

INFORMING MULTI-OBJECTIVE WETLAND DESIGN FOR PHOSPHORUS REDUCTION AND WATERBIRD HABITAT IN THE WESTERN LAKE ERIE BASIN: A CASE STUDY

by

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(Under the Direction of Matthew V. Bilskie & Brian Bledsoe)

ABSTRACT

Constructed wetlands provide valuable ecosystem services such as phosphorus (P) retention and waterbird habitat, particularly in agriculturally dominated watersheds like the Western Lake Erie Basin. This study applied a parsimonious model (MARSH) to evaluate tradeoffs between these services under various management scenarios and wetland sizes across a range of future climate conditions while incorporating external hydrology data to test model performance versus more complex methods. Results indicate that achieving both P retention and habitat objectives in wetland design depends less on wetland size and more on management objectives; static management of shallow water depths (~ 0.1 m) consistently maximizes P retention efficiency ($67.9 \pm 3.2\%$), while dynamic management enhances biodiversity (37 waterbird species supported). Adaptive management strategies are vital for balancing ecosystem service co-provision. MARSH demonstrated reliability as a reduced-complexity decision-support tool for the engineering design of wetlands, offering comparable results to more complex alternatives. These findings contribute to improved multi-objective wetland design guidance, promoting effective restoration practices and supporting efforts to simultaneously mitigate eutrophication and enhance waterbird habitat.

INDEX WORDS: CONSTRUCTED WETLANDS, NUTRIENTS, PHOSPHORUS
RETENTION, WATERFOWL HABITAT, MULTI-OBJECTIVE
DESIGN, TRADEOFF ANALYSIS

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DEDICATION

I dedicate this thesis to my grandmother, Lillian Turner Rice. I love you and miss you every day.

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I want to acknowledge that data for this research was collected and its accompanying project will be constructed on the traditional lands of the Bodwéwadmí, Meškwahki·aša·hina, Myaamia, Kaskaskia, Kiikaapoi, and Peoria peoples, who have stewarded this land throughout the generations. May we follow in their footsteps by taking proper care of this land and its resources.

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CHAPTER 1

INTRODUCTION

Nutrients such as nitrogen (N) and phosphorus (P) are fundamental to life at all levels of the trophic cascade. As the global population continues to grow, more and more fertilizer containing these nutrients is applied to agricultural lands for the purpose of increasing crop yields to sustain the ever-increasing number of hungry mouths. While plants are capable of and dependent on taking up N and P as they grow, over-application of fertilizers can lead to excess nutrients in the environment that cannot be fully assimilated by crops. Excess inputs of N and P into surface waters have long been recognized as a driving force of eutrophication in aquatic ecosystems.

Residual N and P from agricultural operations can leach into groundwater or be transported by storm events into streams, lakes, estuaries, and eventually the ocean. When large amounts of these nutrients are introduced to aquatic systems whose productivity is otherwise limited by low concentrations of such nutrients it enables and promotes the rapid growth of plants and algae. The proliferation of certain types of toxin-producing phytoplankton, such as blue-green algae (cyanobacteria), is referred to as a harmful algal bloom (HAB). Toxins produced by HABs are potent and can harm aquatic animals and even people if they drink or recreate in the affected water (Smyth et al., 2022). These blooms and subsequent oxygen-consuming die-offs of the algae are severely impacting some of the world's most culturally, economically, and ecologically important lakes (Paerl et al., 2016). Among those affected is Lake Erie, one of the five Laurentian Great Lakes on the border of the United States and Canada, comprising the largest freshwater system on earth.

Natural infrastructure, such as treatment wetlands, is becoming increasingly desirable due to their capacity to provide multiple benefits that are sometimes limited by traditional infrastructure or practices. Due to the biogeochemical processes unique to wetlands, they can provide a valuable ecosystem service (ES) through of N and P processing and retention, alleviating downstream nutrient loads. Restoration of destroyed and deteriorated wetlands is a common best management practice to ameliorate environmental problems such as eutrophication and HABs in downstream ecosystems, such as in the agriculturally-dominated Western Lake Erie Basin (WLEB).

Wetlands can provide a suite of benefits from floodwater storage to carbon sequestration, but notably, they are vital ecosystems that serve as valuable foraging, wintering, and breeding habitat for waterfowl and other waterbirds (Soulliere et al., 2017). These birds serve as indicator species for ecosystem health due to their place higher in trophic cascades. Additionally, their presence can allow for recreational and provisional ES in wetlands, such as birdwatching and hunting. Historically, the WLEB contained a massive expanse of wetlands larger than the Everglades known as the Great Black Swamp, but 95% of its original area has been lost due to ditches and drains constructed for improving crop yields in the nutrient-rich but otherwise saturated soils (NOAA, n.d.). This extensive conversion of wetlands into intensive agricultural production has decimated waterfowl populations and left the region with few natural defenses against problems such as eutrophication.

While wetland research is well-established in the literature, the focus is either on nutrient retention capabilities or the provision of habitat for wildlife, rarely exploring tradeoffs between these functions aside from degradation of water quality by way of nutrients excreted by waterbirds (Manny et al., 1994). Efforts to design constructed wetlands for improvement of water quality

(hereafter “water quality wetlands”) are often uncoupled from the design of wetlands whose primary function is to provide habitat for wildlife (hereafter “wildlife wetlands”). In practice, wetland designers commonly follow “rules of thumb” to meet water quality improvement goals, and those who manage these restored wetlands tend to be private landowners with singular objectives (Carpenter, 2024). For example, in 2021 the US Army Corps of Engineers (USACE) finished construction of a water quality wetland in Defiance, OH, to remove P from Colwell Creek, a tributary of the Maumee River that eventually leads to Lake Erie. Phosphorus is removed by means of diverting flow through a series of four wetland cells prior to discharging the effluent back into the creek. The project focused entirely on P removal with no extra consideration for potential wildlife habitat benefits commonly provided by wetlands (LimnoTech, personal communication, 2024). As a result, while the wetland is very effective at retaining P loads and preventing the transport of those nutrients downstream to Lake Erie, there is minimal waterfowl presence at the site.

The disconnect created by designing constructed wetlands to prioritize one ES without consideration of others often results in missed opportunities for providing multiple benefits by a single site. One study has shown that waterfowl populations are positively correlated with ammonia (NH_4^+), nitrite (NH_2^-), organic N, and total phosphorus (TP) concentrations measured at wetland outlets (Loyn et al., 2023), indicating that water quality wetlands and habitat wetlands can be one in the same if designed with both functions in mind. With limited land available for the construction of wetlands due to constraints such as agricultural operations and residential communities, ensuring the provision of multiple ES by individual wetlands is paramount to improving the multi-objective wetland design framework and acting as good stewards of the land available for these projects.

Ducks Unlimited (DU) is a North American nonprofit organization, the global leader in wetland and waterfowl conservation, and the sponsor of this project. They are particularly interested in multi-objective wetland design for the dual purposes of water quality improvement and habitat provision. DU is working alongside the Michigan Department of Natural Resources and the same environmental engineering firm that helped design the Defiance, OH water quality wetland described previously (hereafter “the Contractor”) on a pilot project for both objectives. The project, referred to as the WLEB Project, involves restoration of agriculturally unproductive land in Lenawee County, MI to create a water quality wetland that also provides adequate habitat for waterfowl and waterbirds. The author of this paper is a member of the recently instituted fellowship between DU and the University of Georgia (UGA), and is working alongside DU and the other members of this project to improve design of constructed wetlands for both water quality and habitat suitability purposes.

The goal of this project is to help guide wetland design towards the provision of multiple benefits by providing practitioners with simple tools and approaches that can be used to more robustly analyze and consider ES tradeoffs across a range of future conditions. A model for determining TP retention and waterfowl habitat suitability was first developed by Carpenter (2024). Throughout the design process, this study will follow alongside the work of DU and the Contractor, using and building upon Carpenter’s model to analyze alternative design methodologies. To attain the goal of improving wetland design guidance, this report will 1) analyze tradeoffs in ES for design methods to inform a robust wetland design to best achieve both water quality and habitat goals at the WLEB Project site under a wide range of possible future conditions, 2) determine if reduced-complexity models can provide comparable results to more complex

hydrologic models for wetland design purposes, and 3) make recommendations on how to improve the multi-objective wetland design toolbox for application at other sites.

CHAPTER 2

METHODS

The primary tool used for analyzing ES tradeoffs in the design of the WLEB Project is the Model for Assessment of Retention and Suitable Habitat (MARSH). This section will provide background on how the original version of MARSH operates before detailing how it was modified for this study. It will also describe how inputs were chosen and used within MARSH to determine TP retention and waterfowl habitat suitability. Finally, techniques for comparison of these results in addition to those provided by the Contractor will be outlined. Figure 1 provides a visualization of the methodological steps of this report in the form of a flow-chart; the first steps are at the top of the chart and follow the arrows downward.

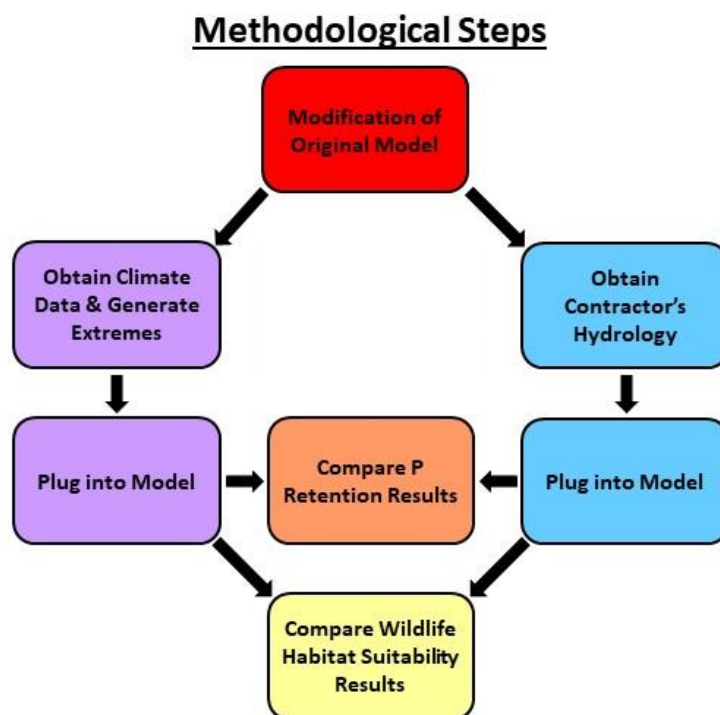


Figure 1: Flow chart depicting methodology of the project. First, the original version of MARSH. The next steps are shown in purple and blue. Once data has been plugged in, P retention estimates from on-board and external hydrology will be compared. Habitat suitability results from the purple and blue paths will be compared last.

2.1 Background on MARSH

The original version of MARSH is a reduced-complexity model for determining tradeoffs in multi-objective wetland design in the WLEB. It comprises two primary sub-models – one for determining P retention and another for waterbird habitat suitability. While MARSH was originally developed for use within the Maumee River Watershed, the WLEB Project is located in the directly adjacent River Raisin Watershed, both of which drain into western Lake Erie. Due to their close proximity, the TP retention sub-model applies seamlessly to this project without requiring alterations to its rudimentary functions. The waterbird habitat suitability sub-model was modified to contain a larger number of species, all of which are known to frequent Lenawee County, whose location is shown in Figure 2.

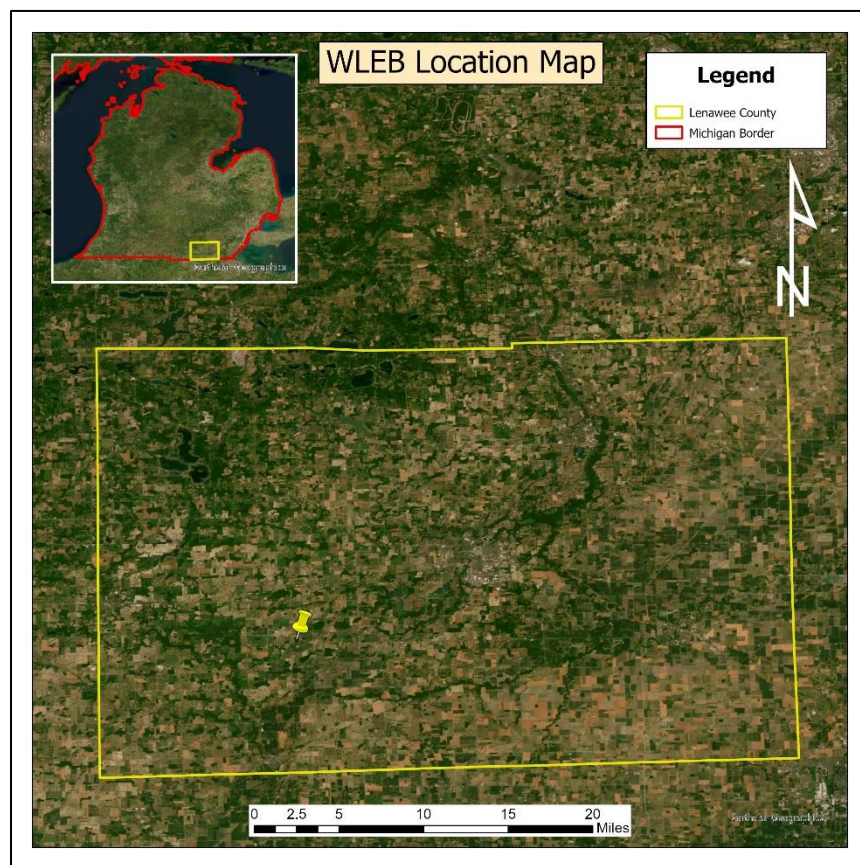


Figure 2: Location of the WLEB Project site within Lenawee County, MI.

MARSH accepts inputs and provides results within a Microsoft Excel spreadsheet. Given the area and curve number of the contributing watershed, alongside climate data taken from a NOAA gauge, the spreadsheet automatically generates runoff and evapotranspiration values via the SCS Curve Number (CN) and Thornthwaite methods respectively. The user can further select from an assortment of four management scenarios: managing for fall flooding and winter/spring drawdown, or maintenance of a maximum of either 2.0 m, 0.2 m, or 0.1 m mean water depth year-round (hereafter the dynamic, static 2.0, static 0.2, or static 0.1 methods, respectively). Despite their “static” moniker, the static management methods are not capable of maintaining a constant water depth – they simply ensure water depths are not deeper than the maximum values. The size of the wetland is defined as a percentage relative to the area of the contributing watershed. Each of the user’s selections and inputs are used to develop an annual water balance that informs monthly mean water depths in the wetland based on methodology from Lewis and Wieben (2008). Groundwater inputs and outputs were assumed to be negligible due to the characteristics of the hydrologic soil groups present in this region and therefore omitted, and water depth was modeled as uniform across the wetland to reduce complexity introduced by microtopographic variability. The calculated water balance informs both the P retention and waterbird habitat suitability sub-models of MARSH. For this project, a watershed area of 2648 acres was provided by the Contractor; land-use data also provided by the Contractor was used in conjunction with the CN method to determine a weighted CN of 85.12 for the entire watershed.

