Sugarcamp	20	9	13 ± 9	0.7
Tipp City	20	10	13 ± 9	0.7
Fruth	18	10	12 ± 8	0.7
Otsego/Fox Shank	16	6	11 ± 11	0.7
Van Order	31	5	10 ± 5	0.3
Weisgerber-Pohlman	75	7	10 ± 5	0.1
Andreoff	278	0	0 ± 0	0.0
Beuler Farms	45	0	0 ± 0	0.0
Bright	11	0	0 ± 0	0.0
Magee Marsh	173	0	0 ± 0	0.0
Ottawa	586	0	0 ± 0	0.0
Brooks Park	5	0	0 ± 0	0.0
Williamsburg*	5	0	0 ± 0	0.0

Note: The Montpelier and Williamsburg H2Ohio Projects were monitored at least in part by partners external to the H2Ohio Wetland Monitoring Program during the 2024 water year, see “About this Report” section (p.10) for details.

Nutrient Filtration

Water Inputs

The most important driver of total nutrient filtration is the volume of water that enters a wetland Project and thus delivers nutrients to the Project (see “Connectivity” section, page 31). In both Water Year (WY) 2023 and WY 2024, side-channel Projects (Williamsburg, Springcreek, Tipp

City, Walnut Creek) and flow-through Projects (Burntwood, Brooks Park) received the largest volumes of water (242,000–1,658,000 m^3, Table 5). Water volume delivered to Magee Marsh coastal Project was entirely driven by management controlling the water intake structure to its adjacent creek, and in WY 2023, dike construction prevented all connection between this Project and its source creek. The Oakwoods East & West Projects are connected to upstream systems in a single location when a nearby stream (Aurand Run) floods into a floodplain pool. Due to structural constraints and drought conditions in 2023 and 2024, Aurand Run rarely flooded sufficiently to connect with the pool. A single event delivering about 7,500 m^3 of water was detected in 2023, and no events occurred in 2024. The Montpelier, Forder Bridge, and St. Joe Restoration Projects received 15,000–31,000 m^3 from their relatively small tile-drained watersheds. Redhorse Bend is a floodplain wetland adjacent to the Sandusky River that received 52,000–53,000 m^3 of floodwater in 2023 and 2024. Over twice as much water was delivered to the Burntwood Project in 2024 than in 2023 because of improved pump use and a structural change (a larger settling pool) that allowed for delivery of water from the adjacent creek to the wetland under non-flood conditions.

Table 5. Estimated surface water input volume to select H2Ohio Projects in Water Year (WY) 2023 and WY 2024. For calculation methods, see Volume 2 of the H2Ohio Wetland Monitoring Program 2024 Annual Report.

Project	Description	Input Volume (m^3)	
		2023	2024
Oakwoods East, West	Multiple isolated pools, one floodplain pool	7,572	0
Montpelier	Tile drain catchment-fed flow-through wetland with P filter at the outlet	-	15,931
Forder Bridge	Tile-drain catchment-fed treatment train	15,657	17,642
St. Joe Restoration	Tile-drain catchment-fed treatment train	28,402	31,082
Redhorse Bend	Floodplain	52,131	53,857
Williamsburg	Side-channel with large storage pool	-	867,905
Magee Marsh	Diked coastal marsh	0	149,224
Springcreek	Side-channel wetland	321,385	241,860
Tipp City	Side-channel wetland	248,251	256,887
Burntwood	Pumped flow-through wetland	194,078	453,821
Brooks Park	Flow-through wetland	984,445	1,214,738
Walnut Creek	Side-channel wetland	770,292	1,657,940

Phosphorus Filtration

In 2024, phosphorus (P) filtration varied from 0 to 1734 total lbs. P per Project, and from 0 to 495 lbs./acre (Table 6). The median total P filtration was 63 lbs. in 2023 and 41 lbs. in 2024 (2 lbs./acre in both years). The Williamsburg Project filtered by far the greatest amount of total P compared to other monitored H2Ohio Projects in terms of both total P filtered (1734 lbs.) and total P per wetland acre (495 lbs./acre). This Project received a moderate volume of water from the eight flooding events captured in 2024 (Table 5), but its source, the East Fork Little Miami River, carries high nutrient concentrations (median total phosphorus (TP) 1.2 mg/L, dissolved reactive phosphorus (DRP) 0.2 mg/L). The Project is highly efficient at removing nutrients due to a combination of a large reservoir with high volume holding capacity (~150,000 m^3 at full capacity) and a long sinuous flow path that allows for long residence time and biological processing after storm events as the reservoir slowly releases the stored floodwaters[8]. The other flow-through and side-channel Projects (Springcreek, Tipp City, Burntwood-Langenkamp, Brooks Park, and Walnut Creek) filtered 41–488 total lbs. of P (1.6–28 lbs./acre). The Walnut Creek side-channel Project filtered the greatest amount of DRP (289 lbs. total and 17 lbs./acre), followed by the Williamsburg Project and the Burntwood-Langenkamp Project. In both 2023 and 2024, the highest TP filtration (165 lbs. P in 2023, 488 lbs. P in 2024) and per-acre TP filtration (9 lbs./acre in 2023, 28 lbs./acre in 2024) occurred in the Walnut Creek Project.

Tile-drain fed H2Ohio wetland Projects and the Redhorse Bend Project removed less total P than other monitored Projects. The Montpelier Project removed 28 lbs. P at maximum (2.8 lbs./acre)[9]. An important feature of the Montpelier Project is that it combines a traditional flow-through wetland with a P filter, a structure at the outflow filled with material that is highly sorptive for phosphate. This design may optimize both particulate and dissolved reactive P filtration. The St. Joe Restoration Project exported a net total of 3 lbs. of P (0.1 lbs./per acre) in WY 2024; over this water year the Project was a net source of TP rather than a net sink. During the same time period, the Project was a net sink for DRP, so the net release of total P was likely due to resuspension and export of particulate P-bearing sediments. Due to the very minimal connections between the Oakwoods floodplain pool and the adjacent stream, Oakwoods filtered the lowest amount of P (2 lbs. total in 2023 during one flood event), and no P was filtered in 2024, because Aurand Run did not flood the floodplain pool. Patterns of DRP filtration largely matched those of TP filtration.

[8] Wallentine et al., 2025. Unpublished raw data.
[9] Stolzfus, Brooker, and Martin, Unpublished Results, 2025

Table 6. Phosphorus filtration by H2Ohio Projects. Phosphorus filtration refers to the phosphorus that is received and then stored by individual Projects, including both total phosphorus and dissolved reactive phosphorus. For calculation methods, see Volume 2 of the H2Ohio Wetland Monitoring Program 2024 Annual Report. Negative values indicate that the Project was a net source of P.

	Total P Filtration				**Dissolved Reactive P Filtration**			
	lbs. P		**lbs. P/acre**		**lbs. P**		**lbs. P/restored acre**	
Project	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**
Oakwoods	2	0.0	0.0	0.0	0.7	0.0	0.0	0.0
Montpelier*	-	28	-	2.8	-	3.2	-	0.3
Forder Bridge	6.4	7.4	1.3	1.5	0.6	0.8	0.1	0.2
St. Joe Restoration	20-50	-3	0.6-1.5	-0.1	4.6	5.1	0.1	0.2
Redhorse Bend	14	6.6	0.5	0.3	4.0	1.6	0.2	0.1
Williamsburg*	-	1734	-	495	-	122	-	35
Magee Marsh	0	43	0	0.2	0	0	0	0
Springcreek	119	41	4.8	1.6	54	33	2.2	1.3
Tipp City	108	37	11	3.7	57	23	5.7	2.3
Burntwood	45	240	1.7	8.9	24	121	0.9	4.5
Brooks Park	14	57	2.8	11	20	22	4.0	4.4
Walnut Creek	165	488	9	28	116	289	6.7	17

Note: The Montpelier and Williamsburg H2Ohio Projects were monitored at least in part by partners external to the H2Ohio Wetland Monitoring Program during the 2024 water year, see "About this Report" section (p. 10) for details.

Nitrogen Filtration

In 2024, the greatest amounts of total nitrogen (TN) were filtered by the side channel and flow-through wetlands, although the Magee Marsh coastal Project filtered at a similar magnitude (Table 7). The greatest TN filtration was measured in the Burntwood-Langenkamp Project at about 5,961 lbs. TN (271 lbs./acre). The floodplain Projects (Oakwoods and Redhorse Bend) and Projects draining smaller agricultural catchments (Montpelier, Forder Bridge, and St. Joe Restoration) removed less N, at 0–410 lbs. TN (0–16 lbs./acre). Although the Redhorse Bend Project was a net sink for N in both 2023 and 2024, results indicate that it was a net source of ammonium-N in both years. In 2023, the Walnut Creek side-channel wetland was a net source of 553 lbs. of N (32 lbs./acre), mostly as ammonium-N (Table 7), which is prone to being released under low-oxygen conditions. The Forder Bridge Project was a net source of nitrate-N in both 2023 and 2024. Wetlands are typically very effective at removing nitrate due to low-oxygen, high-organic matter conditions that promote microbial activity. Thus, export of nitrate may indicate that nitrate-laden water during storm events moves through the system too rapidly for the nitrate to be microbially denitrified.

Table 7. Total nitrogen filtration by H2Ohio Projects. Total nitrogen filtration refers to the bulk sum of nitrogen that is stored or transformed into gaseous forms by individual Projects. For calculation methods, see Volume 2 of the H2Ohio Wetland Monitoring Program 2024 Annual Report. Negative values indicate that the Project was a net source of P.

	Total N Filtration			
	lbs.		lbs./restored acre	
Project	**2023**	**2024**	**2023**	**2024**
Oakwoods East/West	15	0	0.3	0
Montpelier	-	163	-	16
Forder Bridge	12.8	34	2.6	6.8
St. Joe Restoration	600-800	410	18-24	12.4
Redhorse Bend	122	98	4.9	3.9
Williamsburg	-	3,396	-	970
Magee Marsh	0	689	0	4
Springcreek	2,511	1,052	100	42
Tipp City	1,542	1,121	154	112
Burntwood	7,307	5,961	271	221
Brooks Park	3,329	4,316	666	863
Walnut Creek	-553	4,701	-32	270

Note: The Montpelier and Williamsburg H2Ohio Projects were monitored at least in part by partners external to the H2Ohio Wetland Monitoring Program during the 2024 water year, see “About this Report” section (p.10) for details.

Table 8. Inorganic nitrogen filtration by H2Ohio Projects. Inorganic nitrogen filtration refers to the portion of nitrate or ammonium that is stored or transformed into gaseous forms by individual Projects. For calculation methods, see Volume 2 of the H2Ohio Wetland Monitoring Program 2024 Annual Report. Negative values indicate that the Project was a net source of P.

	Nitrate-N Filtration				Ammonium-N Filtration			
	lbs.		lbs./restored acre		lbs.		lbs./restored acre	
Project	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**
Oakwoods East/West	8	0	0.2	0	0	0	0	0
Forder Bridge	-31	-24	-6.2	-4.8	2	6.3	0.4	1.3
St. Joe Restoration	88	88	2.7	2.7	-	18	-	0.5
Redhorse Bend	72	35	2.9	1.4	-2.2	-1.3	-0.1	-0.1
Williamsburg	-	651	-	186	-	127	-	36
Magee Marsh	0	363	0	2.1	0	57	0	0.3
Springcreek	2323	1066	93	43	19	15	0.8	0.6
Tipp City	1710	1162	171	116	24	64	2.4	6.4
Burntwood	6747	5407	250	200	204	5	7.6	0.2
Brooks Park	2821	3718	564	744	64	93	13	19
Walnut Creek	376	6786	22	390	-27	-13	-1.6	-0.7

Note: The Montpelier and Williamsburg H2Ohio Projects were monitored at least in part by partners external to the H2Ohio Wetland Monitoring Program during the 2024 water year, see "About this Report" section (p. 10) for details.

