A SUITABILITY ANALYSIS OF THE WETLANDS ALONG THE MIDDLE MISSISSIPPI RIVER FLOODPLAIN FOR RIVERINE NITRATE ATTENUATION

by

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B.S., Southern Illinois University, 2017

A Thesis
Submitted in Partial Fulfillment of the Requirements for the Master of Science Degree

Department of Geography and Environmental Resources
in the Graduate School
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THESIS APPROVAL

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Approved by:

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Noah Rocco Scalero, for the Master of Science degree in Geography and Environmental Resources, presented on October 29, 2020, at Southern Illinois University Carbondale.

TITLE: A SUITABILITY ANALYSIS OF THE WETLANDS ALONG THE MIDDLE MISSISSIPPI RIVER FLOODPLAIN FOR RIVERINE NITRATE ATTENUATION

MAJOR PROFESSOR: Dr. Jonathan Remo

Persistently elevated nitrogen loads discharged to the Gulf of Mexico from the Mississippi and Atchafalaya rivers have been shown by a vast body of literature to be the cause of recurring hypoxic conditions in the Gulf of Mexico. Riverine wetlands have been shown to be important ecosystems capable of substantially reducing nitrogen loads delivered downstream through N removal processes including denitrification, anaerobic ammonium oxidation, and plant uptake. In order to assess the relative potential of wetland sites for nitrogen attenuation, a suitability analysis was performed to identify the relative nitrogen attenuation potential of wetlands within the Middle Mississippi River (MMR) floodplain. For this assessment, the literature on nitrogen cycling in riverine wetlands was used to identify variables which are associated with denitrification potential. Data for these variables were sourced from publicly available geospatial datasets and floodplain inundation frequency estimates using a hydraulic model. The variables compiled for this analysis included flood frequency, soil drainage class, soil hydrologic class, soil pH, soil texture, land use, and soil organic carbon. Principle component analysis was applied to the dataset to reduce the number of variables in the suitability model. The results of the principle components analysis revealed that the first four components explained 77% of the variation within the dataset of potential denitrification variables. As a result of the PCA analysis, the variables Soil Hydrologic Class, Soil Organic Carbon, Land Cover, Soil pH, SSURGO’s Flood Frequency, and Flood Exceedance Probability were used to
evaluate riverine wetland areas potential for denitrification under two hydrologic connection scenarios, a “with-levee” and a “no-levee” condition. For the with levee scenario, there were 66,146 ha of floodplain that attained a suitability rating of average potential, an additional 16,937 ha of floodplain attained high potential, and 706 ha of floodplain were rated as having very-high potential. The second scenario assumed removal of levees in the study area. In this scenario, there were 65,897 ha in the floodplain that attained a suitability rating of average potential. There were 34,457 ha in the study segment that attained a rating of high potential, whereas 510 ha attained a very-high potential on the suitability scale. These results were then analyzed by levee system, comparing economic and population data with the results of the suitability analysis. In particular, the amount of area within a levee system achieving a rating of high potential vs. the total property value within the levee system was compared to determine which systems would be best candidates for strategic reconnection. This analysis suggests that the Bois & Brule, the Big Five, and the Grand Tower / Degonia Levee systems are the most suitable systems for strategic reconnection efforts in the study area.
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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>i</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vi</td>
</tr>
<tr>
<td>Chapters</td>
<td></td>
</tr>
<tr>
<td>CHAPTER 1 – Introduction</td>
<td>1</td>
</tr>
<tr>
<td>CHAPTER 2 – Study Area</td>
<td>13</td>
</tr>
<tr>
<td>CHAPTER 3 – Methods</td>
<td>19</td>
</tr>
<tr>
<td>CHAPTER 4 – Results</td>
<td>32</td>
</tr>
<tr>
<td>CHAPTER 5 – Discussion</td>
<td>45</td>
</tr>
<tr>
<td>CHAPTER 6 – Conclusions</td>
<td>50</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>51</td>
</tr>
<tr>
<td>VITA</td>
<td>57</td>
</tr>
</tbody>
</table>
LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1 - Six variables and the associated suitability score assigned for corresponding values...</td>
<td>30</td>
</tr>
<tr>
<td>Table 2 - Correlation Matrix (Pearson n) between variables</td>
<td>33</td>
</tr>
<tr>
<td>Table 3 - Eigen values, percentage of variability explained by each component, and cumulative explained variability</td>
<td>33</td>
</tr>
<tr>
<td>Table 4 - Correlations between variables and factors</td>
<td>33</td>
</tr>
<tr>
<td>Table 5 - Correlation Matrix (Spearman) between variables</td>
<td>35</td>
</tr>
<tr>
<td>Table 6 - Areas for each suitability category for the no-levee and w/ levee scenario</td>
<td>37</td>
</tr>
<tr>
<td>Table 7 - Levee systems and the population, number of structures, and property value protected in each levee system</td>
<td>41</td>
</tr>
<tr>
<td>Table 8 - Suitable area (in hectares) and percentage of levee protected area shown for each suitability score for a with levee scenario</td>
<td>42</td>
</tr>
<tr>
<td>Table 9 - Suitable area (in hectares) and percentage of levee protected area shown for each suitability score for no levee scenario</td>
<td>42</td>
</tr>
<tr>
<td>Table 10 - Results of sensitivity analysis showing percent total difference from output model</td>
<td>44</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1 - Hypoxic zone in square kilometers per year from 1985-2019.</td>
<td>2</td>
</tr>
<tr>
<td>Figure 2 - Distribution of bottom-water dissolved oxygen, July 22-July 31, 2019.</td>
<td>3</td>
</tr>
<tr>
<td>Figure 3 - Study area showing the Mississippi River, floodplain, and levee protected area</td>
<td>14</td>
</tr>
<tr>
<td>Figure 4 - Flowchart showing methods of the Principle Components Analysis.</td>
<td>23</td>
</tr>
<tr>
<td>Figure 5 - Flowchart showing methods for the suitability analysis conducted in ArcGIS 10.7.1.</td>
<td>29</td>
</tr>
<tr>
<td>Figure 6 - Scree plot where columns represent Eigen values for each component and the red line shows cumulative variability.</td>
<td>34</td>
</tr>
<tr>
<td>Figure 7 - Correlations between factors and variables for axes F1 and F2.</td>
<td>34</td>
</tr>
<tr>
<td>Figure 8 - Bar chart showing area in square meters per each suitability score under the w/ levee and no levee scenarios.</td>
<td>37</td>
</tr>
<tr>
<td>Figure 9 - Distribution of suitability scores across study region under w/ levee scenario.</td>
<td>39</td>
</tr>
<tr>
<td>Figure 10 - Distribution of suitability scores across study region under no levee scenario.</td>
<td>40</td>
</tr>
<tr>
<td>Figure 11 - Area receiving high potential rating vs the property value in each levee system.</td>
<td>41</td>
</tr>
</tbody>
</table>
CHAPTER 1
INTRODUCTION

The effects of high nutrient loading in the Mississippi River (MR) have been persistent for many decades and have been well documented by the scientific literature (e.g., Mitsch, 2001; Sprague, 2011; Remo, 2016, among others). Nitrogen runoff from both point and nonpoint sources have been shown to be major contributors to recurring hypoxia in the Gulf of Mexico. However, since the early 20th century, the proliferation of corn and soy production in the basin, as well as the implementation of manufactured fertilizers, have greatly increased the amount of nitrogen entering the MR (Goolsby, 1999). The heavy use of fertilizers, typically nitrate or ammonium based, leave high levels of mobile N in the soil. The excess N often ends up in the river via hyporheic zone mixing, channelized flow, or direct runoff. Estimates indicate that approximately 90% of the nitrogen and phosphorous draining into the Gulf of Mexico are from nonpoint sources (Goolsby, 1999). In addition to increased N inputs, the systematic disconnection of the floodplain has substantially reduced its ability to attenuate nitrates before they reach the Gulf. As a result, nitrate inputs from the Mississippi to the Gulf have tripled since the 1950’s (Rabalais, 2002).

1.1 GULF HYPOXIA

Hypoxia in the Gulf occurs seasonally, coinciding with large nutrient fluxes from the Mississippi and Atchafalaya rivers, with the largest hypoxic area occurring from June through late August (Rabalais, 2001). Hypoxia in the Gulf refers to waters with dissolved oxygen concentrations below 2 mg/l – a concentration at which many aquatic life forms can no longer thrive. The hypoxic zone in the Gulf ranges depending on nutrient input from the Mississippi and Atchafalaya and has been estimated to range up to 20,000 km² (Rabalais, 2001). The large spatial
extent of the hypoxic zone in the Gulf of Mexico makes it the second largest coastal hypoxic zone in the world (Rabalais, 2002). Figure 1 displays the variability of the hypoxic zone from year to year, which is affected by numerous factors including N flux from the Mississippi and Atchafalaya, river discharge, ocean circulation patterns in the Gulf, and wind dynamics. The long-term average area of the hypoxic zone is around 14,000 km$^2$ and the EPA’s Hypoxia Task Force goal is to have an average hypoxic zone of 5,000 km$^2$ (EPA Hypoxia Task Force, May 2019). Figure 2 displays the distribution of bottom-water dissolved oxygen content during July 2019. The hypoxic zone in 2019 extended 18,000 km$^2$ – approximately 13,000 km$^2$ above the 5,000 km$^2$ goal of the Hypoxia Task Force.

