American Ecological Engineering Society

Journal of Ecological Engineering Design
journals.uvm.edu/jeed

Research Case Study

Multi-Objective Wetland Design for Water Quality and Waterfowl Habitat

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Received
July 24, 2024
Accepted
January 5, 2025
Published
March 19, 2025

Editors
Sara W. McMillan, Editor in Chief
Anand Jayakaran, Associate Editor

Lake Erie, one of the 5 Laurentian Great Lakes, suffers from harmful algal blooms in its western basin that are associated with phosphorus (P) loading from the Maumee River Watershed (MRW), United States. Additionally, certain waterfowl populations in the MRW have declined significantly in recent decades. Wetlands provide ecosystem services such as reducing P pollution and providing habitat for waterbirds, but these objectives are often treated separately. Simple tools are needed in this region for improved wetland restoration for meeting the dual goals of providing waterfowl habitat and improving water quality through P retention via design and management. This research identified 2 main objectives in support of these goals: 1) create a parsimonious model that assesses wetland P retention and waterfowl habitat suitability simultaneously, and 2) create a spreadsheet tool to implement the model to identify water management and design approaches that improve P retention and waterfowl habitat suitability. A total of 249 observations of wetland P fluxes, with agricultural runoff as the primary pollutant of interest, were input into a first-order pollutant removal model to generate P retention estimates. Waterbird habitat suitability was assessed based on preferred foraging depths. Results show that active, dynamic management of water depth can help reduce tradeoffs between wetland objectives and that larger wetlands (at least 2% – 7% of subbasin area) tend to outperform smaller wetlands in meeting both objectives.

Keywords Eutrophication, Nutrients, Waterfowl, Phosphorus, Waterbirds

Carpenter M, Bledsoe B. 2025. Multi-objective wetland design for water quality and waterfowl habitat. Journal of Ecological Engineering Design. https://doi.org/10.70793/jeed.15

Highlight

This study found that wetlands can be actively managed and designed as 2% – 7% of the incoming watershed area to more optimally meet the dual goals of phosphorus retention and waterfowl habitat provision in a Great Lakes watershed.

1. Introduction

Wetland functions and benefits, including flood risk reduction, water quality, habitat, and recreation, have declined significantly over the last few centuries as agricultural expansion and urbanization have drained or filled these features (USEPA 2024). Wetland loss is concentrated in Europe, China, and the United States, where wetland loss has exceeded 75% in some regions (Fluet-Chouinard et al. 2023). Engineered wetlands, which seek to mimic the functions and benefits of natural wetlands, act as effective sinks for phosphorus (P), a plant nutrient that is commonly found in agricultural fertilizers (Kadlec and Wallace 2009). The loss of wetlands, paired with increasing use of P fertilizers on farmland, has exacerbated cultural eutrophication of freshwater ecosystems, in which high nutrient loads caused by human activity result in excessive productivity in receiving ecosystems, potentially leading to the formation of harmful algal blooms (HABs) (Dodds and Whiles 2020). HABs are toxic to humans, household pets, and wildlife and generally degrade the quality and uses of aquatic ecosystems (e.g., recreation, drinking water supply, and aquatic life). Increasing attention to wetland loss and HABs over the last few decades has spurred recent efforts to engineer wetlands to retain P while also providing suitable habitat for a variety of species.

One of the challenges in using engineered wetlands to retain P is the appreciable uncertainty in wetland P retention capacity and design criteria (Ury et al. 2023). P retention in wetlands is affected by a number of factors such as hydraulic loading rate (HLR), hydrogeomorphic setting, soil type, influent loading rate, and vegetation characteristics (Aldous et al. 2005; Kadlec and Wallace 2009; Land et al. 2016; Ury et al. 2023). The influence of these interacting factors on P retention is not well understood nor accounted for in design guidance. For example, Ury et al. (2023) found that total phosphorus (TP) release from wetlands was more likely to occur with higher HLRs, whereas Land et al. (2016) suggested that TP retention is most effective at high HLRs. Practitioners have tended toward engineering designs based on "rules of thumb" (e.g., wetland area defined as a specific percentage of inflowing surface drainage area) for sizing wetlands to achieve water quality objectives, and wetlands restored on agricultural lands are often passively managed by private landowners for singular objectives such as recreation without intentional manipulation of water levels (Ducks Unlimited, personal communication [unreferenced] 2023).

Wetlands are also extremely important to the survival of waterfowl, the focus of this study, and other waterbirds throughout their lifecycle as breeding, nesting, staging, and wintering habitats; wetlands also provide sustenance in the form of vegetation and macroinvertebrates (Soulliere et al. 2017). Waterbirds are birds found around wetland ecosystems, while waterfowl are a subset of waterbirds that are dependent on the wetland as habitat. Waterfowl and other waterbirds are sensitive to fluctuations in wetland hydroperiod, cover, and food availability (Baschuk et al. 2012), but habitat suitability assessments are based largely on static spatial data such as wetland type and cover data, which are updated infrequently and do not include dynamic hydrologic patterns (Soulliere et al. 2017). Waterbirds are well-studied and can often act as indicator species, responding to environmental changes and tending to occupy higher trophic levels in the wetland environment.

Research on wetlands commonly focuses either on P retention or waterfowl habitat, but it rarely examines interactions or tradeoffs between these functions beyond waterbird degradation of water quality through P excretion (Manny et al. 1994). There exists some uncertainty in the potential for tradeoffs between biodiversity conservation for waterbirds and wetland P retention regarding preferred wetland depth and area (Hambäck et al. 2023). Accordingly, there is a need to simultaneously consider these objectives under varying hydrologic regimes in restoration planning and design as agencies and conservation organizations aim to maximize engineered wetland benefits, especially given the recognized potential for tradeoffs between general nutrient retention and habitat biodiversity services. These tradeoffs are generally thought to occur due to divergences in idealized spatial orientation on the landscape and preferred vegetative density and type (Newbold and Weinberg 2003; Jessop et al. 2015; Hambäck et al. 2023).

Practical wetland planning and design tools based on parsimonious models of P retention and habitat interactions are needed to advance design practice and management of wetland hydroperiods by project owners. We chose 2 main objectives in support of creating accessible tools for wetland restoration with water quality and habitat as primary ecosystem services of interest: 1) create a parsimonious model that assesses wetland P retention and waterfowl habitat suitability under various hydrologic scenarios and 2) create a spreadsheet tool based on the model to allow practitioners to explore water management and design approaches that improve P retention and waterfowl habitat suitability under climate uncertainty. This modeling approach is meant to be widely applicable to engineered wetlands, with the Maumee River Watershed (MRW), United States, serving as a case study to demonstrate the application of a spreadsheet tool to support design and water management.