Nutrient Retention

The cumulative impact of both components of nutrient retention is calculated by adding the amount of phosphorus (P) runoff prevented to the amount of external P filtered by H2Ohio Projects with sufficient data. This retention integrates the effectiveness of a portfolio of design approaches. Although the Oakwoods Project filtered minimal P by percentage, because of its large size, its total P retention of 117–119 lbs. P amounts to about 1.1 lbs. of P retained per acre. Thus, despite its minimal connection to external nutrient sources, this Project is contributing to watershed-scale nutrient load reduction goals. However, among the Projects monitored that remove P at particularly high rates per area (> 10 lbs./acre), all are flow-through or side-channel wetlands receiving greater than 100,000 m^3 of high-nutrient source water each year. Based on these results, **relatively engineered and hydrologically controlled flow-through and side-channel wetlands that receive moderate to large volumes of high nutrient concentration water seem to be most effective at retaining large quantities of nutrients.**

Table 9. Total phosphorus (P) retention calculated by adding the annual estimate of the amount of P runoff prevented to the total P filtration estimate for each of the 2023 and 2024 water years. For calculation methods, see Volume 2 of the H2Ohio Wetland Monitoring Program 2024 Annual Report.

	Total P Retention			
	lbs. P		lbs. P/acre	
Project	2023	2024	2023	2024
Oakwoods	119	117	1.1	1.1
Montpelier	0.3	53	-	3.1
Forder Bridge	42	43	2	2.2
St. Joe Restoration	72–102	49	1.2–2.1	0.5
Redhorse Bend	49	42	1.2	0.9
Williamsburg	-	1734	-	495
Magee Marsh	0	43	0	0.2
Springcreek	165	87	5.6	2.5
Tipp City	121	50	11.5	4.4
Burntwood	102	297	2.3	9.5
Brooks Park	14	57	2.8	11
Walnut Creek	211	534	10.1	29

Note: The Montpelier and Williamsburg H2Ohio Projects were monitored at least in part by partners external to the H2Ohio Wetland Monitoring Program during the 2024 water year, see "About this Report" section (p. 10) for details.

To compare these nutrient retention values to regional goals, consider the Maumee River Total Maximum Daily Load (TMDL). Although the statewide H2Ohio Program is broader than the Maumee watershed, goals established to mitigate eutrophication by reducing nutrient loads from the Maumee watershed should align with goals for nutrient load reduction throughout the state. Across the entire 4.2-million-acre watershed, the Maumee TMDL aims to reduce P loading by about 1.3 million lbs. (3.2 lbs./acre). One specific portion of nutrient load reductions prescribed by the Maumee TMDL comes from "enhancing nonpoint source sinks," which includes the restoration and creation of wetlands. In Fiscal Year 2024, the Ohio Department of Natural Resources aimed to retain between 55,000 and 137,000 lbs. P across all funded Projects (3–10 lbs./acre)[10]. When both prevention of nutrient runoff and filtration of new nutrients are taken into account, results from monitored H2Ohio Projects suggest that these wetland Projects are contributing meaningfully to this goal, but some Projects contribute more than others. There are inherent constraints in the quantity of wetland Projects that can be implemented throughout Ohio and in the structure and capacity of specific Projects. An approach that prioritizes highly effective Projects but continues to support more distributed efforts that contribute moderately, but meaningfully, to watershed-scale nutrient goals is likely to be effective.

[10] Personal Communication, Eric Saas, ODNR

Climatic Drivers of Nutrient Loading and Wetland Function

Water Year 2024 was drier than normal across the state of Ohio. According to the U.S. Drought Monitor (Figure 1), 97.97% of the state by area experienced drought conditions (Drought Intensity D0 to D4) in September 2024, near the end of the water year. The majority (64.3%) of the state suffered droughts categorized as Severe to Exceptional (D2 to D4). Total precipitation measurements in locations throughout Ohio and adjacent states were 1.7–18.14% lower than their long-term annual averages (Table 10). Decreased precipitation leads to lower runoff, which in turn decreases water in depressional and flow-through wetlands, streams, and rivers. Lower peak flow and flooding in streams and rivers inhibit water from reaching floodplain wetlands. Less nutrients are delivered into wetlands when less water is delivered, limiting the total nutrient filtration that Projects can contribute to watershed goals. Striking deviations from long-term averages were observed during specific times of the year (Figure 2). During most winter and summer months (Nov, Dec, Feb, and June through September), accumulated rainfall in most locations was lower than long-term averages. However, in the month of April, most areas saw much greater rainfall than long-term averages. Many areas also observed higher than average rainfall in January.

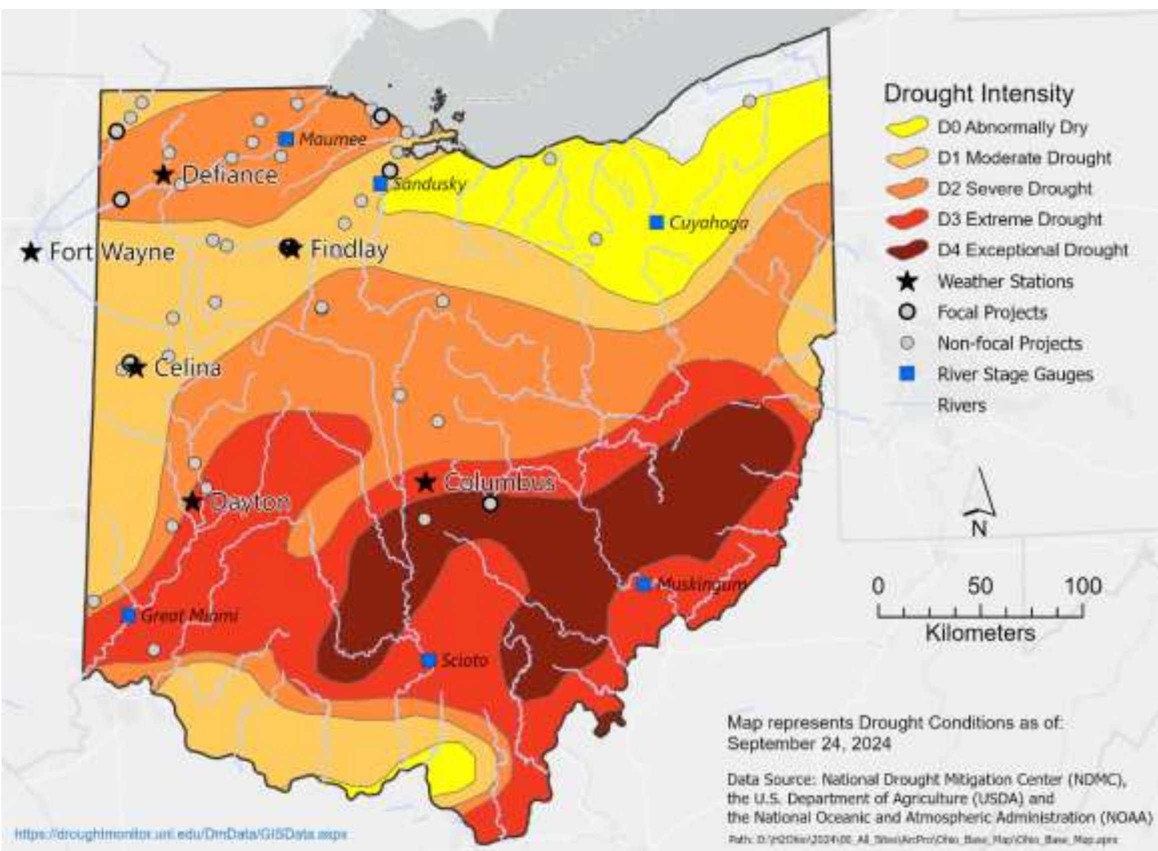

Figure 1. Statewide drought conditions in Ohio as of September 24, 2024, near the peak of drought conditions in the state. The location of Focal and Non-focal monitored H2Ohio Projects, weather stations, river stage gages, and rivers are displayed.

Table 10. Annual total precipitation during Water Year 2024 (October 1, 2023–September 30, 2024) and long-term average annual total precipitation (1995–2024, source: NOAA National Centers for Environmental Information) for select locations near H2Ohio wetland Projects and long-term average annual total precipitation. Note locations depicted were selected due to proximity of H2Ohio Wetland Monitoring Program Sites throughout Ohio.

	Weather Station					
Precipitation	**Ft Wayne, IN**	**Defiance, OH**	**Findlay, OH**	**Celina, OH**	**Dayton, OH**	**Columbus, OH**
2024 Water Year Precipitation (inches)	34.76	31.27	32.26	38.68	38.25	35.19
1995-2024 Average Annual Precipitation (inches)	39.03	38.20	33.27	39.35	40.97	42.19
Percent Precipitation Difference	**-10.94**	**-18.14**	**-3.04**	**-1.70**	**-6.63**	**-16.58**

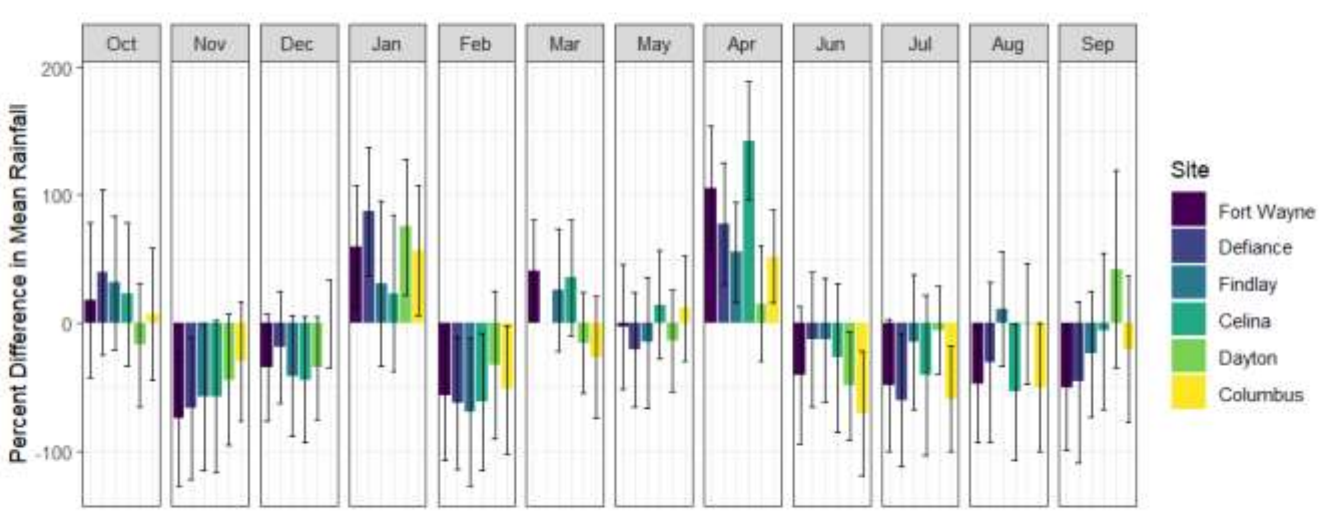

Figure 2. Monthly rainfall percent differences from long-term averages. Error bars represent the percent difference in mean rainfall from one standard deviation higher and one standard deviation lower than the mean.