Figure 1: Hypoxic zone in square kilometers per year from 1985-2019. Hypoxic zone defined as dissolved oxygen < 2.0 mg/L. EPA Hypoxia Task Force goal of reducing the average hypoxic zone to 5,000 square km shown in black. Data source: Nancy N. Rabalais, Louisiana Universities Marine Consortium, and R. Eugene Turner, Louisiana State University.
Low dissolved oxygen in the hypoxic zone has a variety of detrimental impacts for many species. For instance, the habitat loss resulting from hypoxia can range from 25% for brown shrimp, up to 50% for the Atlantic croaker – both of which are important indicator species as they inhabit different zones of the Gulf of Mexico (Craig, 2005). Many other species are impacted by the hypoxic conditions. The impacts on various marine species can range from changes in food supply, mortality due to low DO, habitat reduction, and/or forced migration due to uninhabitable conditions (Diaz, 2011; Rabalais, 2002). The economic ramifications of hypoxia can be difficult to discern from other external complicating factors such as over-fishing, habitat destruction, and other pollutants. These stressors contribute to loss of fisheries; however, hypoxic conditions undoubtedly have a significant economic impact on fisheries affected by high nutrient runoff (Diaz, 2011; Diaz, 1999; Goolsby, 1999; Rabalais, 2002).
1.2 THE ROLE OF WETLANDS IN NITRATE ATTENUATION

While several factors influence the seasonal size of the hypoxic zone in the Gulf - such as ocean currents, wind patterns, and hydrologic conditions - the primary influencing factor is nutrient loading from the Mississippi and Atchafalaya rivers (Rabalais 2002). Numerous strategies have and should continue to be employed to reduce the quantity of nutrient runoff into the MR. These strategies include increasing buffer distance between crops and main water ways, more efficient application of fertilizers, and introduction of engineered wetland treatment cells have all been posed as ways to reduce riverine nitrate levels (Lin et al., 2002; Saeed and Sun, 2012; Tiner, 2003). Though, these measures by themselves are likely insufficient. A large body of research has posited that reestablishing wetlands and reconnecting floodplain area could be a cost-effective tool to attenuate nitrates before they reach the Gulf (Mitsch, 2001; Schramm et al., 2009; Sparks, 1995).

Wetlands can attenuate nitrogen via three primary pathways: plant uptake, anaerobic ammonium oxidation (anammox), and denitrification. Plant uptake refers to the process by which plant life in a wetland utilizes NO$_3^-$, and sometimes NH$_4^+$, thereby holding in place otherwise mobile forms of nitrogen that would have the potential to enter the riverine system. While plant uptake is a viable method of nitrogen attenuation in many other ecosystems, wetlands are highly productive environments and thus have the capacity to retain large amounts of nitrogen in biomass (Lin et al., 2002; Tiner, 2003). In addition, wetlands often receive a greater influx of nitrogen enriched water than other ecosystems. Availability of nitrogen is a limiting step for plant uptake as well as for denitrification and anammox.

Denitrification is the process by which nitrates are converted to atmospheric nitrogen (N$_2$). Unlike plant uptake which only locks nitrogen in place, denitrification results in nitrogen
leaving the riverine system via N$_2$. This is thought to be one of the primary nitrogen removal pathways for most wetland areas (Pinay, 2015). Until the more recent discovery of anammox, denitrification was thought to be the sole removal mechanism of nitrogen in wetland systems. The denitrification process relies on several necessary conditions. The necessary components are availability of nitrates, suboxic soil conditions generally due to saturation, and availability of denitrifying bacteria (Hanson et al., 1994; Hoagland et al., 2019; Jicha et al., 2014). Anammox is a more recently discovered reaction of the nitrogen cycle where ammonium is oxidized to N$_2$. This process relies on the presence of nitrite as an electron acceptor, and like denitrification, requires anoxic conditions. Additionally, anammox requires the presence of nitrogen, particularly in the forms of ammonium and nitrite, as well as the facilitating bacteria (Hoagland et al., 2019; Zhu et al., 2011; Zhu et al., 2013).

As discussed above, the three primary prerequisites influencing denitrification and anammox are availability of nitrate/ammonium enriched water, abundance of facilitating bacteria, and presence of anoxic soil conditions. Despite the simplicity of these conditions, there are numerous complicating factors that can influence the degree to which denitrification or anammox will occur. For instance, connectivity of the wetland to the main channel, occurrence of overbank flooding, and periodicity of flooding all greatly impact the amount of nitrogen available. Nitrogen availability has been shown to be a large limiting factor for denitrification (Hanson et al., 1994). Hanson et al (1994) found that there was approximately a 59% increase in denitrification in two similar wetland sites which differed mainly in the amount of nitrate-enriched water each received. The enriched site showed substantially more denitrification than the non-enriched site, however, the enriched site was still shown to be NO$_3$ limited (Hanson et al., 1994). Similarly, Hoagland et al (2019) found a 7-fold increase in total N mass removed from
a reconnected floodplain between a dry and wet year (2016 and 2017 respectively) in the Consumnes River floodplain. Due to its role in delivering nitrates to wetland areas, flooding and wetland connectivity are crucial influencing factors for nitrogen attenuation in riverine wetlands.

Another critical component for nitrogen attenuation to occur is the presence of anoxic soil conditions. This can be caused by overbank flooding, however there are many other factors which can impact the presence or absence of anoxic conditions such as water table elevation, ponding, runoff, soil texture, and rates of infiltration. A combined fine texture soil percentage (clay/silt) of 65% has been posited as a threshold condition for denitrification to occur. The relationship between soil texture and denitrification is positive, as both increase linearly above 65% soil texture (Groffman and Tiedje, 1989; Pinay et al, 2002; Pinay et al. 1995). This phenomenon is a result of fine textured soils having a greater water filled porosity, which can result in the formation of anoxic conditions in the soil (Parkin and Tiedje, 1984; Pinay et al 2002). Drainage of a wetland is also largely affected by soil type as clay soils will have poorer drainage than silt or sand. Slower drainage can result in a wetland experiencing more frequent and/or prolonged periods of anoxic soil conditions. Drainage of a wetland cell often impacts water residence time, which increases duration of contact between water and sediment. The duration of contact between water and sediment correlates positively with increased N processing (Pinay, 2002).

Removal of nitrogen via denitrification and anammox is also contingent on the presence of the bacteria who facilitate these processes. These microbes are present where there is ample organic matter in the soil for a food source (Tiner, 2003). Soil organic carbon content can be an indicator of vital microbial life in the soil and thus is a valuable measurement for analysis of wetland soils for denitrification. Soil organic carbon has been shown to be an important
component for denitrification to occur (Brettar and Hofle, 2002; Hill and Cardaci, 2004; Lin et al., 2002; Seitzinger, 1994; Stahl, 2000). The oxidation of organic carbon by microbes provides electrons that are needed for denitrification (Rivett et al., 2008). A study by DeLaune et al in 1996 found that denitrification in the floodplain soils of their region were likely carbon limited as adding glucose resulted in a 2-fold increase of nitrate reduction (Delaune et al., 1996).

Other factors that have been shown to influence rates of nitrogen attenuation are soil pH, temperature and seasonality, and land use history. There is not a fully described relationship between pH and denitrification in the literature, however, many studies have shown that a pH close to neutral is ideal. A pH of between 5.5 to 8.0 has been posited as an acceptable range for denitrifying bacteria (Rivett et al., 2008; Rust et al., 2000; ŠImek and Cooper, 2002). Denitrification has been shown to be hindered with pH below 5 or above 8.3 (Rust et al., 2000). Temperature and seasonality are also important influencers of denitrification rates. Denitrification occurs within a wide range of temperatures, between 20 and 500 C, though the ideal range is between 250 and 350 C (Rivett et al., 2008). Because denitrification rates are tied to temperature, seasonal variations in these rates are common. Seasonality also impacts denitrification rates as flooding dynamics are often tied to seasonal hydrologic patterns. This impacts the amount and timing of nitrogen delivery to the floodplain (Schramm et al., 2009). Additionally, farmers generally apply fertilizers in the spring or fall which can cause large seasonal variations in riverine nitrate concentrations.

Lastly, land use history also greatly impacts the nutrient dynamics in a wetland. For instance, a restored wetland that was historically under cultivation using fertilizers may have large amounts of stored nitrogen in the soil. It has recently been posited that there may be nitrogen buildup in agricultural soils near the root zone that can persist for up to 35 years even
after agriculture has ceased (Van Meter, 2016). Nitrogen that was stored deep in old agricultural fields is slowly reintroduced, via subsurface flow and groundwater mixing, back into the riverine system. This may also result in old agricultural fields that are restored to wetlands acting as a source of nitrogen to the river for the first several decades until the legacy nitrate has been depleted. Once that nitrogen has been removed from the root zone over the course of many years, those wetlands may become sinks for nitrogen instead of sources (Van Meter, 2016).

1.3 PREVIOUS WORK ON CLASSIFICATION OF WETLANDS FOR NITROGEN ATTENUATION

Riverine wetlands have been extensively characterized and classified in the literature according to numerous physical and biological characteristics (Brinson, 1993; Cowardin et al., 1979; Federal Geographic Data Committee, 2013). The Classification of Wetlands and Deepwater Habitats of the United States (Cowardin et al. 1979) is one of the seminal pieces of literature on wetland classification in the United States. It lays out a complex classification scheme based on vegetation, soils, frequency of flooding, and other parameters for estuarine, lacustrine, riverine, marine, and palustrine systems. This framework was the basis for the development of the National Wetland Inventory (NWI) which is managed by the US Fish and Wildlife Service (USFWS). The NWI is an extensive inventory of the wetlands of the United States which also provides a web mapping software where publicly available wetland classification data can be accessed or retrieved for use. Wetlands are classified in NWI using remote sensing technologies coupled with field verification measures. NWI allows for the monitoring and management of wetlands over large spatial scales due to its use of remote sensing technologies (Federal Geographic Data Committee, 2013).
The United States Army Corps of Engineers has also developed a wetland classification system but using a hydrogeomorphic approach (Brinson, 1993). This approach focuses on the geomorphic, hydrologic, and chemical parameters that differentiate wetland types to formulate a classification system. While it does not include biological features of a wetland, the geomorphic setting and hydrology undoubtedly underpin the type of biological features a wetland will exhibit. Both the National Wetland Inventory and the USACE approach are valuable inventory and classification tools. However, by themselves they are not assessment tools for wetland ecosystem function such as nutrient attenuation.

The ability to utilize these comprehensive inventory resources for predicting a wetland’s nitrogen attenuation potential, based on its inventory classification, would be extremely advantageous for decision makers and researchers alike. More recent work by the USFWS has attempted to correlate wetland function with the classification system of the NWI (Tiner, 2003). However, this work only discusses nutrient processing in general, not specifically nitrogen attenuation. Additionally, this resource categorizes wetlands’ nutrient processing ability into only two categories – moderate and highly productive (Tiner, 2003). A more clear linkage of nitrogen attenuation potential to wetland classification attributes is a needed tool for the improvement of floodplain management, specifically and water resource planning in general.