Phosphorus retention in MARSH follows the k-C model, a first-order removal model developed by Kadlec and Knight (1996) that estimates effluent concentrations and wetland contaminant loadings while assuming plug flow. The k-C model was fit to data on nutrient retention information collected by previous studies (Land et al., 2016; Ury et al., 2023), filtered to

include 249 wetlands similar to the study region (i.e., agriculturally-dominated watersheds) in order to generate monthly P retention values. The Excel plug-in @RISK developed by Lumivero allows for the dataset's parameters for detention time, inlet TP concentration, and areal removal rate constant to be utilized in Monte Carlo simulations to determine a range of probabilistic monthly estimates of TP retention (Carpenter, 2024).

Calculated water depth values inform a sub-model in MARSH that determines which waterbird species known to be present in the region are likely to be found within the wetland at a monthly timestep. Seasonality, distribution, and behavior of these waterbirds were obtained from the Cornell Lab of Ornithology (*All About Birds*, 2019). Waterbirds are known to occupy and prefer habitats with water depths conducive to their foraging behaviors, whether dabbling, diving, grazing, or otherwise (Baschuk et al., 2012; Soulliere et al., 2017). Water depth preferences for foraging were obtained from an NRCS report on bird diversity in wetland design and validated via personal communication with DU Great Lakes/Atlantic Regional Office (GLARO) staff members (Streever & Harrington, 1999). The calculated water depths also inform a table of vegetative species likely to be present; however, this list is dependent solely on mean monthly water depth and does not take seasonality into account.

To most accurately analyze tradeoffs in ES for the WLEB Project, enhancements were made to MARSH. Historical climate data needed to be updated to more accurately inform climate scenarios at the new site. Additional extreme scenarios were also generated for stress-testing designs under more extreme potential future conditions. To compare the TP retention outputs based on the water-balance hydrology modeled by MARSH with alternate hydrologic data provided by the Contractor, another input sheet was added to the spreadsheet to accept external hydrology as an input and convert it to a format compatible with MARSH's P retention sub-model.

Flows resulting from overtopping the wetland's channels replace runoff in this external hydrology water balance. The waterbird habitat suitability sub-model was updated to include 48 species of birds known to visit Lenawee County, the location of the WLEB Project site. The following sections will provide more details.

2.2 Obtaining Climate Data and Generating Extreme Scenarios

Climate data for informing the water balance in MARSH was obtained from the Global Historical Climatology Network – Daily version 3, available from the NOAA National Centers for Environmental Information (NCEI) database in the form of a .csv file for analysis in Microsoft Excel. The gauge used to collect data is located at station USC00200032 in Adrian, MI, which is the county seat of Lenawee County and located approximately 8 miles from the WLEB Project site. This gauge was chosen due to its close proximity to the site and its long period of record. Values from January 1, 1900 until December 31, 2023 were used for determining climate scenarios. Five years in the dataset (1908, 1916, 1919, 1924, and 1928) were omitted from analysis due to a lack of precipitation data for one or more months. The remaining 119 years of data were organized in ascending order according to inches of rainfall throughout the year. Snow was not considered in the original design of MARSH and therefore was not included in the precipitation values due to the difficulty associated with determining an accurate water balance with delayed snowmelt and subsequent runoff generated. The average annual rainfall over the entire period of record was 33.62 (SD = 5.73) inches. Each climate scenario used in MARSH (dry, wet, and average) also required daily mean temperature values for calculating ET, so years missing any of these values were not used. The year with rainfall closest to the average annual value was 1900, with a total of 33.88 inches; its precipitation and temperature data inform the average climate scenario.

Monthly precipitation patterns for each of the 10 driest and wettest years were analyzed to decide which reference years would be used as the dry and wet year scenarios, as well as the basis for generating the extreme scenarios. The generation of extreme climate scenarios was undertaken to ensure a robust design for MARSH that can appropriately examine tradeoffs over a wide range of possible future climate conditions. Figure 3 shows the variability between each year and the average values for each scenario (dry, wet, and average). The wet and average years show a distinct swell in precipitation during the growing season (defined as April – September), while the dry years are a little less variable but still appear to have their highest values during the growing season. Based on these monthly rainfall patterns, one dry year and one wet year were selected to serve as representative climate scenarios and the basis for generating the extreme scenarios.

The dry year scenario utilized data from 1930, which saw only 21.59 inches of rainfall. This year was chosen from the other top 10 driest years due to the exceptional dryness of the summer months (only 2.83 inches from July to September), which, combined with increased ET from higher temperatures, would lead to less water available for plant growth and, therefore, reduced uptake of TP via accumulation in living biomass. This would imply a lower water table, resulting in a greater exposed area, allowing for oxidation of the wetland substrate. While changes in redox potential do not directly alter P itself, it is indirectly affected by its association with elements subject to fluctuating redox conditions, such as iron (Mitsch et al., 2023). Drying of these sediments can temporarily improve P retention through the oxidation of ferrous Fe(II) to ferric Fe(III), creating sorption sites for phosphate ions (De Groot & Fabre, 1993; Kinsman-Costello et al., 2016). Aerobic conditions also allow for the precipitation of insoluble phosphates with calcium and aluminum (Mitsch et al., 2023). However, when dried and re-wetted,

this sorbed P can be released in a pulse of inorganic nutrients transported downstream in a phenomenon called the “Birch effect” (Birch, 1960).

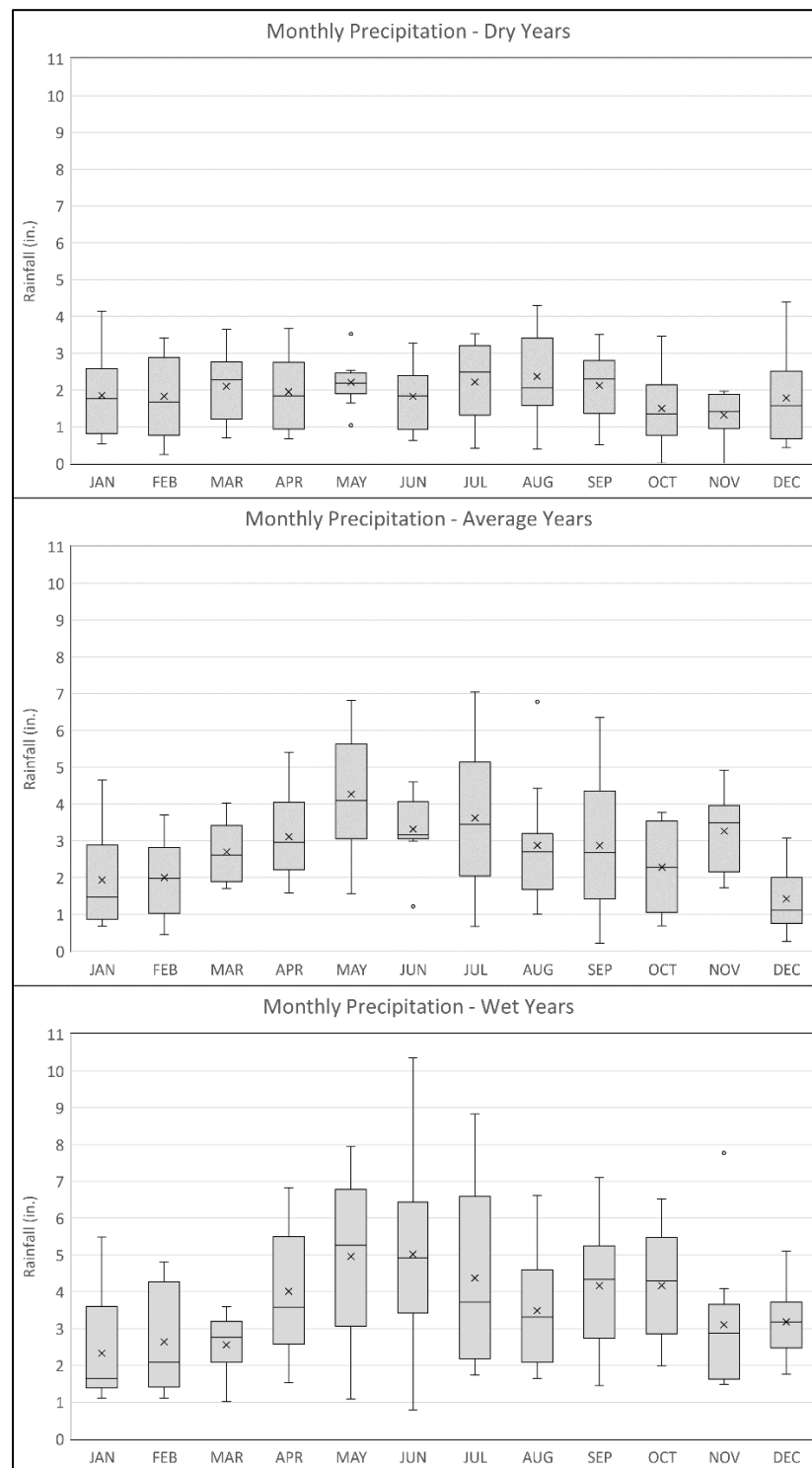


Figure 3: Box-and-whisker plots visualizing the monthly rainfall patterns of the 10 most dry, average, and wet years from the NCEI dataset.

The year 2018 had 44.45 inches of rain and was used as the wet year scenario. It was chosen instead of one of the other 10 wettest years due to the higher-than-average precipitation during October and November. These months are when temperatures in Michigan begin to drop to levels low enough to kill vegetation. Plant die-offs and subsequent input of necromass into wetlands means an increase in P influx due in part to more runoff (fewer plants to buffer flows to increase infiltration and uptake water for ET) and also the decomposition of organic matter and subsequent mineralization of previously plant-bound P into inorganic orthophosphates by microbes in the soils (Mitsch et al., 2023). The inflow of higher amounts of water into a wetland during this seasonal release of P means there is higher potential for export to downstream systems.

Based on the historical data for the dry and wet year scenarios, two extreme scenarios following the same patterns of these representative years were generated. These extreme scenarios were used as stress tests for MARSH to see how tradeoffs in P retention and waterbird habitat suitability may vary under more extreme conditions brought about by climate change. The extreme dry year scenario involves a 40% reduction in total precipitation across the growing season (May-September), with the rest of the year's precipitation exhibiting a 6.9% decrease, amounting to a total annual decrease in rainfall of 20%. This results in a total annual rainfall of 17.27 inches for the extreme dry scenario. The extreme wet year was generated using an increase of 40% over the months October-February, resulting in an increase of 7.6% over the rest of the year and total annual rainfall of 53.34 inches, a 20% increase over the wet year scenario. Additional detail for generating these extreme climate scenarios is outlined in appendix A. It is also intended to guide MARSH users in creating custom scenarios based on climate data from a different NOAA gauge.

A sensitivity analysis was conducted on both the extreme dry and extreme wet years to determine wetland mean water depth and waterbird species abundance responses to different

values of increased temperature in each scenario. Increases of 3, 3.5, and 4 °C were tested while holding management method and regime constant to compare the differences in monthly number of potential waterbird species that would be present. This sensitivity analysis indicated that the difference between these three temperature increases were minimal – evapotranspiration increased by about 1 inch per 0.5-degree Celsius increase, with a mean water depth variation of 0.27 inches maximum between the lowest and highest temperature increases. Additionally, there was no difference in the number of waterbird species supported between the increased temperature scenarios. Due to the minimal sensitivity to this testing, the daily minimum and maximum temperatures for the reference years were averaged and the resulting mean daily temperature was adjusted to be 3.5 °C warmer than the historical record for both extreme scenarios based on climate projections for the Great Lakes region (Zhang et al., 2020). The value of 3.5 °C was chosen as a middle-ground option because it fell within the predicted range of temperature increase for both mid- and late-century projections.

2.3 Phosphorus Retention Assessment

The phosphorus retention sub-model of MARSH hinges on a water balance that is informed by one of two hydrologic methods: 1) precipitation, runoff, and evapotranspiration from one of five climate scenarios informed by data from a NOAA gauge and the k-C model fit to wetland data from studies by Land et al. (2016) and Ury et al. (2023), hereafter referred to as the “MARSH method,” or 2) the results of an external Generalized Watershed Loading Functions – Enhanced (GWLFE) model run alongside precipitation and evapotranspiration, hereafter referred to as the “GWLFE method.” MARSH takes the user-specified management method, sizing scenario, and climate scenario and feeds them into @RISK to generate probabilistic estimations of total phosphorus (TP) retention in units of g/m^3 (reduction in concentration, C), $\text{g}/\text{m}^2/\text{year}$ (areal

retention rate) and retention efficiency ($C_{\text{reduction}}/C_{\text{in}} * 100\%$). This is done by running 10,000 Monte Carlo simulations and analyzing the resulting values within the interquartile range (IQR) to remove outliers resulting from untruncated distributions (Carpenter, 2024). **Error! Reference source not found.** outlines the process from inputs into MARSH to results from the model runs. Combining the ten wetland sizing scenarios (1 – 10% of watershed area) and four management methods, and counting the GWLF-E method as a sixth “climate scenario” alongside the five from the MARSH method, there are a total of 240 unique scenarios. For each of these scenarios, the average of each month’s 5,001 values in the IQR was summed across the calendar year and used as the estimated annual TP retention.

2.3.1 Making External Hydrology Compatible with MARSH

The Contractor performed hydrologic modeling at the WLEB Project site using two different methods. A 2D HEC-RAS model was used to obtain volumetric flow rate (Q) and water surface elevation (WSE) data at the wetland outlet for storms with annual exceedance probabilities (AEPs) of 1.0, 0.1, and 0.01. The GWLF-E model was utilized to model long-term flows and loading estimates for nitrogen, phosphorus, and sediments for 19 years (2005-2023). Since MARSH operates on a monthly timestep, the external hydrology input (EHI) section that was added to the program was structured to accept GWLF-E model results and convert flows to a mean depth over the wetland for use in the MARSH method of TP retention estimation.

The flow and WSE data from the provided HEC-RAS run was used to determine a flow threshold value at which any higher flows would result in overtopping of the channels at the project site and flooding into the wetland. The Contractor provided a top of bank elevation of 800.5 ft for the wetland channels. Among the three storms modeled in HEC-RAS, the 1.0 AEP storm leads to the lowest Q that results in a WSE greater than 800.5 ft; the first flow that results in a WSE higher

than this elevation was 41.7 cfs, and it was chosen as the threshold flow rate. The reason for using the 1.0 AEP storm's flow data instead of the 0.1 or 0.01 AEP storms' data was to avoid underestimating the frequency of overtopping into the wetland.

