USING GEOGRAPHIC INFORMATION SYSTEMS FOR THE FUNCTIONAL ASSESSMENT OF TEXAS COASTAL PRAIRIE FRESHWATER WETLANDS AROUND GALVESTON BAY

Nicholas Enwright, B.S.

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APPROVED:

Paul F. Hudak, Major Professor and Chair of the
    Department of Geography
Pinliang Dong, Committee Member
Bruce Hunter, Committee Member and Director,
    Center for Spatial Analysis and Mapping
Michael Monticino, Dean of the Robert B.
    Toulouse School of Graduate Studies

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The objective of this study was to deploy a conceptual framework developed by M. Forbes using a geographic information system (GIS) approach to assess the functionality of wetlands in the Galveston Bay Area of Texas. This study utilized geospatial datasets which included National Wetland Inventory maps (NWI), LiDAR data, National Agriculture Imagery Program (NAIP) imagery and USGS National Land Cover data to assess the capacity of wetlands to store surface water and remove pollutants, including nitrogen, phosphorus, heavy metals, and organic compounds.

The use of LiDAR to characterize the hydrogeomorphic characteristics of wetlands is a key contribution of this study to the science of wetland functional assessment. LiDAR data was used to estimate volumes for the 7,370 wetlands and delineate catchments for over 4,000 wetlands, located outside the 100-yr floodplain, within a 2,075 square mile area around Galveston Bay.

Results from this study suggest that coastal prairie freshwater wetlands typically have a moderate capacity to store surface water from precipitation events, remove ammonium, and retain phosphorus and heavy metals and tend to have a high capacity for removing nitrate and retain\remove organic compounds. The results serve as a valuable survey instrument for increasing the understanding of coastal prairie freshwater wetlands and support a cumulative estimate of the water quality and water storage functions on a regional scale.

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INTRODUCTION

Wetlands, environments with flooded or saturated soils, are found globally. Wetland types vary based on geomorphic setting and hydrology. Three main classes of wetlands are depressional, riparian, and fringe wetlands. Depressional wetlands are depressions that receive water from local runoff and direct rainfall. Riparian wetlands are found proximal to rivers and store water from floods and runoff in route to the river. Fringe wetlands are found on the fringe of lakes and coastal areas. Historically, wetlands have been drained and filled for agricultural development; however studies conducted over the past few decades have shown the inherent value of wetlands to the environment. The main functions of wetlands include surface water storage, aquifer recharge, buffering storm related flooding, soil erosion reduction, water filtration, and biologic productivity (Mitsch and Gosselink, 2000).

Wetlands in the Galveston Bay area are an integral component to the overall health of the Galveston Bay. While the watershed for Galveston Bay stretches from the coast to far north Texas, about a third of the freshwater entering the bay arrives as surface flows from the coastal clay plain (Sipocz, 2005). Lester and Gonzalez (2002) found that pollution from runoff is the major contributor to degraded waters in Galveston Bay. The loss of wetlands in the Galveston Bay area may lead to increased severity of water quality issues in the Galveston Bay in the future, which could prove detrimental to the lucrative fishing industry of the Galveston Bay. Galveston Bay accounts for one-third of the commercial fishing incomes in the State of Texas (Lester and Gonzalez, 2002). Estimates of Texas' annual commercial fishing yield for the years 1994 – 1998 are approximately 19.7 million dollars (Robinson et al., 2000).

Additionally, depressional wetlands of the coastal plain collect runoff and filter the water, which in the absence of wetlands would flow as runoff to larger bodies of water, including the bay. The Houston-Galveston area is in a high risk location for coastal inundations along the Gulf of Mexico and is frequently struck by hurricanes and tropical storms, including Hurricane Rita in 2005 and Hurricanes Ike and Gustav in 2008. Coastal prairie freshwater wetlands (CPFW) can provide a valuable buffer for hurricane storm surges.