1.4 A SPATIAL APPROACH FOR IDENTIFYING WETLANDS SUITABILITY FOR NITRATE ATTENUATION

The major variables contributing to denitrification and other nitrogen removal pathways are generally understood. While the research community continues to work on regional-scale calculations of nitrogen processes in riverine systems, there is a present need for decision-making tools and assessments that can allow policy-makers to discern which wetland ecosystems provide the greatest nitrate attenuation capabilities. For this study, the nitrate attenuation
capability of a wetland refers to the ability of a wetland to reduce riverine nitrate levels through processes including plant uptake, denitrification, annamox, and other geochemical pathways. Given many of the major components that are necessary for denitrification are known, regional-scale assessment of relative suitability of floodplain and floodplain wetlands for nitrate attenuation are both possible and likely useful for research planning and environmental management.

A suitability assessment using GIS allows for the evaluation of multiple overlapping criteria or components to, ideally, achieve the best outcomes possible for a given land area (Eastman, 1998; Malczewski, 2004). For this application, a successful suitability analysis would illuminate which floodplain regions and associated wetlands are likely to be relatively more or less suitable for nitrate attenuation. Such an analysis could be used in multiple decision making pathways such as advocating for restoring land that was previously a wetland ecosystem, deciding which potential restoration sites would be more efficient, or for computing relative value (in terms of ecosystem services provided) to floodplain and their wetlands.

Few studies have used suitability analyses specifically for nitrate attenuation, however, there is a vast body of literature that shows the benefits of suitability analysis for land-use and environmental planning (Malczewski, 2004). One study has used a suitability analysis to determine ideal sites to construct wetlands for nutrient and pollutant filtration in Adige-Bacciglione, Italy and Neuwuhrener Au, Germany (Trepel and Palmeri, 2002). This study formulated their “Land Score System” for wetlands based on geologic, climatic, environmental, hydrologic, social, and economic data. This research provides a useful methodology for suitability analysis of sites for wetland restoration; however, it needs some considerable adaptation for the context of wetland reconnection for floodplain nitrogen attenuation. For
instance, the study used distance from a river and elevation as two of their primary physical parameters (Trepel and Palmeri, 2002). Using elevation as a suitability variable is only broadly indicative of ponding or presence of water. This will necessarily skew suitable sites to downstream catchments as they are at lower elevations. Also, using distance from the river as a variable is perhaps too generalized and may not be indicative of local conditions. Along the MR specifically, levees and other river training structures make simple estimations of hydrology (i.e. distance from river) ineffective. No studies that specifically used suitability analysis for regional-scale assessment of nitrogen attenuation ability in floodplain wetlands were identified during this research.

1.5 PURPOSE STATEMENT FOR THIS RESEARCH

The purpose of the following research is to conduct a suitability analysis of the MMR floodplain between St. Louis and Thebes, IL, to identify the most suitable sites for nitrate attenuation. Eight key variables were formulated based on the denitrification literature and available datasets. Principle component analysis was used to assess the variance explained by each of these variables to reduce the number of parameters used in the suitability model. Floodplain wetland suitability for nitrogen attenuation will be relatively assessed based on suitability criteria for two scenarios: 1) without levees, and 2) with current levee scenario. This will provide bounding assessments for a business-as-usual scenario, but also for a floodplain–reconnection scenario where abandoning certain levees in the floodplain to reestablish wetlands may be more economically sound due to increasing flood occurrence, levee maintenance costs, and unpredictable crop yields. The development of a successful suitability analysis tool relies on the incorporation of relevant and spatially explicit data. Additionally, the variables used should
be based on data that is relatively accessible in other regions as well – this ensures that other regions can adapt the methodology to suit their context.
CHAPTER 2

STUDY AREA

This study will focus on the MMR floodplain from south of St. Louis, MO to Thebes, IL as shown in Figure 3. The use of this study segment provides many advantages. First, this is a large section of floodplain and is generally representative of floodplain connectivity issues along many segments of the MR. This segment comprises a total area of approximately 145,700 hectares with ~ 55% or 79,300 hectares being used for agricultural purposes. Development in this area is low, however there are some small towns such as Grand Tower and Thebes, IL among others. Levees keep the floodplain in this study region largely disconnected from the river. River training structures through this segment have deepened the river channel along some reaches potentially causing some floodplain areas still connected to the river to drain more rapidly after a flood pulse than may have happened historically (Remo 2016). However, despite many of these areas being protected by levees there has been significant flooding in recent years, namely the floods of 2011, 2015 / 2016, 2017, and 2019. This recent flooding of these levee protected areas are not due to direct inundation from the river. Many of the agricultural levees which protect floodplain areas along this study segment are gravity drained. Precipitation and groundwater collected within the levee system during floods can only be drained after river levels drop to near or below bankfull conditions. The inability to drain the excess water behind these levee systems has resulted in internal drainage flooding during large, prolonged flooded events such as the 2011, 2017 and 2019 floods. These floods resulted in substantial crop losses and damage to buildings in low-lying developed areas in the region such as Grand Tower and East Cape Girardeau.
Figure 3: Study area showing the Mississippi River, MMR floodplain, and levee protected area.
2.2 GEOMORPHIC SETTING OF THE MIDDLE MISSISSIPPI RIVER

The current geomorphology of the MMR is the product of both recent glaciations and subsequent climatic changes. As the Laurentide ice sheet reached its maximum extent about 25,000 years ago, the MR floodplain started to aggrade as it received large amounts of glaciofluvial deposits mainly consisting of sand and gravel. This large supply of glacial water and coarse sediments resulted in a braided channel morphology for the MMR. As the climate began to transition from full glacial to the early Holocene approximately 12,400 years ago, the MMR assumed an island-braided morphology as the floodplain sedimentation transitioned to being dominated by overbank deposits of fine-grained sediments. Then, approximately 5,700 years ago, the MMR below the junction with the Missouri River transitioned to a meandering morphology. This change is hypothesized to be a result of large volumes of Great Plains’ sediment transported by the Missouri River. Approximately 1,000 years ago, a reduction in supplied suspended sediment from the Missouri River resulted in the MMR morphology transitioning back to island braided (Bettis III et al, 2008; Remo, 2016; Remo et al., 2018). This morphology lasted until river engineering commenced on the MR approximately 200 years ago (Remo 2016).

2.3 A BRIEF HISTORY OF ENGINEERING ON THE MISSISSIPPI RIVER

To better understand the hydrologic, land-use, and nitrogen dynamics along the MMR, it is first imperative to discuss the historic development of flood control structures and measures along the river. The MR has been managed for the past 200 years for purposes of navigation and flood risk management efforts largely aimed at reducing flood risk to floodplain agriculture.
River engineering in the forms of dams, channel incision, and levees have led to significant decreases in floodplain area for many large low-lying rivers worldwide (Buijse, 2002). Since congressional approval in the early 1820s, the United States Army Corps of Engineers (USACE) has been tasked with different river improvement projects. Initially, this work consisted of removing obstacles and snags in the river that hindered transportation (USACE, 2020). However, the engineering of the MR has become more prominent in the last 100 – 150 years. The USACE has implemented river engineering structures including dikes, chevrons, bendway weirs, revetments, dams, levees, and cutoff channels to manipulate the depth and width of the MR (Remo, 2016). These structures, along with dredging, maintain minimum depths for barges and other vessels to safely navigate the channel (Meade, 1995). Federal regulation requires that the USACE maintain a channel that is a minimum of 2.7 meters deep during all discharge conditions. This ensures that the river is a reliable corridor for the transport of goods. In addition to ensuring that the river is reliably navigable, the USACE seeks to confine the river to its channel and reduce inundation of the floodplain. This has given rise to vast agricultural development in the MR’s floodplain, as well as commercial and residential infrastructure development. The protection of development in the floodplain has necessitated a disconnection of the river from its floodplain, which causes significant externalities. Navigation and floodplain agriculture have been the primary objectives for the USACE, at the expense of the many other important ecosystem services that can be provided by a more well-connected floodplain (Remo, 2016).

2.4 STRATEGIC FLOODPLAIN RECONNECTION

Recent studies have posited strategic floodplain reconnection as a way to achieve a more equitable balance between riverine habitat, agricultural, and ecosystem service benefits that
floodplains can provide (Guida et al., 2016; Opperman et al., 2009; Remo et al., 2017). Strategic reconnection in this study refers to the reconnection of portions of the floodplain, through levee setbacks or removal, to achieve a more equitable balance between the services floodplains can provide. This present study focuses primarily on strategic reconnection for nitrate attenuation capabilities provided by well-connected wetlands in the floodplain. However, other important ecosystem services can also be gained from strategic reconnection such as flood mitigation, wildlife habitat restoration, and recreation opportunities (Guida et al., 2016; Opperman et al., 2009; Remo et al., 2017).

2.5 EFFECTS OF A DISCONNECTED FLOODPLAIN ON NITRATE ATTENUATION

Well connected, large-river floodplains provide many invaluable ecosystem services. Unaltered floodplains provide services such as flood mitigation, provide habitat that fosters one of the most biodiverse landscapes in the world, filter and retain sediment and nutrients, and provide economic benefit through increased recreation opportunities such as fishing and hunting (Sparks, 1995). The engineering of the MR has resulted in reduced connectivity, loss of habitat and biodiversity, problematic sediment scouring and aggradation, and higher nutrient loads (Sparks, 1995).