Lower than Average Flow Conditions Across Ohio

Researchers observed impacts of drought in flow, water level, flooding data, and flooding imagery. In every month except January and April, the average daily flow across six major rivers throughout Ohio was lower in Water Year (WY) 2024 than the average over the prior decade (WYs 2015–2023, Figure 3). These major rivers accumulate water from smaller creeks, streams, and tributaries; they reflect hydrologic processes occurring over large areas of the state. Daily average flow rates were much lower than the respective decadal average in most months, ranging from 28 to 68% lower (Figure 3). However, greater than average precipitation in April 2024 drove higher than average stream flows (nearly 80% higher than decadal averages). Thus, conditions during WY 2024 were both drier than average but punctuated with extreme, but less frequent, greater-than-average flow and flooding events (Table 11).

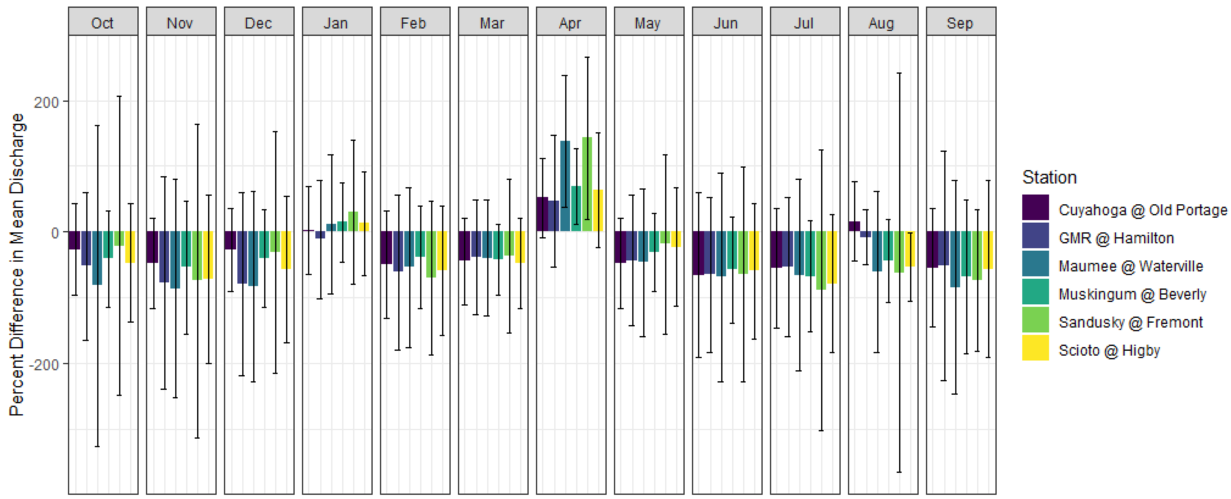

Figure 3. Monthly discharge percent differences from long-term (2015–2023) averages. Error bars represent the percent difference in mean discharge from one standard deviation higher and one standard deviation lower than the mean.

Table 11. Average decadal inflow events for Water Years (WYs) 2015–2023 compared with recent WY 2024.

Project	USGS Station Name	USGS Station Number	Mean Number of WY Inflow Events - Decadal Average (SD)	2024 WY Inflow Events
Burntwood-Langenkamp Wetland Conservation Area	Chickasaw Creek at St. Marys	4.03E+14	13.7 (3.7)	6
Tipp City Off-Channel Wetland	Great Miami River at Troy	3262700	12.1 (3.4)	5
Redhorse Bend	Sandusky River at Fremont	4198000	7.6 (3.3)	6
Walnut Creek Wetland	Walnut Creek at Ashville	3229796	9.8 (3.7)	5

Many H2Ohio wetland Projects are designed to capture high nutrient loads when rivers or streams connected to wetland areas flood during high flow events. Therefore, in low flow years, as observed in 2024, there are fewer opportunities for wetlands to capture runoff[11, 12, 13, 14]. In years with low flow, wetlands designed to flood naturally, rather than through pumps or other methods, receive fewer nutrients. In agricultural watersheds, particularly in most Ohio Lake Erie watersheds, non-point source nutrient runoff predominates, creating a direct correlation between nutrient concentration and discharge; thus, higher flow rates mobilize more nutrients.

Aerial imagery of H2Ohio Projects over multiple years illustrates how drought conditions shape vegetation and inundation status. Images capture the widespread vegetation senescence and limited extent of inundations during Water Year 2024 (Figure 4). For example, the Forder Bridge Floodplain Restoration functions as a flow-through wetland along the Maumee River in northwest Ohio. The key wetland feature in this Project, Wetland Complex 4 (Figure 4), is a treatment train that receives inflows from a drainage tile, and all pools typically hold water. However, in July 2024 only one pool had any amount of standing water, albeit minimal, while all other pools had no standing water and were mostly covered by dried vegetation. For comparison, all pools had standing water in images from July 2021 and 2022.

[11] Jacquemin, S. J., L. T. Johnson, T. A. Dirksen, and G. McGlinch. 2018. Changes in Water Quality of Grand Lake St. Marys Watershed Following Implementation of a Distressed Watershed Rules Package. Journal of Environmental Quality 47:113–120.
[12] Johnson, L. T., N. Manning, J. Dezse, J. Boehler, E. Clark, T. Fulton, N. Miller, and A. Roerdink. 2024. Drivers of annual suspended sediment and nutrient yields in tributaries to Lake Erie. Aquatic Ecosystem Health & Management 26:5–19.
[13] D'Amario, S. C., H. F. Wilson, and M. A. Xenopoulos. 2021. Concentration-discharge relationships derived from a larger regional dataset as a tool for watershed management. Ecological Applications 31:e02447.
[14] Ohio, EPA. 2016. Nutrient mass balance study for Ohio's major rivers. Ohio Environmental Protection Agency Division of Surface Water, Ed., (Ohio Environmental Protection Agency Division of Surface Water, Columbus, OH, 2018).

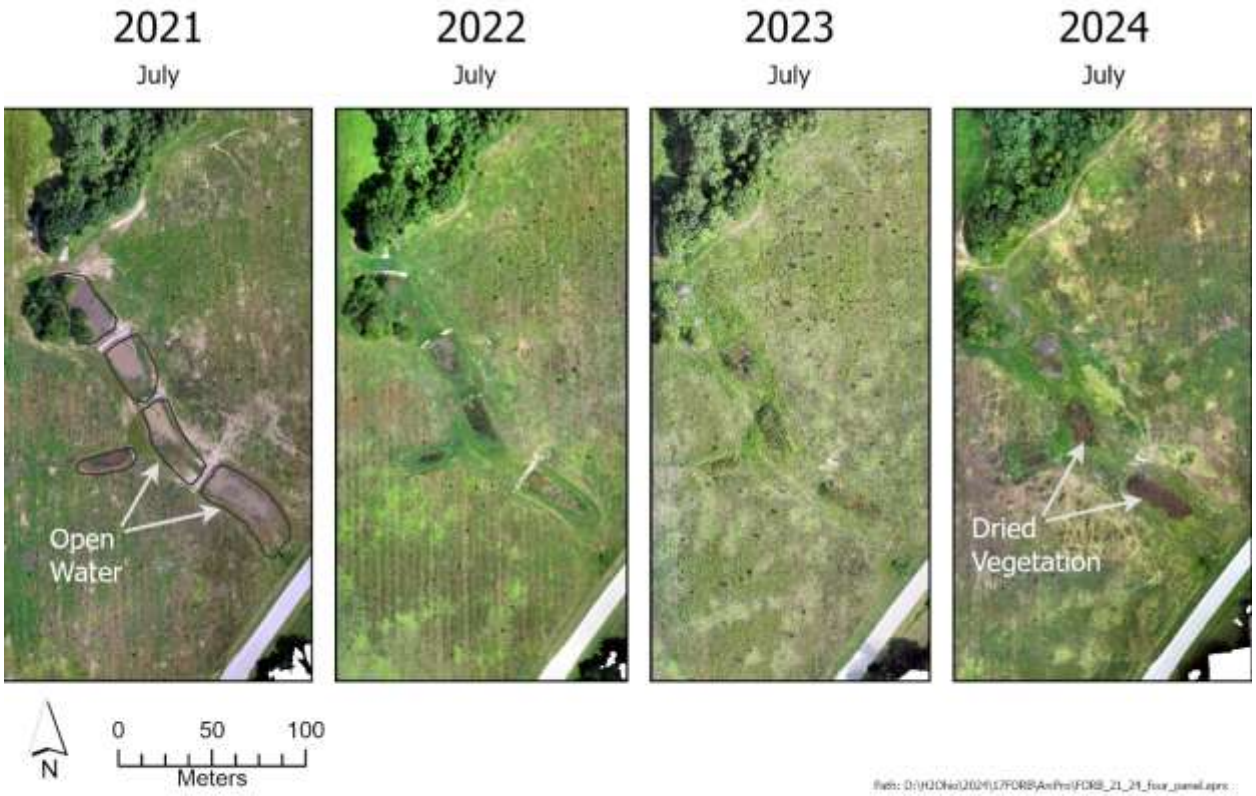

Figure 4. Unmanned aerial vehicle (UAV) images from Forder Bridge Floodplain Restoration Project in July 2021–2024 show pool extent and the effects of different water availability. In the wetter years of 2021 and 2022, larger areas of open water in treatment train pools are visible.

Long-term Data and Understanding Wetland Function Under Different Climatic Conditions

The H2Ohio Wetland Monitoring Program (WMP) has completed sufficient monitoring to meaningfully estimate total nutrient retention in Projects for the Water Years 2023 and 2024, both of which happened to experience drier than average conditions. Thus, current nutrient retention results potentially skew estimates lower than researchers would see over more years of monitoring. Continued collection of long-term data collected by the H2Ohio WMP will inform the management of wetlands across a wider variety of climatic conditions, providing an understanding of how Projects will function in future, wetter years.

Connectivity to Nutrient Sources Drives Nutrient Filtration by H2Ohio Wetlands

The nutrient retention of an H2Ohio wetland Project is limited by the nutrient load it receives; a wetland cannot treat nutrients which do not enter the wetland. In most H2Ohio wetlands, the majority of nutrient loading comes from surface water entering the wetland as runoff, inflow from streams, and/or floodwater from nearby lakes or rivers. The nutrient load to an H2Ohio wetland Project is the total mass of all of the nutrients delivered to that wetland Project from outside its boundaries over a period of time (usually a year). Nutrient loads carried by water are calculated by multiplying the total volume of water entering a wetland by the concentration of nutrients measured in surface water samples. Nutrient loading can be increased in two main ways: more nutrients or more water.

Internal processes affect the efficiency of the wetland at retaining nutrients (i.e., the proportion of the nutrient load retained). Even low retention efficiency (i.e., percentage of total nutrients that enter and are retained by the wetland) can lead to a high mass of nutrient transformed or removed by the wetland, if there is enough loading. Many H2Ohio wetland Project design plans focus heavily on features within the wetland that will increase the efficiency of nutrient retention of a wetland (e.g., settling pools, pumps) but have given less attention to how the wetland is connected to nutrient loading from the surrounding landscape. Increasing internal nutrient retention efficiency does not change the scale at which a Project receives nutrients. For example, if a wetland receives 5,000 lbs. of phosphorus (P), and it only retains 10% of that input, it is still retaining 500 lbs. phosphorus in total. In comparison, a very efficient Project that receives a lower nutrient load, say retaining 90% of 500 lbs. phosphorus, retains 450 lbs. phosphorus.

Maximizing wetland nutrient retention requires connection to a small-volume, high-nutrient concentration source (e.g., a tile or storm drain outlet) and/or a large-volume source of moderate- to high-nutrient concentration water (roughly > 0.5 mg P/L or > 5 mg nitrogen (N)/L), like a river or stream draining an agricultural catchment. High-concentration non-point nutrient sources are often "hot spots" on the landscapes, typically constrained to small areas such as individual, privately owned farm fields[15,16,17]. On the other hand, large volumes of water delivery require that the wetland be large enough (in area and/or volume) to slow down the flow of water and hold the water (i.e., residence time) sufficiently long for nutrient processing to occur. Although optimal holding times are likely to vary based on vegetation communities and sediment characteristics, seven to 10 days[18] for retention of dissolved reactive phosphorus (DRP) and 11 to 35 days[19] for retention of inorganic nitrogen have been demonstrated to be effective in small treatment wetlands.