2. Case Study Site

Lake Erie, one of the 5 Laurentian Great Lakes, North America, suffers degraded water quality as a result of cultural eutrophication and HABs in its western basin. HABs within Lake Erie are highly associated with excessive P loading (Kane et al. 2014; Scavia et al. 2014). One of the dominant sources of P to the western Lake Erie basin comes from the Maumee River Watershed (MRW) (41°41′58″N, 83°27′36″W), which covers about 15,800 km^2 in parts of Michigan, Indiana, and Ohio, United States. A large portion of the MRW was known by settlers as the "Great Black Swamp" (Figure 1), indicating that hydric soils exist in this region that have a high potential for wetland restoration (Mitsch 2017). The wetlands that existed in the MRW were drained and today at least 72% of the MRW is in row crop agriculture, which typically requires high amounts of fertilizer and contributes significantly to nutrient loadings (Cousino et al. 2015).

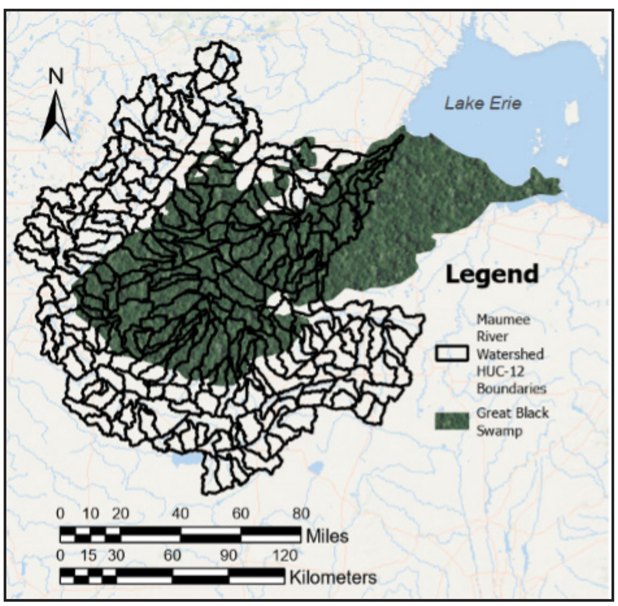

Fig. 1 The Maumee River Watershed, United States, with the historical extent of the Great Black Swamp, adapted from "Great Black Swamp estimated boundary layer" by Hohman and Messina (2019) and from "Watershed Boundary Dataset" by the USGS (2023).

In addition to water quality benefits, wetlands in the MRW also provide habitats for several wildlife species of interest. Waterfowl species of interest in the MRW include the Wood Duck (*Aix sponsa)*, Mallard (*Anas platyrhynchos)*, and American Black Duck (*Anas rubripes)*. Secondary waterbirds of interest include the American Bittern (*Botaurus lentiginosus)*, Great Blue Heron (*Ardea herodias)*, and Sandhill Crane (*Antigone canadensis)*. Many of these species are in decline in the Great Lakes region primarily due to habitat loss from urban development and agricultural expansion (Beillke et al. 2021), making research on wetland habitat suitability even more important.

3. Materials and Methods

3.1 Phosphorus Retention and Waterfowl Habitat Model

We developed an intermediate complexity model that links P retention and waterfowl/waterbird habitat suitability under various climate, management, and design scenarios by combining 3 sub-models (Figure 2). A hydrologic model based on a wetland water balance informed by climate, management, and design scenarios generated monthly hydroperiods, which were used to inform P retention and waterfowl/waterbird habitat sub-models. We applied the modeling framework to the MRW as a case study with the use of a spreadsheet tool. The process for model development and its implementation as a practical spreadsheet tool in the MRW case study is described in the subsections that follow.

3.1.1 Hydrologic Sub-model

Hydroperiod, or the seasonal pattern of water levels in wetlands, can be calculated from a simple water balance as follows:

$$\Delta S = P_i + R_i - ET - R_o \quad (1)$$

Where ΔS is the change in storage (m), P_i is precipitation (m), R_i is inflowing runoff from the watershed into the wetland (m), ET is evapotranspiration (m), and R_o is runoff out of the outlet structure (m). We adapted the methodology for this wetland water balance from NJDEP (2008), R_i and ET data was compared to USGS stream gage data in the MRW to corroborate seasonal patterns in runoff and annual runoff volumes versus ET. Groundwater inputs and outputs were not considered in this water balance due to insufficient data on site-scale groundwater fluxes and dominance of surface runoff processes in this context. P_i and ET informed climate scenarios, with data for the case study coming from the National Centers for Environmental Information Climate Data Online. The Thornthwaite method