The disconnection of the Mississippi’s floodplain has resulted in a two-pronged assault on the river system’s ability to maintain healthy concentrations of riverine nitrogen. First, the growth of agriculture in the floodplain has greatly increased the quantity of nitrogen entering the system due to fertilizer runoff (Goolsby et al., 1999; Sparks, 1995). In addition to increasing inputs of nitrogen, the disconnection of the floodplain has substantially reduced its ability to effectively attenuate the large amount of additional nitrogen being pumped into the river system.
Wetlands and riparian zones that become disconnected from the river often will not receive as frequent flooding from the river and thus will not be supplied with the river’s nitrogen enriched water (Schramm et al., 2009). Disconnected wetlands, then, can only attenuate nitrates from precipitation, runoff, and/or groundwater mixing – except in the rare event of a flooding event that overwheels over tops or breaches the agricultural levee system. The strategic reconnection of suitable wetland and riparian areas in the floodplain could greatly increase the ability of the floodplain to attenuate excess nitrogen in the system (Remo et al., 2017)
CHAPTER 3

METHODS

3.1 DATA SOURCES

3.1.1 NATIONAL WETLAND INVENTORY

The National Wetlands Inventory (NWI), produced by the U.S. Fish and Wildlife Service (USFWS) and the Federal Geographic Data Committee, was designed to provide researchers and the public with a database of the wetlands and marine environments of the U.S. In addition to identifying and classifying over 34 million features, the NWI also offers a web mapping application. This mapping program allows users to access, view, and/or download spatial and classification data for wetlands in their area of interest. Identification of wetlands and deep-water bodies for use in the NWI are compiled via remote sensing. For much of the MMR, wetlands were interpreted and classified using color infrared images from 1983 at 1:58,000 scale (USFWS, 2019). Images were interpreted manually by analysts from the USFWS. Characteristics such as vegetation and other smaller features are identified using methods based on interpreting tone, size, shape, texture, spatial arrangement, shadow, geographic location, and association displayed in the images (Dahl et al., 2015). Polygons are created in ArcGIS by analysts to represent wetland area. Classification data interpreted by the analyst is then associated with the polygon. All data then undergoes a review process by another analyst. For the contiguous U.S., a resolution of one-meter is used for all source imagery. Additionally, the target mapping unit for the contiguous U.S. is 0.2 ha with a feature accuracy of 98%. The classification system used in the NWI began being developed in 1976 by Cowardin et al. (1979). The classification system uses an alpha-numeric code to represent the system, subsystem, class, subclass, and special modifiers which describe the wetland. This coded system ties large
amounts of information about the wetland into a shortened code, giving users of the NWI the ability to relate wetlands to each other based on defining characteristics.

3.1.2 SOIL SURVEY GEOGRAPHIC DATABASE (SSURGO)

The SSURGO dataset was developed by the National Cooperative Soil Survey and is currently overseen by the U.S. Department of Agriculture’s (USDA) Natural Resources Conservation Service. SSURGO was developed through meticulous field work consisting of soil observation and laboratory testing. This data was collected at scales ranging from 1:12,000 – 1:63,360 (Soil Survey Staff, 2020). This research utilized gSSURGO which contains similar features to SSURGO but packaged in a file geodatabase compatible with ESRI’s ArcMap. This raster dataset contains spatial data for the U.S. regarding soil types and numerous soil characteristics. The raster cell size for this gSSURGO product was ten meters. SSURGO aggregates soil data into “Map Units” which describe areas with distinctive soil properties. As the gSSURGO databases are packaged by state, Illinois and Missouri gSSURGO files were merged and then clipped in ArcMap to the study segment.

3.1.3 LAND COVER DATA

Land cover data was obtained from the USGS’s Upper Midwest Environmental Sciences Center which collaborated with the USACE’s Long Term Resource Monitoring Program (LTRMP) to produce this dataset. This dataset was developed through analysis of aerial photographs which were collected at 20cm and 40 cm/ pixel. These photographs were interpreted by the LTRMP using a 31-class land cover classification. The minimum mapping unit for this dataset is one hectare. This dataset was chosen over the USGS’s National Land Cover Dataset because it is a higher resolution dataset specifically developed for the management of the MMR.
3.1.4 THE NATIONAL LEVEE DATABASE

Socioeconomic data including population, number of structures, and the total economic value of these structures within each levee system were compiled from the National Levee Database (NLD). The NLD is a geospatial database which contains information on over 2000 levee systems throughout the US. This database is published and maintained by the USACE. The NLD contains all components of the levee system, its maintenance status, its vulnerabilities and socioeconomic information for the lands and communities in which these systems mitigate flood risk (USACE, 2020).

3.1.5 CALCULATED FLOOD EXCEEDANCE PROBABILITIES

A one-dimensional hydraulic model was developed to estimate floodplain inundation depths and frequency for the USFWS assessment of the potential for the Conservation Lands in MMR Floodplains for the Mitigation of Flood Flows for Ecosystem Services Project. Two inundation scenarios were assessed using this model: 1) present day conditions; and 2) a no levee scenario from just south of the St. Louis Metropolitan Region to the start of the Mississippi River and Tributary Project Levees near Commerce, Missouri. The MMR hydraulic model was compiled from three existing USACE HEC-RAS models. These models included the Upper Mississippi River Floodway Computation, the Upper Mississippi River Flood Risk Management, and the Ohio River Community models (USACE, 2004; USACE, 2018; and USACE 2012, respectively). The MMR Model was calibrated and validated using observed water surface elevations (WSELs) from 17 hydrologic monitoring stations for three annual hydrographs (2011, 2013, and 2016). The uncertainty in these models WSEL predictions are within the typical range of error ($\geq 0.1$ m to $\leq 0.6$ m), as measured using the root-mean squared error of the predicted
verses the observed WSELs, for 1-D hydrodynamic simulations of long segments (>100 km) of the Mississippi River under the full range of flow conditions (Remo et al., 2009).

Discharge hydrographs for the period 1936 through 2016 were run through the hydraulic model to generate daily water-surface elevations. These daily-water-surface elevations were interpolated and then mapped across the floodplain to create daily waters-surface raster grid files in a GIS. Then using the Upper Midwest Environmental Sciences Center (UMESC) high resolution (2 m) topobathy (topography + bathymetry) DEM (USACE, 2016), the daily water-surface raster grid files were then subtracted from this DEM in GIS to create a daily inundation map for the entire MMR study segment. These daily inundation maps were then compiled into a large dataset and the probability of inundation for a given 30 m² area of the MMR floodplain where calculated for both the with and without levee scenarios in GIS resulting in maps of floodplain inundation exceedance probability for both modeled scenarios. These maps where use to quantify the frequency in which MMR floodplain wetlands were inundated by riverine inundation for this study’s suitability model.

3.2 PRINCIPAL COMPONENT ANALYSIS METHODS

Principle Component Analysis (PCA) can be an effective dimensionality reduction method and has been used in many studies (Jolliffe and Cadima, 2016; Rahman, 2015; etc.). It is commonly used to reduce the number of variables used in an analysis without reducing variability in the dataset. Due to the large number of raster cells in this analysis, it would have been impractical to run a PCA analysis for the eight variables for each raster cell. Instead, PCA was performed using the established NWI polygons merged with SSURGO and land cover data (Figure 4). Using the zonal statistics tool in ArcGIS, the SSURGO data was joined to the NWI
polygons. The attribute table was then exported and analyzed in XLSTAT version 21.4.63912. XLSTAT is a statistical analysis add-in software for Microsoft Excel. A PCA analysis was performed on eight variables (SURGGO flood frequency class, drainage class, soil hydrologic class, soil organic carbon, soil texture, pH, land cover, and modeled flood recurrence interval). Variables with data as text were coded to integer format to allow for processing in PCA. A correlation matrix was then constructed to standardize the data and account for differing units among variables. Using the Kaiser Rule, only the first four components from the PCA analysis were used (e.g. parameters with an Eigen score > 1).

Figure 4: Flowchart showing methods of the Principle Components Analysis.
3.3 VARIABLE DESCRIPTIONS

The following variables were sourced from the data sources discussed in previous sections. The variables were then analyzed using PCA in an attempt to reduce the number of variables used in the suitability model. These variables represent the final set of variables to be used in the model.

3.3.1 FLOOD FREQUENCY CLASS

The Flood Frequency variable was sourced from the gSSURGO dataset. In this study area, there were four classes present: “None”, “Rare”, “Occasional”, and “Frequent”. According to USDA documentation, “None” refers to an area in which flooding should occur less than every 500 years and the probability of flooding in any given year is approaching 0%. “Rare” refers to an area in which the probability of flooding in any given year is 1 to 5%. “Occasional” refers to an area in which the probability of flooding is 5 to 50% for any given year. Lastly, “Frequent” refers to an area in which the probability of flooding exceeds 50% for a given year, but where no month of the year has a flooding probability of 50% or greater (Soil Survey Staff, 2020). This variable was selected due to the importance of flooding for wetland nutrient buffering capabilities. Periodic flooding provides several necessary conditions for denitrification to occur. Flooding can be a primary source of nitrogen load delivered to a wetland and has been shown to be a limiting factor for a wetland’s ability to denitrify (Hanson et al., 1994; Hoagland et al., 2019; Jicha et al., 2014). Additionally, flooding can produce the suboxic soil conditions necessary for denitrification to take place.

3.3.2 DRAINAGE CLASS

The Drainage Class variable was sourced from the gSSURGO dataset. There are seven classes expressed in our study: “Excessively drained”, “Somewhat excessively drained”, “Well
drained”, “Moderately well drained”, “Somewhat poorly drained”, “Poorly drained”, and “Very poorly drained”. These classes describe the degree of wetness maintained by the soil throughout the year. More well-drained soil classes are characterized by very high hydraulic conductivities and more rapid removal of water from the topsoil layers. In contrast, more poorly drained soils are characterized by lower hydraulic conductivities and a higher water table (Soil Survey Staff, 2020). This variable was selected as it can serve as a proxy for water residence time. Wetlands with poorly drained soils are likely to have longer water residence times as it takes water longer to percolate through the soil. Longer contact between soil and nitrate rich water can lead to increased denitrification rates (Hopkinson, 1992; Pinay et al., 2002).

3.3.3 SOIL HYDROLOGIC GROUP

The Soil Hydrologic Group variable was also sourced from gSSURGO. There are four main classes (Group A, Group B, Group C, and Group D) as well as three dual classes (A/D, B/D, and C/D). The Hydrologic Soil Group describes the runoff potential and the rate of infiltration of a given soil. Group A soils are generally comprised of very well drained course sediments such as sand or gravel. Group B soils are generally comprised of both course and fine soil textures however, they still have a moderate infiltration rate and are usually well drained. Group C soils have a slow infiltration rate and generally have a very fine textured layer (clay) that may slow vertical water movement. Group D soils are very slow infiltrators and are usually comprised of predominately clays or impervious materials. The first letter of a dual hydrologic group refers to conditions if the area is drained and the second letter refers to conditions if the area is undrained (Soil Survey Staff, 2020). This variable was selected because, like drainage class, it has the potential to be a useful proxy for water residence time and for duration of contact between water and soil sediment.
3.3.4 SOIL ORGANIC CARBON

This variable was sourced from the gSSURGO related “VALU1” table. This dataset contains the estimated organic carbon (in grams per square meter) for the entire reported soil profile depth (Dobos et al, 2012). Soil organic carbon availability has been shown by many studies to be an important prerequisite for denitrification to occur (Brettar and Hofle, 2002; Hill and Cardaci, 2004; Lin et al., 2002; Seitzinger, 1994; Stahl, 2000).