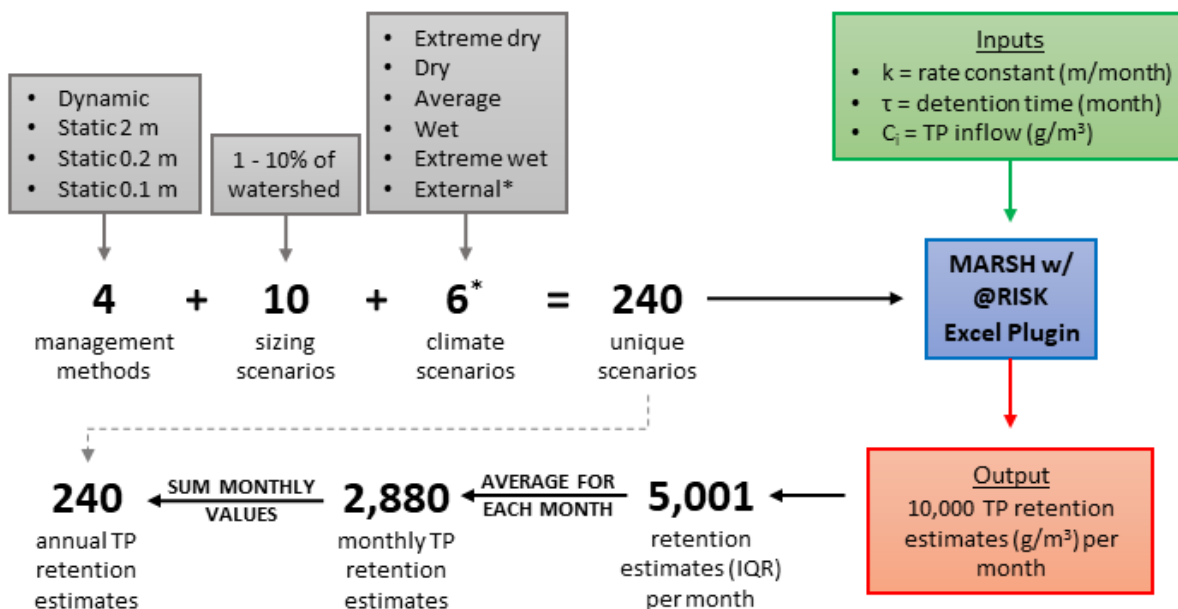


Figure 4: Flowchart of steps for determining annual phosphorus retention estimates.

The flow data from the GWLF-E model run was provided as three values for each date in the 19-year period – one for each of the three drains flowing through the project site. Since none of the drains' catchments overlap, these values were summed to determine the overall flow through the wetland on any given date over the model's time frame. Using the threshold Q of 41.66 cfs, the GWLF-E data was filtered to determine the frequency with which the wetland received flooding from the channels over the 19-year model run. Over the entire time period, there were 40 days with flows high enough to result in overtopping.

The year 2008 was chosen as the input for the GWLF-E method, as it contained the maximum instances of flooding into the wetland with six days of flows exceeding the threshold. These flows had the threshold Q subtracted from them to determine the flow rate of water into the

wetland, which was then converted into a depth over the wetland. The same water balance used in the MARSH method was used for determining monthly MWD estimates based on the GWLF-E runs, except that runoff determined by the CN method was replaced with the flood values. This MWD was then used to determine P retention and waterbird habitat suitability estimates following the same steps as in the MARSH method.

2.4 Waterbird Habitat Suitability Assessment

The Waterbird Habitat Suitability Assessment (WHSa) sub-model of MARSH allows the program to provide a list of waterbird species likely to be present in the designed wetland at the WLEB Project site during each month of the year. The WHSA accounts for 48 species with varying foraging behavior, seasonality, and conservation status that have been sighted in Lenawee County and recorded on the birding platform eBird since 2020. The species are further distinguished within the WHSA sheet of MARSH as either waterfowl (ducks, geese, and swans) or other waterbirds.

Table 1: Waterbird seasonality codes and their descriptions/months. Compound codes include EBEF, EBLF, LBEF, and LBLF.

Within the WHSA is a complete bird list containing each species' common name, range of preferred foraging depths, conservation status, and seasonality. Preferred foraging depths were obtained from an NRCS report on bird diversity in wetland design and verified through personal communication with DU GLARO staff (Streever & Harrington, 1999). The conservation status for each species was obtained from Michigan's Wildlife Action Plan 2015-2025. A seasonality matrix detailing which months each species is likely to be present in the region was developed through consulting with staff at the DU GLARO and validating them with information from the Cornell Lab of Ornithology (*All About Birds*, 2019). Each species is assigned a seasonality code corresponding to its potential presence during specific months. A function looks at the seasonality code of each species and populates each month of the matrix for that species with either "Present" or "Absent" depending on the species' seasonality. Table 1 contains the seasonality codes, their

descriptions, and which months they correspond to for presence in the region. Some species are

Seasonality Code	Description	Months
EB	Early breeder/spring migrator	March - June
LB	Late breeder/spring migrator	May - August
EF	Early fall migrator	August - September
LF	Late fall migrator	October - December
YR	Year-round	January - December

only assigned one code (two letters) while others are assigned a compound code, a combination of two codes (four letters); those with a compound code are likely to be found during the months associated with both of the constituent two-letter codes. For example, a species who arrives in April and leaves around November would receive the compound code EBLF, whereas a different species that only passes through during May/June would receive the code LB.

Both the MARSH method's and GWLF-E method's water balances were used with the WHSA sub-model to estimate the annual number of unique species expected to be present based on wetland MWD at the WLEB project site.

2.5 Tradeoff Comparisons

2.5.1 Phosphorus Retention Scoring

For the MARSH method, each of the 200 estimated P retention values was scaled from 0 – 1 to compare the results between different runs, with 1 being the highest value amongst all combinations and zero being the lowest of these values. These scaled values were then multiplied by a user-decided probability of each climate scenario's occurrence in a given year (0.5 for the average scenario, 0.2 for the wet/dry scenarios, and 0.05 for the extreme scenarios). Once the scaled values were multiplied by their respective probabilities, they were summed across all

climate scenarios to calculate a “P score” for a more effective comparison of P retention capabilities across varying management scenarios and wetland sizes. In total, there were 40 P scores (1 for each wetland size from 1-10% of watershed area times 4 different management methods).

For the GWLF-E method, since there was only one “climate scenario” (the provided GWLF-E flow data), there were only 40 estimated P retention values. These were also scaled from 0-1, but were not multiplied by any probabilities, resulting in a total of 40 P scores for the GWLF-E method results as well.

2.5.2 Waterbird Habitat Suitability Scoring

Similar to the MARSH method for P retention, 200 runs were performed to gather data on the total number of waterbird species present for each climate, management, and sizing scenarios by month. When populating the list of potentially present species, MARSH outputs the number of new species that would find the wetland suitable each month. For example, Mallards are found year-round in the project area, so they first appear in January and count as 1 species, and are not counted again towards the total species count for the rest of the year. These numbers were summed to determine the total number of species that may be present in the wetland in a given year. A near-identical process as used to determine P scores was used to determine a “bird score” for each combination of management method and sizing scenario. The number of birds was scaled from 0-1 (with 0 being the fewest birds and 1 being the most) and multiplied by the probability of each climate scenario’s occurrence in a given year. There are again a total of 40 bird scores, one for each combination of wetland size and management method over each of the five climate scenarios.

Once again, the GWLF-E method followed a similar process for determining bird scores of each of the 40 combinations of wetland sizing and management scenarios.

2.5.3 Overall Tradeoff Scoring and Comparison

Each of the MARSH method's 40 different combinations of management method and wetland size had their P score and bird score summed to determine an overall tradeoff score. The tradeoff score's constituent values can be weighted if either P retention or waterbird habitat suitability is deemed more important or desirable than the other. The default weight is 1 for both P score and bird score; if one is increased, the other decreases by the same amount (maximum weight = 2, minimum weight = 0). The same weighting mechanism was used for the results of the GWLF-E method. These tradeoff scores were used as to compare tradeoffs between scenarios, with higher scores associated with better co-provision of the two ecosystem services.

CHAPTER 3

RESULTS

3.1 Phosphorus Retention Results

Estimates of mean annual TP retention rates and efficiencies are provided in Table 2. These values are the raw results for mean annual TP retention in the wetland for each of the 240 scenarios' model runs (200 using the MARSH method and 40 using the GWLF-E method). The table also contains annual mean water depth values across the wetland for each scenario. For simplicity, the GWLF-E method will be considered a climate scenario, hereafter the “external scenario”. The scaled values for these retention results are shown in Figure 5 (retention rate) and Figure 6 (retention efficiency). Scaled values close to 0 or 1 represent TP retention near the minimum or maximum estimated annual mean across all combinations of management method, climate scenario, and sizing scenario; lower values are in red while higher values are in green. Inspection of these figures allows for the interpretation of trends across climate and sizing scenarios under each of the four management methods.

The mean annual areal TP retention rate P is calculated by:

$$P = (MAX - MIN) * S + MIN$$

where MAX and MIN are 0.23 g/m²/year and 1.34 g/m²/year, respectively, and S is the scaled retention value.

For mean annual TP retention efficiency the same equation is used except MAX and MIN are replaced by 71.3% and 10.5%, respectively.

Table 2: Phosphorus retention & waterbird habitat suitability results for all 240 scenario model runs. Maximum values for P retention and waterbird habitat suitability are shown in green, minimum values are shown in red.

ANNUAL TP RETENTION AND WATERBIRD ABUNDANCE RESULTS																									
MGMT	WSHD %	EXTREME DRY						DRY						MARSH METHOD						GWLF-E METHOD					
		MWD (m)	RATE (lg/m ² /yr)	% RET	# BIRDS	MWD (m)	RATE (lg/m ² /yr)	% RET	# BIRDS	MWD (m)	RATE (lg/m ² /yr)	% RET	# BIRDS	MWD (m)	RATE (lg/m ² /yr)	% RET	# BIRDS	MWD (m)	RATE (lg/m ² /yr)	% RET	# BIRDS				
DYNAMIC	1%	0.30	0.55	33.9	45	0.36	0.67	49.4	48	0.52	0.82	40.4	35	0.52	0.82	39.9	35	0.53	0.83	38.9	35	0.49	0.83	39.1	35
	2%	0.19	0.45	40.3	44	0.27	0.61	52.7	48	0.48	0.79	41.2	35	0.50	0.82	40.4	35	0.51	0.82	39.7	35	0.45	0.81	39.7	35
	3%	0.14	0.38	44.6	44	0.22	0.57	55.4	48	0.46	0.79	41.6	35	0.49	0.80	41.3	35	0.49	0.82	40.2	35	0.42	0.79	40.7	35
	4%	0.11	0.35	39.3	44	0.18	0.51	51.1	48	0.45	0.78	41.9	35	0.47	0.78	42.3	35	0.48	0.80	41.3	35	0.40	0.78	41.5	35
	5%	0.10	0.32	41.0	36	0.15	0.46	46.9	45	0.44	0.77	42.3	35	0.44	0.76	43.9	35	0.46	0.77	42.7	35	0.38	0.77	42.0	35
	6%	0.09	0.30	42.3	36	0.14	0.43	49.1	37	0.43	0.77	42.5	35	0.41	0.73	45.5	35	0.43	0.75	44.2	35	0.37	0.77	42.6	35
	7%	0.08	0.29	43.3	36	0.12	0.40	51.0	37	0.42	0.77	42.8	35	0.39	0.71	46.8	36	0.40	0.73	45.7	36	0.37	0.76	43.0	35
	8%	0.08	0.27	44.2	36	0.12	0.38	52.2	37	0.41	0.76	43.5	35	0.38	0.69	48.1	36	0.39	0.71	47.0	36	0.36	0.75	43.3	35
	9%	0.07	0.27	44.9	36	0.11	0.37	53.3	37	0.40	0.75	44.0	35	0.36	0.68	49.2	36	0.37	0.69	48.2	36	0.35	0.74	43.7	35
	10%	0.07	0.26	45.3	35	0.10	0.35	54.3	37	0.39	0.73	44.4	35	0.34	0.65	50.4	36	0.36	0.67	49.2	36	0.35	0.74	44.0	35
STATIC 2.0	1%	1.00	1.10	22.9	21	1.46	1.21	17.5	21	1.78	1.25	16.2	22	1.73	1.26	16.4	22	1.76	1.29	15.3	22	1.84	1.34	10.5	21
	2%	0.43	0.84	37.6	32	1.03	1.11	23.1	27	1.52	1.22	18.4	22	1.60	1.22	18.0	22	1.61	1.27	15.3	22	1.48	1.27	14.1	21
	3%	0.25	0.62	43.7	48	0.69	1.00	28.6	27	1.38	1.16	20.5	22	1.53	1.20	19.2	22	1.67	1.25	16.2	22	1.35	1.22	16.7	21
	4%	0.19	0.53	42.4	48	0.52	0.91	33.1	27	1.30	1.13	22.1	22	1.44	1.17	20.4	22	1.61	1.24	17.0	22	1.27	1.19	18.7	21
	5%	0.16	0.47	46.1	48	0.42	0.84	37.2	27	1.25	1.11	23.5	22	1.32	1.14	21.7	22	1.55	1.22	17.7	22	1.10	1.13	20.9	21
	6%	0.14	0.42	49.2	47	0.35	0.78	41.0	32	1.15	1.08	24.9	22	1.22	1.13	22.9	22	1.46	1.20	18.5	22	0.96	1.09	22.9	21
	7%	0.13	0.39	43.4	47	0.30	0.72	44.3	33	1.05	1.05	26.2	22	1.15	1.10	23.9	22	1.37	1.18	19.5	22	0.86	1.07	24.5	21
	8%	0.12	0.38	44.8	47	0.26	0.68	47.4	33	0.94	1.02	27.7	22	1.08	1.08	24.7	22	1.29	1.17	20.3	22	0.78	1.04	26.0	21
	9%	0.11	0.36	45.9	47	0.23	0.64	50.5	47	0.85	1.00	29.0	22	1.02	1.06	25.6	22	1.22	1.15	21.1	22	0.72	1.01	27.2	21
	10%	0.10	0.35	47.0	37	0.21	0.60	53.1	48	0.78	0.98	30.1	22	0.95	1.06	26.6	22	1.17	1.13	21.8	22	0.68	1.00	28.4	21
STATIC 0.2	1%	0.15	0.46	46.9	37	0.16	0.47	46.0	37	0.18	0.56	55.5	23	0.19	0.57	55.1	23	0.19	0.58	54.2	23	0.19	0.58	54.2	37
	2%	0.14	0.43	41.0	37	0.16	0.48	45.9	37	0.18	0.56	55.5	23	0.19	0.56	55.1	23	0.19	0.58	54.5	23	0.19	0.58	54.2	37
	3%	0.13	0.41	42.7	37	0.15	0.47	46.1	37	0.18	0.55	55.6	23	0.19	0.57	55.2	23	0.19	0.57	54.7	23	0.19	0.58	54.1	37
	4%	0.12	0.39	43.4	37	0.15	0.47	46.6	37	0.18	0.56	55.4	23	0.19	0.56	55.3	23	0.19	0.57	54.8	23	0.19	0.58	54.0	37
	5%	0.12	0.38	44.4	37	0.15	0.46	46.9	37	0.18	0.56	55.5	23	0.19	0.56	55.3	23	0.19	0.57	54.6	23	0.19	0.58	54.0	37
	6%	0.11	0.37	45.4	37	0.14	0.45	47.5	37	0.18	0.56	55.5	23	0.19	0.56	55.2	23	0.19	0.57	54.8	23	0.19	0.58	54.1	37
	7%	0.10	0.35	46.6	37	0.14	0.44	47.9	37	0.18	0.56	55.6	23	0.19	0.57	55.2	23	0.19	0.57	54.7	23	0.19	0.58	54.1	37
	8%	0.10	0.34	47.5	37	0.14	0.44	48.5	37	0.18	0.55	55.8	23	0.19	0.57	55.1	23	0.19	0.57	54.7	23	0.19	0.58	54.1	37
	9%	0.09	0.33	48.2	37	0.13	0.43	49.2	37	0.18	0.55	56.1	23	0.19	0.57	55.2	23	0.19	0.57	54.7	23	0.19	0.58	54.3	37
	10%	0.09	0.32	48.9	37	0.13	0.42	49.7	37	0.18	0.55	56.2	23	0.19	0.56	55.2	23	0.19	0.57	54.8	23	0.19	0.58	54.4	37
STATIC 0.1	1%	0.07	0.27	52.1	28	0.07	0.28	51.6	28	0.09	0.35	70.2	28	0.09	0.36	69.9	28	0.10	0.38	69.0	28	0.09	0.34	63.1	28
	2%	0.07	0.26	53.3	28	0.07	0.28	51.5	28	0.09	0.35	70.3	28	0.09	0.36	69.9	28	0.10	0.37	69.1	28	0.09	0.34	63.1	28
	3%	0.06	0.24	54.5	28	0.07	0.28	51.5	28	0.09	0.35	70.3	28	0.09	0.36	69.8	28	0.10	0.37	69.2	28	0.09	0.34	63.1	28
	4%	0.06	0.24	46.9	28	0.07	0.28	51.5	28	0.09	0.35	70.3	28	0.09	0.36	69.9	28	0.10	0.37	69.4	28	0.09	0.34	63.1	28
	5%	0.06	0.23	46.9	28	0.07	0.28	51.5	28	0.09	0.35	70.3	28	0.09	0.36	69.8	28	0.10	0.37	69.5	28	0.09	0.34	63.1	28
	6%	0.06	0.23	47.1	28	0.07	0.29	51.4	28	0.09	0.35	70.2	28	0.09	0.36	69.8	28	0.10	0.37	69.4	28	0.09	0.34	63.0	28
	7%	0.06	0.24	47.0	28	0.07	0.28	51.6	28	0.09	0.35	70.3	28	0.09	0.36	69.9	28	0.10	0.37	69.4	28	0.09	0.35	63.0	28
	8%	0.06	0.24	47.0	28	0.07	0.28	51.5	28	0.09	0.35	70.7	28	0.09	0.36	69.8	28	0.10	0.36	69.5	28	0.09	0.34	63.1	28
	9%	0.06	0.23	47.2	28	0.07	0.28	51.5	28	0.09	0.34	70.9	28	0.09	0.36	69.9	28	0.10	0.37	69.5	28	0.09	0.35	63.2	28
	10%	0.06	0.23	47.3	28	0.07	0.28	51.5	28	0.09	0.34	71.3	28	0.09	0.36	69.8	28	0.10	0.37	69.7	28	0.09	0.34	63.0	28