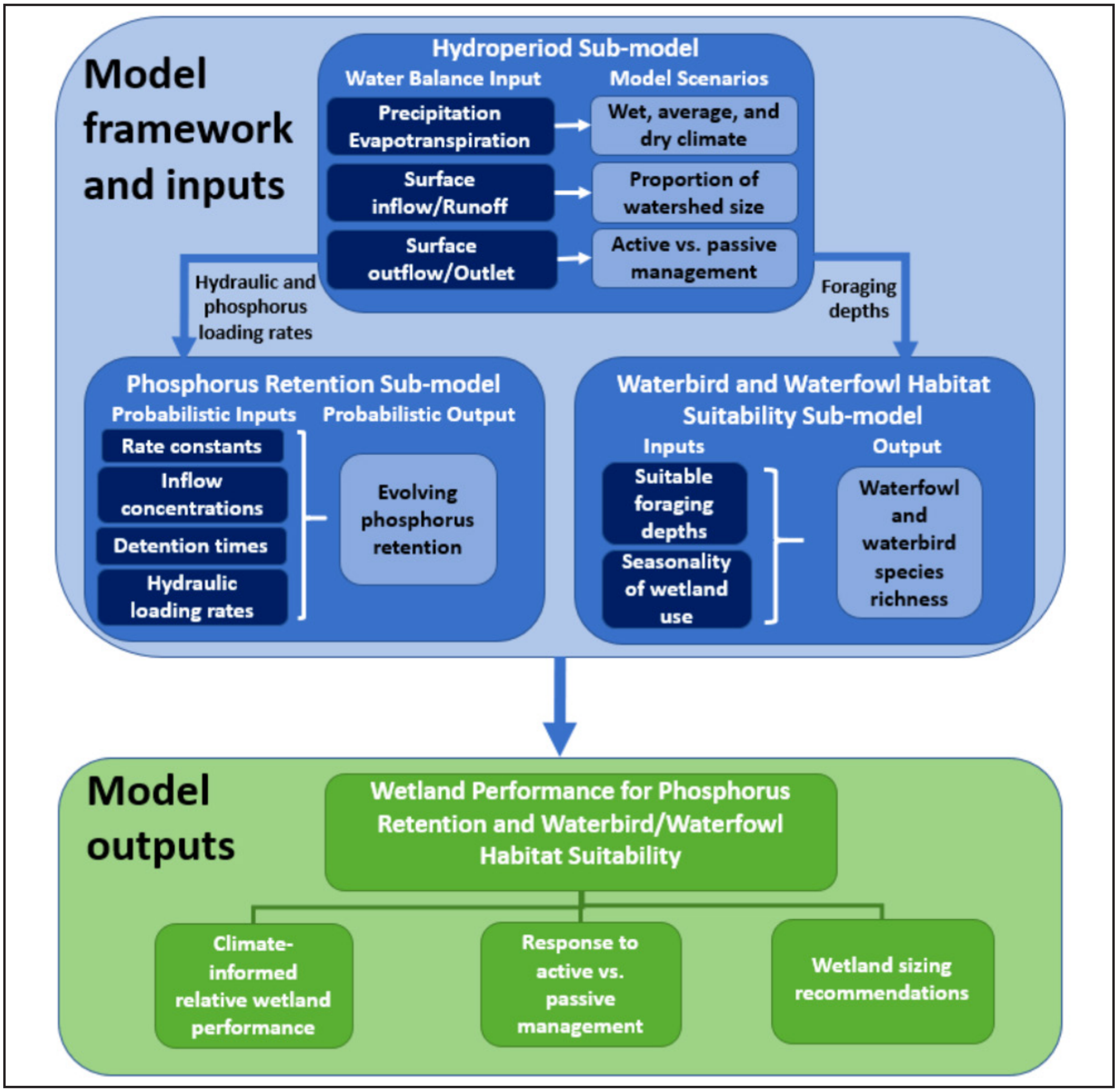

Fig. 2 Framework for modeling interactions among hydrologic and future climate forcing, phosphorus retention, and waterbird/waterfowl habitat to inform wetland design and water management.

(Thornthwaite 1948) was used to calculate ET, and R_i was estimated daily based on precipitation data, contributing drainage area, and design size of the wetland using a site-specific NRCS curve number (NRCS 1986). Lastly, R_o acted as a boundary condition for outlet structure management and generated the outflow for the wetland. We combined daily data to form monthly water balances for a given precipitation year of interest to form the basic connection between the P retention and waterfowl/waterbird habitat suitability sub-models.

3.1.2 Phosphorus Retention Sub-model

P retention in wetlands can be modeled using the k-C model outlined in Kadlec and Knight (1996). The k-C model is a parsimonious, first-order removal model that is used to estimate effluent concentrations or loadings of contaminants in wetlands while assuming plug flow (Kadlec and Knight 1996). The representative equation can be generally written as:

$$\frac{C_{out}}{C_{in}} = e^{\frac{-k}{q}} \tag{2}$$

where C_{in} is the inflowing concentration of pollutant (in this case, TP) into the wetland (mg/L), C_{out} is the outflowing concentration of TP (mg/L), k is the areal removal rate constant associated with first-order removal (m/y), and q is the HLR (m/y). The removal rate constant behaves like settling rate constants found in sedimentation models and does not include biotic features (Kadlec and Wallace 2009; Mitsch and Gosselink 2015); it is the most widely used by practitioners to model the long-term dynamics of P retention in wetlands due to its reduced complexity (Stein et al. 2006; Babatunde et al. 2011). Variations of Eq. 2 have emerged since the introduction of the k-C model in 1996, including the P-k-C model, the k-C* model, and the k^{Ψ}-C model (Kadlec and Wallace 2009; Zhang et al. 2023). We evaluated the use of all these variations of the model and ultimately decided that the original k-C model was most appropriate for this application, as data were insufficient to support the use of more complex models.

By calculating an estimate of C_{out}, P retention can be calculated as either a rate or an efficiency. P retention efficiency is the percentage of incoming P into a wetland that is retained, whereas a P retention rate is the mass of P retained on an areal basis over a period of time (typically in g/m^2*y). Our approach has P retention broken down on a monthly timescale, with k expressed in m/month and q expressed in m/month, to incorporate seasonality of hydrologic scenarios and waterfowl habitat suitability.

3.1.3 Waterfowl/Waterbird Habitat Suitability Sub-model

Waterfowl and other waterbird habitat suitability is known to be largely dependent on water depth due to foraging behavior (Baschuk et al. 2012; Kaminski and Elmberg 2014; Soulliere et al. 2017). Preferred foraging water depths were gathered for a total of 19 waterfowl and waterbird species (Table 1), which were selected for the case study applied to the MRW based on expert judgment (Dr. John Coluccy and Ducks Unlimited, personal communication [unreferenced] 2024). Species seasonality, distribution, and behavior were determined from the Cornell Lab of Ornithology (Cornell 2024). Species' preferred water depths were determined from previous studies and

Table 1. Waterfowl and waterbird species used in the model, with preferred foraging depths and seasonality in the Maumee River Watershed, United States (Fredrickson and Reid 1986; Fredrickson and Dugger 1993; Dr. John Coluccy, personal communication [unreferenced] 2024)

Common Name	Scientific Name	Behavior	Preferred Depths (cm)	Seasonality	Months
Blue-winged Teal	*Spatula discors*	Dabbler	13 – 20	Breeding	Apr – Aug
Ring-necked Duck	*Aythya collaris*	Diver	51 – 183	Migration	Sep – Apr
American Black Duck	*Anas rubripes*	Dabbler	8 – 18	Year round	Jan – Dec
Canada Goose	*Branta canadensis*	Ground forager	0 – 10	Year round	Jan – Dec
Green-winged Teal	*Anas crecca*	Dabbler	5 – 10	Migration	Sep – Apr
Wood duck	*Aix sponsa*	Dabbler	8 – 18	Year round	Jan – Dec
Mallard	*Anas platyrhynchos*	Dabbler	8 – 18	Year round	Jan – Dec
Northern Pintail	*Anas acuta*	Dabbler	15 – 25	Migration	Sep – Apr
Northern Shoveler	*Spatula clypeata*	Dabbler	18 – 28	Migration	Sep – Apr
Pied-billed Grebe	*Podilymbus podiceps*	Diver	25 – 36	Breeding	Apr – Aug
American Coot	*Fulica americana*	Diver	28 – 41	Breeding	Apr – Aug
Redhead	*Aythya americana*	Diver	33 – 305	Year round	Jan – Dec
Ruddy Duck	*Oxyura jamicensis*	Diver	41 – 508	Breeding	Apr – Aug
Virginia Rail	*Rallus limicola*	Prober	0 – 5	Breeding	Apr – Aug
Long-billed Dowitcher	*Limnodromus scolopaceus*	Prober	5 – 10	Migration	Sep – Apr
American Bittern	*Botaurus lentiginosus*	Stalker	0 – 10	Breeding	Apr – Aug
Wilson's Phalarope	*Phalaropus tricolor*	Dabbler	3 – 23	Breeding	Apr – Aug
Great Blue Heron	*Ardea herodias*	Stalker	10 – 28	Year round	Jan – Dec
Sandhill Crane	*Antigone canadensis*	Prober	0 – 20	Breeding	Apr – Aug

evaluations (Fredrickson and Reid 1986; Fredrickson and Dugger 1993), as well as via personal communication with Dr. John Coluccy, Director of Conservation Planning for Ducks Unlimited (unreferenced 2024).