In the decision of *Solid Waste Agency of Northern Cook County v. U.S. Corps of Engineers* 531 U.S. 159 (2001) the U.S. Supreme Court overturned the Migratory Bird Rule used by the U.S. Corps of Engineers to extend federal protection to isolated wetlands based on migratory bird use. As a result the U.S. Corps of Engineers Galveston District removed protection from isolated wetlands outside of the 100-year floodplain. Based on this decision, much of the 3.3 million acres of freshwater wetlands on the Texas coastal plain are no longer regulated (Sipocz, 2002). The risk of wetland loss is exasperated by the rate of growth of the Houston-Sugar Land-Baytown metropolitan area (Greater Houston). The Texas State Data Center estimated the population of Greater Houston in July 2008 to be approximately 5.72 million people and grew at a rate of 21.3% from 2000 to 2008 (Texas State Data Center, 2010).

More recently in *Rapanos v. United States* 547 U.S. 715 (2006), the U.S. Supreme Court could not reach a majority decision concerning the filling of several wetlands in Michigan. The pluralist opinion was to limit jurisdictional waters to navigable waters and wetlands continuously linked to navigable waters. Disagreeing with this opinion, Justice Kennedy introduced a "significant nexus" test. Explaining the test in the decision, Justice Kennedy wrote that wetlands have a significant nexus and would be considered jurisdictional waters if they "significantly affect the chemical, physical, and biological integrity of waters more readily understood as 'navigable.'"

Sipocz (2002) pointed out that when ruling that isolated wetlands were not part of the connected hydrologic system, the Supreme Court did not dispute the ability of wetlands to positively affect the nation's water, but rather wanted evidence of their ability to do so. As is discussed in the literature review chapter, this ruling laid the groundwork for a number of studies by environmental scientists to assess wetland functionality, such as water storage and nutrient and pollution mitigation.

In 2007, the Texas Commission on Environmental Quality (TCEQ) funded the Department of Biology at Baylor University to develop conceptual models and functional assessments to understand the capacity of CPFW of the Galveston Bay area to store surface water, reduce nutrient and heavy metals loadings. The models developed were based on theoretical concepts of water movement and storage, and nutrient and pollutant removal in wetland environments. Relevancy to CPFW required the application of the models over a large aerial extent; the coastal plains of Galveston Bay.

The objective of this research was to incorporate the conceptual framework and models, developed by M. Forbes of Baylor University, using the spatial analytical capabilities of geographic information systems (GIS) technology to assess the functionality of wetlands in the Galveston Bay area. Spatial modeling using GIS allows geographers and environmental scientists to overlay multiple layers of data and explore spatial relationships over large areas of landscape. Models, based upon overlaid combinations of land cover characteristics, describe and assess functionality of wetland systems.

Watershed and hydrologic modeling, soil parameters, land use/land cover, and vegetation play a large role in the models utilized in this study. The models employed assessed the capacity of wetlands to store surface water, attenuate storm related flooding and remove pollutants, including nitrogen, phosphorus, heavy metals, and organic compounds. Understanding the geography of wetlands and the functions they are capable of providing in the Galveston Bay area may prove insightful for local officials and regulatory agencies concerning the “significant nexus” of CPFW.

LITERATURE REVIEW

Wetland Defined

In 1956, the U.S. Fish and Wildlife Service developed one of the first definitions of wetlands. The following definition is still used today by wetland scientists and managers: (Mitsch and Gosselink, 2000):

> The term "wetlands"…refers to lowlands covered with shallow and sometimes temporary or intermittent waters. They are referred to by such names as marshes, swamps, bogs, wet meadows, potholes, sloughs, and river-overflow lands. Shallow lakes and ponds, usually with emergent vegetation as a conspicuous feature, are included in the definition, but the permanent waters of streams, reservoirs, and deep lakes are not included. Neither are water areas that are so temporary as to have little or no effect on the development of moist-soil vegetation.

In 1979, the U.S. Fish and Wildlife Service adopted the following more comprehensive definition of a wetland (Mitsch and Gosselink, 2000):

> Wetlands are lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water . . . Wetlands have one or more of the following three attributes: (1) at least periodically, the land supports predominantly hydrophytes; (2) the substrate is predominately undrained hydric soil; and (3) the substrate is nonsoil and is saturated with water or covered by shallow water at some time during the growing season of each year.

In this definition hydrophytes are plants adapted to saturated conditions, and hydric soils are soils that are formed under saturated conditions long enough for the upper part of the soil to become anaerobic (Mitsch and Gosselink, 2000).