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[15] Carpenter, S. R., N. F. Caraco, D. L. Correll, R. W. Howarth, A. N. Sharpley, and V. H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecological applications 8:559–568.
[16] Kovacs, A., M. Honti, M. Zessner, A. Eder, A. Clement, and G. Blöschl. 2012. Identification of phosphorus emission hotspots in agricultural catchments. Science of The Total Environment 433:74–88.
[17] Luo, M., X. Liu, N. Legesse, Y. Liu, S. Wu, F. X. Han, and Y. Ma. 2023. Evaluation of Agricultural Non-point Source Pollution: a Review. Water, Air, & Soil Pollution 234:657.
[18] Reinhardt, M., Gächter, R., Wehrli, B., & Müller, B. (2005). *Phosphorus retention in small constructed wetlands treating agricultural drainage water*. Journal of Environmental Quality, 34(4), 1251–1259. https://doi.org/10.2134/jeq2004.0325
[19] Kovacic, D.A., David, M.B., Gentry, L.E., Starks, K.M., & Cooke, R.A. (2000). Effectiveness of constructed wetlands in reducing nitrogen and phosphorus export from agricultural tile drainage. *Journal of Environmental Quality*, 29(4), 1262–1274.

However, the P and N in sediments can often make up a large proportion of nutrients stored by wetlands when they settle out as flow decreases upon entering wetlands. This nutrient settling is unlikely to require residence times as long as other processes. H2Ohio Monitoring Program researchers have not yet monitored an H2Ohio Project where researchers believe residence time is too short to retain nutrients. Many H2Ohio Projects have sufficient capacity for internal nutrient processing but are limited in the nutrient load they receive because of low or no connections to nutrient sources.

The following are case studies from intensively monitored H2Ohio Wetland Monitoring Program Focal Projects. They highlight differences in connectivity and their impact on the nutrient retention of H2Ohio wetlands.

Large Flow-Through Wetlands: Magee Marsh and Old Woman Creek Comparison

The Magee Marsh Turtle Creek Bay Wetland Reconnection Project (Magee Marsh) and the Old Woman Creek wetland are a useful comparison of two similar systems near the extreme edges of the gradient of disconnected to connected: water level control structures (WLCSs) can completely disconnect the diked Magee Marsh Project from nutrient sources, while the Old Woman Creek wetland directly receives all flow from its 69 km^2 of largely agricultural catchment. The Old Woman Creek Wetland and Magee Marsh H2Ohio Projects are of similar size, are both vegetated, and mostly persistently inundated ~1-2 m deep (Table 12). Old Woman Creek receives large portions of water from its source while Magee Marsh does not (Figure 5). Magee Marsh has higher holding capacity (volume) than the Old Woman Creek wetland (Table 12). Despite these similarities, the Old Woman Creek wetland retains far more phosphorus (P) than Magee Marsh because of basic differences in connectivity. In Water Year (WY) 2023, the Magee Marsh wetland was never connected to Turtle Creek, and thus it filtered 0 lbs. of P. In WY 2024, the Magee Marsh wetland was briefly connected to Turtle Creek but still only retained about 43 lbs. of phosphorus, even though it retained almost 100% of the nutrients that entered the wetland. On average, Old Woman Creek received 11,000 lbs. P annually, of which it filtered 4,000 lbs. (36% efficiency)[5]. On average, Turtle Creek carries 7,000 lbs. P annually from its agricultural watershed into Lake Erie. If Magee Marsh were designed to receive the entire flow of Turtle Creek (e.g., the berm between the creek and the wetland were removed) and it filtered at the same efficiency as the Old Woman Creek wetland, it could filter around 2,500 lbs. of phosphorus annually. While this maximum capacity scenario is unrealistic for Magee Marsh, it demonstrates that increasing the amount of flow received by the wetland from Turtle Creek (e.g., with different hydrologic management regimes) could considerably improve nutrient retention beyond the current 43 lbs. P estimate.

Figure 5. Aerial imagery and current flow paths at Magee Marsh Turtle Creek Bay Wetland Reconnection Project and Old Woman Creek.

Table 12. Summary statistics for comparison of phosphorus filtration of Magee Marsh Turtle Creek Bay Wetland Reconnection (MAGM) and Old Woman Creek (OWC). Loading and retention for MAGM are estimated for a scenario where all water from Turtle Creek flowed through MAGM. This scenario assumes that MAGM would retain the same percentage of nutrients as OWC (36%). Numbers marked as ** are hypothetical estimates for if MAGM were to receive the entire flow from Turtle Creek. Actual phosphorus loading and retention to MAGM was 43 lbs. in 2024.

Project	Area	Depth	Holding Capacity	Annual Creek flow	Phosphorus Loading	Phosphorus Filtration
OWC	130 acres	0.5 m	190,000 m^3	18 m^3	11,000 lbs.	4,000 lbs.
MAGM	173 acres	1 m	700,000 m^3	20 m^3	7,000 lbs. **	2,500 lbs. **

This hypothetical scenario does not take other Project stakeholder priorities for the wetland into account. For example, the scenario may adversely affect water availability for the nearby marina or management of the marsh for waterfowl, both of which are relevant and valid concerns. High nutrient loading and variable hydrology would both alter the vegetation distribution in a way that may be unfavorable for waterfowl. This scenario is not a management suggestion, but rather a "back-of-the-envelope" illustration of the potential impact that increasing connectivity could have on nutrient retention at any H2Ohio wetland.

Off-Channel Wetland Connectivity and Maintenance

H2Ohio data shows that off-channel wetlands (e.g., Tipp City Off-Channel Wetland (Tipp City), Walnut Creek Treatment Wetland Restoration (Walnut Creek)) can retain large quantities of nutrients, but the amount retained depends on their connectivity to the channel. Three H2Ohio Focal Projects (Forder Bridge Floodplain Reconnection (Forder Bridge), Redhorse Bend Preserve Restoration (Redhorse Bend), and Tipp City) along with the partner-sampled Project

Williamsburg wetland, highlight a range of connectivity and the effects of connectivity on nutrient loading and retention.

The success of off-channel wetlands at filtering nutrients is determined largely by their connection to water. Nutrient retention increases as the inflow threshold for the wetland to receive water decreases, leading to higher volumes of inflowing water (Table 13). As an extreme example, the floodplain wetlands at Forder Bridge are disconnected from the river because of their high elevation next to the riverbanks; they do not retain any nutrients because they do not receive any. At the other end of the connectivity spectrum, the Williamsburg off-channel wetland combines high connectivity to water with high nutrient concentrations in its source of water, leading to very high nutrient loading and retention at the Project. Notably, the number of inflow events alone does not necessarily predict the amount of nutrient retention, because the volume of water delivered is key to determining nutrient delivery.

Table 13. Off-channel wetland connectivity to floodwaters determines the success of the wetland at nutrient filtration. At Forder Bridge Floodplain Reconnection, the *** indicates that the floodplain section of the project has not flooded since monitoring began so researchers do not yet know its inflow threshold.

Project	**Inflow Threshold**	**Inflow Events 2024**	**Volume inflow 2024 (m)**	**TP Load (lbs.)**	**TN Load (lbs.)**	**TP Filtration (lbs.)**	**TN Filtration (lbs.)**
FORB	***	0	0	0	0	0	0
REDB	3,000 cfs	6	53,857	37	3,201	7	98
TIPC	2,500 cfs	6	257,653	136	3,036	37	1,121
EFLA	1,700 cfs	8	867,905	2,269	6,290	1,734	3,396

The performance of wetlands that receive high flow, especially during events, often relies on regular Project maintenance. Much of the nutrient retention during high-loading storm events comes from the settling of sediment within wetlands. This means that the sediment needs to be periodically cleared. For example, managers of the Williamsburg wetland have needed to clear sediment from the inflow to the wetland in both 2023 and 2024 to maintain functionality. Without regular maintenance of the inlet, the number of inflow events during the year as well as the volume of inflow during events will decrease. However, the removal of sediment has the potential to release nutrients back into the river if the sediment is not placed carefully. Sediment excavated from the Williamsburg inflow channel was placed on the berm in between the wetland and the river. Another maintenance concern is the ability for wetland structures to withstand the kinetic energy of high-flow events without breaking, which can lead to further maintenance costs and a loss of ability to retain nutrients.

Active Connectivity Management: Pumps and Droughts

The H2Ohio portfolio includes Projects that are both actively and passively managed. Active management includes features such as water level control structures (WLCSs) and pumps to actively transport water into a wetland. Passive management refers to wetland designs that receive water from runoff or floods without human intervention. Active management allows for more responsive changes to the connectivity of a wetland. The increase in total nutrient retention at the Burntwood-Langenkamp Wetland Conservation Area (Burntwood-Langenkamp) from Water Year (WY) 2023 to WY 2024 highlights how valuable active management can be for managing nutrient retention. In WY 2023 Burntwood-Langenkamp filtered 45 lbs. of phosphorus and 7,307 lbs. of nitrogen, while in WY 2024 it filtered 240 lbs. of phosphorus and 5,961 lbs. of nitrogen. The large difference in nutrient retention was caused by increased nutrient loading to the system because pumping was increased in WY 2024. This means that despite WY 2024's drought, the Project was able to retain more nutrients in WY 2024 than in WY 2023 because managers actively increased the connectivity of the wetland to its source of nutrients. The use of WLCSs and pumps may have additional costs, both in the cost of the infrastructure components themselves and in ongoing labor and maintenance. However, these infrastructure components can provide improved connectivity and controlled residence time, particularly under increasingly variable hydrologic conditions, in which droughts are becoming longer and more pronounced, and rain events are becoming less frequent but more intense.

Cryptic Drainage and Wetland Connectivity

For passively managed Projects, an understanding of the source and volume of water is necessary to predict nutrient retention. The design of the Forder Bridge Floodplain Reconnection was predicated on the supposition that the Project would drain runoff from a large farm field to the south of the Project. The runoff was expected to travel through a sub-surface tile drain network to a culvert leading into a treatment chain of wetlands. Researchers found that local expert knowledge of a wetland Project, specifically boots-on-the-ground during storm events, was better able to predict the area drained by the Project than high resolution digital elevation models (Figure 6) because of subsurface engineered drainage (i.e., tile drains). Sensor data directly measuring water at the Project confirmed that boots-on-the-ground knowledge of the Project was correct. The difference in drainage was due to a culvert outside the Project boundaries of which researchers were unaware. The culvert could not be detected on the digital elevation model, either. So, although the Project was expected to drain a large agricultural field and receive agricultural runoff with high nutrient concentrations, it actually drains a small partially wooded residential area, leading to lower nutrient concentrations (for more details, see Volume 2 of the H2Ohio Wetland Monitoring Program 2024 Annual Report). This project highlights the importance of taking the time to understand the connectivity of passively managed wetlands prior to construction. Expert local knowledge is most valuable at Projects with cryptic subsurface drainage features such as tile drains, culverts, and storm sewers that cannot be detected with remote sensing, and whose flow is primarily visible during storm events.