3.2 Phosphorus Retention and Waterfowl Habitat Modeling Tool

We applied the modeling approach described above to a case study for the MRW via a spreadsheet-based tool for use by wetland designers and managers in the region. Accordingly, the modeling tool is designed to use widely available meteorological and ecological data and representative of wetlands in the MRW. The sections that follow describe the setup and functionalities of the modeling tool.

3.2.1 Hydrologic Sub-model Spreadsheet Setup

We chose a representative precipitation gauge within the MRW to generate simple climate scenarios and stress tests to examine relative performance of wet, dry, and average precipitation years. To provide monthly precipitation inputs, we chose the USC00334551 gauge in Lima, Ohio, United States, for its long period of record (1901 – 2024). Precipitation regimes from 1902 – 2022 were analyzed to identify representative average (2006), wet (2015), and dry (1963) years.

We estimated daily surface inflow that was aggregated on a monthly basis using daily precipitation data and site-specific NRCS curve numbers based on hydrologic soil group D with row crop agriculture (the dominant soil type and land use across this region), which was adjusted based on wetland to watershed area ratios. Wetland area scenarios were based on a percentage or fraction of the incoming watershed area that the spreadsheet user would enter. This is a common rule-of-thumb method used to size wetlands for pollutant management. (Ducks Unlimited criteria deem that 0% – 2% of the watershed area is ideal for wetland P retention [Ducks Unlimited, personal communication (unreferenced) 2023], whereas others have said 2% – 7% is ideal [Verhoeven et al. 2006]). We chose a watershed area of approximately 2 km^2 across all scenarios for consistency, and wetland areas were subsequently tested on the range of 1% – 10% of this value (0.02 km^2 – 0.2 km^2), which is a representative range for the size of wetlands on agricultural lands in the MRW (Ducks Unlimited, personal communication [unreferenced] 2023).

Water depths acted cumulatively from month to month, i.e., the previous month's water balance informed the next month's water balance. The model assumed that no P retention or release occurred at a water depth of zero, and release was quantified when calculated retention values were negative. Water depths were assumed to be equal throughout the wetland, including at the outlet, given the absence of detailed microtopographic data and additional complexity that accompanies spatially explicit P retention modeling at that scale. Final water depth was determined largely by the outlet structure acting as a boundary condition in accordance with 4 management scenarios. One management scenario was a passive management scenario, where a stoplog structure was set to a constant maximum height of 2.0 m. (Above this, the water depth is unlikely to be classified as a wetland and is more likely to be a pond.) We developed 3 active management scenarios: one dynamic management scenario and 2 static management scenarios. The dynamic active management scenario (referred to as Active 1) represents outlet structure management for flooding of up to 1.0 m during waterfowl hunting season (e.g., September – January), with a gradual drawdown to 0.10 m in the springtime to support foraging. The 2 static management scenarios (referred to as Active 2 and Active 3) represent a case in which the outlet structure is managed for consistent hydrology. We set the depth for Active 2 at 0.20 m and for Active 3 at 0.10 m to compare performance for P retention and habitat benefits, as these water depth ranges are known to support dabbling duck foraging. Water depths informed hydraulic loading rates in the k-C model along with simulated detention times.

3.2.2 Phosphorus Retention Sub-Model Spreadsheet Setup

To generate monthly P retention values, we fit the k-C model to wetland data that were chosen from the gathered efforts of Land et al. (2016) and Ury et al. (2023) and assumed average monthly P retention values from the annual data. These 2 studies provided high-quality literature reviews on nutrient behavior in wetlands throughout the world. We filtered the data to have similar conditions as the MRW (i.e., only wetlands with agricultural watersheds were used). The final dataset contained 249 observations of wetland P fluxes, with 112 data points available for detention time. We tested the sensitivity of these data points to extreme outliers and repeated measurements from the same site in these data, and we found that the results were not sensitive.

3.2.3 Monte Carlo Simulation Approach

We used Lumivero's @RISK add-in for Excel to fit distributions to k-C model parameters (τ, k, and C_{in}) for Monte Carlo simulations. Distributions were fit to continuous functions, with the criterion for best data fit being the Akaike information criterion (AIC) (see Supplementary Material, Table S1). The @RISK software was used to run 10,000 Monte Carlo simulations for each scenario type based on fit distributions. Most results were analyzed in the interquartile (IQR) range, with some analyzed in the interdecile (IDR) range due to extreme outliers resulting from the untruncated distributions. We focused on the central tendency of the distributions, but the skew and ranges of the distributions along with value probabilities are analyzed in the sections that follow.

3.2.4 Waterfowl/Waterbird Sub-model Spreadsheet Setup

The spreadsheet is set up so that any chosen hydrologic scenario automatically informs the user which species prefer the water depth during a month that they would be likely to be found in the MRW (Table 1). Additionally, the spreadsheet tool generates information given on vegetation preferred water depths in submergent marsh, emergent marsh, and wet meadow zones based on flood tolerance and water depth ranges for marsh types in The Michigan Natural Features Inventory (MSU 2024). Plant species respond to growing season hydrologic regimes and fine scale elevational gradients; however, seasonality is not explicitly incorporated into the analysis (see Supplementary Material, Table S2). Accordingly, designs must be tempered with careful consideration of relationships between plant assemblages (including invasive species) and seasonal hydroperiod.

3.2.5 Modeled Scenario Runs

We ran a total of 12 main scenario types with the Monte Carlo simulation approach: 3 representative wet, dry, and average precipitation years, and 4 management scenarios as previously described. Additionally, 10 wetland-size scenarios were analyzed for the average-year climate scenario with passive management for consistency. This scenario is considered representative of current, on-the-ground management in this region.

We ran several trials of test scenarios to make sure that the model was reporting reasonable results. The form of the k-C model (Eq. 2) assumes that P retention efficiency will increase with decreasing HLRs, and that negative retention (or release) occurs with negative rate constants. We made sure model responses adhered to the mathematical properties of the k-C equation. We also ensured that retention values aligned with those reported in the literature (Land et al. 2016; Ury et al. 2023), where median P retention efficiencies typically ranged from 30% – 45% and rates averaged 2.0 g-P/m2*y. Additionally, k-values aligned with data extracted from other large wetland datasets (Kadlec and Wallace 2009), with a shift in our data to predict more release. Our median values also aligned with Kadlec and Wallace's (2009) 40th percentile values, but our 0th percentile values predicted far more release.