National Wetland Inventory, Wetland Delineation and Hydroperiods

The National Wetland Inventory (NWI) is an extensive project, begun in 1977 by the U.S. Fish and Wildlife Service, to map and classify wetlands according to the *Classification of Wetlands and Deepwater Habitats of the United State* developed by Cowardin et al., (1979). This classification scheme categorizes wetlands into "systems," "subsystems," and "classes." A "system" groups wetlands with similar geomorphology, chemical properties (salinity), and vegetation. Wetland systems include: marine, estuarine, riverine, lacustrine, and palustrine. A wetland “subsystem” further describes the hydrology/frequency of flooding of the wetland. Subsystems include the following: tidal, subtidal, intertidal, lower perennial, upper perennial, intermittent, limnetic, and littoral. A wetland “class” describes the cover of the wetland ecosystem, such as forested or emergent wetland, and bottom characteristics, such as streambed or rocky shore.

NWI maps are created by analyzing 1:60,000 color infrared aerial photography imagery coupled with field reconnaissance (Mitsch and Gooselink, 2000). Available at a scale of 1:24,000 and 1:100,000, NWI maps and data offer a basic understanding of the location and types of wetlands. The development of the NWI has played a crucial role in monitoring of temporal trends of national wetlands. When delineating jurisdictional wetlands (those covered by Section 404 of the Clean Water Act, discussed in the next section), field delineations are often the preferred method for determining wetland boundaries. The 1987 *Wetlands Delineation Manual* drafted by the U.S. Corps of Engineers outlines guidelines for on-site wetland delineations.

Vegetation, hydrology, and soils are the three major components of the 1979 U.S. Fish and Wildlife definition of a wetland and thus these three components comprise the wetland indicators used in wetland delineation. Hydrophytic vegetation is vegetation that is adapted to wet or saturated conditions. Certain plants have the ability to survive low oxygen (anoxic) conditions by undergoing internal and external morphologic changes. Only species of plants able to adapt to the anoxic conditions of wetlands will be found in and around wet, saturated, and/or flooded areas. A wetland hydroperiod indicates the flooding frequency of a wetland. Hydroperiods include: permanently flooded, semi-permanently flooded, seasonally flooded, temporarily flooded, and intermittently flooded. Indicators of wetland hydrology may include:

drainage patterns, historic records, stream gauge data, rainfall data, observation of saturated soil, observation of water/flooding, and observation of water marks on trees (U.S. Army Corps of Engineers, 1987).

National Wetland Trends and Wetland Environmental Policy

Prior to the 1970s and the formation of the U.S. Environmental Protection Agency (EPA), concern about human impacts to the environments tended to be minimal. Beginning in the late 20th century, the U.S. Fish and Wildlife Services began to track wetland losses. Thomas Dahl, a scientist for the U.S. Fish and Wildlife Services, is one of the authorities on wetland trends in the conterminous United States. Dahl (1990) estimates that from pre-settlement periods, during the 1780s, to the 1980s approximately 47,300,000 hectares of wetlands were lost. Substantial wetland loss has been attributed to draining and conversion of wetlands to agricultural land and other non-wetland land uses.

Modern wetland loss has been slowed by the development of key regulatory policy, specifically Section 404 of the Clean Water Act (CWA). Passed in 1974, Section 404 of the CWA mandates that anyone dredging or filling in “waters of the United States” obtain a permit from the U.S. Army Corps of Engineers. Upon first draft of the act, wetlands were not formally mentioned in the act. Two court decisions, *United States v. Holland* (1974) and *Natural Resources Defense Council v. Calloway* (1975), led to the inclusion of wetlands into the act. The court decisions helped to establish the requirement of land development project proposals that involving impacts to wetlands, developers must adhere to three approaches in the following order: 1) avoidance of wetland impacts; 2) minimization of wetland impacts; and 3) mitigation of wetland impacts (Mitsch and Gosselink, 2000).

In 1987, President George Bush helped draft a “no net loss” policy for wetlands, which set a goal to achieve no overall net loss in wetlands, to create and restore wetlands, and where possible increase the quantity and quality of the nation’s wetlands (Mitsch and Gosselink, 2000). Recent findings by the U.S. Fish and Wildlife found that the historical losing trend of wetlands has been reversed and national acreage of wetlands has been increasing. In 2004, a total of 43.6 million hectares of wetlands were found in the conterminous U.S. and from 1998 to 2004; wetland area increased by approximately 32,000 acres a year (Dahl, 2005).