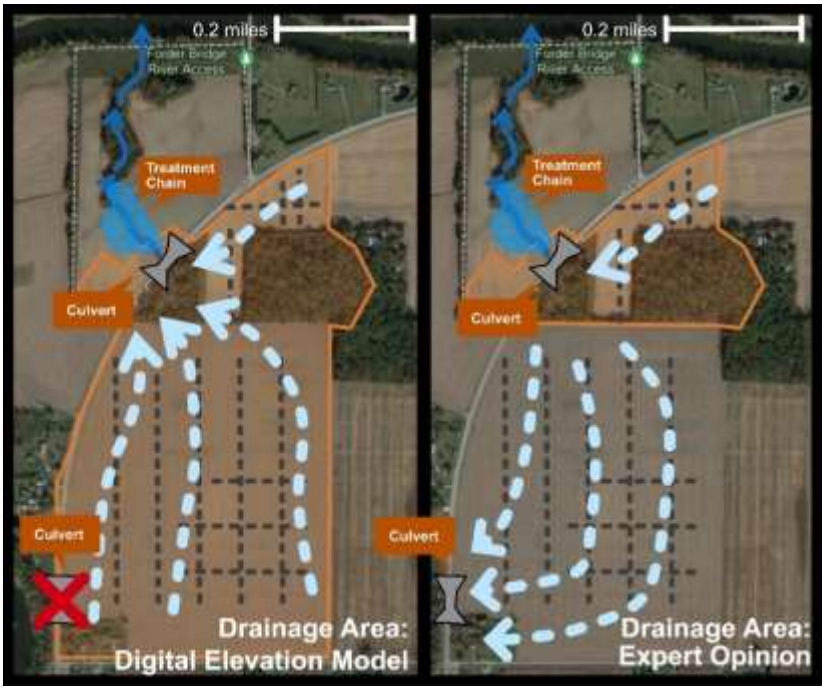

Figure 6. Comparison of the drainage area of the Forder Bridge Floodplain Restoration wetland restoration calculated solely based on topography of the surrounding area using a digital elevation model (left) and calculated by reducing the drainage area as indicated by the District Administrator of the Paulding Soil and Water Conservation District after consulting drainage maps and visual inspection of the Project (right). Dark blue arrows indicate the flow of water through the Project. The dark dashed lines indicate tile drained areas. The light blue dashed arrows indicate surface and subsurface flow of water in the drainage area, and the orange outline represents the drainage area of the Project. White dashed lines indicate the parcel boundary of the wetland Project.

Storms and Long-Term Nutrient Retention

Across passively managed H2Ohio Projects, storm events account for a major proportion of nutrient loading to wetlands; many Projects only receive nutrient inputs during storm flow. A quantitative literature synthesis performed by H2Ohio researchers shows that storm events are not often captured in the literature[5]. Across 207 published studies, 70% of nutrient budgets did not explicitly account for storm events. Further analysis of the Old Woman Creek estuary shows that wetland nutrient budgets are especially vulnerable to error when missing storm events, because wetlands filter nutrients best when they hold water for an extended period of time (Figure 7). Wetlands receive storm flow typically over the course of a single day but release water for multiple days. This means that there's a higher likelihood of missing storm events for inflow concentrations than there is for outflow concentrations, which can lead to excessive underestimates of nutrient loading compared to nutrient release. When nutrient loading is underestimated because storms are not adequately represented in sampling, wetlands may be misdiagnosed as sources of nutrients when they are actually nutrient sinks[5] (Figure 8). The reason that storm events are understudied is that they are difficult to measure, but the H2Ohio

Wetland Monitoring Program is building its capacity to account for storm events and improve accuracy of nutrient budgets.

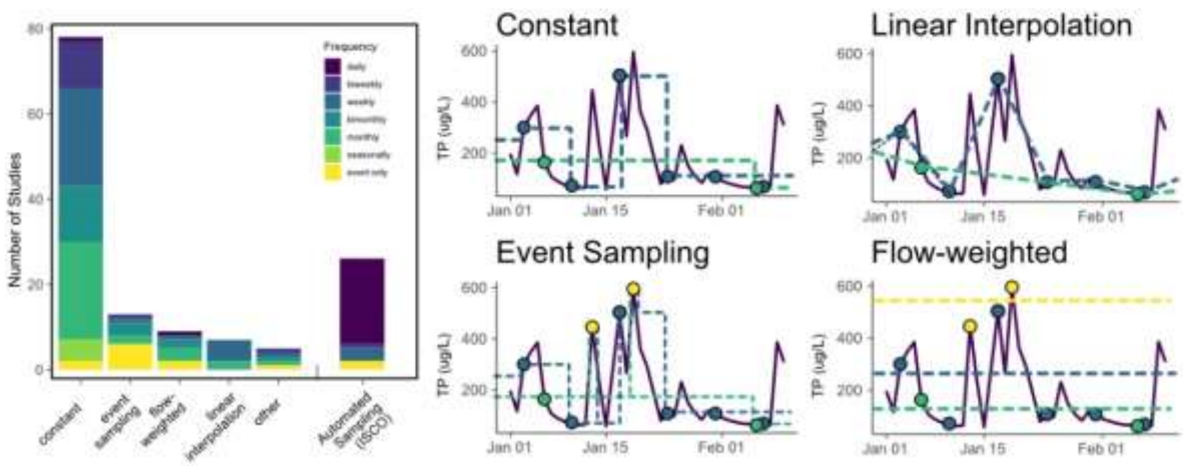

Figure 7. Gap-filling methods for a wetland inflows and outflows sampled at different sampling frequencies compared to Projects with "continuous" ISCO-collected flow-weighted composite phosphorus concentrations and examples of what those gap-filling methods look like in a real dataset at monthly, weekly, and event sampling time frames. Colors indicate frequency on both sides of the figure. Dashed lines represent either weekly (in blue) or monthly (in green) sampling, while the solid purple line is the daily data that weekly and monthly variations are derived from. Constant refers to an assumption that concentrations remain constant between sampling points, event refers to an assumption that concentrations remain constant between sampling points, except during storm events. The flow-weighted approach calculates flow-weighted mean concentrations to calculate the mean concentration over time. The linear interpolation approach computes a linear model between points and fills in gaps using the linear model.

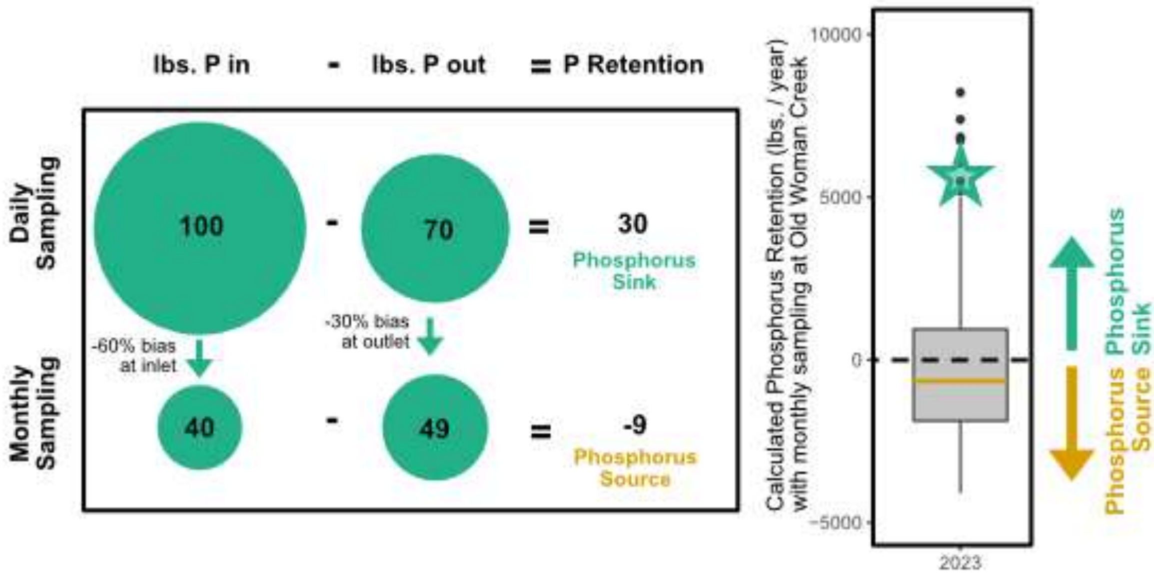

Figure 8. Conceptual diagram illustrating that a mismatch in bias at the inlet and outlet of wetlands can lead to an inaccurate calculation of the phosphorus retention status of wetlands, accompanied by resampled data from Old Woman Creek illustrating this happening in a real system. Bias estimates in the conceptual diagram approximate the average biases researchers measured when converting from daily to monthly sampling. Resampling estimates from Old Woman Creek were resampled at a monthly frequency from daily data. The boxplot represents the interquartile range of the 10,000 replicate resamples of the original daily data, the solid line is the median, error bars represent the 95% confidence interval, and black points represent outliers. The green star indicates the true phosphorus retention value for the year calculated using daily data. This pattern was evident in all years measured. Discharge data was not resampled and was constant across all resampling replicates.

Connectivity Changes Over Years

The connectivity of Projects to both water and nutrient sources is not static, it varies over time. To predict the long-term function of wetlands constructed by H2Ohio, researchers and managers need long-term data from wetland Projects. The quantitative synthesis of constructed wetland phosphorus retention found that 70% of sites from the literature were monitored for three years or less. An analysis of available long-term data in the literature found that three years was not sufficient to predict long-term trends[5]. The analysis also found that, on average, researchers can predict long-term trends of phosphorus retention two years into the future for every one year of monitoring only after at least five years of monitoring. The reasons for this are likely tied to changing connectivity between water and nutrients but also to changing pools of nutrients within the wetland itself. Nitrogen can be processed and removed from wetlands as a gas, but long-term phosphorus retention relies on the transformation of phosphorus into organic matter by vegetation and permanent burial of phosphorus-laden particles.

Analysis demonstrates that the long-term datasets which are just beginning to be built by the H2Ohio Wetland Monitoring Program (WMP) will be vital to understanding long-term wetland nutrient storage and the factors that can lead to declining nutrient retention over time. The H2Ohio WMP work builds on long-term datasets from the smaller watershed of Grand Lake St. Marys, which show that constructed wetlands have the potential to treat significant portions of nutrient loading to aquatic systems[20]. Long-term datasets collected by the Monitoring Program will expand that understanding to include wetlands with a broad range of connectivity to both water and nutrients. A record of the storage and transformation of nutrients by vegetation is vital to creating wetlands that will function both now and in the future to treat water quality issues in Ohio waterways. This combination of datasets will lead to a mechanistic understanding of wetlands that are able to retain nutrients, both long-term and at a scale that can have a meaningful impact on Great Lakes water quality.

Simulating Hydrologic Scenarios Reveals Connectivity

The H2Ohio Wetland Monitoring Program (WMP) has developed three dimensional hydrodynamic models integrating subsurface flow dynamics measured with geophysical techniques to examine wetland function of as-built Projects in detail. Models have not been fully calibrated, but their capability of simulating complex hydrology enables researchers to identify wetland features that are "idle", i.e., the wetland pools that do not receive or participate in filtering nutrient-rich water released into the wetland Projects, particularly under drier conditions. These models have been deployed so far at two focal Projects: the Forder Bridge Floodplain Reconnection (Forder Bridge), and Oakwoods Nature Preserve East (Oakwoods East) and West (Oakwoods West). At Forder Bridge, models indicate that pools within two complexes are basically idle and do not play a role in nutrient filtration as expected. At Oakwoods East and West models indicate that most Oakwoods West pools are idle and do not play an active role in nutrient filtration as expected. At Oakwoods, simulations suggest that increasing the connectivity between pools through the installation of culverts or pipes could lead to an increase of phosphorus storage efficiency from 64% to 84%, however due to the low nutrient concentrations in Aurand Run the total phosphorus retention is still relatively low. Overall, 3-D hydrologic models built by the Monitoring Program can be used to test a variety of hypothetical scenarios and their potential impacts on nutrient filtration within Projects. More details on modelling approaches for individual Projects can be found in Volume 2 of the H2Ohio Wetland Monitoring Program 2024 Annual Report.