SCALED MEAN TP RETENTION RATE (g/m ² /yr)															
		MARSH METHOD					GWLf-E			MARSH METHOD					GWLf-E
MGMT	WSHD %	ED	D	A	W	EW		MGMT	WSHD %	ED	D	A	W	EW	
DYNAMIC	1%	0.29	0.40	0.53	0.53	0.54	0.54	STATIC 0.2	1%	0.21	0.22	0.29	0.31	0.31	0.31
	2%	0.20	0.35	0.51	0.53	0.53	0.52		2%	0.18	0.22	0.30	0.30	0.31	0.32
	3%	0.14	0.30	0.50	0.51	0.53	0.51		3%	0.16	0.21	0.29	0.30	0.31	0.32
	4%	0.11	0.26	0.50	0.50	0.51	0.50		4%	0.15	0.21	0.30	0.30	0.31	0.31
	5%	0.08	0.21	0.49	0.47	0.49	0.49		5%	0.13	0.21	0.29	0.30	0.31	0.32
	6%	0.06	0.18	0.49	0.45	0.47	0.48		6%	0.13	0.20	0.30	0.30	0.31	0.32
	7%	0.05	0.16	0.48	0.43	0.45	0.48		7%	0.11	0.19	0.30	0.30	0.31	0.32
	8%	0.04	0.14	0.48	0.42	0.43	0.47		8%	0.10	0.19	0.29	0.30	0.31	0.31
	9%	0.03	0.13	0.47	0.40	0.41	0.46		9%	0.09	0.18	0.29	0.30	0.31	0.31
	10%	0.03	0.11	0.45	0.38	0.40	0.46		10%	0.08	0.17	0.29	0.30	0.30	0.32
STATIC 2.0	1%	0.78	0.88	0.92	0.92	0.95	1.00	STATIC 0.1	1%	0.04	0.05	0.11	0.12	0.13	0.10
	2%	0.55	0.79	0.89	0.89	0.93	0.94		2%	0.02	0.05	0.11	0.12	0.13	0.10
	3%	0.35	0.69	0.84	0.87	0.92	0.89		3%	0.01	0.05	0.11	0.12	0.12	0.10
	4%	0.27	0.61	0.81	0.84	0.91	0.86		4%	0.01	0.05	0.11	0.12	0.12	0.10
	5%	0.22	0.55	0.79	0.82	0.89	0.81		5%	0.01	0.05	0.11	0.12	0.12	0.10
	6%	0.17	0.50	0.76	0.80	0.87	0.78		6%	0.01	0.05	0.11	0.12	0.12	0.10
	7%	0.15	0.45	0.74	0.78	0.86	0.76		7%	0.01	0.05	0.11	0.12	0.12	0.10
	8%	0.13	0.40	0.71	0.76	0.84	0.73		8%	0.01	0.05	0.11	0.12	0.12	0.10
	9%	0.12	0.37	0.69	0.75	0.83	0.70		9%	0.00	0.05	0.10	0.12	0.12	0.10
	10%	0.11	0.33	0.68	0.74	0.81	0.69		10%	0.00	0.05	0.10	0.12	0.12	0.10

Figure 5: Mean annual TP retention rate (g/m²/yr) estimates scaled using min-max scaling.

SCALED MEAN TP RETENTION EFFICIENCY (%)															
		MARSH METHOD					GWLf-E			MARSH METHOD					GWLf-E
MGMT	WSHD %	ED	D	A	W	EW		MGMT	WSHD %	ED	D	A	W	EW	
DYNAMIC	1%	0.38	0.64	0.49	0.48	0.47	0.47	STATIC 0.2	1%	0.60	0.58	0.74	0.73	0.72	0.72
	2%	0.49	0.69	0.50	0.49	0.48	0.48		2%	0.50	0.58	0.74	0.73	0.72	0.72
	3%	0.56	0.74	0.51	0.51	0.49	0.50		3%	0.53	0.58	0.74	0.73	0.73	0.72
	4%	0.47	0.67	0.52	0.52	0.51	0.51		4%	0.54	0.59	0.74	0.74	0.73	0.72
	5%	0.50	0.60	0.52	0.55	0.53	0.52		5%	0.56	0.60	0.74	0.74	0.72	0.72
	6%	0.52	0.63	0.53	0.58	0.55	0.53		6%	0.57	0.61	0.74	0.73	0.73	0.72
	7%	0.54	0.67	0.53	0.60	0.58	0.53		7%	0.59	0.62	0.74	0.73	0.73	0.72
	8%	0.55	0.69	0.54	0.62	0.60	0.54		8%	0.61	0.62	0.74	0.73	0.73	0.72
	9%	0.56	0.70	0.55	0.64	0.62	0.55		9%	0.62	0.64	0.75	0.73	0.73	0.72
	10%	0.57	0.72	0.56	0.66	0.64	0.55		10%	0.63	0.64	0.75	0.73	0.73	0.72
STATIC 2.0	1%	0.20	0.12	0.09	0.10	0.07	0.00	STATIC 0.1	1%	0.68	0.68	0.98	0.98	0.96	0.87
	2%	0.45	0.21	0.13	0.12	0.08	0.06		2%	0.70	0.67	0.98	0.98	0.96	0.87
	3%	0.55	0.30	0.16	0.14	0.09	0.10		3%	0.72	0.67	0.98	0.97	0.97	0.86
	4%	0.52	0.37	0.19	0.16	0.11	0.14		4%	0.60	0.67	0.98	0.98	0.97	0.86
	5%	0.59	0.44	0.21	0.18	0.12	0.17		5%	0.60	0.67	0.98	0.98	0.97	0.87
	6%	0.64	0.50	0.24	0.20	0.13	0.20		6%	0.60	0.67	0.98	0.98	0.97	0.86
	7%	0.54	0.56	0.26	0.22	0.15	0.23		7%	0.60	0.67	0.98	0.98	0.97	0.86
	8%	0.56	0.61	0.28	0.23	0.16	0.25		8%	0.60	0.67	0.99	0.98	0.97	0.86
	9%	0.58	0.66	0.30	0.25	0.17	0.28		9%	0.60	0.67	0.99	0.98	0.97	0.87
	10%	0.60	0.70	0.32	0.27	0.19	0.29		10%	0.61	0.67	1.00	0.98	0.97	0.86

Figure 6: Mean annual TP retention efficiency (%) estimates scaled using min-max scaling.

Trends for areal TP retention rate and TP retention efficiency are inverse of each other across management, sizing, and climate scenarios (see Figure 7); for example, static 2.0 management yields the highest retention rates across all climate scenarios (including the GWLF-E method), but has the lowest retention efficiencies.

Across all management methods, TP retention rates and efficiencies from the GWLF-E method simulations runs are comparable to those using the average, wet, and extreme wet climate scenarios from the MARSH method.

Phosphorus retention rates are highest under the static 2.0 management method at lower wetland sizes (and therefore higher MWDs), yet retention efficiency is at its worst under these conditions. Retention rates are lowest under the static 0.1 method, but retention efficiencies peak with this style of management regardless of wetland size.

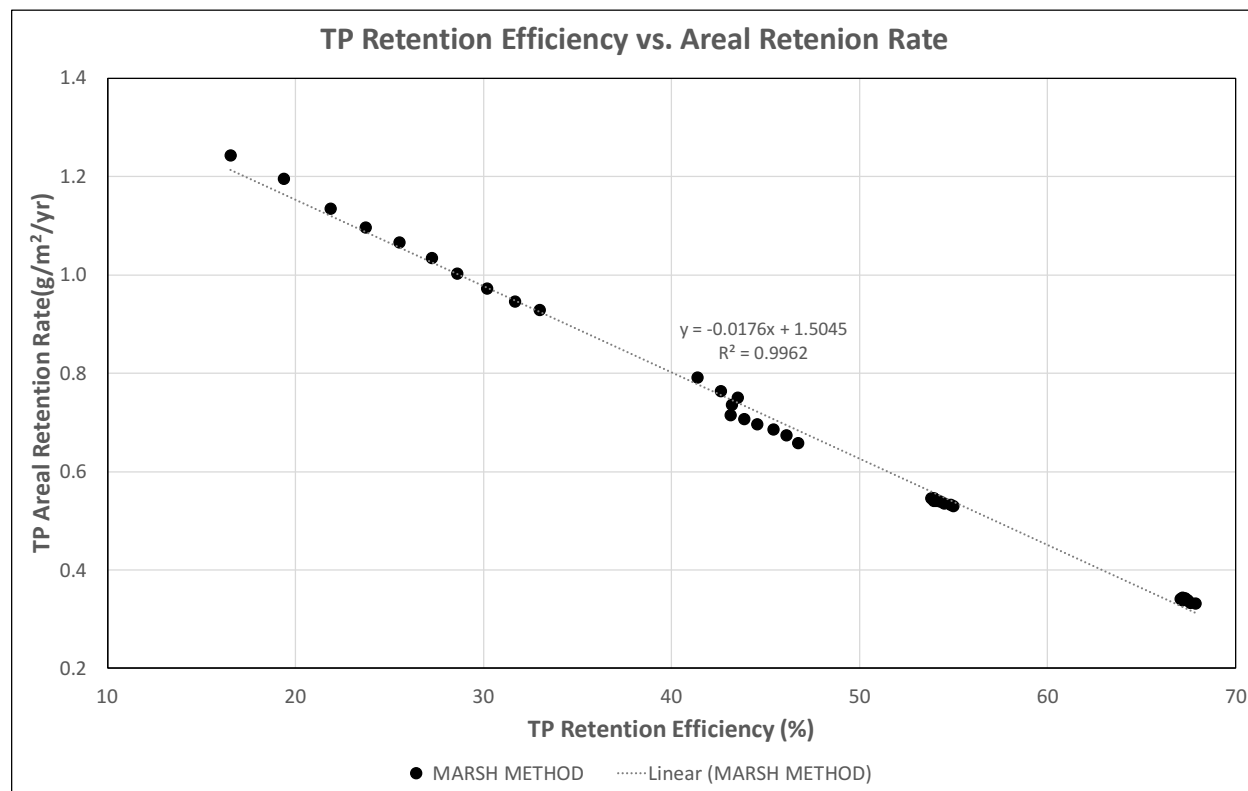


Figure 7: Scatter plot of annual TP retention efficiencies vs. areal retention rates.

3.2 Waterbird Habitat Suitability Results

Table 2 contains the number of unique waterbird species the wetland supports in a given year. The scaled values for these habitat suitability results are shown in Figure 8. Scaled values close to 0 represent a number of supported species near the minimum, while values close to 1 indicate the habitat supports near the maximum number of species; lower values are in red while higher values are in green.

The number of species S is calculated by:

$$B = (MAX - MIN) * S + MIN$$

where MAX and MIN are 48 species and 21 species, respectively, and B is the scaled species value.

SCALED # BIRD SPECIES SUPPORTED																
		MARSH METHOD					GWLF-E			MARSH METHOD					GWLF-E	
MGMT	WSHD %	ED	D	A	W	EW		MGMT	WSHD %	ED	D	A	W	EW		
DYNAMIC	1%	0.89	1.00	0.52	0.52	0.52	0.52	STATIC 0.2	1%	0.59	0.59	0.07	0.07	0.07	0.59	
	2%	0.85	1.00	0.52	0.52	0.52	0.52		2%	0.59	0.59	0.07	0.07	0.07	0.59	
	3%	0.85	1.00	0.52	0.52	0.52	0.52		3%	0.59	0.59	0.07	0.07	0.07	0.59	
	4%	0.85	1.00	0.52	0.52	0.52	0.52		4%	0.59	0.59	0.07	0.07	0.07	0.59	
	5%	0.56	0.89	0.52	0.52	0.52	0.52		5%	0.59	0.59	0.07	0.07	0.07	0.59	
	6%	0.56	0.59	0.52	0.52	0.52	0.52		6%	0.59	0.59	0.07	0.07	0.07	0.59	
	7%	0.56	0.59	0.52	0.56	0.52	0.52		7%	0.59	0.59	0.07	0.07	0.07	0.59	
	8%	0.56	0.59	0.52	0.56	0.56	0.52		8%	0.59	0.59	0.07	0.07	0.07	0.59	
	9%	0.56	0.59	0.52	0.56	0.56	0.52		9%	0.59	0.59	0.07	0.07	0.07	0.59	
	10%	0.52	0.59	0.52	0.56	0.56	0.52		10%	0.59	0.59	0.07	0.07	0.07	0.59	
STATIC 2.0	1%	0.00	0.00	0.04	0.04	0.04	0.00	STATIC 0.1	1%	0.26	0.26	0.26	0.26	0.26	0.26	
	2%	0.41	0.22	0.04	0.04	0.04	0.00		2%	0.26	0.26	0.26	0.26	0.26	0.26	
	3%	1.00	0.22	0.04	0.04	0.04	0.00		3%	0.26	0.26	0.26	0.26	0.26	0.26	
	4%	1.00	0.22	0.04	0.04	0.04	0.00		4%	0.26	0.26	0.26	0.26	0.26	0.26	
	5%	1.00	0.22	0.04	0.04	0.04	0.00		5%	0.26	0.26	0.26	0.26	0.26	0.26	
	6%	0.96	0.41	0.04	0.04	0.04	0.00		6%	0.26	0.26	0.26	0.26	0.26	0.26	
	7%	0.96	0.44	0.04	0.04	0.04	0.00		7%	0.26	0.26	0.26	0.26	0.26	0.26	
	8%	0.96	0.44	0.04	0.04	0.04	0.00		8%	0.26	0.26	0.26	0.26	0.26	0.26	
	9%	0.96	0.96	0.04	0.04	0.04	0.00		9%	0.26	0.26	0.26	0.26	0.26	0.26	
	10%	0.59	1.00	0.04	0.04	0.04	0.00		10%	0.26	0.26	0.26	0.26	0.26	0.26	

Figure 8: Number of unique waterbird species supported by the wetland annually scaled to minimum and maximum values.