However, during the course of time, a major change in wetland policy was the removal of isolated wetlands from federal protection. In *Solid Waste Agency of Northern Cook County v. U.S. Corps of Engineers* (2001), the U.S. Supreme Court ruled that the old gravel pits which had developed into seasonal ponds and provided habitat for migratory birds were not a part of the definition of “navigable waters” in the CWA. This decision had the effect of removing federal protection from wetlands. More recently, in *Rapanos v. United States* 547 U.S. 715 (2006), the U.S. Supreme Court was unable to reach a majority decision concerning the filling of several wetlands in Michigan. The pluralist opinion was to limit jurisdictional waters to navigable waters and wetlands continuously linked to navigable waters. Disagreeing with this opinion, Justice Kennedy introduced a “significant nexus” test. Explaining the test in the decision, Justice Kennedy wrote that wetlands have a significant nexus and would be considered jurisdictional waters if they “significantly affect the chemical, physical, and biological integrity of waters more readily understood as ‘navigable.’”

Important Functions and Values of Wetlands

Beginning in the 1970s, increased interest in the functions of wetlands as critical ecosystems helped to trigger a reversal of wetland loss. Over the past few decades studies have shown the inherent value of wetlands to the environment. The main functions of wetlands include surface water storage, aquifer recharge, buffering storm related flooding, soil erosion reduction, water filtration, and biologic productivity (Mitsch and Gosselink, 2000).

With the increased scarcity of useable water resources, wetlands can offer a natural source of surface water storage. Additionally, wetlands have been viewed as a means by which rainfall seeps through the subsurface to recharge aquifers. However, groundwater recharge in wetlands has been debated. Besides studies on cypress swamps, groundwater recharge from wetlands has been found to often be minimal. Typically, soils underlying most wetlands tend to be impermeable (Larson, 1982). Weller (1981) found that recharge occurred mainly along the edges of wetlands and was related to the edge:volume ratio of a wetland. This finding suggests that groundwater recharge may be more significant in small shallow wetlands, such as prairie pothole wetlands than in deeper wetland systems. However, the amount of recharge is dependent upon a number of factors including saturated hydrologic conductivity of the substrate and hydraulic gradient of the aquifer.

During intense rainfall associated with storms, wetlands can store rainfall and mitigate flooding. This buffering mechanism is especially important to coastal areas in the event of a hurricane making landfall. Brody et al. (2007) conducted a preliminary investigation into the relationship of altering wetland hydrology and flooding in coastal Texas and Florida. They found a weak positive relationship between the total number of georeferenced permits for wetland alteration with the degree of flooding measured by stream gauges within watersheds.

Another key concern for the importance of wetlands is soil erosion control. One of the factors influencing soil erosion is vegetation; it binds soil and prevents soil from eroding in the presence of wind or runoff. Hopefensperger et al. (2006) analyzed the impacts of uncontrolled grazing in wet meadow in the Salmon River subbasin in Idaho using the revised universal soil loss equation (RUSLE). The results of the study show that uncontrolled grazing are impacting the watershed and lead to an increase of sediment erosion.

As some of the most productive ecosystems in the world, intense biological activity enables wetlands to filter water. Pollutants such as nitrate, phosphorus, and heavy metals can be taken up by plants and bound in sediments. Alvarez-Rogel et al. (2006) found a coastal salt marsh to be very effective at reducing nitrogen and phosphorus loads received from agricultural and urban land uses. In the driest months, the marsh reduced the nutrient concentrations by 100 percent.

Wetlands cover only about 3.5% of the U.S., yet provide an essential habitat for about 50% of the 209 animals species listed as endangered in 1986 (Mitsch and Gosselink, 2000). Wetlands also provide habitat for rare plant populations. To many, wetlands are synonymous with water fowl. Eighty percent of the breeding bird species in U.S. rely on wetlands (Wharton et al., 1982). Wetlands provide abundant habitat for fish, particularly marine shell fish and freshwater catfish, which are commercially fished.