4. Results and Discussion

4.1 Results

Modeled scenarios indicated that P retention efficiencies and rates have opposite relationships to water depth (Figure 3). P retention efficiency decreases asymptotically with water depth whereas P retention rates increase asymptotically with water depth.

From month to month in all climate scenarios, active management of 0.10 m of water depth (Active 3), which corresponded to a median HLR of 0.34 m/month and a

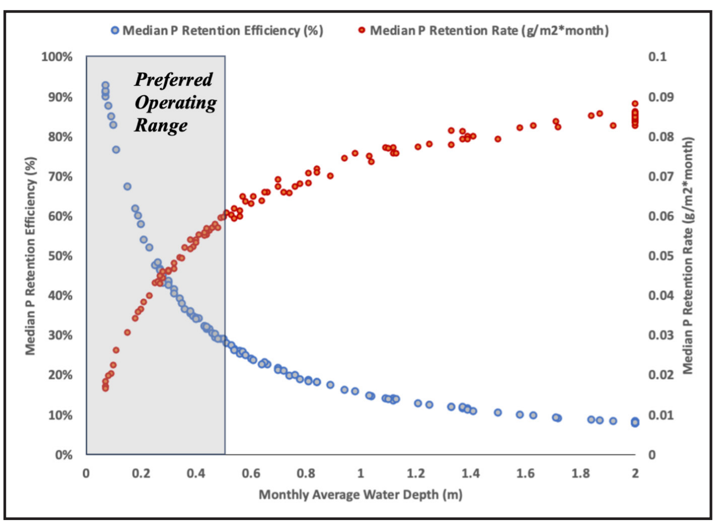

Fig. 3 Inverse relationship between P retention efficiency and P retention rates relative to wetland water depth, where <0.5 m indicates an operating range with both lower HLRs and suitable water depths for waterfowl, waterbirds, and vegetation.

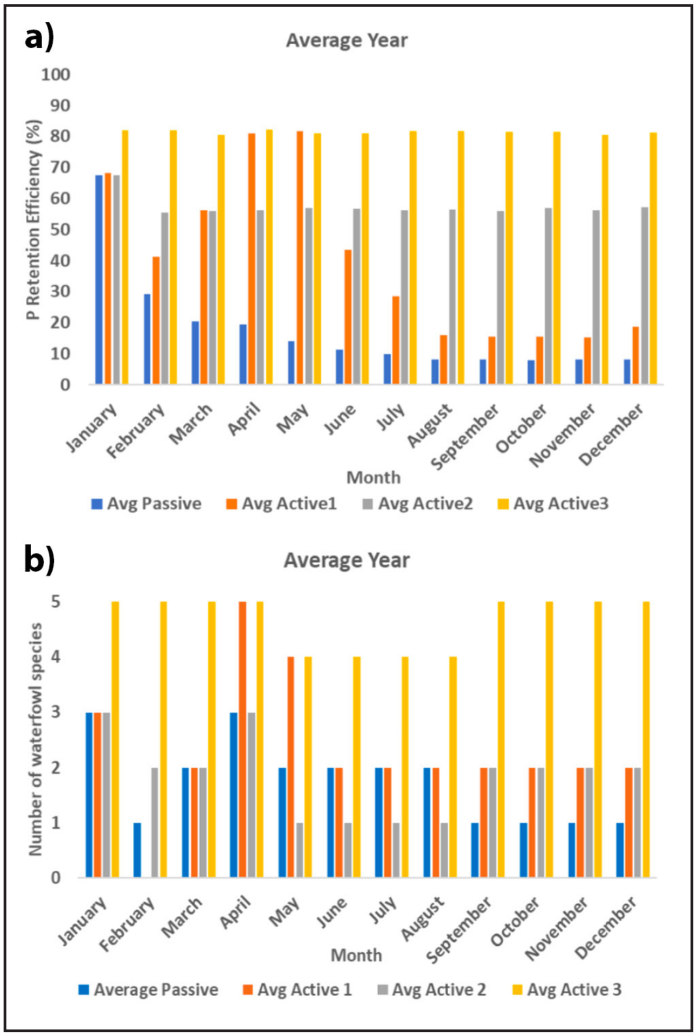

Fig. 4 (a) Monthly phosphorus retention efficiency and (b) waterfowl species richness under varying management scenarios.

PLR of 0.068 g/m^2*month in the IQR, achieved the best results for both P retention efficiency (Figure 4a) and waterfowl habitat provisioning (Figure 4b). However, when looking over the entire year at management and climate scenarios, dynamic active management (Active 1) performed the best for waterfowl and waterbird habitat provision while still providing appreciable relative P retention rate benefits (Figure 5a). Additionally, dynamic active scenarios (Active 1) supported the greatest number of plant species, which were assessed separately.

A general trend across wetland size scenarios emerged in which waterfowl, waterbird, and vegetative species richness were all generally better supported by increasing wetland per watershed area (Figure 5b). Species richness for waterbirds and waterfowl effectively doubles when going from 2% to 6% (4 ha – 12 ha), and vegetative species richness reaches a cap at the 3% mark. P retention rates decreased with increased wetland area ($R^2 = 0.95$), while increases in P retention efficiency tended toward diminishing returns past the 7% mark in analysis of varying water depth series. These diminishing returns were less evident at increased runoff depths.

Our model underpredicted runoff depths, likely due to tile drainage being unaccounted for, which presents the potential for wetlands to be sized larger than 7% without diminishing returns.

However, when we accounted for the increasing area in P retention rates, the total mass of P retained increased (Figure 6). Increased wetland size appeared to not have any negative consequence in terms of increased P release (or increased loading of unretained P), as P outflows remained stable for wetland to watershed area ratios exceeding 3% (Figure 6). Lower water depths (~0.5 m and below) also began to exhibit much higher probabilities of P retention around the median operating range for P retention efficiency in wetlands (Figure 7a).

However, the probability of P release remained stable and consistent across water depths (IDR = 21% and IQR = 4%). Skewing occurred with P retention distributions when data were left unfiltered, with the lowest water depths tested (0.03 m) having a strong negative skew toward high P retention efficiency, and a less negative skew for the highest water depth tested (2.0 m). When we filtered data in the IDR, skews became moderately negative at 0.03 m and slightly positive at 2.0 m, which coincide with the major jumps in probabilities demonstrated in Figure 7a.