3.3.5 SOIL TEXTURES

Soil texture was determined based on the soil description provided for each “MUKEY” in the gSSURGO dataset. Soil descriptions were interpreted using a soil texture triangle as well as the NRCS Soil Description Series, and then were given a representative texture percentage. In this research, the reported texture percentage refers to the combined percentages of clay and silt. Studies have shown that fine textured soils are beneficial for increased denitrification. Several studies have found that a combined clay/silt texture of 65% was the threshold for denitrification to occur, and that above that percentage, denitrification increased in a linear fashion (Groffman and Tiedje, 1989; Pinay et al, 2002; Pinay et al. 1995). It has been posited that this relationship exists due to fine textured soils having a higher percentage of water filled porosity which may cause anaerobic conditions to form (Parkin and Tiedje, 1984; Pinay et al 2002).

3.3.6 SOIL pH

Soil pH was sourced from the gSSURGO and values of pH ranged from 4.6 to 7.9 within the study region. The data was classified into four categories based on information from the literature. The four classes were <5.0, 5 to 5.5, 5.5 to 6.0, and 6.0-8.0. Between pH 5.5 to 8.0 has been proposed as an acceptable range for denitrifying bacteria, though a pH closer to neutral is thought to be ideal (Rivett et al., 2008; Rust et al., 2000; ŠImek and Cooper, 2002).
3.3.7 LAND COVER CLASS

The land cover class variable was sourced from the LTRMP. The 31 classes provided by the LTRMP land cover layer were distilled into six general classes for the purpose of this study. The six classes were developed, agriculture, flooded agriculture, wet meadow, floodplain forest, and marsh/aquatic vegetation. The LTRMP land cover data provides classes for many different types of agriculture (i.e. plantations, pasture, etc.) – these were aggregated to just represent agriculture. Similarly, the roadside and levee classes were reclassified as developed, as these areas are not suitable for wetland restoration. The relative ranking of land cover classes for denitrification potential as shown in Table 1, was derived from the denitrification literature. Particularly, a study in 2006 conducted by Hernandez and Mitsch found that denitrification potential varied by vegetation type (Hernandez and Mitsch, 2006). They found that wetland ecosystems dominated by shallow water and emergent macrophytes displayed higher denitrification potential rates than open water or forested zones. Using the definitions of land cover types from Dieck and Robinson 2004, Marsh/Aquatic vegetation was ranked as higher than wet meadow, which in turn was ranked higher than floodplain forest (Dieck and Robinson, 2004).

3.3.8 RIVERINE FLOOD EXCEEDANCE PROBABILITY

The riverine flood exceedance probability was sourced from the GIS layer described in the Inundation Layer section above. For this variable layer, areas behind the levee were masked in ArcGIS and were given a value of >1.0% (>100-year flood). The value was assigned given the levee flood protection levels described in the USACE’s National Levee Database (2020). For this study, areas with a >10.0% exceedance probability (10-year flood) were considered very-low suitability, while areas with a 99% (1.01-year flood) exceedance
probability were considered most suitable. For a wetland to be a highly productive environment for nitrate attenuation, it should experience frequent flooding as it will provide enriched nitrate water and possibly anoxic soil conditions. This variable only represents direct flooding of the wetland from the river and does not represent flooding due to ponding of runoff or precipitation. Those scenarios are better represented by the flood frequency, drainage class, and/or soil hydrologic group variables.

The riverine flood exceedance probability no levee scenario, represents an alternative floodplain management scenario with the agricultural levees removed south of the St. Louis Metropolitan region. Removing levees leads to greater connectivity between the river and its floodplain. It also would result in lower flood heights due to increased flooding area. While the suitability scores are the same as in the with levee scenario, there is greater area in the floodplain receiving more frequent flooding due to the removal of the levees.

3.4 SUITABILITY ANALYSIS METHODS

The suitability analysis was conducted in ArcGIS version 10.7.1. Each variable was extracted from larger datasets into individual raster files using the Reclassify tool in the Spatial Analyst toolbox (Figure 5). The data in each reclassified raster was separated into classes corresponding to a suitability score ranging from 1 (very low potential) to 6 (very high potential) as seen in Table 1. After all the variables were extracted, they were overlaid together in ArcGIS using the Weighted Overlay tool in the Spatial Analyst toolbox. All variables were given an equal weight using the Weighted Overlay tool. Analyses for two levee scenarios were conducted first. One scenario assumed an inundation layer controlled by current levees and water control
structures (w/ levee), while the other scenario used an inundation layer assuming a situation with no levees in this study segment (no levee).

Figure 5: Flowchart showing methods for the suitability analysis conducted in ArcGIS 10.7.1

Following this analysis, results were analyzed by levee system within the study area. Socioeconomic data was compiled from the National Levee Database for each levee system. To assess the suitability of strategic reconnection, each levee system was analyzed based on total
property value protected by the system vs. the area in the system attaining high potential. Results of this analysis were shown in a scatterplot to identify the most suitable levee systems for strategic reconnection based on nitrate attenuation potential and economic feasibility.

Table 1: Six variables and the associated suitability score assigned for corresponding values.

<table>
<thead>
<tr>
<th>Suitability Score</th>
<th>Suitability Description</th>
<th>Soil Hydrologic Class</th>
<th>Soil Organic Carbon (g/m²)</th>
<th>Flood Exceedance Probability (yrs)</th>
<th>Land Cover Class</th>
<th>Flood Frequency</th>
<th>Soil pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Very Low Potential</td>
<td>A</td>
<td>0 - 5,000</td>
<td>&gt;= 10</td>
<td>Developed</td>
<td>None</td>
<td>&lt;5.0</td>
</tr>
<tr>
<td>2</td>
<td>Low Potential</td>
<td>B</td>
<td>5,001 - 10,000</td>
<td>5</td>
<td>Agriculture</td>
<td>Rare</td>
<td>5.0 - 5.5</td>
</tr>
<tr>
<td>3</td>
<td>Below Average Potential</td>
<td>B/D</td>
<td>10,001 - 15,000</td>
<td>2.3</td>
<td>Flooded Agriculture</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>Average Potential</td>
<td>C</td>
<td>15,001 - 20,000</td>
<td>2</td>
<td>Floodplain Forest</td>
<td>Occasional</td>
<td>5.5-6.0</td>
</tr>
<tr>
<td>5</td>
<td>High Potential</td>
<td>C/D</td>
<td>20,001 - 25,000</td>
<td>1.5</td>
<td>Floodplain Forest</td>
<td>Occasional</td>
<td>5.5-6.0</td>
</tr>
<tr>
<td>6</td>
<td>Very High Potential</td>
<td>D</td>
<td>25,001 - 32,000</td>
<td>1.01</td>
<td>Marsh/Aquatic Veg</td>
<td>Frequent</td>
<td>6.0-8.0</td>
</tr>
</tbody>
</table>

3.5 SENSITIVITY ANALYSIS METHODS

In order to determine the sensitivity of the model to variable choice, a series of modified model runs were conducted for the business-as-usual scenario (with levee). Each model run omitted one of the six variables used in the original model. This allows for analysis of the impacts of each variable on the model output. The first run omitted land cover, the second omitted soil organic carbon, the third omitted flood frequency, the fourth omitted pH, and the fifth omitted, hydrologic soil class.

For each model run, the total area per suitability score was calculated. This was then compared to the original output from the with-levee suitability model to assess the percentage difference in results per category. In this case, percentage difference of the total refers to the difference between the sensitivity analysis area (per suitability score category) and the corresponding area from the suitability categories of the original model results, divided by the total area from all suitability categories in the sensitivity analysis (Equation 1). Then the percentage difference of the total for each suitability category were combined and averaged to
calculate the average percent total difference for each sensitivity analysis scenario. The greater the percentage calculated, the greater the deviation of the sensitivity scenario from the original model. This analysis provides insight to the sensitivity of the model to input variable choice, as well as the robustness of the model results.

Equation 1

\[
Percent \ Diff \ erence \ of \ Total = \frac{\text{suitability score area}_{\text{sensitivity run}} - \text{suitability score area}_{\text{original output}}}{\text{sum of total area}}
\]
CHAPTER 4

RESULTS

4.1 PRINCIPLE COMPONENT ANALYSIS RESULTS

Components F1 - F4 accounted for 77.0% of the total cumulative variability as seen in Table 3 and Figure 6. Based on Table 4, F1 characterized soil characteristics, F2 characterized soil wetness, F3 characterized land cover, and F4 characterized riverine inundation probability. The first component of the PCA contained 34.7% of the variability within the dataset. Drainage Class, Soil Hydrologic Class, and Texture Percentage were highly correlated to the first component (> 0.75) as seen in Table 4. Soil Organic Carbon was also correlated to F1 but, was also apparent in the third component (F3). As seen in the correlation matrix in Table 2 as well as in Figure 7, Drainage Class, Soil Hydrologic Class, and Texture were all highly correlated to each other – though, Soil Organic Carbon was not highly correlated to those variables despite its .566 correlation to F1. For this reason, Drainage Class and Texture Percentage were removed from the analysis, as Soil Hydrologic Class sufficiently explains F1. Flood Frequency was positively correlated with F2, while pH was negatively correlated. The pH class was also apparent in the third component. Both pH and Flood Frequency were retained as variables. Land Cover explained F3 well with a correlation of 0.709, and thus was kept as a variable. Lastly, Flood Recurrence was strongly correlated with F4 and so was also retained as a variable in the suitability model.
Table 2: Correlation Matrix (Pearson n) between variables. Values in bold are different from 0 with a significance level alpha = 0.05