Coastal Prairie Freshwater Wetlands (CPFW) and Trends

Similar in geomorphology to prairie pothole wetlands of the upper midwestern U.S., CPFW are depressional freshwater wetlands found on the coastal plain in Texas. The depressions were formed on ancient river and bayou systems and were shaped mainly by aoelian and biotic forces. The intricate fabric of depressions is most pronounced on the Beaumont and the Lissie Formations. Depressions on the Beaumont Formation range from 15,000 to 30,000 years old and the depressions on the Lissie Formation are more than 100,000 years old.

Direct precipitation and local runoff are the main hydrologic inputs into coastal depressional wetlands. While the role of groundwater input into wetlands is largely unknown, water loss to the ground table is thought to be minimal due to high clay content in soils. Greater topographic relief is found in prairies on the upper coast, consisting of small hummocks of several feet and intermound flats. Deeper wetlands found along the upper coast can remain saturated for more than six months of the year. Wetlands along the lower coast have less relief and inundated for much shorter durations.

Vegetation within the wetlands forms concentric bands based on suitability to inundation patterns. Wetlands seasonally to semi-permanently flooded often have floating and submerged vegetation in the open water zone and emergent vegetation in the emergent zone. (Moulton and Jacob, 2000).

Moulton et al. (1997) conducted a survey of trends in Texas coastal wetlands from 1955 to 1992. This survey was done by comparing black and white aerial photos from 1955 and color infrared photos from 1992. The wetlands were classified by water chemistry (marine/estuarine or palustrine) and by land cover using methods developed by the NWI. Field verification was done for 10% of the sample plots. The survey found a 5.1% loss in all wetlands (marine/estuarine and palustrine). Overall palustrine wetlands experienced a loss of 4.3%. Of all palustrine wetlands, emergent and forested wetlands have experienced a large loss in acreage, while ponds, scrub-shrub, and aquatic bed wetlands have gained acreage. This is mainly due to the conversion of emergent wetlands to other wetland types such as man-made stock tanks and ponds. Farmed wetlands increased by 5.9 percent in coastal Texas and were responsible for Texas ranking as the fourth largest rice producer in the U.S. in the 1990's (Texas Agricultural Statistics Service, 1994). Urban, rural, and agricultural development account for much of the loss in palustrine wetlands, especially in the Galveston Bay area.

As result of the *Solid Waste Agency of Northern Cook County v. U.S. Corps of Engineers* (2001) ruling, the U.S Corps of Engineers Galveston District of Texas declared that freshwater wetlands lying outside of the 100-year floodplain of rivers and streams are isolated from interstate waters and therefore are no longer protected by the Section 404 of the CWA. Based on this decision, much of the 3.3 million acres of freshwater wetlands on the Texas coastal plain are no longer regulated (Sipocz, 2002).

Wetland Functional Assessment

Wetlands have been assessed using numerous methods over the past 25 years. Wetlands are typically assessed in two manners: economically and ecologically (functional). Economical wetland assessments aim to put a monetary value on the ecological functions performed by the wetland. Because of the numerous important functions and values a wetland offers, a wetland can be worth more in monetary value than upland of equivalent area. Functional assessments evaluate a wetland's capacity to perform a function. As mentioned previously, common functions assessed include the water storage, flood water mitigation, and reduction of pollutants.

Adamus et al. (1987) developed a rapid wetland assessment called wetland evaluation technique (WET). Wetlands within WET are evaluated for eleven functions on a qualitative scale ranging from low to high. Functions are grouped into three categories: social significance, effectiveness, and opportunity. Social significance is a measure of the probability that the wetland has social value. Effectiveness is the capacity for which a wetland can perform a given function. Opportunity is the likelihood a wetland will perform a given function based on the characteristics of the surrounding area or watershed. For instance, a wetland receiving agricultural runoff typically receives more nutrients (nitrogen and phosphorus) than a wetland receiving runoff from undeveloped land, and thus has a greater opportunity to remove nutrients. Using this valuation process, the wetland receiving agricultural runoff will have a greater value than the wetland receiving runoff from undeveloped land even though characteristics of the wetlands may suggest both wetlands are equally capable of removing nutrients. WET was once widely by the used by U.S. Army Corps of Engineers and is still drawn from when developing state and regional wetland assessment methods.