Despite the promising results of high P retention at lower water depths, the potential amount of P that could be released increased drastically, with both percent P release and release rate increasing non-linearly at lower water depths (Figure 7b). Though these maxima were unlikely to happen (distributions were skewed so that lower probabilities were associated with maximums and near-maximums), this represents an additional tradeoff that is discussed further below.

Overall, model results indicated that lower (<0.5 m) water depths, corresponding to lower HLRs, larger wetland sizing, drier climate years, and active management, generally had the highest potential to simultaneously achieve both P retention and waterfowl/waterbird habitat objectives. Direct tradeoffs occurred when considering P retention rates vs. P retention efficiency, which subsequently revealed direct tradeoffs between P retention rates and waterfowl/waterbird habitat suitability. Tradeoffs with waterfowl/waterbird

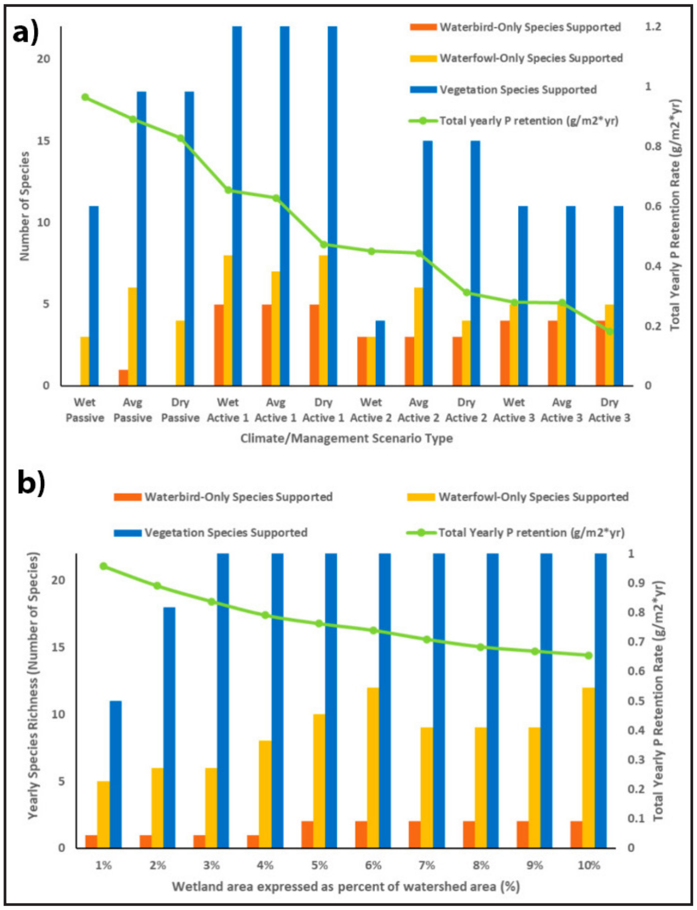

Fig. 5 Waterfowl, waterbird, and vegetation species richness over the entire year, demonstrating tradeoffs with P retention rates (a) under climate and management scenarios and (b) under various wetland sizes.

habitat suitability and P retention changed depending on timescale and species prioritization.

4.2 Discussion

In the MRW, wetlands are typically passively managed and sized at <12 ha and <2% of the contributing watershed area (Ducks Unlimited, personal communication [unreferenced] 2023). The results from this case study indicate that these common design and management practices are not robustly serving waterfowl/waterbird habitat and P retention objectives.

Model simulations indicated that dynamic, active management of water depths from 0.10 m – 1.0 m has the potential to reduce tradeoffs between waterfowl/waterbird habitat suitability and P retention rates, while larger wetland sizing of at least 2% – 7% of the incoming watershed area increased P retention efficiency, total P retention, and generally increased species richness while balancing tradeoffs with P retention rates. However, management (Figure 5a) appears to have a larger effect on habitat suitability and P retention as opposed to wetland area (Figure 5b). Positive outcomes related to increased wetland size and lower water depth management appear to be primarily driven by lower HLRs which influence P retention. Lower water depth management (<0.5 m) coincides with suitable water depths for waterfowl, waterbirds, and vegetation and show the potential to optimize between P retention efficiency and rates (Figure 3).

It is widely recognized that increasing P loading rates correspond to increasing P retention rates up to some threshold, with lower retention efficiencies as a consequence (Richardson et al. 1996). P loading rates recommended by wetland design experts have held steady over the decades in the range of 0.5 g-P/m^2*y – 5.0 g-P/m^2*y, with the lower end of this range generally recommended for biological diversity and system stability (Richardson et al. 1996; Mitsch et al. 2014; Mitsch and Gosselink 2015). The results of the case study aligned with this metric, with a determined threshold efficiency from 120 data points (10 model simulations for 12 months) corresponding to median P loading rates of 0.56 g-m^2*y – 4.1 g-m^2*y for water depths of 0.07 m – 0.5 m. Therefore, wetland sizing and depth management scenarios likely have more to do with desirable P loading rates on a case-by-case basis, as opposed to design rules of thumb.

4.2.1 *Climate Scenarios*

Climate models in the MRW predict increased evapotranspiration and precipitation, resulting in drier years which are predicted to decrease the mobility of P on the landscape (Kalcic et al. 2019). The findings from our case study showed similar results: In drier years P retention rates were minimal and P retention efficiency peaked, thus resulting in less loading of P on the landscape. However, drier years also presented the threat of larger amounts of P being released (Figure 7b). Because the model was fed with empirical data, very low water depths (<0.1 m) could be demonstrating wetland P release behavior under excessively dry conditions. Under dry conditions, wetland soils are oxidized and encourage the activity of aerobic microbes that increase organic matter decomposition rates, resulting in P release from this broken-down organic matter upon rewetting (Reddy 1983; Aldous et al. 2007; Bostic and White 2007; Kadlec and Wallace 2009). Dry periods also impact the crystallinity of minerals associated with P storage, potentially impacting P release upon rewetting.