<table>
<thead>
<tr>
<th>Variables</th>
<th>Flood Frequency</th>
<th>Drainage Class</th>
<th>Soil Hydrologic Class</th>
<th>Soil Organic Carbon</th>
<th>Texture Percentage</th>
<th>pH</th>
<th>Land Use</th>
<th>Flood Exceedance Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood Frequency</td>
<td>1</td>
<td>0.002</td>
<td>0.322</td>
<td>0.108</td>
<td>-0.110</td>
<td>-0.180</td>
<td>-0.088</td>
<td>0.006</td>
</tr>
<tr>
<td>Drainage Class</td>
<td>0.002</td>
<td>1</td>
<td>0.770</td>
<td>0.324</td>
<td>0.708</td>
<td>-0.373</td>
<td>-0.050</td>
<td>0.136</td>
</tr>
<tr>
<td>Soil Hydrologic Class</td>
<td>0.322</td>
<td>0.770</td>
<td>1</td>
<td>0.430</td>
<td>0.583</td>
<td>-0.245</td>
<td>-0.090</td>
<td>0.180</td>
</tr>
<tr>
<td>Soil Organic Carbon</td>
<td>0.108</td>
<td>0.324</td>
<td>0.430</td>
<td>1</td>
<td>0.375</td>
<td>0.061</td>
<td>-0.131</td>
<td>0.067</td>
</tr>
<tr>
<td>Texture Percentage</td>
<td>-0.110</td>
<td>0.708</td>
<td>0.583</td>
<td>0.375</td>
<td>1</td>
<td>-0.089</td>
<td>-0.092</td>
<td>0.072</td>
</tr>
<tr>
<td>pH</td>
<td>-0.180</td>
<td>-0.373</td>
<td>-0.245</td>
<td>0.061</td>
<td>-0.089</td>
<td>1</td>
<td>-0.022</td>
<td>0.033</td>
</tr>
<tr>
<td>Land Use</td>
<td>-0.088</td>
<td>-0.050</td>
<td>-0.090</td>
<td>-0.131</td>
<td>-0.092</td>
<td>0.022</td>
<td>1</td>
<td>0.052</td>
</tr>
<tr>
<td>Flood Exceedance Probability</td>
<td>0.006</td>
<td>0.136</td>
<td>0.180</td>
<td>0.067</td>
<td>0.072</td>
<td>0.033</td>
<td>0.052</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3: Eigen values, percentage of variability explained by each component, and cumulative explained variability. Generally, F1 represents soil characteristics, F2 represents soil wetness, F3 represents land cover, and F4 represents riverine inundation probability.

<table>
<thead>
<tr>
<th></th>
<th>F1</th>
<th>F2</th>
<th>F3</th>
<th>F4</th>
<th>F5</th>
<th>F6</th>
<th>F7</th>
<th>F8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eigenvalue</td>
<td>2.779</td>
<td>1.225</td>
<td>1.132</td>
<td>1.026</td>
<td>0.839</td>
<td>0.567</td>
<td>0.294</td>
<td>0.138</td>
</tr>
<tr>
<td>Variability (%)</td>
<td>34.739</td>
<td>15.316</td>
<td>14.155</td>
<td>12.825</td>
<td>10.486</td>
<td>7.085</td>
<td>3.675</td>
<td>1.721</td>
</tr>
<tr>
<td>Cumulative %</td>
<td>34.739</td>
<td>50.055</td>
<td>64.209</td>
<td>77.034</td>
<td>87.520</td>
<td>94.605</td>
<td>98.279</td>
<td>100.000</td>
</tr>
</tbody>
</table>

Table 4: Correlations between variables and factors. Correlations > 0.5 shown in bold. Generally, F1 represents soil characteristics, F2 represents soil wetness, F3 represents land cover, and F4 represents riverine inundation probability.

<table>
<thead>
<tr>
<th>Variables</th>
<th>F1</th>
<th>F2</th>
<th>F3</th>
<th>F4</th>
<th>F5</th>
<th>F6</th>
<th>F7</th>
<th>F8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood Frequency</td>
<td>0.192</td>
<td>0.770</td>
<td>-0.366</td>
<td>0.333</td>
<td>0.219</td>
<td>-0.212</td>
<td>0.160</td>
<td>0.085</td>
</tr>
<tr>
<td>Drainage Class</td>
<td>0.899</td>
<td>-0.047</td>
<td>0.243</td>
<td>-0.133</td>
<td>-0.075</td>
<td>-0.089</td>
<td>-0.168</td>
<td>0.268</td>
</tr>
<tr>
<td>Soil Hydrologic Class</td>
<td>0.896</td>
<td>0.133</td>
<td>-0.037</td>
<td>0.119</td>
<td>0.078</td>
<td>-0.186</td>
<td>-0.269</td>
<td>-0.225</td>
</tr>
<tr>
<td>Soil Organic Carbon</td>
<td>0.566</td>
<td>-0.232</td>
<td>-0.447</td>
<td>0.116</td>
<td>0.374</td>
<td>0.522</td>
<td>0.014</td>
<td>0.022</td>
</tr>
<tr>
<td>Texture Percentage</td>
<td>0.792</td>
<td>-0.355</td>
<td>0.074</td>
<td>-0.199</td>
<td>0.011</td>
<td>-0.207</td>
<td>0.393</td>
<td>-0.061</td>
</tr>
<tr>
<td>pH</td>
<td>-0.346</td>
<td>-0.629</td>
<td>-0.451</td>
<td>0.245</td>
<td>0.231</td>
<td>-0.394</td>
<td>-0.095</td>
<td>0.062</td>
</tr>
<tr>
<td>Land Cover</td>
<td>-0.153</td>
<td>-0.046</td>
<td>0.709</td>
<td>0.282</td>
<td>0.625</td>
<td>-0.009</td>
<td>0.020</td>
<td>-0.001</td>
</tr>
<tr>
<td>Flood Exceedance Probability</td>
<td>0.202</td>
<td>-0.186</td>
<td>0.162</td>
<td>0.831</td>
<td>-0.441</td>
<td>0.094</td>
<td>0.061</td>
<td>0.005</td>
</tr>
</tbody>
</table>
Figure 6: Scree plot where columns represent Eigen values for each component and the red line shows cumulative variability. Generally, F1 represents soil characteristics, F2 represents soil wetness, F3 represents land cover, and F4 represents riverine inundation probability.

Figure 7: Correlations between factors and variables for axes F1 and F2. There is a strong correlation between soil hydrologic class, drainage class, and texture percentage.
Table 5: Correlation Matrix (Spearman) between variables.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Flood Frequency</th>
<th>Drainage Class</th>
<th>Soil Hydrologic Class</th>
<th>Soil Organic Carbon</th>
<th>Texture Percentage</th>
<th>pH</th>
<th>Land Use</th>
<th>Flood Exceedance Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood Frequency</td>
<td>1.000</td>
<td>0.105</td>
<td>0.392</td>
<td>0.238</td>
<td>0.084</td>
<td>-0.116</td>
<td>-0.295</td>
<td>0.061</td>
</tr>
<tr>
<td>Drainage Class</td>
<td>0.105</td>
<td>1.000</td>
<td>0.732</td>
<td>0.288</td>
<td>0.694</td>
<td>-0.362</td>
<td>-0.091</td>
<td>0.126</td>
</tr>
<tr>
<td>Soil Hydrologic Class</td>
<td>0.392</td>
<td>0.732</td>
<td>1.000</td>
<td>0.437</td>
<td>0.735</td>
<td>-0.134</td>
<td>-0.177</td>
<td>0.167</td>
</tr>
<tr>
<td>Soil Organic Carbon</td>
<td>0.238</td>
<td>0.288</td>
<td>0.437</td>
<td>1.000</td>
<td>0.462</td>
<td>0.180</td>
<td>-0.182</td>
<td>0.010</td>
</tr>
<tr>
<td>Texture Percentage</td>
<td>0.084</td>
<td>0.694</td>
<td>0.735</td>
<td>0.462</td>
<td>1.000</td>
<td>0.010</td>
<td>-0.167</td>
<td>0.099</td>
</tr>
<tr>
<td>pH</td>
<td>-0.116</td>
<td>-0.362</td>
<td>-0.134</td>
<td>0.180</td>
<td>0.010</td>
<td>1.000</td>
<td>-0.002</td>
<td>0.000</td>
</tr>
<tr>
<td>Land Use</td>
<td>-0.295</td>
<td>-0.091</td>
<td>-0.177</td>
<td>-0.182</td>
<td>-0.167</td>
<td>-0.002</td>
<td>1.000</td>
<td>0.092</td>
</tr>
<tr>
<td>Flood Exceedance Probability</td>
<td>0.061</td>
<td>0.126</td>
<td>0.167</td>
<td>0.010</td>
<td>0.099</td>
<td>0.000</td>
<td>0.092</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Spearman correlation was performed due to the presence of ordinal data in the dataset and to address the possibility of nonlinear relationships between the variables. A Spearman Matrix was calculated to consider nonlinear correlations within the datasets (Table 5). In both the Pearson and Spearman matrices, Drainage Class, Soil Hydrologic Class, and Texture are highly correlated with each other. This infers that only one of these variables may be needed to explain F1. Incorporating all three variables in the model may lead to overfitting.

4.2 SUITABILITY ANALYSIS RESULTS

Two wetland suitability analyses were performed in this study. The first scenario assumed current levee conditions and associate hydrologic connections. This provides the other end of ranges for possible floodplain management scenarios (business as usual). While the model based on this scenario produces less area suitable for wetland restoration (Figure 8 and Table 6), there is still ample suitable area. There were 66,146 ha of floodplain that attained a suitability rating of average potential, an additional 16,937 ha of floodplain attained high potential, and 706 ha of floodplain were rated as having very high potential (Table 6 and Figure 8) As seen in Figure 9, due to the constraint of levees, many highly suitable areas are located directly adjacent to the river in the floodway.
The second suitability analysis was predicated on a scenario in which all agricultural levees were removed downstream of the Metro St. Louis Region. The total population within the eight levee systems located along the MMR study segment was approximately 14,200 people and the value of levee protected structures was estimated to be $1.24 billion (Table 7). The estimate $1.24 billion of building exposure does not take into account the economic value of farmland within the levee systems. A no levee scenario represents a more natural hydrologic connectivity regime which existed before the agricultural levee systems were completed in the mid-20th century. As can be seen in Figure 8, most of the floodplain in this study segment attained at least *average potential*. It was expected the resulting hydrologic connectivity would increase the suitability for wetlands in a well-connected river floodplain. For this analysis, a suitability score exceeding *average potential* is considered a preferred restoration site for nitrate attenuation.