The hydrogeomorphic approach for assessing wetland functions (HGM) was developed by the U.S. Army Corps of Engineers to assess wetland functions as part of the Section 404 of the CWA Regulatory Program (Smith et al., 1995). Since the U.S. Army Corps of Engineers manages the wetland regulatory program, HGM assessments are designed to evaluate the impact of proposed projects on wetlands by evaluating the "pre-project" functions and predicting how the project will change the functionality of the wetland. Brinson (1993) developed the hydrogeomorphic classification system to group wetlands that function similarly based on geomorphic setting, water source, and hydrodynamics. Seven hydrogeomorphic classes defined include: riverine, depressional, slope, mineral soil flats, organic soil flats, estuarine fringe, and lacustrine fringe. While wetlands in the same hydrogeomorphic classification will have a similar model, models need to be created for regional wetland subclasses (ecosystems). For example, depressional wetlands include playa lakes in arid west Texas and prairie potholes in Minnesota. Extensive data is collected at reference wetlands believed to be performing at a high functional capacity. These are used to develop a functional profile and assessment models for similar wetlands in the region (Smith et al., 1995). For example, the capacity of a wetland to attenuate floodwater is related to a number of factors such as hydrologic regime, plant population, soil type, and volume of depression. A multivariate model can be developed, based upon reference data, to assess the capability of a wetland to perform this function. Assessment models in HGM are quantitative; the result of assessment is a functional capacity index (FCI) which ranges from 0 to 1.0, with functionality being directly related to FCI (Smith et al., 1995). Currently, about 20 regional guidebooks or HGM models have been developed for specific regions; however, to date no models have been developed for CPFW. While HGM offers a very thorough functional assessment, they often include many elaborate variables which must be determined from field visits.

Zahina et al. (2001) developed functional assessment models for South Florida freshwater wetlands to estimate pollution risk and the capacity to remove pollutants. In contrast to HGM, the models used qualitative data. Models were created with variables based on archived or readily available geospatial data such as soils and land use/land cover. Output of the model is displayed in a map that so regional assessment can be easily interpreted.

Wetland assessments have evolved over time and will no doubt continue to do so. The CPFW model draws from the strengths of the above models. Models deployed in this study are consistent with previous HGM models derived for depressional wetlands (Gilbert et al., 2006, Lin 2006, Stutheit et al., 2004). For example, the quantitative FCI approach from HGM was utilized. One major difference between this assessment and HGM approach, is this study did not evaluate an extensive number of reference wetlands to create a functional profile for the region; instead M. Forbes and researchers at Baylor University sampled several reference wetlands and plan to evaluate the conceptual models using in-situ data for future comparison with results from the geographic information systems (GIS) model deployed in this study. The use of GIS and geospatial data, as found in the south Florida functional assessment, was incorporated in this study. While, the CPFW model may be not be as complete and extensive as an HGM model, the use of GIS makes the models less complicated and allows for model replication by other users.

CPFW Model Variables

This section introduces variables used in the conceptual models and the rationale behind their use. The conceptual models contain four variables related to hydrology. Table 1 defines each variable and shows the data source. All variables were converted to unit less values or “scores” based on literature and professional judgement (covered in more detail in Methodology chapter), except V_{clay}, V_{buff}, and V_{mac} which already were between 0 and 1.0 due to being percentages of soil clay content and vegetative cover, respectively.

Table 1
Overview of Variables Used in Conceptual Models

Variable	**Variable Name**	**Definition**	**Data Source**
V_{vol}	Wetland Volume	Storage volume capacity of the wetland	LiDAR Data
V_{wet}	Water Regime	Duration of Inudation in a wetland	National Wetlands Inventory
V_{catch}	Wetland Area to Catchment Area Ratio	Ratio of wetland surface area of that wetland's catchment	LiDAR Data
V_{dry}	Wet-Dry Potential	Tendency of a wetland to periodically dry out or draw down	National Wetlands Inventory
V_{mac}	Macrophyte Density	Relative coverage of wetland area by erect vegetation	NAIP Imagery
V_{buff}	Buffer Density	The extent to which the area immediately adjacent to the wetnalnd (30 meters from wetland perimeter) is vegetated	NAIP Imagery
V_{LU}	Land Use	Dominant land use in the catchment area (including the wetland)	USGS National Land Cover Dataset
V_{clay}	Soil Clay Content	Percent of soil that has a particle size less than 0.002 mm in diameter (clay) at the surface layer of the soil	Soil Survey Geographic Database (SSURGO)
V_{soilpH}	Soil pH	The pH at the surface layer of the soil	Soil Survey Geographic Database (SSURGO)