Dynamic management of water levels provides high species abundance for smaller wetland sizes in the extreme dry and dry climate scenarios while also being suitable for about half of the maximum number species across all other sizing and climate scenarios.

The static 2.0 management method allows for high species abundance from wetland sizes of 3-9% in the extreme dry scenario and 9-10% in the dry scenario. All other sizing and climate scenarios under this method result in very poor to middling numbers of bird species being supported.

The static 0.2 management method supports more than half of the maximum number of species across all sizing scenarios under the extreme dry, dry, and external scenarios while supporting near the minimum in the other climate scenarios.

Static 0.1 management supports the same number of species across every sizing and climate scenario, although that number is only about a fourth of the maximum number of species.

3.3 Ecosystem Service Tradeoff Results

Following the methodology outlined in section 2.5.3, the P scores and bird scores for each combination of management method and wetland size were used to determine a weighted tradeoff score for the MARSH and GWLF-E methods. The P scores, bird scores, and tradeoff scores when TP retention is twice as important as habitat provision for the wetland design are provided in Figure 9. The corresponding values for mean annual TP retention and the number of species supported are also provided, with the maximum tradeoff score and its corresponding values highlighted. Figure 10 presents bar charts for visualization of the differences between the scenarios' minima and maxima under each hydrology method.

MARSH METHOD TRADEOFF SCORING							GWLF-E METHOD TRADEOFF SCORING		
P:B = 2:1							P:B = 2:1		
MGMT	WSDH %	P SCORE	BIRD SCORE	TRADEOFF SCORE	% RET	# BIRDS	TRADEOFF SCORE	% RET	# BIRDS
DYNAMIC	1%	0.51	0.59	1.07	41.4	37	0.97	39.1	35
	2%	0.53	0.59	1.10	42.6	37	0.99	39.7	35
	3%	0.54	0.59	1.12	43.5	37	1.01	40.7	35
	4%	0.54	0.59	1.11	43.2	37	1.03	41.5	35
	5%	0.54	0.57	1.10	43.1	36	1.04	42.0	35
	6%	0.55	0.53	1.08	43.8	35	1.05	42.6	35
	7%	0.56	0.53	1.10	44.5	35	1.06	43.0	35
	8%	0.57	0.54	1.12	45.4	35	1.06	43.3	35
	9%	0.58	0.54	1.14	46.1	35	1.07	43.7	35
	10%	0.60	0.53	1.15	46.7	35	1.08	44.0	35
STATIC 2.0	1%	0.10	0.03	0.15	16.5	22	0.00	10.5	21
	2%	0.15	0.07	0.24	19.4	23	0.08	14.1	21
	3%	0.19	0.08	0.30	21.8	23	0.14	16.7	21
	4%	0.22	0.08	0.35	23.7	23	0.18	18.7	21
	5%	0.25	0.08	0.38	25.5	23	0.23	20.9	21
	6%	0.27	0.11	0.44	27.2	24	0.27	22.9	21
	7%	0.30	0.11	0.47	28.6	24	0.31	24.5	21
	8%	0.32	0.11	0.51	30.2	24	0.34	26.0	21
	9%	0.35	0.18	0.59	31.6	26	0.37	27.2	21
	10%	0.37	0.18	0.61	33.0	26	0.39	28.4	21
STATIC 0.2	1%	0.71	0.16	1.06	53.9	25	1.35	54.2	37
	2%	0.71	0.16	1.05	53.8	25	1.35	54.2	37
	3%	0.71	0.16	1.06	53.9	25	1.35	54.1	37
	4%	0.71	0.16	1.06	53.9	25	1.35	54.0	37
	5%	0.72	0.16	1.06	54.0	25	1.35	54.0	37
	6%	0.72	0.16	1.06	54.1	25	1.35	54.1	37
	7%	0.72	0.16	1.06	54.3	25	1.35	54.1	37
	8%	0.72	0.16	1.07	54.5	25	1.35	54.1	37
	9%	0.73	0.16	1.08	54.8	25	1.36	54.3	37
	10%	0.73	0.16	1.08	55.0	25	1.36	54.4	37
STATIC 0.1	1%	0.93	0.26	1.41	67.2	28	1.33	63.1	28
	2%	0.93	0.26	1.42	67.3	28	1.33	63.1	28
	3%	0.93	0.26	1.42	67.3	28	1.32	63.1	28
	4%	0.93	0.26	1.41	67.2	28	1.33	63.1	28
	5%	0.93	0.26	1.41	67.1	28	1.33	63.1	28
	6%	0.93	0.26	1.41	67.0	28	1.32	63.0	28
	7%	0.93	0.26	1.41	67.2	28	1.32	63.0	28
	8%	0.94	0.26	1.42	67.4	28	1.33	63.1	28
	9%	0.94	0.26	1.42	67.6	28	1.33	63.2	28
	10%	0.94	0.26	1.43	67.9	28	1.32	63.0	28

Figure 9: Ecosystem service tradeoff results from the MARSH method (left) and GWLF-E method (right). The tradeoff score is weighted under the assumption that TP retention is twice as important as waterbird habitat provision (P:B = 2:1). % RET is the estimated annual mean TP retention efficiency and # birds is the mean number of unique species supported annually by the wetland.

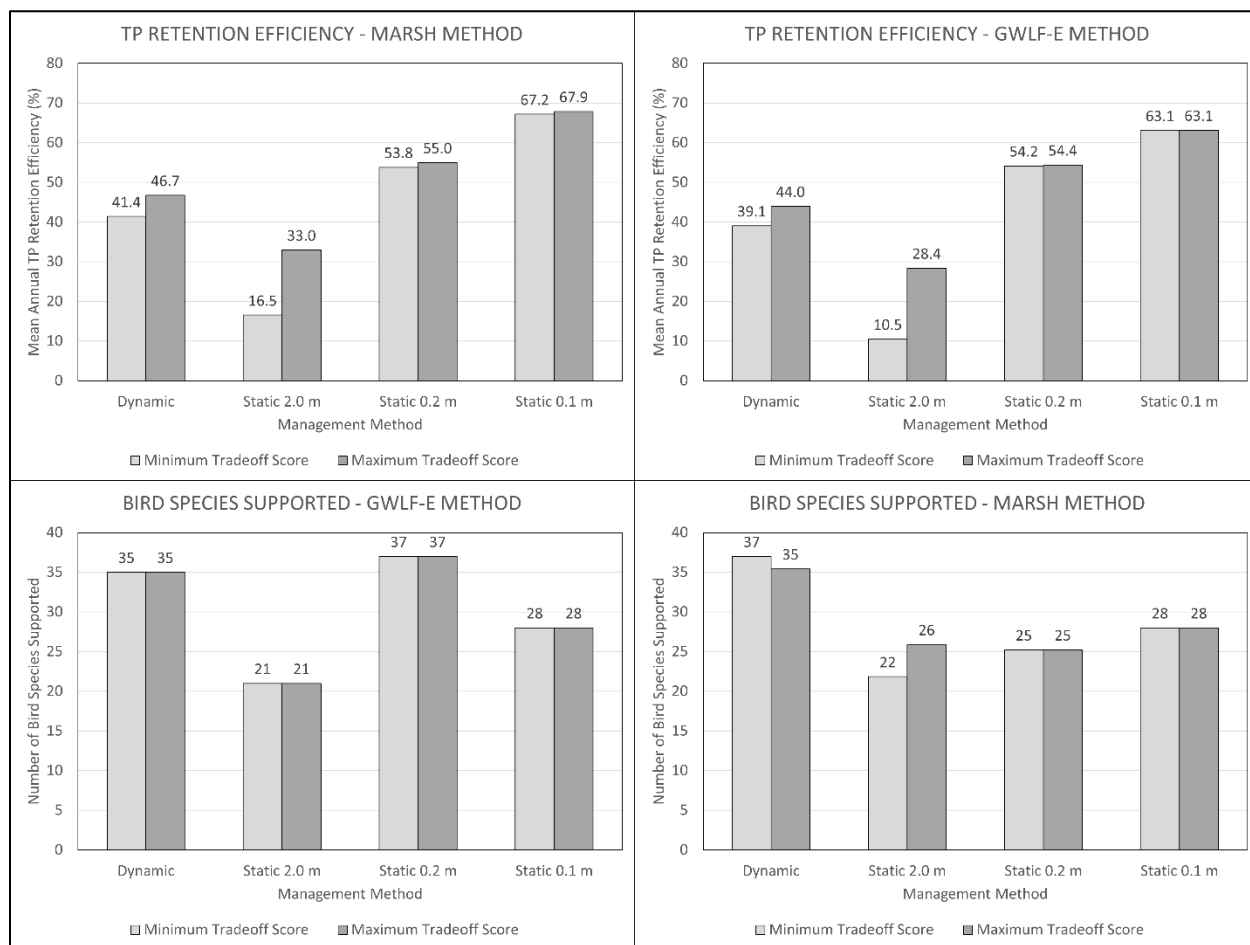


Figure 10: Bar charts visualizing the differences in TP retention efficiency (top) and number of bird species supported (bottom) between wetland sizes with minimum and maximum tradeoff scores for each management method. The number at the base of each bar is the wetland size that yields these results. MARSH method results are on the left and GWLF-E method results are on the right.

3.3.1 MARSH Method Tradeoff Results

Using the MARSH method for hydrologic assessment and analyzing retention efficiencies, static 2.0 management yields the lowest tradeoff scores out of all management methods by far; the lowest score is 0.15 at 1% watershed size while the highest is 0.61 at a size of 10%. The corresponding mean TP retention efficiencies are the lowest at every watershed size across all management methods, and all sizing scenarios except 9% and 10% support the smallest number of waterbird species across all management methods as well.

Both dynamic and static 0.2 management result in very similar tradeoff scores across all sizing scenarios, with dynamic having the slight edge. However, looking at the constituent P scores and bird scores details where the differences in the two management methods lie; dynamic management of water levels yields TP retention levels 26.6% - 33.4% lower than the maximum values, while static management for 0.2 m of water yields retention levels only 14.9 - 16.8% lower than the maximum. Conversely, dynamic management consistently supports the largest number of bird species across all sizing scenarios (between 35 – 37 species), with larger wetland sizes leading to fewer species supported. Static 0.2 management rivals the static 2.0 method in terms of poor habitat provision – only 25 species are supported across all sizing scenarios.

The static 0.1 management method shows the highest tradeoff scores across all sizing scenarios. With tradeoff scores ranging from 1.41 – 1.43 and 28 bird species being supported no matter the wetland size, this management method is the most consistent for both TP retention and waterbird habitat provision across all sizing scenarios.

3.3.2 GWLF-E Method Tradeoff Results

Under the GWLF-E method, static 2.0 management remains the lowest scoring management method with a range of 0.00 – 0.39, with the score increasing alongside wetland size. Both the TP retention efficiencies and number of species supported are lower than any other method of water management across all wetland sizes.

Although dynamic management yields the second-lowest tradeoff scores (0.97 – 1.08), they are still vastly higher than that of the static 2.0 method. Phosphorus retention under this management method is respectable but not great, ranging from 24.3% – 35.9% lower than the maximum values. It also provides suitable habitat for the second-highest number of waterbird species amongst all the tradeoff methods (35).

Static 0.1 management once again has a consistent range of very high tradeoff scores, ranging from 1.32 – 1.33 across all wetland sizes. This management method yields the highest TP retention of all the scenarios under the GWLF-E method, but supports significantly fewer bird species (28) than dynamic and static 0.2 management methods, albeit still higher than the static 2.0 method.

The static 0.2 management method has the highest tradeoff scores under the GWLF-E method. With a range of 1.35 – 1.36, it is also incredibly consistent. Phosphorus retention under this method is nearly identical across all wetland sizing scenarios, and it also supports a consistent 37 species of waterbirds across all sizes.

CHAPTER 4

DISCUSSION

4.1 Ecosystem Service Tradeoffs

This research contributes to a multi-objective wetland design for wildlife use of water-quality wetlands in the Midwest. It focuses on waterbird habitat provision, whereas previous work has considered only amphibians (Reeves et al., 2016; Swanson et al., 2018). Given the lack of extensive research on designing treatment wetlands for co-provision of ecosystem services (Janke et al., 2021), specifically water quality improvement through nutrient retention and habitat provision for waterbirds, appropriately interpreting the results presented in chapter 3 is paramount to improving our understanding of tradeoffs between these needs. The tradeoff scores alone are not enough to adequately inform differences in ES provision – they must be viewed alongside their constituent P scores and bird scores to truly understand their upsides and shortcomings.

Due to the desire for the wetland being constructed at the WLEB to improve water quality via P retention, the tradeoff scores and retention estimates being discussed here are those for retention efficiency. This is because while higher efficiencies are correlated with lower retention rates (Figure 7), efficiency is a better indicator of water quality improvement since it takes into account P export, unlike retention rate. Higher retention rates are desirable, but if they are accompanied by a decline in retention efficiency, this means a lower percent of inflowing phosphorus is retained and therefore more is transported downstream, something this project is trying to mitigate.

The low tradeoff scores (and therefore P and bird scores) associated with the static 2.0 management method for both the MARSH and GWLF-E methods indicate that passively managing for high mean water depths across the wetland is undesirable if TP retention and waterbird habitat provision are priorities. With maximums for mean annual TP retention efficiency ($33.0 \pm 2.7\%$) and number of birds supported (26) both occurring at a wetland size of 10% under this management method, we see that larger areas of land must be allocated for wetland construction to achieve middling ES benefits relative to other management styles. This finding aligns with previous research that found shallower wetlands capable of supporting more wading bird and dabbling duck species, and deeper wetlands supporting more diving duck species (Colwell & Taft, 2000). Increased water depth also decreases nutrient storage and cycling effectiveness (Richardson et al., 1996). While this may not be an issue for some projects, wetland construction in agricultural watersheds should aim to minimize the required land area to minimize impacts on surrounding landscapes. It is evident that even if one were to design such a large wetland, they would be better served by managing water levels via another method to achieve higher TP retention while providing habitat to a comparable, if not vastly higher, number of waterbird species. For these reasons, passive management of wetlands for deeper water levels should be avoided when attempting to maximize co-provision of TP retention and waterbird habitat.