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[20] Jacquemin, S.J., Grunden, M.C. & Dirksen, T.A. Wetland Conservation in the Grand Lake St. Marys Watershed: Long Term Monitoring Data from Coldwater Creek Restored Wetland. *Wetlands* 45, 37 (2025). https://doi.org/10.1007/s13157-025-01917-9

Wetland Vegetation Monitoring Management Considerations

Preliminary Planting & Wetland Design Recommendations for Vegetation Nutrient Removal

The H2Ohio Wetland Monitoring Program has identified 10 native wetland plant species recommended for planting, based on species-specific traits for plant size, density, and nutrient concentration which promote high vegetation nutrient stock per unit area (nutrient density, Figure 9[21]).

[21] Photo credits: *Sagittaria latifolia* (Photo by Ryan Hodnett/ CC BY-SA 4.0); *Alisma subcordatum* (Ethan Glassman); *Juncus effusus* (Photo by Petr Brož/ CC BY 3.0); *Scirpus cyperinus* (Photo by Krzysztof Ziarnek/ CC BY-SA 4.0); *Pontederia cordata* (Photo by Malcom Manners/ CC BY 2.0); *Asclepias incarnata* (Photo by Katja Schulz/ CC BY 2.0); *Ammannia robusta* (Photo by John Scholze/ CC BY 2.0); *Eleocharis palustris* (Photo by Matt Lavin/ CC BY-SA 2.0); *Bidens cernua* (Photo by Rob Routledge/ CC BY 3.0); *Penthorum sedoides* (Helen Michaels)

Native Plant Species Beneficial for Vegetation Nutrient Stock

H2Ohio researchers recommend planting these ten native species in wetlands to enhance vegetation nutrient stocks. Increasing the number and frequency of these species will increase the net vegetation nutrient stock for a Project.

Figure 9. Native plant species beneficial for nutrient stock. Photos are Creative Commons or used with the permission of the photographer.

The first five species of native plants recommended for planting promote nutrient stock values because of high nutrient content and high biomass, without dominating the wetland and lowering diversity: Broadleaf arrowhead (*Sagittaria latifolia*), American water plantain (*Alisma subcordatum*), Soft rush (*Juncus effusus*), Woolgrass (*Scirpus cyperinus*), and Pickerelweed (*Pontederia cordata*). Five additional native species have high nutrient content but grow at lower density or smaller sizes, so they need to be planted at higher density or have an increased relative proportion of seed in wetland seed mixes to be effective: Swamp milkweed (*Asclepias incarnata*), Grand redstems (*Ammania robusta*), Spikerushes (*Eleocharis* spp.), Nodding bur marigold (*Bidens cernua*), and Ditch stonecrop (*Penthorum sedoides*). Table 14 summarizes these species and the measured traits that led to the recommendations and indicates whether a plant has an annual or perennial life cycle. While longer lived plants (perennials) are more likely to store nutrients in their own tissues over multiple years, shorter lived plants (annuals) still promote nutrient retention by rapidly transforming nutrients into forms that are less likely to leave the wetland, especially in the short-term, which could reduce losses of nutrients from the wetland in particular seasons.

Increasing species with high-nutrient stock per unit area in a Project will likely increase the net nutrient stock in vegetation for a Project. However unintended nutrient stock decreases are possible (e.g., increases in these native plants reduce non-natives with high nutrient stock potential), because these recommendations are based on species-level data and recommended management has not yet been field tested. Additionally, these recommendations pertain only to increasing nutrient stock in vegetation during peak biomass (July-August), and the ultimate impacts of plant species traits on annual Project nutrient retention are not yet understood. The longevity of vegetation stock nutrient storage, plant decay and nutrient release rates, contributions of perennial and annual species, and effects of plants on other aspects of nutrient function (e.g., sedimentation) are being investigated as part of supplementary funding received by Monitoring Program researchers to improve understanding of system-wide processes (Harmful Algal Bloom Research Initiative). Wetland practitioners can consult Project-specific summaries (Volume 2 of the H2Ohio Wetland Monitoring Program 2024 Annual Report) or Program-wide summaries (Volume 4 of the H2Ohio Wetland Monitoring Program 2024 Annual Report) for a full list of observed species. This information is meant to promote management actions that favor higher-nutrient density species over lower nutrient density species.

Certain species can be successfully established from seed mixes; wetland practitioners or suppliers may consider developing seed mixes tailored towards restoration for nutrient remediation which include these species at higher proportions (Table 14). However, care is needed in design and management to ensure proper conditions to encourage vegetation establishment following post-construction seeding. Wetland designs that are conducive to wetland vegetation include large areas of shallow, slow-moving water, or large areas that flood regularly or seasonally. Designs should explicitly consider hydrologic connectivity to support wetland vegetation habitat. In practice, this involves ensuring that nutrient-laden waters flow through areas with abundant vegetation and that water is held for an adequate residence time to allow for vegetative nutrient removal. To maximize wetland vegetation habitat, steep slopes and deep channels should be minimized. In cases where channelization is necessary, two-stage designs should be incorporated.

Although Cattails (*Typha sp.*) can have high nutrient content and biomass, researchers do not explicitly recommend use of Cattails for nutrient removal, as they can dominate wetlands and lower overall plant diversity, presenting a trade-off between biodiversity and water quality improvement goals.

Table 14. Plant Species Beneficial for Vegetation Nutrient Stock

Reason for Recommendation	**Common Name**	**Scientific Name**	Life Cycle
High nutrient density and concentration	Broadleaf arrowhead	*Sagittaria latifolia*	*Perennial*
	American water plantain	*Alisma subcordatum*	*Perennial*
High nutrient density	Soft rush	*Juncus effusus*	*Perennial*
	Woolgrass	*Scirpus cyperinus*	*Perennial*
	Pickerelweed	*Pontederia cordata*	*Perennial*
High nutrient concentration	Swamp milkweed	*Asclepias incarnata*	*Perennial*
	Grand redstems	*Ammania robusta*	*Annual*
	Spikerushes	*Eleocharis compressa* or *Eleocharis palustris*	*Perennial*
	Nodding bur marigold	*Bidens cernua*	*Annual*
	Ditch stonecrop	*Penthorum sedoides*	*Perennial*

Soil Drivers of Wetland Phosphorus Retention Across H2Ohio Projects

Wetland soils store phosphorus (P) in two ways: through the accumulation and burial of particle-associated P and by sorption of inorganic phosphate ions to minerals, especially iron and aluminum oxides.

Particulate Phosphorus Storage

The deposition of sediments carried to wetlands from upstream and the accumulation of organic detritus are both processes that occur over years and require long-term monitoring to be accurately measured. The H2Ohio Wetland Monitoring Program is developing protocols for measuring rates of particulate phosphorus (P) filtration and storage. Data has currently been collected at a single Project and, if resources allow, sedimentation measurement will be expanded to additional H2Ohio Projects. Preliminary results align with published studies and affirm that substantial quantities of total phosphorus (TP) are retained by sedimentation and burial of particulate material. Pools within the St. Joseph River Restoration Project accumulated about 1–37 mm of newly deposited material during Water Year (WY) 2024. A pool that acts as a floodplain to the St. Joseph River during extreme flood events accumulated the most material. Chemical analysis of the material is in progress and will allow researchers to measure the rate of P storage associated with this accumulation of sediment. Leveraged resources, such as the Ohio Department of Higher Education Harmful Algal Bloom Research Initiative, also support research into how plants promote sedimentation and particulate P burial.

Soil Phosphate Sorption Capacity

Researchers measured soil phosphate sorption capacity (SPSC), which indicates soil potential to sorb or release phosphate, in all sampled H2Ohio Projects. Specifically, SPSC indicates how much additional phosphate could be retained through sorption to minerals, specifically iron and aluminum oxides[22, 23]. The calculation of SPSC is based on a ratio of the mass of Mehlich-3-extractable iron (M3-Fe) and Mehlich-3-extractable aluminum (M3-Al) to the mass of Mehlich-3-extractable phosphorus (M3-P), which indicates the concentration of reactive minerals in the soil that can readily bind phosphate. Soils with positive SPSC values, particularly values greater than 100 mg phosphorus (P)/kg soil, are expected to sorb additional phosphate, while soils with negative SPSC values are vulnerable to releasing phosphate. SPSC is not a measure of actual soil phosphorus storage, but it is a convenient and relatively low-cost estimate of a soil's capacity to sorb phosphate.

Soils in all sampled H2Ohio Projects overwhelmingly indicate at least moderate capacity to retain phosphate through sorption to soil minerals. SPSC values measured over four years in 42 monitored H2Ohio Projects ranged from -117 to 321 mg P/kg (Figure 10). Soils in most of the

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[22] Nair, V. D., Clark, M. W., & Reddy, K. R. (2011). *Wetland Soils Nutrient Index Development and Evaluation of "Safe" Soil Phosphorus Storage Capacity* (014820; FDACS Contract). Social and Water Science Department-IFAS, University of Florida. https://www.fdacs.gov/content/download/76280/file/14820_FinalReport.pdf

[23] VanZomeren, C. M., & Berkowitz, J. F. (2020). *Evaluating Soil Phosphorus Storage Capacity in Constructed Wetlands: Sampling and Analysis Protocol for Site Selection* (Technical Note ERDC/EL TN-20-3). U.S. Army Corps of Engineers Engineer Research and Development Center.

monitored wetlands have the potential to sorb additional phosphate, although a few indicate a risk of releasing phosphate. Out of 1860 soil samples, only 67 indicated a risk of phosphate release (SPSC < 0 mg/kg). Most soils (1153 samples) indicated low but positive sorption capacity (0 mg/kg < SPSC < 100 mg/kg), which implies a low risk of release but also reduced ability to sorb additional phosphate. Soils with the greatest phosphate sorption capacity (SPSC > 100 mg/kg) were found both in areas that were considered formerly-agricultural land and in areas that were not considered formerly-agricultural (Figure 13). Eight different Projects have at least one soil sample with a negative SPSC value. Of those Projects, only two have negative SPSC values in more than 20% of soil samples (Figure 14).