Hydraulic characteristics:

- Wetland volume (V_{vol}) is defined as the storage volume capacity of the wetland. Wetlands with a greater volume have potential to store water.

- Water regime (V_{wet}) refers to the duration of inundation (hydroperiod) in a wetland. Wetlands that are permanently flooded have a reduced capacity to receive water from precipitation events.

- Wetland area to catchment area ratio (V_{catch}) is the ratio of wetland surface area of that of the wetland catchment area. This variable is used to understand runoff potential and hydraulic retention time. For instance, a small wetland with a large catchment (V_{catch} = small ratio) will receive more water during precipitation events and is likely to have a longer hydraulic retention period. The greater hydraulic retention means a lower capacity for a large influx of water from a storm event can be stored in the wetland. This variable appears in numerous HGM and other wetland functional assessments (Bradshaw 1991; Fennessy et al., 2004; Lin 2006).

- Wet-dry potential (V_{dry}) is a variable related to hydroperiod and is used to evaluate the tendency for a wetland to dry out. As a wetland dries out, oxygen, which facilitates nitrification, is introduced into the system.

Vegetative cover:

- Macrophyte density (V_{mac}) is the relative coverage of wetland area by erect vegetation. Wetland vegetation introduces dissolved oxygen and leads to a buildup of organic matter. Highly vegetated wetlands tend to be better suited for phosphorus storage, sequestration of metals, partitioning of organic contaminants, and denitrifcation. Vegetation that emerges above the water in the wetland, such as cattails plays a large role in evapotranspiration. Towler et al. (2004) found that wetlands with abundant cattail coverage demonstrated double or triple evapotranspiration rates of wetlands lacking significant emergent vegetation. Additionally, emergent vegetation provides hydraulic roughness that slows the water velocity aiding in phosphorous retention.

- Buffer density (V_{buff}) refers to the extent to which the area immediately adjacent to the wetland (30 meters from wetland perimeter, in this study) is vegetated. Wetland buffer vegetation contributes to the filtration of water entering wetland via surface runoff and may also enhance evapotranspiration.

Land use:

- Land use (V_{LU}) is defined as the dominant land use in the catchment area (including the wetland). Land uses in the area can predict the quality of runoff that enters the wetlands. In this study the variable was used to determine whether high levels of phosphorus or ammonium were present in the wetland or catchment.

Soil characteristics:

- Soil clay content (V_{clay}) is the percentage of the surface layer of soil that has a particle size less than 0.002 mm in diameter (clay). Clay particles are a key component to sorption of polar molecules including ammonium, phosphates, heavy metals, and certain organics (Reddy and Patrick, 1984; Richardson, 1985; Faulkner and Richardson, 1989; Lesage et al., 2007; Zuidervaart et al., 1999; Kadlec and Knight, 1996).

- Soil pH (V_{soilpH}) is the pH at the surface layer of the soil. Acidic conditions lead to many pollutants being more soluble and thus remaining in the water column. Alkaline soils provide a favorable environment for the removal of many pollutants, especially phosphates and metals, by forming precipitates with calcium and magnesium (Stumm and Morgan, 1996).

CPFW Conceptual Models

This section outlines the conceptual models used in the study. Models use assumptions, data, and inferences to simulate and understand complex phenomena. Conceptual models used in this study utilize theoretical concepts of hydrology and wetland biogeochemistry to estimate effectiveness of a wetland to perform functions. Model results are reported as a functional capacity index (FCI). FCI values range from 0 to 1.0, where 0 indicates the functionality is absent and a 1.0 indicates that the wetland functions at a high level. Table 2 lists variables included in each conceptual model.