Under the MARSH method hydrology, dynamic and static 0.2 management have similar tradeoff scores. The static management of shallow water depths throughout the year permits higher TP retention compared to dynamic management of varying (and generally increased) water levels, as mentioned above. Conversely, dynamic management results in habitat provision that is suitable for a much higher number of waterbird species; this is consistent with research presented by Colwell and Taft (2000) as the drawdown of water levels in the winter and spring provides habitat

for shorebirds, waders, and dabbling ducks while fall flooding of the wetland provides desirable conditions for diving duck species. Notably, TP retention and the number of species supported under static 0.2 management is consistent across all wetland sizes. In contrast, dynamic management increases TP retention efficacy and slightly reduces habitat provision as wetland size increases. In terms of minimizing tradeoffs, dynamic management is likely to be preferred over static 0.2 management, as a small decrease in TP retention results in a substantial increase in the total number of waterbird species supported. However, those designing the wetland must also consider the increased operation and maintenance costs associated with dynamic management as opposed to the cheaper and less time-demanding fire-and-forget nature of static management, in addition to the variation in efficacy linked to different wetland sizes under dynamic management.

Using the GWLF-E method for hydrologic analysis, dynamic management provides robust TP retention efficiencies that gradually increase with wetland size alongside consistently excellent habitat suitability. Dynamic management also still provides suitable habitat for waterbird species under this hydrologic regime, with 35 species supported across all wetland sizes. However, static 0.2 management performs the best in both categories.

The static 0.2 management method has the highest tradeoff scores of all management methods when using external hydrology. These scores result from the high TP retention efficiency ($\sim 55 \pm 3.1\%$) and quality waterbird habitat (37 species supported) provided by this management style across all sizing scenarios. However, the waterbird habitat provision under this management method is contingent upon channel flows in the wetland overtopping multiple times throughout the year, with fewer instances of flooding leading to less water in the wetland and fewer bird species supported.

Static 0.1 management yields the highest tradeoff and P scores amongst all management methods under MARSH method hydrology. While tradeoffs are minimized with a wetland area that is 10% of its contributing watershed, TP retention efficiency ($67.9 \pm 3.2\%$) and number of bird species supported (28) are consistent across all sizes, indicating that static 0.1 management can attain almost identical results for both regardless of the wetland's size (Figure 9). When analyzing the results of MARSH method runs, this method is a one-size-fits-all approach for ensuring maximum TP retention and solid habitat provision across both small and large wetlands alike. Under the GWLF-E method, static 0.1 management still yields the highest TP retention efficiency of the management methods ($63.2 \pm 8.8\%$) and the same number of bird species supported (28) across all sizing scenarios, but has lower tradeoff scores than static 0.2 management due to the latter's support of more bird species (37) resulting from increased variability in water levels throughout the year. While the GWLF-E method has more robust waterbird support under static 0.2 management than static 0.1, this is due to the nature of the GWLF-E method only using one year's flows as its only "climate scenario" – that is, if the flows chosen for this method result in less frequent overtopping, waterbird abundance will decline in tandem.

Whether focusing on TP areal retention rate or retention efficiency, the static 2.0 management method can be dismissed as a viable management strategy due to high water depths associated with it resulting in minimal, if any, vegetative support, which is a necessary consideration for both TP retention and habitat provision. If one were to value areal retention rate over retention efficiency due to the capacity of the former to directly quantify mass load reduction independent of inflow flux-based concentration reduction, dynamic management of water depths is capable of more adequately balancing TP retention with waterbird habitat provision.

4.2 Applying Model Results

4.2.1 WLEB Project Site Recommendations

Based on the presented results and subsequent analysis, and accounting for TP retention as the primary goal and waterbird habitat provision as a secondary objective, the static management of 0.1 m MWD in a wetland that is 10% of the contributing watershed is the ideal and most robust design for the WLEB Project site. This combination of management method and sizing scenario co-provides high-end TP retention efficiency and consistently sufficient habitat for a variety of waterbird species across a wide range of future conditions that align with the project's desired outcomes. As a result of static water level management, operational and maintenance costs will be minimized. A wetland size that is 10% of the contributing watershed equates to 264.8 acres, which is well below the constraint of approximately 368 acres available for construction on land parcels that have been acquired at the time of writing. Additionally, if the wetland manager desires to maintain the site with an adaptive management approach (e.g., managing for variable water depths provided by dynamic or static 0.2 methods to support more bird species), the 10% sizing scenario allows for maximum TP retention under alternate management methods. However, if dynamic management is out of the question and a smaller wetland is preferred, the design size can be reduced without tradeoffs in TP retention or wildlife habitat.

These recommendations corroborate previous findings that water level management practices have a larger impact on TP retention and waterbird suitability than wetland size (Carpenter, 2024). Maintenance of lower MWD coincides with higher phosphorus retention, while more variability in depths results in the support of more bird species. Regardless of the management approach taken, a monitoring plan should be devised and implemented to ensure

adequate co-provision of these ES and to properly inform adaptive management techniques to get the most out of the constructed wetland.

4.2.2 Applicability to Other Sites

MARSH is a tool developed to inform design not only at the WLEB Project site but also at other constructed wetland sites around the nation. The general trends revealed by the results of this research should hold at other sites with agriculturally-dominated watersheds as well, such as the management method being more important than wetland sizing and the general increase of TP retention with shallower water levels. Since the data employed to model rate constants, detention times, and phosphorus inflow concentrations are gathered from diverse geographical areas, the tool should be widely applicable to most areas with agricultural watersheds. Waterbird data needs to be tailored to specific regions and the species present within them, and climate scenarios need to be spatially determined and generated; otherwise, the model is a useful reduced-complexity tool to utilize in rapid tradeoff analysis at constructed wetlands across the country.

4.3 Uncertainties, Limitations, and Future Directions

4.3.1 Uncertainties in Extreme Climate Scenarios

The probability of occurrence in a year for each climate scenario was used to determine tradeoff scores for the MARSH method's TP retention and waterbird habitat suitability results (section 2.5.1). The probabilities were initially based on the hydrologic risk of each scenario's occurrence, informed by AEPs and a project lifespan of 30 years. The historical precipitation data was fit to both the Log- Pearson Type III (LP3) distribution and the Generalized Extreme Value (GEV) distribution using the Python programming language, both as one large dataset of the 119-year period of record and as two separate datasets, split into years pre- and post-1980 (with the post-1980 dataset being inclusive). All three precipitation datasets (whole and both sides of the

split) were found to reasonably fit both distributions according to the Kolmogorov-Smirnov goodness-of-fit test, albeit the LP3 distribution was a marginally better fit than the GEV distribution. Despite the high confidence that the precipitation data came from a population with an LP3 distribution ($p = 0.9864$), the generated extreme climate scenarios' precipitation values were too extreme for the fitted distribution to accurately predict reasonable return periods – the extreme dry scenario was predicted to have an AEP = 0.00018 and the extreme dry scenario was predicted to have an AEP = 0.00014. While this may raise concern that the extreme climate scenarios' extrapolated precipitation values are outside the feasibility realm, this is not the case. The 20% increase in precipitation is within predictions for precipitation in the Great Lakes region within the next 75 years (Zhang et al., 2020). The distribution fitting was also validated using the HEC-SSP software package developed by the USACE (**Error! Reference source not found.**).

Figure 11: Total annual precipitation vs. exceedance probability fit to the LP3 distribution from the frequency analysis results of the post-1980 precipitation data in HEC-SSP.

Exceedance probabilities for rainfall used for distribution-fitting were determined under the assumption of stationarity, but future conditions under climate change must take into account non-stationarity – that is, a storm one may have considered uncommon 50 years ago likely has an increased AEP when compared to the magnitude of today’s storms (Salas & Obeysekera, 2014). This is evidenced by the difference in AEPs when looking at the pre- and post-1980 precipitation data fitted to the LP3 distribution; the average year climate scenario of 33.88 inches of rain had an $AEP = 0.37$ for the former, but an $AEP = 0.67$ for the latter. When designing for the hydrologic future, changing conditions must be considered, as the 0.01 AEP storm of the past 30 years may be the 0.02 AEP storm of the near future, for example.

4.3.2 Limitations of MARSH

The phosphorus retention sub-model of MARSH was developed based on the first-order k-C model developed by Kadlec and Knight and presented in the first edition of their *Treatment Wetlands* textbook (1996) (section 2.1). This model operates under the assumption of plug flow as opposed to an intermediate between plug flow and completely mixed flow, which is generally the case in constructed wetlands (Knight et al., 2000). Since virtually no treatment wetlands are known to actually test as plug flow, the second edition of *Treatment Wetlands* notes that this assumption can in some instances lead to “very bad” extrapolations that should not be used in wetland design (Kadlec & Wallace, 2009). Despite the issues with being predicated on the assumption of plug flow, the k-C model has been found to provide conservative design estimates and is still the best-available and most widely used treatment wetland pollutant model due to its reduced complexity and minimal required input parameters (Babatunde et al., 2011). Since the scope of this project includes expanding upon and adding to the original version of MARSH, the k-C model was

deemed acceptable for use in the context of using a reduced-complexity model to determine design tradeoffs for phosphorus retention and habitat provision.

In addition to the limited scope of the k-C model, MARSH is further removed from a wholistic analysis by virtue of its simple water budget that omits variables such as groundwater exchange, snowfall inputs, and snowmelt outputs. The WHSA sub-model also is limited in its predictions due to only basing habitat suitability on preferred foraging depths and seasonality, while in reality waterbird preferences depend on numerous other factors such as food availability (both plants and animals) and vegetative density, which has also been found to be an important factor in phosphorus retention (Sabokrouhiyeh et al., 2020).

4.3.3 Future Directions

The non-stationarity of precipitation frequencies introduces uncertainties regarding designing wetlands for specific capacities and characteristics such as retention time. Future endeavors to fully incorporate non-stationarity in the AEPs of climate scenarios for the MARSH method would improve the robustness of MARSH's design capabilities for these changing times.

Additionally, experimentation with pollutant removal models other than the k-C model (e.g., the k-C* model) is warranted for future work with MARSH, as other models may prove better estimators of TP retention as more data on wetland hydraulic characteristics are gathered and disseminated.

Incorporating additional inputs/outputs to the simple water balance, such as snowfall/snowmelt and groundwater exchange, would also lend more accuracy to the estimations of both TP retention and habitat provision. One method to do this would entail obtaining historical flow data from a gauge on a nearby low-order stream and scaling its flows by the ratio of watershed areas for the gauge and wetland outlet. Once scaled, these flows can replace the precipitation and

runoff inputs in MARSH's water balance. The flow data will naturally account for snow and properly account for the timing of melting snowpack inputs in the spring. Incorporating the influence of vegetative cover on both food availability and habitat provision would also allow for more accurate predictions of waterbird species richness.

Regarding the use of MARSH at other sites, the WHSA sub-model is tailored specifically to the species of birds present in Lenawee County, MI – if MARSH were to be used at other sites, one must take this into account and update the sub-model accordingly to match the local fauna.

CHAPTER 5

CONCLUSIONS

This study highlights the importance of tradeoff consideration when balancing phosphorus retention and waterbird habitat provision in the design of constructed wetlands. Through application of the updated MARSH model developed in this study, both with historical climate data and incorporation of external hydrology data, I assessed ecosystem service tradeoffs under various management scenarios and wetland sizes across a wide range of potential future climate conditions. Results demonstrate that static management at lower water depths generally provides higher phosphorus retention, while dynamic management of water levels supports greater waterbird species richness. Notably, the static 0.1 management method (maintaining a maximum of 0.1 m water depth) consistently achieved the highest phosphorus retention across all scenarios, making it a robust choice for maximizing water quality improvements while minimizing impacts to habitat provision at the WLEB Project site.

Comparative evaluation of results between the MARSH method and GWLF-E method was performed to compare and contrast reduced-complexity modeling approaches with more complex models in this application. Findings confirm that MARSH is a reliable and effective tool for analyzing ecosystem service tradeoffs, providing results comparable to those generated by more complex models. This study demonstrates MARSH's utility as an accessible decision-support tool for practitioners working in wetland restoration and management seeking to design multi-objective constructed wetlands with minimal tradeoffs in ecosystem service provision.

Future research should explore the long-term performances of these management strategies under evolving climate conditions, and assess the potential for adaptive management in achieving multi-objective goals. Ultimately, through integration of ecological and hydrological considerations, wetland designers and managers can enhance both water quality and habitat provision, contributing to the restoration of impaired aquatic ecosystems in the Western Lake Erie Basin and beyond.

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APPENDIX A

EXTREME CLIMATE SCENARIO GENERATION WALKTHROUGH

This appendix is meant to serve as a walkthrough for a user of the Model for Assessment of Retention and Suitable Habitats (MARSH) spreadsheet to follow in order to generate extreme climate scenarios based off historical data.

Step 1: Obtaining Climate Data

The climate data source used for this study was the National Centers for Environmental Information (NCEI), a database maintained by NOAA. The NCEI's home page is located at <https://www.ncei.noaa.gov/>, or by searching "NOAA NCEI" in the search engine of a web browser and navigating to said link. Once on the main page, hover the cursor over "Services" near the top of the page and select "Access" from the menu that drops down beneath. This takes us to the Access page of the NCEI, which contains tools for both discovery and development.

Once on the Access page, scroll down and find "Data Access" under the "Discovery Tools" heading. There is a blue button underneath the brief description of the Data Access tool that reads "Launch Data Access" (shown in figure A1) – click this.

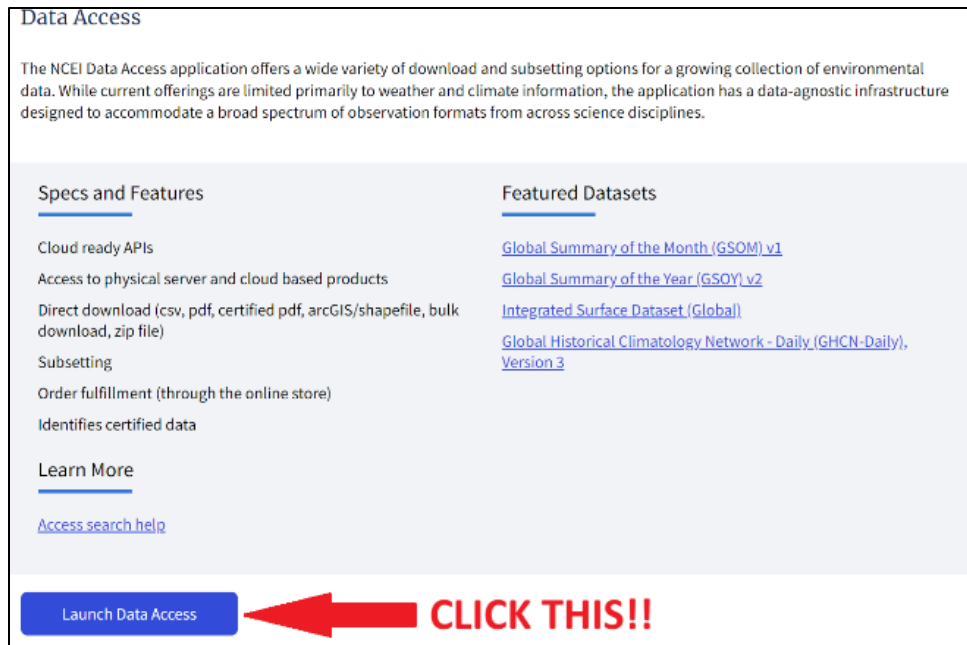


Figure A1: How to launch Data Access tool on NCEI website.

Once on the Data Access page, scroll down to the “Featured Datasets” subheading. The first dataset listed should be the Global Historical Climatology Network – Daily (GHCN-Daily), Version 3; this dataset is also listed on the previous Access page. Click the blue “Search Data” button (shown in figure A2) to open the dataset from the Data Access page.