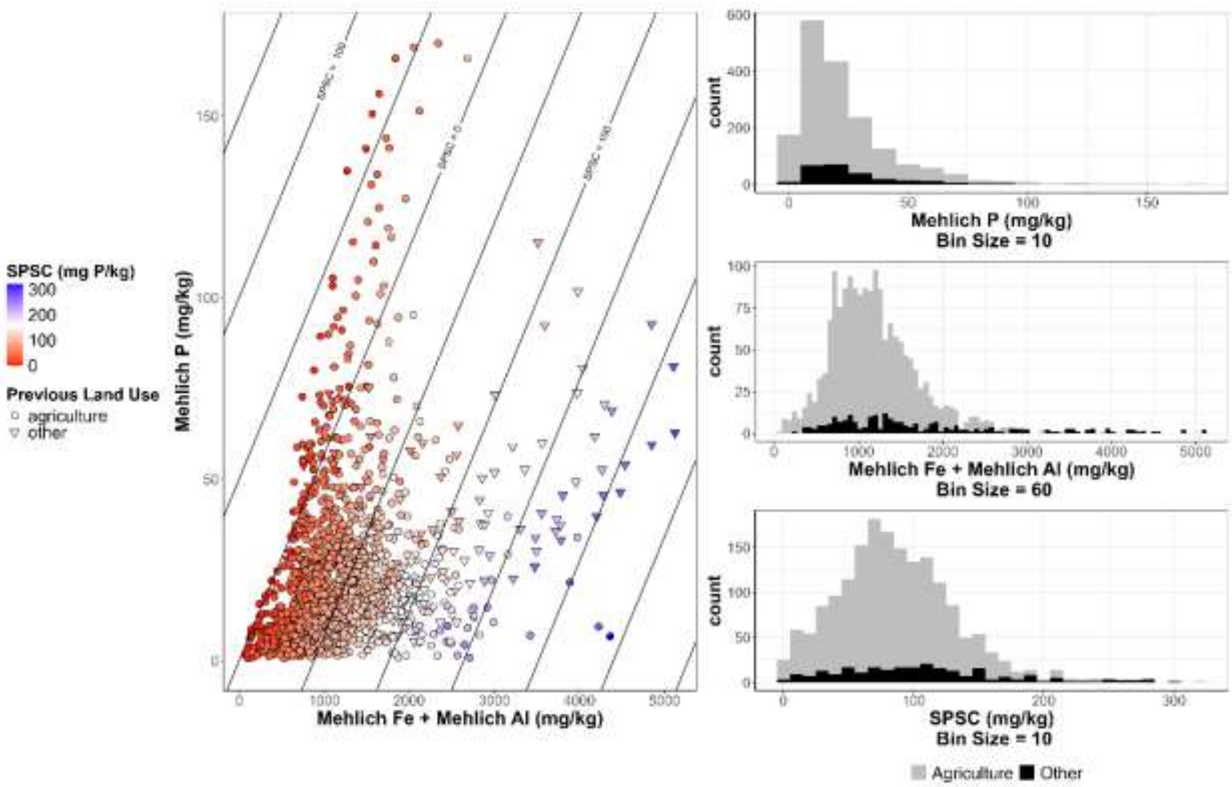

Figure 10. Indices of phosphorus storage via soil phosphate sorption. Plot comparing the Mehlich-3-extractable iron (M3-Fe) and Mehlich-3-extractable aluminum (M3-Al) concentrations against the Mehlich-3-extractable phosphorus (M3-P) concentrations of all H2Ohio soil samples. Points represent samples collected after Project construction. The soil phosphate sorption capacity (SPSC) contour lines represent an approximate value based on the average ratio of M3-Fe to M3-Al across all H2Ohio Projects. The color of the points is based on the actual calculated SPSC value for each sample. Previous land use classifications are based on base crew characterization of each Project from discussions with conservation partners, evaluation of pre-construction aerial imagery and wetland proposal documents.

Multiple Years of SPSC Monitoring

To assess how soil phosphate sorption capacity (SPSC) changes after wetland restoration, researchers compared pre-construction to post-construction SPSC values where available. More samples were collected after construction than before construction in most Projects because of increased post-construction sampling capacity and the greater topographic variability to assess. Thus, in all Projects, the variability in post-construction SPSC values was much greater than in pre-construction samples (Figure 11). The average of SPSC values suggests increasing SPSC after restoration, which could be due to a decrease in Mehlich-3-extractable phosphorus (M3-P) in soils (e.g., from plant uptake, leaching, and/or the deposition of sediment with low M3-P) or due to an increase in Mehlich-3-extractable iron (M3-Fe) and Mehlich-3-extractable aluminum (M3-Al) in new sediment deposition over time. On the other hand, if a wetland system consistently receives and retains dissolved phosphorus (P) loads, the capacity for the wetland to retain P would diminish over time as available sorption Projects in soil oxide minerals (i.e., Fe and Al) saturate, unless new sediment arrives with more sorption capacity or if sorbed P is taken up by vegetation. It is important for any monitoring scheme to measure SPSC over many years because the concentrations of M3-P, M3-Fe, and M3-Al that go into the net SPSC value may shift in different directions each year, and stored phosphorus may move between ecosystem pools (e.g., from soil to plant tissue). Further, it is often too resource-intensive under agency-funded budget constraints to do further mechanistic studies of all the factors (i.e., plant uptake, sediment arrival) that contribute to the net value of phosphorus sorbed to sediment.

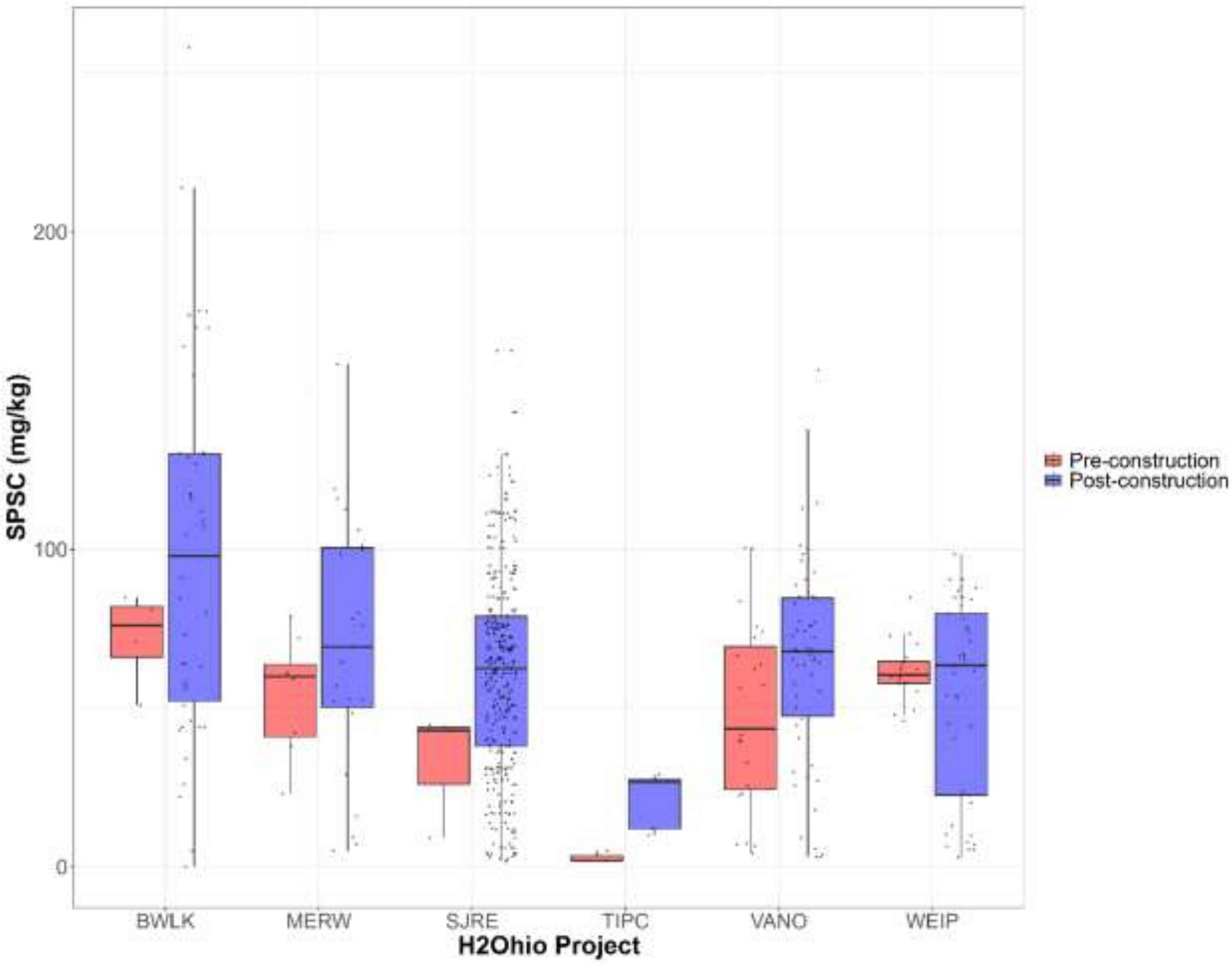

Figure 11. Boxplots displaying the distribution of soil phosphate sorption capacity (SPSC) values measured in pre- (pink) and post-construction (purple) soil samples (0–5 cm) across six H2Ohio Project for which pre- and post-construction data is available. All six Projects listed are formerly agricultural fields on which new wetland pools were excavated. For each boxplot, the thick line represents the median (middle) surface water depth across all measurements. The boxes indicate the value range for 50% of the measured depths and the whiskers show the spread of depth values that are outside the 50% of the data points. Each overlying point represents individual SPSC measurements.

After four years of data, there is an apparent slight trend of increasing SPSC values over time at monitored H2Ohio wetland Projects, but long-term data is needed to see if and at which Projects this trend continues. Future analyses of these data differentiate true changes through time from variability associated with increased sampling effort and changing sampling designs. Additionally, these initial inferences and analyses have been leveraged to secure additional funding (e.g., U.S. EPA Great Lakes Restoration Initiative) to support additional data collection and improved data synthesis toward products that are meaningful to managers and other stakeholders.

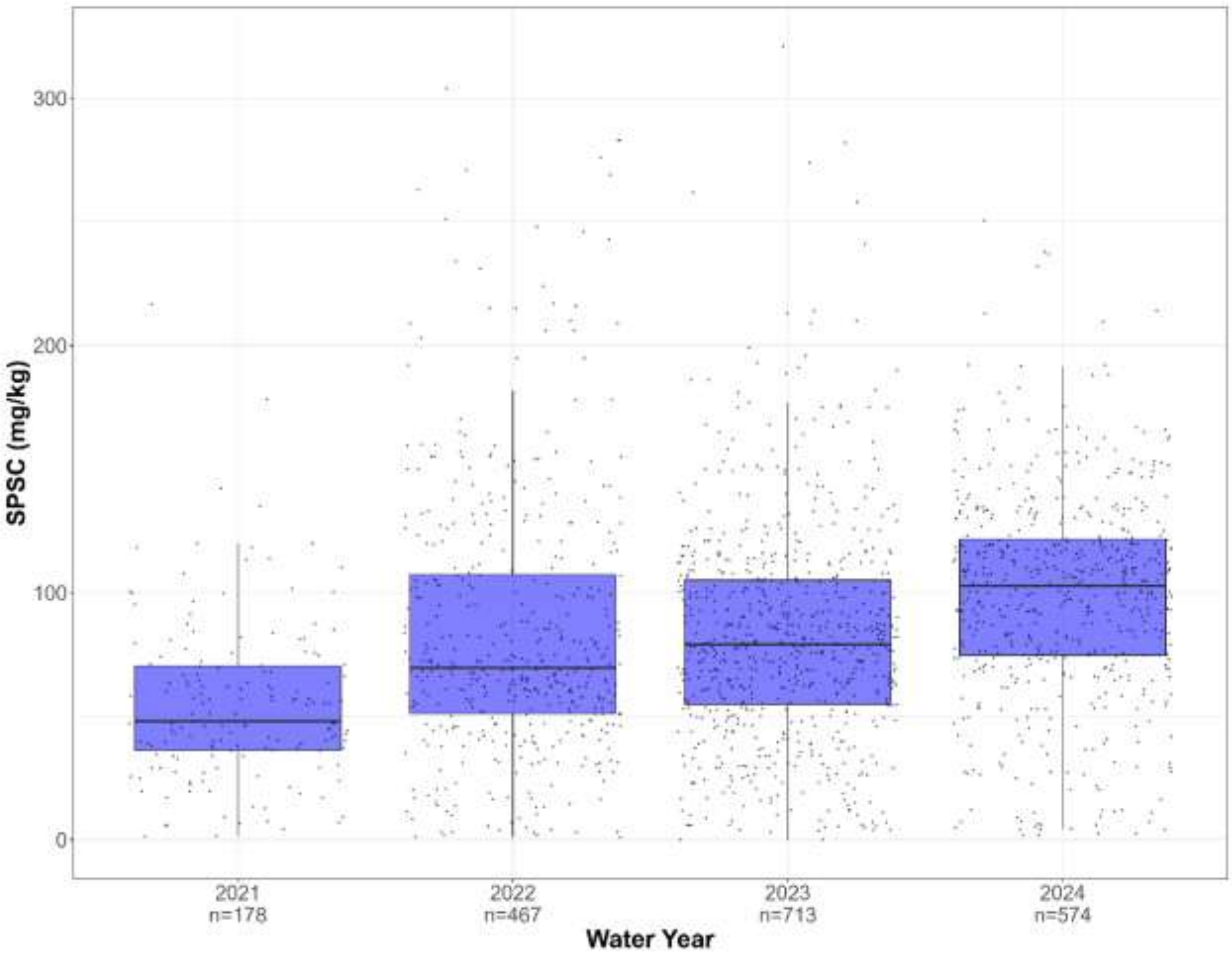

Figure 12. Boxplots displaying the change in soil phosphate sorption capacity (SPSC) values measured in soil samples (0–5 cm) of H2Ohio wetland Projects across the 2021–2024 water years (Oct 1–Sep 30). For each boxplot, the thick line represents the median (middle) surface water depth across all measurements. The boxes indicate the value range for 50% of the measured depths and the whiskers show the spread of depth values that are outside the 50% of the data points. Each overlying point represents individual SPSC measurements. The number of soil samples included in each boxplot is shown in the x-axis.