There were 65,897 ha in the floodplain that attained a suitability rating of *average potential* (Table 6 and Figure 8). There were 34,457 ha in the study segment that attained a rating of *high potential*, whereas 510 ha attained a *very high potential* on the suitability scale (Table 6 and Figure 8). There is a higher concentration of highly suitable sites between Chester, IL and Thebes, IL than in the northern reach of the study segment (Figure 10). Additionally, the highly suitable areas are somewhat dispersed throughout the width of the floodplain due to the absence of the levees’ influence on flood frequencies.
Figure 8: Bar chart showing area in square meters per each suitability score under the w/ levee and no levee scenarios. Area units in hundreds of square meters.

Table 6: Areas for each suitability category for the no-levee and w/ levee scenarios. Percentages of each category’s area to the total study area is also shown.

<table>
<thead>
<tr>
<th>Score</th>
<th>No Levee (hectares)</th>
<th>% of Total Floodplain (No Levee)</th>
<th>W/ Levee Area (hectares)</th>
<th>% of Total Floodplain (w/ levee)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>0.0%</td>
<td>5</td>
<td>0.0%</td>
</tr>
<tr>
<td>2</td>
<td>1,170</td>
<td>1.0%</td>
<td>1,474</td>
<td>1.2%</td>
</tr>
<tr>
<td>3</td>
<td>18,261</td>
<td>15.2%</td>
<td>35,070</td>
<td>29.1%</td>
</tr>
<tr>
<td>4</td>
<td>65,897</td>
<td>54.8%</td>
<td>66,146</td>
<td>55.0%</td>
</tr>
<tr>
<td>5</td>
<td>34,457</td>
<td>28.6%</td>
<td>16,937</td>
<td>14.1%</td>
</tr>
<tr>
<td>6</td>
<td>510</td>
<td>0.4%</td>
<td>706</td>
<td>0.6%</td>
</tr>
</tbody>
</table>
An analysis of the suitability results within distinct levee protected areas was conducted to analyze the relative suitability of potential reconnection scenarios. Under conditions as usual, much of the levee protected areas were rated as average potential or lower on the suitability scale (Table 8). The levee system with the greatest percentage area receiving a score of high potential was Prairie du Pont & Fish Lake system with 3.5% (129 hectares) of the total area. The Grand Tower / Degonia levee system had the highest suitable area with 423 hectares (2% of total area) of high potential sites within the protected area. However, the reconnection scenario produced greatly different results. Every levee system, other than the Cape Floodwall, received significantly greater area receiving a score of high potential than under business-as-usual scenario (Table 9). Of particular note, the Big 5 Levee System, Bois Brule L&DD, and the Grand Tower / Degonia levee systems contained 6015 ha (31.7%), 5,605 ha (52.5%), and 6,303 ha (30.4%) of area scoring high potential, respectively (Table 9). In the Big 5 Levee system, the high potential sites are generally dispersed throughout the area, except for a large concentration to the northeast of East Cape Girardeau. In the Bois Brule L&DD levee system, the high potential sites tended to be clustered on the northwest side of the protected area. In the Grand Tower / Degonia levee system, the high potential sites were generally well distributed in the northern half of the levee system (Figure 10).

Then, population and economic data was obtained from the National Levee Database for each levee system in the study area (Table 7). This was then compared to the area in each system that was rated as having high potential. This analysis is shown in Figure 11, where levee system in the upper left portion of the plot are more suitable for reconnection. As seen in Figure 11, the Bois & Brule system rated as being the most suitable for reconnection, while the Big Five and Grand Tower/ Degonia levee systems were also highly suitable.
Figure 9: Distribution of suitability scores across study region under w/ levee scenario. Scores range from 1 (very low potential) to 6 (very high potential). Levee systems are bounded in black polygons.
Figure 10: Distribution of suitability scores across study region under no levee scenario. Scores range from 1 (very low potential) to 6 (very high potential). Levee systems bounded in black polygons.
Table 7: Levee systems and the population, number of structures, and property value protected in each levee system.

<table>
<thead>
<tr>
<th>Levee System</th>
<th>Population</th>
<th>Structures</th>
<th>Property Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prairie du Pont / Fish Lake System</td>
<td>7,009</td>
<td>2,756</td>
<td>$611M</td>
</tr>
<tr>
<td>Columbia D&amp;L No.3</td>
<td>116</td>
<td>73</td>
<td>$11M</td>
</tr>
<tr>
<td>Harrisonville / Ft Chartres</td>
<td>510</td>
<td>398</td>
<td>$76.8M</td>
</tr>
<tr>
<td>Prairie du Pont</td>
<td>592</td>
<td>335</td>
<td>$70.5M</td>
</tr>
<tr>
<td>Kaskaskia</td>
<td>47</td>
<td>27</td>
<td>$3.15M</td>
</tr>
<tr>
<td>Bois Brule L&amp;DD</td>
<td>487</td>
<td>43</td>
<td>$6.14M</td>
</tr>
<tr>
<td>Grand Tower / Degonia</td>
<td>1,390</td>
<td>928</td>
<td>$122M</td>
</tr>
<tr>
<td>Big 5 Levee System</td>
<td>1,664</td>
<td>990</td>
<td>$145M</td>
</tr>
<tr>
<td>Cape Floodwall</td>
<td>2,374</td>
<td>215</td>
<td>$194M</td>
</tr>
</tbody>
</table>

Figure 11: Area receiving a high potential rating vs the property value within each levee system. Levee systems shown in upper left portion of plot are most suitable for reconnection as they have lowest property value and highest nitrate attenuation potential.
Table 8: Suitable area (in hectares) and percentage of levee protected area shown for each suitability score for a with levee scenario

<table>
<thead>
<tr>
<th>Levee Protected Area Suitability (with Levee)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score 1</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>Area (ha)</td>
</tr>
<tr>
<td>Big 5 Levee System</td>
</tr>
<tr>
<td>Bois Brule L&amp;DD</td>
</tr>
<tr>
<td>Cape Floodwall</td>
</tr>
<tr>
<td>Columbia D&amp;LD No.3</td>
</tr>
<tr>
<td>Grand Tower / Deagonia</td>
</tr>
<tr>
<td>Harrisonville / Ft Chartres</td>
</tr>
<tr>
<td>Kaskaskia</td>
</tr>
<tr>
<td>Prairie Du Pont &amp; Fish Lake</td>
</tr>
<tr>
<td>Prairie Du Rocher</td>
</tr>
<tr>
<td>Total Area</td>
</tr>
</tbody>
</table>

Table 9: Suitable area (in hectares) and percentage of levee protected area shown for each suitability score for a no levee scenario

<table>
<thead>
<tr>
<th>Levee Protected Area Suitability (no Levee)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score 1</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>Area (ha)</td>
</tr>
<tr>
<td>Big 5 Levee System</td>
</tr>
<tr>
<td>Bois Brule L&amp;DD</td>
</tr>
<tr>
<td>Cape Floodwall</td>
</tr>
<tr>
<td>Columbia D&amp;LD No.3</td>
</tr>
<tr>
<td>Grand Tower / Deagonia</td>
</tr>
<tr>
<td>Harrisonville / Ft Chartres</td>
</tr>
<tr>
<td>Kaskaskia</td>
</tr>
<tr>
<td>Prairie Du Pont &amp; Fish Lake</td>
</tr>
<tr>
<td>Prairie Du Rocher</td>
</tr>
<tr>
<td>Total Area</td>
</tr>
</tbody>
</table>
4.3 SENSITIVITY ANALYSIS RESULTS

The results of the sensitivity analysis illustrate that the model is sufficiently sensitive to input variable choice. The percent difference of the total was calculated for five separate model runs. Each run omitted a different variable for the levee scenario. This allowed for the isolation of the impacts of each variable to the model output. In Figure 10, the area and percent difference of the total are shown for each analysis. The fourth model run, where pH was omitted, displayed the highest average percent difference of the total (10%), averaged over all suitability categories. This suggests that the model was most sensitive to pH out of the variables analyzed. Model runs with the Hydrologic Soil Class and Land Cover variables omitted had an average percent change of the total of 8.2% and 5.4%, respectively. The model runs with SOC and Flood Frequency omitted were the least sensitive with an average percent difference of the total of only 1.4% and 1.7%, respectively. These results suggest that the parameters of this suitability model range from most to least sensitive are pH, Hydrologic Soil Class, Land Cover, Flood Frequency, and Soil Organic Carbon, respectively. The greatest variability was seen in the areas receiving a three or four on the suitability scale. However, this is a result of the extremes of the suitability index constituting smaller areas. When divided by the total wetland area, this mutes the magnitude of the percentages for areas scoring either very low or very high on the suitability scale.
Table 10: Results of sensitivity analysis showing percent total difference from output model