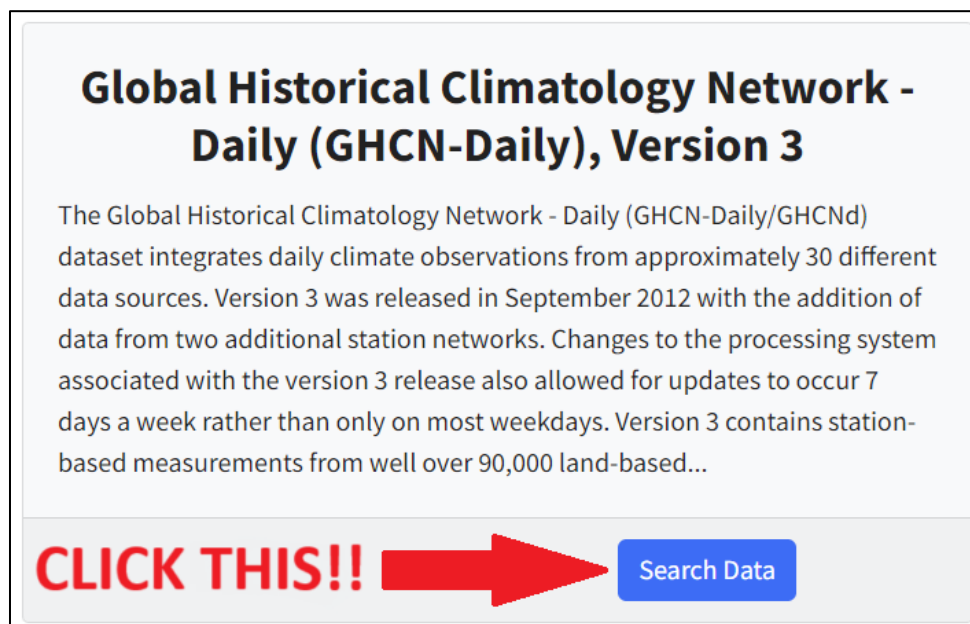


Figure A2: How to launch the GHCN-Daily database.

The main web page for finding data within the GHCN-Daily database is shown in figure A3 below. Once on this page, you can click the “Show List” button to filter stations by what metrics they have available. Under “Where”, you can enter the name of a city or county to find nearby gauges, or click on the button beneath it to find the locations on a map. Checking the box next to “Select Date Range” allows you to filter data by when it was recorded – use this to select the period of record for which you want data. You can also search for a specific station if you know its ID.

The screenshot shows the main search interface for the GHCN-Daily database. The header includes the NOAA logo and navigation links: Home, Access, Search, Dataset Search, Data Search, Order Status, Help, Guide, and Cart. The main title is "Global Historical Climatology Network - Daily (GHCN-Daily), Version 3". Below the title are three main filter sections: "What" (Data Types), "Where" (Location), and "When" (Date Range). The "What" section has a "Show List" button. The "Where" section has a text input field with "Ex: New York, NY" and a "Find Location Using Map" button. The "When" section has three date pickers for Year (YYYY), Month (MM), and Day (DD), and a "Select Date Range" checkbox. A "Station Search" field with "Ex: Airport" is also present. At the bottom, there are three view options: "List View", "Summary View", and "Map View".

Figure A3: The main page of the GHCN-Daily database.

Figure A4 (next page) depicts an example of a data record entry for the town of Adrian, MI. Clicking on the “Show Data Type” button shows a list of all data recorded by the gauge during the period of record (precipitation, temperature, etc.). Clicking on the “Preview” button and selecting a month and year allows for a visual preview of the data in the form of a table.

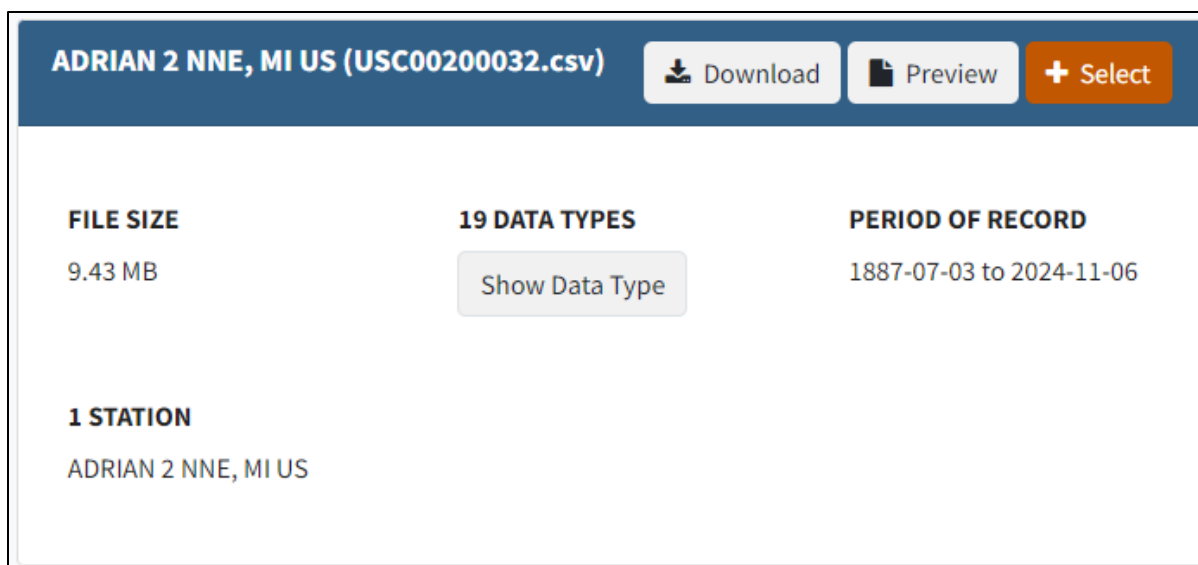


Figure A4: Data record entry for a station in Adrian, MI.

Click the orange “Select” button to choose the dataset, then choose “csv” as the desired output format at the bottom of the web page and click “Configure and Add”. In the menu that pops up, click the blue “Edit Data Types” button. Click “Select None” and manually re-add these 6 data types: maximum temperature, minimum temperature, precipitation, snow depth, snowfall, and temperature at the time of observation. If the last option is missing, ignore it and only select the first 5 data types. Click “Accept” to save the selected data types. Include attributes should be set to no, include station location and station name should both be set to yes, and units should be set to standard. Once your order options match these parameters, click the orange “Add Order To Cart” button in the bottom right. Click the “Proceed to Cart” button that pops up at the bottom of the screen or the “Cart” button in the top right of the web page to proceed to the Order Review page. Provide a suitable email address and click “Submit” in the bottom right of the page to place your order (don’t worry – it’s free!). Within a few minutes you should receive an email confirming your order followed shortly by another with a link to download the requested data. Once you receive the second email you will have one week to download the file, so do it ASAP or you will have to go through the steps to order the data again!

Once the .csv file has been downloaded, move it to the folder where you want it to be stored and open the file in Microsoft Excel. A banner will pop up at the top of the application warning of possible data loss from working with a .csv file in Excel – to avoid this and preserve the original copy of the data for future reference, click “Save As...” and save the file in the Excel Workbook (*.xlsx) format with an appropriate file name. Once the file has been saved as an Excel Workbook, it should automatically reopen in this format – double check the name of the workbook in the top of the window is “your_file_name.xlsx” and you are ready to move to step 2!

Step 2: Manipulating Data and Selecting Reference Year(s)

Before any changes have been made to the data, you should have 12 columns that match those shown in figure A5 below (tip: double click the line separating the column letters to auto-size them for better readability). PRCP stands for precipitation and is recorded in inches, while TMAX and TMIN stand for maximum temperature and minimum temperature, respectively, and are recorded in degrees Fahrenheit. Right-click the sheet at the bottom of the window that contains the raw data and rename it RAW.

	A	B	C	D	E	F	G	H	I	J	K	L
1	STATION	NAME	LATITUDE	LONGITUDE	ELEVATION	DATE	PRCP	SNOW	SNWD	TMAX	TMIN	TOBS
2	USC00200032	ADRIAN 2 NNE, MI US	41.91636	-84.01635	231.6	1/1/1900	0	0	1	16	0	
3	USC00200032	ADRIAN 2 NNE, MI US	41.91636	-84.01635	231.6	1/2/1900	0	0	1	24	14	
4	USC00200032	ADRIAN 2 NNE, MI US	41.91636	-84.01635	231.6	1/3/1900	0	0	1	27	16	
5	USC00200032	ADRIAN 2 NNE, MI US	41.91636	-84.01635	231.6	1/4/1900	0	0	1	34	12	
6	USC00200032	ADRIAN 2 NNE, MI US	41.91636	-84.01635	231.6	1/5/1900	0	0	0	42	31	
7	USC00200032	ADRIAN 2 NNE, MI US	41.91636	-84.01635	231.6	1/6/1900	0	0	0	37	21	
8	USC00200032	ADRIAN 2 NNE, MI US	41.91636	-84.01635	231.6	1/7/1900	0.01	0	0	47	34	
9	USC00200032	ADRIAN 2 NNE, MI US	41.91636	-84.01635	231.6	1/8/1900	0	0	0	33	22	
10	USC00200032	ADRIAN 2 NNE, MI US	41.91636	-84.01635	231.6	1/9/1900	0.01	0	0	43	20	

Figure A5: This is what your data should look like before any changes have been made.

Select the latitude, longitude, and elevation columns by holding down the CTRL button and clicking all three of them (on the letters C, D, and E). Right click and delete these columns – they are not necessary. This should shift the remaining columns to the left, so that you have data

only populating columns A-I. In column J, create a header titled “TAVG” in the first row. Below the header (cell J2), type the equation “=AVERAGE(G2:H2)” to set the cell’s value equal to the average of the maximum and minimum temperatures for that day. While cell J2 is selected with the equation filled out and displaying the average temperature, double click the green square in the bottom right corner of the cell to autofill the formula the rest of the way down for each date in the dataset.

Create a new sheet in the workbook by clicking the + button in a circle at the bottom of Excel – name it “BINNED”. Go back to the RAW sheet and select all rows of the DATE column by clicking on the cell containing the header and pressing CTRL + SHIFT + ↓ on the keyboard (*note: sometimes when there is a row missing data in one or more cells, this command doesn’t select the entire column. If this happens, continue holding CTRL + SHIFT and press the down arrow until the entire column is fully selected*). Select copy or press CTRL + C on the keyboard, go back to the BINNED sheet, and paste the values in cell A1. Repeat this for the PRCP column and the TAVG column that you just made, making sure that your selection goes to the bottom of the dataset for each column (*note: when copying values that reference other values, such as the case with TAVG, to avoid errors with pasting you should right-click and select “Values” under paste options*).

Name cell D1 “YEAR” and cell E1 “MONTH” as headers. In D2, below YEAR, enter the equation “=YEAR(A2)” and autofill it all the way to the bottom of the dataset in the same manner you did with TAVG above. In E2, below MONTH, enter the equation “=MONTH(A2)” and do the same. This should leave you with 5 columns of DATE, PRCP, TAVG, YEAR, and MONTH, as seen in figure A6 below.

	A	B	C	D	E
1	DATE	PRCP	TAVG	YEAR	MONTH
2	1/1/1900	0	8	1900	1
3	1/2/1900	0	19	1900	1
4	1/3/1900	0	21.5	1900	1
5	1/4/1900	0	23	1900	1
6	1/5/1900	0	36.5	1900	1
7	1/6/1900	0	29	1900	1
8	1/7/1900	0.01	40.5	1900	1
9	1/8/1900	0	27.5	1900	1
10	1/9/1900	0.01	31.5	1900	1

Figure A6: The 5 rows of data that should be present in the BINNED sheet.

Once all 5 columns are created and populated in the BINNED sheet, select the entirety of your data *except for the date column* (this can be done by selecting each of the column headers and pressing CTRL + SHIFT + ↓ on the keyboard). While the data is selected, navigate to the “Insert” tab in the ribbon at the top of Excel and select “PivotTable” (top-left). The Table/Range selection should already be selected – select “Existing Worksheet” under where you want it to be placed, click the arrow at the end of the input bar, and select cell F1 (directly next to the MONTH column header) and hit OK. Within the PivotTable fields menu that opens, drag YEAR and MONTH into the “Rows” box, and PRCP and TAVG into the “Values” box. Click the arrow next to “Sum of TAVG” in the PivotTable Fields window and click “Value Field Settings” then select count instead of sum. You can collapse/expand all of the years to show the breakdown of TAVG and sum of PRCP by month by right-clicking on the chart and selecting “Expand/Collapse -> ...Entire Field”. If the “Count of TAVG” field isn’t equal to 365 (or 366 if it’s a leap year), there is missing temperature data and the year should not be used as a reference year. If you expand a

Row Labels ▼	Count of TAVG	Sum of PRCP
1900	365	33.88
1901	365	24.92
1902	365	32.72
1903	#DIV/0!	26.69
1	31	0.4
2	28	1.4
3	31	0.5
4	30	4.02
5	31	1.37
6	30	2.83
7	31	6.19
8	31	5.25
9	30	1.88
10	31	0.85
11	30	1.4
12	31	0.6
1904	366	24.44
1905	365	31.34
1906	365	36.48

Figure A7: Even though the year 1903 has 365 counts of TAVG, when expanded it shows there is missing data and therefore it should not be used as a reference year.

year and the “Count of TAVG” field reads “#DIV/0!”, it also means there is missing temperature data and the year should not be used as a reference year.

Clicking the arrow by “Row Labels” allows for sorting from the lowest year to the highest or vice-versa, and more sorting options are available by clicking “More Sort Options” (e.g., sorting by highest/lowest precipitation). If looking for a dry year to use/reference, select More Sort Options and choose “Ascending By: Sum of PRCP” – for a wet year choose “Descending By:” instead. Look through the PivotChart for a year with 365 (or 366) valid

TAVG values (e.g., no #DIV/0! when expanded). Once this year has been identified, create a new sheet in the workbook titled “WET” or “DRY” depending on which you have chosen to do – for this example we will be using the DRY year. Once the sheet has been created and renamed, copy and paste the headers from the RAW sheet (excluding the TAVG column we made earlier) into the DRY sheet. Then, select all the values from the RAW sheet for the entire reference year (again excluding the TAVG values we calculated) and paste them underneath the headers in the DRY sheet. There should now be all variables for one calendar year in the DRY sheet, and we are now ready to move to the final step – calculating the adjusted precipitation values.

	A	B	C	D	E	F	G	H	I
1	STATION	NAME	DATE	PRCP (in)	SNOW	SNWD	TMAX	TMIN	TOBS
2	USC00200032	ADRIAN 2 NNE, MI US	1/1/1930	0.31	0	0	45	33	45
3	USC00200032	ADRIAN 2 NNE, MI US	1/2/1930	0.38	0	0	48	34	35
4	USC00200032	ADRIAN 2 NNE, MI US	1/3/1930	0.04	0	0	37	25	29
5	USC00200032	ADRIAN 2 NNE, MI US	1/4/1930	0	0	0	32	17	32
6	USC00200032	ADRIAN 2 NNE, MI US	1/5/1930	0	0	0	45	25	42
7	USC00200032	ADRIAN 2 NNE, MI US	1/6/1930	0	0	0	48	37	48
8	USC00200032	ADRIAN 2 NNE, MI US	1/7/1930	0.31	0	0	52	31	32
9	USC00200032	ADRIAN 2 NNE, MI US	1/8/1930	0.54	0	0	33	31	32
10	USC00200032	ADRIAN 2 NNE, MI US	1/9/1930	0.66	1	1	33	20	20

Figure A8: Example of what the DRY (or WET) sheet should look like after finishing step 2.