Informing Site Selection and Wetland Design

Knowledge of past land use and soil chemistry can support wetland Project site selection and design to maximize soil phosphorus (P) retention and minimize risk of P release. Soil analyses confirm that wetlands restored on formerly agricultural land with high-phosphorus soils have less capacity to sorb additional phosphate than wetlands restored on non-agricultural land. The 67 negative soil phosphate sorption capacity (SPSC) values observed across the last three years were almost all from former agricultural lands (Figure 14). Not all soils from formerly agricultural areas had low or negative SPSC values, but nearly all the samples that were in this “red zone” were collected from formerly agricultural areas. Generally, the most negative SPSC values were associated with the highest Mehlich-3-extractable phosphorus (M3-P) values, whereas SPSC was positive across a range of Mehlich-3-extractable iron (M3-Fe) and Mehlich-3-extractable aluminum (M3-Al) values (Figure 10). Soils with high M3-P likely reflect a legacy of historic application of P fertilizer or manure above agronomic rates[24]. In Projects with high soil P where SPSC indicates low sorption potential or phosphate release risk, nearby soils in the same parcel often indicate capacity to sorb phosphate. Thus, even Projects with legacy P "hot spots" have adjacent soils with capacity to sorb phosphate that will likely mitigate localized release from hot spots.

If a site where wetland restoration is planned has high-phosphate, low-SPSC soils throughout, phosphate release risk can be mitigated by minimizing surface water export from the designed wetland and/or by enhancing the sorption capacity of surface soils. The best way to prevent P loss is to prevent export of water from the restored wetland. Converting areas with high-phosphate, low-SPSC soils to wetlands that store water rather than filter water from upstream can thus still contribute to watershed scale P retention goals by preventing the loss of P from the formerly agricultural lands. Removing artificial drainage and creating isolated pools which receive surface runoff from surrounding areas can increase water storage capacity, given that the water does not immediately flow out downstream or into adjacent systems. This will prevent loss of existing soil P to downstream systems and increase the chance of retaining any additional P delivered to the Project. However, this may result in lower quality habitat within the Project because of high internal nutrient conditions.

In wetland features that are designed to filter nutrient loads from upstream via sedimentation, like in floodplains, newly deposited material may have higher phosphate sorption capacity than the formerly agricultural soils underneath. Designing wetlands that accumulate sediment without re-releasing it can thus increase SPSC and retain particulate P simultaneously.

[24] Sharpley, A., Jarvie, H.P., Buda, A., May, L., Spears, B. and Kleinman, P. (2013), Phosphorus Legacy: Overcoming the Effects of Past Management Practices to Mitigate Future Water Quality Impairment. J. Environ. Qual., 42: 1308-1326. https://doi.org/10.2134/jeq2013.03.0098

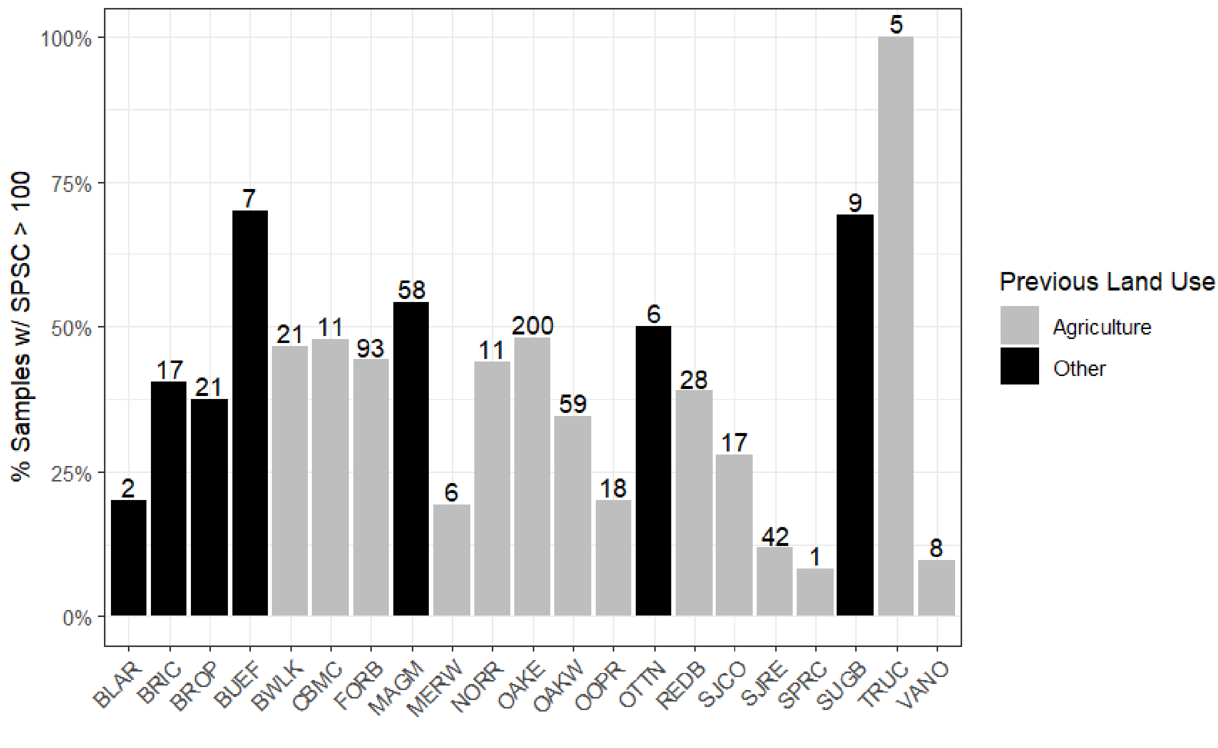

Figure 13. Bar plot representing the percentage of samples from each Project with a soil phosphate sorption capacity measurement of greater than 100 mg phosphorus/kg. The values on top of each bar reflect the total number of soil samples taken at each respective Project. Project codes are listed with their respective Project name in Table 3.

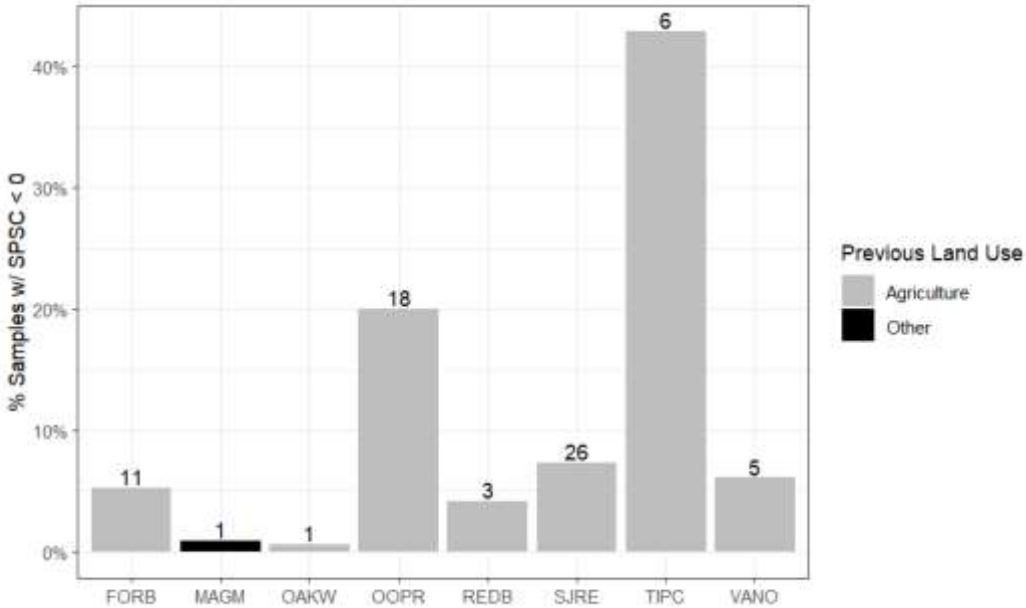

Figure 14. Bar plot representing the percentage of samples from each Project with a negative soil phosphate sorption capacity (SPSC) value, indicating vulnerability to releasing phosphate. The values on top of each bar reflect the total number of soil samples taken at each respective Project. Project codes are listed with their respective Project name in Table 3.

Predicting and Assessing Nutrient Function

Comparison Between ODNR and Monitoring Program Predictions

Current Ohio Department of Natural Resources (ODNR) predictions for wetland function are separate wetland Projects into three categories: flow-through wetlands, floodplain wetlands, and coastal wetlands. Data from the H2Ohio Wetland Monitoring Program (WMP) can improve ODNR predictions of Project function. The new framework presented in this report separates the ability for a wetland to filter nutrients from its ability to prevent nutrient loss via runoff. This approach could be applied to ODNR wetlands to more accurately account for the distinct ways new wetlands contribute to nutrient load reduction. In particular, accounting for the prevention of nutrient loss by runoff in isolated restored wetlands may meaningfully contribute to watershed-scale nutrient load reduction goals, even when the Project is not connected to upstream nutrient sources. Estimates of runoff prevention only require basic soil information and knowledge of the area that has been converted from agricultural land (see Volume 2 of the H2Ohio Wetland Monitoring Program 2024 Annual Report). Monitoring Program data suggests that water source would be a more valuable framework around which to shape predictions than wetland type. The WMP has demonstrated that the water volume a Project receives, and its drainage area are not always linked. Boots-on-the-ground data, specifically during storm events, is crucial (see “Connectivity” section, p. 31). Projects with different water sources require different approaches and different predictive variables to accurately predict Project function.

Nutrient retention for Projects that are actively managed through water level control structures or pumps cannot be predicted based on drainage area or streamflow; predictions must come from the management plan for water delivery to the Project. Researchers calculating nutrient retention for Projects that receive runoff can rely on estimates from drainage area but should be careful of the impact of sub-surface drainage pathways on the volume of water a Project receives and the area it drains. Predicting nutrient retention of floodplain and off-channel wetlands involves understanding the frequency at which wetlands will receive water. Data suggests that the inflow threshold for a wetland better predicts its nutrient loading than the number of events during which a wetland receives stream water (see “Connectivity” section, p. 31). It is also important to consider whether coastal Projects function as coastal wetlands, with continuous connection to lake water, or if they function as flow-through wetlands that outflow into a lake with only occasional connection to lake water during seiche events. The Magee Marsh Turtle Creek Bay Wetland Reconnection Project is an example of a Project that is often categorized as a coastal wetland but functions as an actively managed flow-through wetland.