<table>
<thead>
<tr>
<th>Suitability Score</th>
<th>Original Output Area (ha)</th>
<th>Model Run 1 Area (ha)</th>
<th>% Total Difference</th>
<th>Model Run 2 Area (ha)</th>
<th>% Total Difference</th>
<th>Model Run 3 Area (ha)</th>
<th>% Total Difference</th>
<th>Model Run 4 Area (ha)</th>
<th>% Total Difference</th>
<th>Model Run 5 Area (ha)</th>
<th>% Total Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>-</td>
<td>0.0%</td>
<td>5</td>
<td>0.0%</td>
<td>1</td>
<td>0.0%</td>
<td>480</td>
<td>0.4%</td>
<td>64</td>
<td>0.0%</td>
</tr>
<tr>
<td>2</td>
<td>1,474</td>
<td>880</td>
<td>0.5%</td>
<td>914</td>
<td>0.5%</td>
<td>2,177</td>
<td>0.6%</td>
<td>14,494</td>
<td>10.8%</td>
<td>2,437</td>
<td>0.8%</td>
</tr>
<tr>
<td>3</td>
<td>35,070</td>
<td>23,108</td>
<td>9.9%</td>
<td>32,962</td>
<td>1.7%</td>
<td>38,408</td>
<td>2.8%</td>
<td>57,374</td>
<td>18.5%</td>
<td>61,417</td>
<td>21.9%</td>
</tr>
<tr>
<td>4</td>
<td>66,146</td>
<td>82,381</td>
<td>13.5%</td>
<td>63,628</td>
<td>2.1%</td>
<td>68,824</td>
<td>2.2%</td>
<td>37,748</td>
<td>23.6%</td>
<td>36,518</td>
<td>24.6%</td>
</tr>
<tr>
<td>5</td>
<td>16,937</td>
<td>10,012</td>
<td>5.7%</td>
<td>19,061</td>
<td>1.8%</td>
<td>11,375</td>
<td>4.6%</td>
<td>9,504</td>
<td>6.2%</td>
<td>18,870</td>
<td>1.6%</td>
</tr>
<tr>
<td>6</td>
<td>706</td>
<td>4,296</td>
<td>3.0%</td>
<td>3,715</td>
<td>2.5%</td>
<td>688</td>
<td>0.0%</td>
<td>209</td>
<td>0.4%</td>
<td>1,074</td>
<td>0.3%</td>
</tr>
<tr>
<td>Avg % Total Difference</td>
<td></td>
<td></td>
<td>5.4%</td>
<td></td>
<td>1.4%</td>
<td></td>
<td>1.7%</td>
<td></td>
<td>10.0%</td>
<td></td>
<td>8.2%</td>
</tr>
</tbody>
</table>
CHAPTER 5
DISCUSSION

5.1 LIMITATIONS

There are several assumptions that were made to formulate this suitability model. 1) The parameters that were selected are likely predictors of floodplain nitrate attenuation based on the literature. However, more field work is needed to validate these assumptions. 2) The data selected realistically portray the parameter distribution on the landscape. This also requires future field work for validation. 3) This study assumed equal importance of the predictors in describing nitrate attenuation suitability. It is possible that certain predictors are more important than others. 4) The use of the NWI wetland polygons to determine the principle components of the suitability parameters may have biased the suitability results towards wetlands and away from other floodplain locations. 5) The hydrologic and corresponding hydraulic analyses assume stationary over time. This can have significant impacts on model accuracy over time due to climate and land use changes which can impact the hydrologic system.

5.2 OVERALL SUITABILITY WITHIN THE FLOODPLAIN

There was a very slight decrease in areas attaining average potential and very high potential for the no levee scenario - this was an unexpected result. We hypothesize that the slight decrease (0.37%) in areas attaining average potential is a result of the large shift of areas increasing from average potential to high potential as a result of the reconnection scenario. The decrease in areas attaining very high potential (196 ha) was negligible compared to the 17,520 hectares increase in areas attaining high potential for the no levee scenario. However, we hypothesize that this slight decrease could be a result of areas that, under the with levee scenario, receive artificial ponding or more consistent inundation than they would under a more natural
river-floodplain connection. Overall, there was a substantial net increase (~ 49.5%) of area being rated as at least high potential for the with levee scenario. This result suggests that there would be significant benefits in terms of nitrate attenuation under a full, and likely, a partial reconnection scenario.

5.3 DISTRIBUTION OF THE MOST SUITABLE AREAS FOR NITRATE ATTENUATION

The total reconnection of levee systems resulted in modest increases in suitable area throughout the whole floodplain. The greatest increases resulted in the amount of area receiving a rating of high potential. Under this scenario, 25.7% of the total levee protected area rated as having high potential – a 24.4% increase from the current levee scenario (Tables 7 and 8). This represents a substantial area that could perform as highly functioning wetland systems – particularly for nitrate attenuation - under a reconnection scenario. The increase in suitability within the floodplain was largely a function of floodplain geomorphology. This resulted in a few of the levee systems being substantially more suitable than the others. In particular, the Big Five, Grand Tower / Degonia, and Bois & Brule levee systems had the greatest increase in area receiving a rating of high potential. Of the total area within the Big Five system, 31.7% achieved a rating of high potential under the reconnection scenario. For the Bois & Brule and Grand Tower / Degonia systems, 52.5% and 30.4% respectively, achieved a score of high potential. All systems other than the Cape Girardeau Floodwall system experienced moderate increases in area elevated to a rating of high potential (Table 8).

Within levee systems, the distribution of highly suitable areas was not homogenous. In particular, Bois & Brule had a cluster of high potential areas in the northwest portion of the systems. The Grand Tower / Degonia system had high potential areas that were well distributed
throughout the northern half of the system (Figure 8). And finally, the Big Five system had *high potential* areas well distributed throughout the whole system, except for a large cluster to the northeast of East Cape Girardeau, Illinois (Figure 8). Because only certain portions of the floodplain area within the levee system are highly suitable for nitrate attenuation, strategic reconnection of these areas, whilst still protecting the remainder of the systems, may be a more palatable and effective management strategy.

5.4 RECONNECTION SCENARIOS BASED ON NITRATE ATTENUATION POTENTIAL AND PROPERTY VALUE

To assess the viability of reconnecting portions of specific levee systems, the economic and social ramifications must be assessed. In this study, the economic ramifications were analyzed using data from the USACE’s National Levee Database, which provides population and structure value for each levee system in the study area. In this cursory assessment, property value within the levee system was used as a proxy for the economic impacts of reconnection. The property value within each system was then compared to the area within the system that was rated as having *high potential* for nitrate attenuation. This analysis found that the Bois & Brule Levee system is the best candidate for strategic reconnection based on the relatively low property value and high amount of suitable area (Figure 9 and Table 6). The northwest portion of the system contains a higher density of highly suitable areas, and thus, reconnection efforts should be focused on this portion of the system (Figure 8). The Big Five and Grand Tower / Degonia systems were also good candidates for strategic reconnection (Figure 9). The cluster of highly suitable area in the southern portion of the Big Five levee system should be the focus of potential reconnection efforts in this system. In the Grand Tower / Degonia system, highly suitable areas were well distributed in the northern half (Figure 8). However, there were not significant clusters
of these areas which may make the economic costs of strategic reconnection of this system more costly. More area may have to be reconnected to achieve the same level of nitrate attenuation potential. The economic costs of reconnection will likely increase with the greater area reconnected due to the opportunity costs associated with restoring more agricultural and/or developed area to wetland ecosystems.

This analysis is a preliminary approach and there are several limitations to using property value as a proxy for the total economic costs of reconnection. First, these values are aggregated at the levee system scale, and thus may not be representative of the costs of reconnecting only specific portions of the system. A higher resolution dataset for property value would be very beneficial in this regard. Second, and more importantly, using only property value does not account for agricultural losses that would result under various reconnection scenarios. Future studies could use an approach like Guida et al., 2016 which utilized the National Commodity Crops Productivity Index (NCCPI), agricultural profit values, and degree of development by levee system to identify whole or portions of levee systems which may be more suitable for reconnection. However, this approach would need to be coupled with an economic analysis of the ecosystem services associated with wetland reconnection, which include nitrate attenuation. Additionally, there are numerous complicating socioeconomic factors that can obscure the true costs of agricultural land use. Since the U.S. Flood Control Act of 1928, much of the responsibility for levee maintenance and flood mitigation has been relegated to the federal government. Beginning in 1938, the Federal Crop Insurance Program provided farmers with federally backed insurance in the event of floods, disaster, or declining crop prices (Glauber, 2013). These two measures serve to protect farmers in the floodplain of the Mississippi, spreading out the risk associated with flooding events among American taxpayers. While
advantageous to farmers, these measures can obscure market forces and prevent unproductive and frequently flooded cropland from being restored to wetland or riparian ecosystems, even when it would be economically sensible to do so. A holistic approach that accounts for these complex socioeconomic factors is needed for effective policy regarding strategic reconnection of levee systems for nitrate attenuation potential and associated ecosystem services.

5.5 RECOMMENDATIONS FOR FUTURE RESEARCH

As discussed above, future research should assess the complex socioeconomic factors combined with a suitability model for nitrate attenuation potential. A better understanding of these two aspects is important for more effective decision making regarding strategic reconnection. For instance, an approach similar to work done by Guida et al in 2016 could be coupled with a nitrate suitability model for enhanced analysis of strategic reconnection scenarios (Guida et al., 2016b). Secondly, more research is needed to validate this study’s suitability model. Specifically, collection and analysis of field data is needed to determine the accuracy of this model. Field measurements of denitrification using mass balance approaches would be useful to validate this suitability model. Additionally, collection of field data would likely shed light on the importance of each variable in the suitability model. This may allow for weighting of the variables for future model runs. Lastly, different hydraulic modeling scenarios could be analyzed to further the effectiveness of this model. Particularly, hydrologic models under climate change and land use change scenarios should be employed to determine the impacts of changing hydrology on the outputs of this suitability model.
CHAPTER 6
CONCLUSIONS

The results of this suitability analysis demonstrate that there are already ample suitable locations for wetland restoration, despite a predominately disconnected floodplain. The two connection scenarios provide a bounding range for possible outcomes ranging from business-as-usual to total floodplain reconnection (extremely unlikely). The reconnection scenario modeled in this study suggests that removal of levees in the study area could result in ~65,897 hectares having average potential, ~34,457 hectares having high potential, and ~510 hectares having very high potential. These results suggest that there could be a 2x increase in areas having at least high potential under a complete reconnection scenario.

Strategic reconnection, a middle-ground solution, could maximize benefits of restoring wetland ecosystems, while still maintaining the most productive agriculture in the floodplain. This analysis suggests that the Big 5, Bois and Brule L&DD, and the Grand Tower / Degonia Levee Systems would be the best candidates for strategic reconnection. For all three systems, >85% of their total area was rated as at least average potential, and >30% rated as high potential. Reconnection strategies should focus on areas within these systems that exhibit clustering of high potential areas. Future research should combine this suitability model with an examination of the economic and political factors influencing the viability of reconnection scenarios – weighing the influences of ecosystem services, agricultural profits, subsidies, insurance, water control structure costs and maintenance, and disaster relief aid to determine the best uses for various floodplain areas.
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Thesis Paper Title:
A SUITABILITY ANALYSIS OF THE WETLANDS ALONG THE MIDDLE MISSISSIPPI RIVER FLOODPLAIN FOR RIVERINE NITRATE ATTENUATION

Major Professor: Dr. Jonathan Remo