Step 3: Calculating Adjusted Precipitation Values

Create another sheet for calculating the adjusted precipitation values for your extreme wet year climate scenario – name it something like EXT-DRY. Copy and paste the final data from the DRY sheet in the first columns of the new sheet for easier reference during this process. For this tutorial, we will be adjusting the precipitation during the months in the growing season to be 40% less than what was actually observed in the reference year and finding a multiplier for the rest of the months that will amount to a total *yearly* decrease of 20% in precipitation. The growing season used for this tutorial is May through September (months 5-9), but you should research which months constitute the growing season for your location and use those instead – it will just require changing the month values in the equations used for adjustment.

A couple rows over from the raw data you pasted in the EXT-DRY sheet, make a row of headers following the layout in figure A9 below (make sure to change the months and percentages in the header names as needed to fit your data). Copy and paste the dates under the DATE column and the raw precipitation data under the ORIGINAL PRCP column. Under the ORIGINAL PRCP TOT column, sum the precipitation values for the whole year from the ORIGINAL PRCP column (for example, if your precip values are in cells L3 through L367, type in =SUM(L3:L367) to sum

them). Under the 20% DEC PRCP TOT column, adjust the summed total precipitation down (if your total summed precip is in cell M3, type in cell N3 =M3*0.8). Here comes the more involved part – for the MAY-SEP DECREASE (or whatever months you end up using as the growing season) we need to adjust *only the values for May through September* to be decreased by 40% while leaving the rest of the values unchanged. For reference, my DATE data is in column K and my ORIGINAL PRCP data is in column L; change these letters as necessary in your equation.

Adjustment Procedure								
DATE	ORIGINAL PRCP (in)	ORIGINAL PRCP TOT	20% DEC PRCP TOT	MAY-SEP DECREASE	TOT W/ MAY-SEP DECREASE	MULTIPLIER	REST OF YEAR	WHOLE YR ADJ PRCP

Figure A9: Headers for the data adjustment table.

Under the MONTH-MONTH DECREASE column, in the first cell, enter the following equation:

$$=IF(AND(MONTH(K3)>=5,MONTH(K3)<=9),L3*0.6,L3)$$

Make sure the K3 and L3 values are replaced with the location of the first date and original precipitation values of your dataset, respectively. Ensure the 5 (May) and 9 (September) values for the month are replaced with the start and end months of your growing season, respectively. If you are also doing a 40% decrease for the growing season precipitation values, leave the 0.6 in the equation alone; otherwise, replace it with a decimal corresponding to the desired percent decrease in precipitation over that time period. Once this equation has been entered and updated, hit enter and select the cell again. Grab the small green square in the lower right of the cell that appears and drag it down to the end of your dataset to apply this equation to every entry in the dataset. Scroll through the filled values to ensure that only precip values that fall in the months you chose for your growing season have changed and those outside of it have remained the same. In the cell underneath the TOT W/MONTH-MONTH DECREASE header, enter the sum of these new values

(for example, since my MAY-SEP DECREASE values are in column O, I would enter =SUM(O3:O368)). The sum of these values should be less than the ORIGINAL PRCP TOT value. If it is higher than the 20% DEC PRCP TOT value, that means the rest of the precip values need to be adjusted down to reach an annual precip total of 20% lower than the original; if it is lower (but still lower than the original!) this means that they need to be increased to account for the large loss in precipitation during the growing season. Either way, the next step will be the same.

Enter a value of 1 in the first cell under the MULTIPLIER header – this is just an initial guess and it will change later. In the first cell under the REST OF YEAR header, enter the following equation:

$$=IF(OR(MONTH(K3)<=4,MONTH(K3)>=10),L3*Q3,O3)$$

Again, make sure the K3 and L3 values are replaced with the location of the first date and original precipitation values, respectively. Replace the Q and the 3 with the column and row that correspond to the MULTIPLIER value of 1, making sure to leave the \$ symbols in place. Replace O3 with the cell location of the first value of your MONTH-MONTH DECREASE column (the first cell where we typed the previous equation). Make sure that the numbers 4 and 10 are replaced with the numbers corresponding to the months before and after the start and end of the growing season, respectively (for example, if your growing season starts in April and ends in October, replace the 4 with a 3 and the 10 with an 11). Under the WHOLE YR ADJ PRCP column, sum all of the values in the REST OF YEAR column (since my REST OF YEAR column begins at cell R3, the equation I typed into S3 was =SUM(R3:R368)). Select the summed value you just created. In the top ribbon of Excel, go to the Data tab. Click What-If Analysis under the Forecast options on the right side and select “Goal Seek” (see figure A10 below). For the “Set Cell:” option, choose the WHOLE YEAR ADJ PRCP value if not already populated. For “To value:”, enter the desired

number (e.g., the value in the 20% DEC PRCP TOT column). For “By changing cell:”, choose the MULTIPLIER value. Click OK to let Excel work its magic and voila! You will have a growing period whose precipitation is decreased by 40% and a remaining annual precipitation that is decreased by $((1-\text{MULTIPLIER}) \times 100)$ percent. If the multiplier is over 1, that means the precipitation over the rest of the year had to increase to make up for the 40% (or however much you chose) decrease in the growing season.

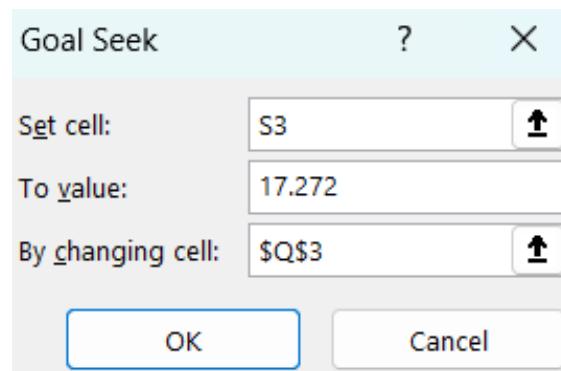


Figure A10: The Goal Seek window for finding the correct multiplier value.

A cell or two to the right of your adjustment procedure, create one last three-column table with the headings DATE, PRCP (in), and TAVG (C). Copy and paste the dates under the DATE column. Copy and paste the REST OF YEAR values under the PRCP column. For the TAVG column, enter the equation $=(((G3+H3)/2)-32)*5/9$ (making sure G3 and H3 correspond to the first data of TMAX and TMIN) to find the average daily temperature and convert it to Celsius. Hit enter, select this cell, and double click the little green box to fill those values down to the end of the dataset. This three-column is your final adjusted data and all you need to paste into the CS-ED and CS-EW sheets of the Model for Assessing Retention and Suitable Habitats (MARSH) excel file for informing your extreme dry and wet climate scenarios!

Repeat the steps for the WET and WET-EXT scenarios to generate an extreme wet scenario, making sure to change month values to ensure you have the right time period and the

number by which you multiply the original totals and months within your adjusted time frame to match the percent increase you desire (e.g., if you want a 20% increase in precipitation for the extreme wet year to complement a 20% decrease in precipitation for the extreme dry year, you would multiply the original precipitation value by 1.2 instead of 0.8).

APPENDIX B

MARSH ACRONYMS, DEFINITIONS, AND SOURCES

This appendix contains a one-page “cheat sheet” for new users of the Model for Assessing Retention and Suitable Habitat to easily understand acronyms and definitions used in the model/accompanying thesis. It also contains links to data sources, resources for use with MARSH, and downloads for the model and results analysis templates.

Model for Assessing Retention and Suitable Habitat – Cheat Sheet

Acronyms

- **DU:** Ducks Unlimited
- **EH:** External Hydrology Input
- **ES:** Ecosystem Service(s)
- **GWLF-E:** Generalized Watershed Loading Functions – Enhanced
- **MARSH:** Model for Assessing Retention and Suitable Habitat
- **MWD:** Mean Water Depth
- **NCEI:** National Centers for Environmental Information
- **TP:** Total Phosphorus
- **UGA:** University of Georgia
- **WHS:** Waterbird Habitat Suitability Assessment
- **WLEB:** Western Lake Erie Basin

Definitions

- **# BIRDS:** number of unique waterbird species supported throughout a year
- **% MEAN:** annual mean TP retention efficiency
- **% STDEV:** standard deviation in annual mean TP retention efficiency
- **Bird Score:** scaled (from 0 – 1) number of species supported for comparing habitat provision results
- **External Hydrology Method:** hydrologic method used with external model data as climate input
- **k-C model:** first-order wetland pollutant removal model developed by Kadlec and Knight (1996) used for TP retention estimates in MARSH
- **MARSH Method:** hydrologic method used with the precipitation- and runoff-driven climate scenarios
- **P Score:** scaled (from 0 – 1) TP retention values for comparing retention effectiveness
- **Q:** Volumetric Flow Rate (units: ft³/s)
- **TP MEAN:** annual mean TP retention (g/m²/year)
- **TP STDEV:** standard deviation in annual TP retention (g/m²/year)
- **Tradeoff Score:** weighted value for comparing tradeoffs in TP retention and habitat provision
- **Wetland Management Methods:**
- **Wetland Size/Sizing Scenario (%):** area of wetland as a percent of contributing watershed area
 - **Dynamic:** MWD managed for fall flooding in hunting season and spring/winter drawdown
 - **Static 2.0:** MWD managed for maximum water depth of 2.0 meters year-round
 - **Static 0.2:** MWD managed for maximum water depth of 0.2 meters year-round
 - **Static 0.1:** MWD managed for maximum water depth of 0.1 meters year-round

Links to Data/Resources

- [@RISK Excel Plug-In](#) (15-day free trial available; licenses purchasable from Lumivero)
- [MARSH Template, Results Analysis Template, and VBA Scripts \(edit to change file/sheet names\)](#)
- [MARSH Simulation and Results Analysis Video Tutorial](#)
- [NOAA NCEI Global Historical Climatology Network – Daily \(Version 3\)](#)
- [Climate Scenario Generation Walkthrough](#)
- [Curve Number Method](#) (for determining runoff)
- [Thornthwaite Method](#) (for determining evapotranspiration)
- Wetland data used to fit k-C model: [Land et al., 2016](#); [Ury et al., 2023](#)
- Foraging depths and seasonality for WHSA determined in conjunction with John Coluccy and Kali Rush of DU Great Lakes/Atlantic Regional Office

APPENDIX C

WLEB PROJECT SITE-SPECIFIC FINDINGS

This appendix contains a one-page document presenting important results and recommendations regarding tradeoffs in phosphorus retention and waterbird habitat suitability specifically for the WLEB Project site in Lenawee County, MI.

WLEB Pilot Project – Site-Specific Findings from MARSH

Hunter Kunzelmann

Hydrologic Scenario	MARSH Method	MARSH Method	GWLF-E Method	GWLF-E Method
Importance of TP retention vs. bird habitat provision	Retention > Birds	Birds > Retention	Retention >> Birds	Retention >= Birds
Recommended Management	Static 0.1 (MWD = 0.1 m)	Dynamic	Static 0.2 (MWD = 0.2 m)	Static 0.1 (MWD = 0.1 m)
Recommended Wetland Size	10%	10%	10%	10%
Mean Annual TP Retention (g/m ² /year)	0.33 ± 0.29	0.87 ± 0.42	0.58 ± 0.15	0.34 ± 0.09
Mean Retention Efficiency (%)	67.9 ± 3.2	46.7 ± 2.9	54.4 ± 8.7	63.0 ± 8.9
Bird species supported (#)	28	35	37	28
Notes	Lower MWD means higher retention but fewer species; same results at any size	Lower retention but most species; larger sizes increase retention but reduce species; requires active water level management	Both retention & habitat provision contingent on rate of channel overtopping	Both retention & habitat provision contingent on rate of channel overtopping

APPENDIX D

WATERBIRD HABITAT SUITABILITY ASSESSMENT – SPECIES LIST

This appendix contains a full list of all 48 species of waterbirds known to frequent the WLEB Project site in Lenawee County, MI. The WHSA uses information on minimum and maximum preferred foraging depths for each species and cross-examines it with the chosen scenario's water balance and seasonality charts to determine which species may be present in the wetland during any given month. Species in *italics* are species of greatest conservation need.

WATERFOWL			OTHER WATERBIRDS		
Species	Foraging Depth (in.)	Seasonality	Species	Foraging Depth (in.)	Seasonality
American Black Duck	0-10	EBLF	<i>American Bittern</i>	0-10	LBEF
American Wigeon	10-80	EBEF	American Coot	10-80	EBLF
Blue-Winged Teal	0-10	LBEF	<i>Black-Crowned Night Heron</i>	0-5	YR
Bufflehead	5-80	EBLF	Dunlin	0-5	EF
Canada Goose	10-80	YR	Great Blue Heron	10-80	YR
Canvasback	5-80	EBLF	Great Egret	10-80	EBEF
Common Goldeneye	5-80	EBLF	Greater Yellowlegs	0-10	EBEF

WATERFOWL			OTHER WATERBIRDS		
Species	Foraging Depth (in.)	Seasonality	Species	Foraging Depth (in.)	Seasonality
Gadwall	5-80	LBEF	Green Heron	0-5	EBEF
Green-Winged Teal	0-10	LBLF	Hudsonian Godwit	0-10	EB
Hooded Merganser	10-80	YR	<i>Least Bittern</i>	10-80	LB
Lesser Scaup	10-80	EBLF	Least Sandpiper	0-5	EBEF
Mallard	0-80	YR	Lesser Yellowlegs	0-10	LBEF
Northern Pintail	0-10	EBEF	Long-Billed Dowitcher	0-5	EF
Northern Shoveler	0-10	EBEF	Pectoral Sandpiper	0-5	LBLF
Red-Breasted Merganser	5-10	EBLF	Pied-Billed Grebe	10-80	EBLF
Redhead	5-80	YR	Ruddy Turnstone	0-5	EF
Ring-Necked Duck	5-80	EBLF	Sandhill Crane	10-80	EBLF
Ruddy Duck	5-80	LBLF	Semipalmated Plover	0-5	EF
<i>Trumpeter Swan</i>	10-80	EBLF	Semipalmated Sandpiper	0-5	EF
Wood Duck	5-80	EBEF	Short-Billed Dowitcher	0-5	EF
			Solitary Sandpiper	0-5	EF
			Sora	0-5	EF

	OTHER WATERBIRDS		
	Species	Foraging Depth (in.)	Seasonality
	Spotted Sandpiper	0-10	EF
	Stilt Sandpiper	0-5	EF
	Virginia Rail	0-5	EF
	Willet	0-10	EF
	<i>Wilson's Phalarope</i>	0-80	EF
	Wilson's Snipe	0-5	EF

Depending on a species' anticipated presence in the region throughout the year, each species is assigned either a single code or a combination of two codes from the table below.

SEASONALITY CODES		
Code	Definition	Months Present
EB	Early breeder/spring migrator	March – June
LB	Late breeder/spring migrator	May – August
EF	Early fall migrator	August – September
LF	Late fall migrator	October – December
YR	Year-round	January – December