Wet- and average-year scenarios performed similarly across management scenarios, but wet-year scenarios yielded the highest P retention rates for all management

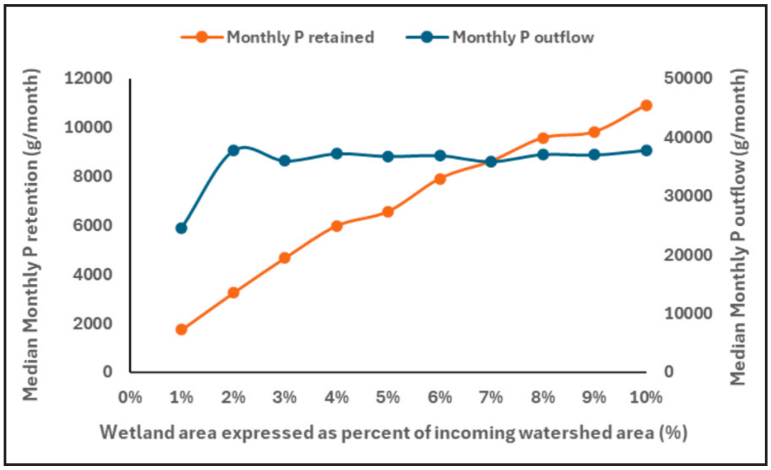

Fig. 6 Median amount of P retained (g/month) and amount of unretained P versus wetland area expressed as a percent of the incoming watershed area.

scenarios and lowest P retention efficiencies (Figure 5a). Increased HLRs, and thus, P loading rates, during wet years likely accounts for the decreased efficiency of wetlands to retain P. With climate change resulting in increased precipitation *and* increased evapotranspiration in the MRW, insights from our wet- and dry-year scenarios can become applicable to adaptive management and design of wetlands in the MRW.

Average-year scenarios appeared to benefit waterfowl and waterbird species the most (Figure 5a). This makes sense because waterbirds and waterfowl tend to have highly specific ranges for preferred foraging depths, and so any scenario that is too wet or too dry would be nonideal (Table 1). Actively managing wetlands is one proposed solution to mitigate the effects of climate change on P retention and waterfowl/waterbird habitat suitability.

4.2.2 Management Scenarios

In minimizing tradeoffs, dynamic active management was the most effective strategy among the management scenarios tested in this case study. Dynamic active management balanced both P retention efficiency and P retention rates, and provided the most suitable habitat for waterfowl, waterbird, and vegetation species throughout the year. Because the dynamic active management scenario tested was with just one type of drawdown series, it can be tailored with adaptive management.

It is unsurprising that dynamic depth management resulted in the highest species richness for waterfowl and waterbird species over the entire year. Other studies involving the same waterfowl and waterbirds have concluded that managing with a drawdown series is the best strategy for biodiversity (Baschuk et al. 2012). Additionally, drawdown routines are a common way that some publicly owned wetlands are managed for waterfowl use (Ducks Unlimited, personal communication [unreferenced] 2023). The high labor costs associated with actively managing wetlands can be counterbalanced by including simple monthly flooding and drawdown routines in landowner contracts. More intensive active management styles can be employed in those wetlands which are specifically designed and optimized for multiple objectives, in which intensive monitoring can inform adaptive management.

Passive management scenarios resulted in the highest P retention rates, likely because these scenarios generated overall higher water depths (typically 1.0 m and above) and thus higher HLRs and P loading rates. Although higher P loading rates result in higher P retention rates, they reduce the efficiency of wetlands to retain P. The finding that higher water depths coincide with lower P retention efficiency appears somewhat consistent with the literature (Richardson and Craft 1993; Kadlec and Knight 1996; Parsons et al. 2017). While consistent, low depth management of 0.10 m – 0.20 m (scenarios Active 2 and Active 3) appears attractive to increase P retention efficiency, especially since this is more or less another form of passive management, dynamic management allows the risk of unexplored depth effects to be reduced.

4.2.3 Sizing Scenarios

The results of our case study support sizing wetlands at least 2% – 7% of the incoming watershed to account for potential diminishing returns in wetland areas larger than 7% of the watershed. Wetlands of this size effectively doubled waterbird and waterfowl species richness (from one to 2 species and from 5 to 12 species, respectively) and offered balanced average P retention efficiencies and rates of 31% and 0.07 g-P/m^2*month. Sizing wetlands by this criterion offers a much wider range of options than operating on the 0% – 2% sizing criterion that is prevalent in practice. Reviews of P retention in wetlands have stated that sizing wetlands at least 2% – 7% of the incoming watershed is a good metric supported worldwide to increase chances of P retention (Verhoeven et al. 2006; Parsons et al. 2017), but other studies have argued that small wetlands (<0.05 ha) may have a disproportionately large role in landscape nutrient processing (Cheng and Basu 2017). Thus, the benefits of small wetlands should be considered in a systems context, even if our case study and other studies have found the opposite effect (Kadlec and Wallace 2009). A case-by-case analysis is recommended before operating on any rule of thumb, and multiple factors need to be considered such as

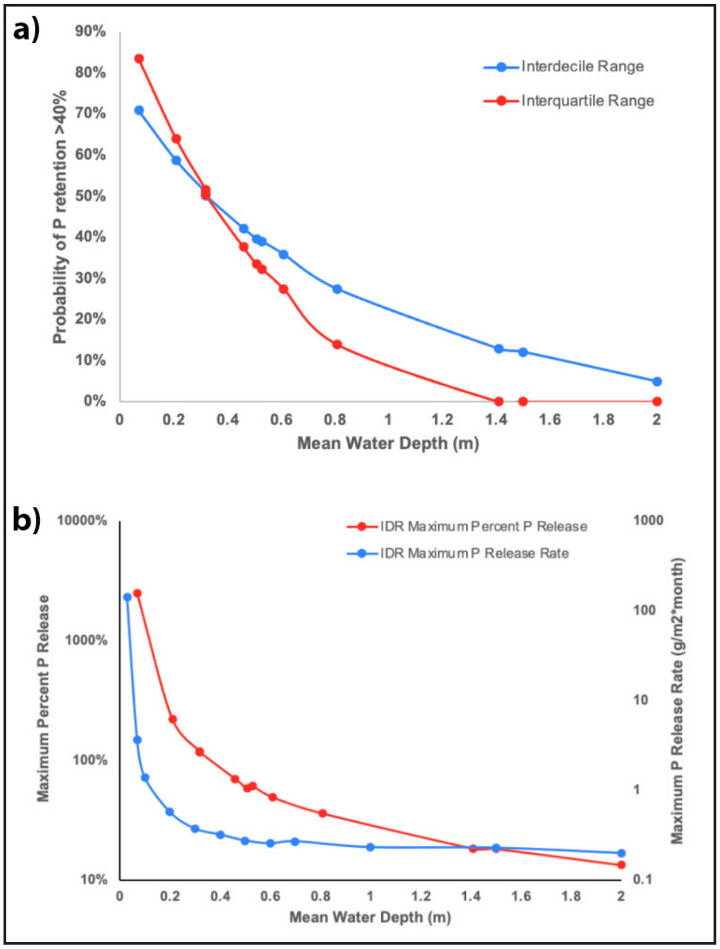

Fig. 7 Data filtered in the IDR and IQR demonstrating (a) probability that wetlands retain >40% of inflowing P over varying water depths and (b) the maximum amount of P released as a percentage and as a rate over varying water depths.

upland connectivity, watershed type, and P loading rates. Given the value of farmland in the MRW, restoring many small wetlands may be the most practicable approach for increased P retention in this region.

Our findings that increased wetland area corresponded with increased waterbird species richness are consistent with other studies (Hamza and Selmi 2018; Cerda-Peña and Rau 2023). However, it has been asserted by Ducks Unlimited, a major leader in wetland conservation in North America, that "[s]tudies show unequivocally that 10 one-acre ponds support three times more breeding pairs of ducks than one 10-acre pond" (Walker 2013). Our model did not account for breeding pair density but instead focused on species richness, which informs wetland restoration for at-risk species. This is yet another factor that should be considered in sizing wetlands given the potential for direct tradeoffs to occur between species richness and abundance.

4.2.4 Future Work and Recommendations

In the course of this research and case study, we identified several opportunities for refining the reduced complexity model. For example, our hydrologic sub-model does not account for groundwater, streamflow, or snowmelt inputs and outputs, and it is limited in scale of application given the need to input a single representative rainfall regime. While we found these simplifications suitable for the purposes of this study, we would recommend improvements to more accurately resolve wetland water balances when applying this methodology to specific wetlands.

The k-C model has many shortcomings, including the plug-flow assumption and a lack of mechanistic detail on soil-water-plant interactions, but is still the most widely used treatment wetland pollutant model for its reduced complexity and lack of input parameters (Babatunde et al. 2011). Additionally, the k-C model (Kadlec and Knight 1996) is recommended for use on an annual basis since it cannot account for the stochastic seasonal variability from microbial and vegetative pools (Reddy et al. 1999; Kadlec and Wallace 2009). We used the k-C model on a monthly basis but recommend that future research explore the benefits of incorporating more mechanisms in the model to account for seasonal stochasticity. Seasonal data varies from wetland to wetland so much that data reported in large-scale wetland literature reviews do not show strong correlations with seasonality and P retention (Audet et al. 2020; Page et al. 2023; Ury et al. 2023). Additionally, there is mixed evidence of temperature effects on P retention in wetlands (Kadlec and Reddy 2001; Bai et al. 2017). This lack of certainty influenced our decision to not include seasonal or temperature effects in the model. High-quality monitoring data could help to close these gaps.

Accounting for the habitat suitability correlation with vegetation types as well as including vegetative P uptake as a stochastic pool and a function of vegetation characteristics could advance the model, though it has generally been accepted that vegetative density is a more important factor in P retention than species type (Davis 1995), with thresholds beyond which increased vegetative density does not offer increased benefit of P retention (Sabokrouhiyeh et al. 2017). Increasing vegetative density should be tempered with considerations of wildlife preferences of open area to cover ratios.

While P is the primary cause of HABs in this region, we emphasize the importance of jointly managing both nitrogen (N) and P, as recent studies have concluded that such an approach could reduce the overall toxicity of blooms in Lake Erie (Paerl et al. 2018; Hellweger et al. 2022). Additionally, dissolved reactive P loadings (the biologically available form of P that encourages HABs) have been increasing in the MRW (Reutter 2019). Large-scale data on dissolved reactive P and N retention in wetlands exist (Land et al. 2016; Ury et al. 2023) and should be further explored in future versions of this model.

Lastly, projections based on long-term P retention behavior found that restoring 40,000 ha of wetlands in the Great Black Swamp could potentially reduce annual P loading to Lake Erie by 37% (Mitsch 2017), contributing significantly to meeting TMDLs set for the Maumee River (EGLE et al. 2021; OHEPA 2023). Our modeling efforts indicated a median performance, across all scenarios of 0.79 P/m^2*y, meaning to meet the same 37% load reduction, we would need 120,000 ha restored, presenting a challenge and opportunity to effectively reduce HABs in Lake Erie.

5. Conclusion

There have been many calls for "engineering design guidance" to fill knowledge gaps in the standardization of practices for nature-based solutions (van Rees et al. 2023). Developing balanced guidance that is neither too prescriptive nor too vague is essential for the success of multi-purpose nature-based solution projects, including those involving wetlands. The reality of wetland management and rapid, large-scale wetland restoration is that practitioners are unlikely to use highly complex models and tools to optimize wetland designs and operations for waterfowl habitat and P retention benefits. Parsimonious models and tools represent a pragmatic step toward more robust projects that effectively meet multiple wetland objectives in a changing operating environment. The intermediate complexity model and tool developed in this study for assessing wetland P retention and waterfowl habitat suitability demonstrated that simple changes to design and management practices—increasing wetland sizing to at least 2% – 7% of the incoming watershed on a case-by-case basis and using active dynamic water level management—can enhance both water quality and habitat benefits while mitigating the potential effects of climate change on P retention and waterfowl. The potential for the model and tool to help practitioners predict and improve designs for wetland P retention and waterbird habitat would be enhanced by more high-quality monitoring data. Development and application of pragmatic tools for multi-objective wetland design and management is an important step towards simultaneously supporting wildlife conservation and reducing the risk of eutrophication and harmful algal blooms.

Supplementary Material

The online version of this article contains a link to supplementary material that includes: **Table S1:** Continuous distributions for k-C model variables with modeled vs. actual data statistic comparisons; **Table S2:** Vegetation species used in model with preferred water depths.

Acknowledgments

We would like to thank the Sunshine Charitable Foundation and Ducks Unlimited (DU) for supporting this research. We would also like to thank specific members of DU's staff: Dr. John Coluccy, for his help with all things waterfowl; Brian Nicholson, for his knowledge on wetland design in the Maumee River Watershed; and Sara Burns, for her assistance in identifying research needs in the study region.

Personal communications listed as "Ducks Unlimited" came from multiple members of Ducks Unlimited's Great Lakes staff during several meetings. Citations for "Parsons et al. 2017" came from an unpublished report, "Wetland features and their role in mitigating nutrient impacts on Lake Erie: an assessment of best management practices and monitoring for wetlands," prepared by B. Parsons, A. Smith, and T. Karst-Riddoch of Hutchinson Environmental Science Ltd. for Environment and Climate Change Canada, which was provided by Ducks Unlimited.

Author Contributions Statement

Conceptualization: MC, BB; methodology: MC, BB; data analysis: MC; writing original draft: MC; review/editing original draft: BB; supervision: BB; funding acquisition: BB. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest Statement

This project was funded by the Sunshine Charitable Trust and Ducks Unlimited.

Data Availability Statement

Supporting data can be accessed from FigShare, an open-access data repository, at this link: https://doi.org/10.6084/m9.figshare.26364430

Related Publication Statement

This paper was submitted to the University of Georgia as one chapter of Madlyn Carpenter's master's thesis. The thesis has a delayed release of 2 years for publishing to the University of Georgia to avoid potential copyrighting issues with publishing to *JEED*.

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