Table 2
Variables in each Conceptual Model

Conceptual Model	**Variables**
Water Storage (FCIws)	Wetland Volume (Vvol) Water Regime (Vwet) Wetland Area to Catchment Area Ratio (Vcatch) Macrophyte Density (Vmac)
Ammonia Removal (FCInh3)	Wet-dry Potential (Vdry) Wetland Buffer (Vbuff) Macrophyte Density (Vmac) Wetland and Catchment Land Use (Vlu)
Nitrate Removal (FCIno3)	Wetland Buffer (Vbuff) Macrophyte Density (Vmac)
Phosphorus Retention (FCIp)	Wetland and Catchment Land Use (Vlu) wetland Area to Catchment Area Ratio (Vcatch) wetland Buffer (Vbuff) Macrophyte Density (Vmac) Soil Clay Content (Vclay)
Heavy Metal Retention (FCIme)	Wetland Buffer (Vbuff) Macrophyte Density (Vmac) Soil Clay Content (Vclay) Soil pH (VsoilpH)
Organic Retention/Removal (FCIorg)	Macrophyte Density (Vmac) Wetland Area to Catchment Area Ratio (Vcatch)

Surface Water Storage

During rainfall events wetlands can capture and store water from direct precipitation and overland flow (runoff). The ability of a wetland to store water can become crucial for attenuating storm-related flooding. Without these wetlands, overland flow would flow to the nearest water body, possibly a stream or river, and greatly increase potential for hazardous flooding to areas downstream. Additionally, wetlands have the capability of intercepting, storing, and filtering polluted water which can potentially contaminate downstream or down gradient water bodies.

Water storage capacity in wetlands can be understood using a hydrologic budget. Similar to an economic budget, a hydrologic budget records deposits and withdrawals from an account, in this case a wetland. Inputs (deposits) in the budget include direct precipitation, runoff, groundwater discharge, surface water inflow; outputs (withdrawals) of the budget include evapotranspiration, seepage, and surface water outflow. Due to the geomorphology of the CPFW, which tend to be small local depressions, surface water outflow is typically not a large factor in the hydrologic budget. Additionally, since the Texas coast sits on a clay plain, loss of water through seepage to the subsurface is not a major factor, thus evapotranspiration is the main method of water loss for this study.

Equation 1 assesses the functionality of a wetland to store surface water. The equation contains four variables: V_{vol} , V_{wet}, V_{catch}, and V_{mac}. Seasonally/temporarily inundated wetlands with a catchment area proportionate to wetland surface area with dense macrophyte cover will commonly be able to accommodate an influx of storm water. Additionally, wetlands with a greater volume have a greater potential to store water.

$$FCI_{WS} = V_{vol} \times V_{wet}\left(\frac{V_{catch} + V_{mac}}{2}\right) \tag{1}$$

Ammonia Removal and Nitrate Retention/Removal

Nitrogen retention/removal is the capacity of a wetland to reduce the ammonium and nitrate concentrations in the water column. Sources of nitrogen in wetlands include precipitation, surface runoff, and direct deposition. Reddy and Patrick (1984) found nitrogen retention/removal in aquatic systems occurred mainly though four processes: (1) uptake by plants; (2) immobilization by microorganisms during decomposition of plant material (nitrogen mineralization); (3) absorption of (positively charged) ammonium unto organic matter and clay particles; and (4) most importantly, through the nitrification-denitrification process.

Nitrification is the oxidation of the ammonia and ammonium to nitrate and nitrate. This process occurs in oxidized areas in the water column and soil layers (Cronk and Fennessy, 2001). Denitrification occurs when nitrate enters anaerobic areas (oxygen deficient) in a wetland. When this occurs nitrate is reduced by bacteria to nitrous oxide (N_2O) or dinitrogen gases (N_2), which are then released to the atmosphere (Mitsch and Gosselink, 2000). Nitrogen is removed from the water column through four pathways: (1) the nitrification-denitrification process; (2) absorption to clay particles; (3) uptake by plants; and (4) immobilization by microorganisms (Reddy and Patrick, 1984).

The CPFW assessment contains separate equations for ammonium removal (Equation 2) and nitrate removal (Equation 3). Ammonium removal is thought to be greatest in wetlands that have a fluctuating hydroperiod. Periods of frequent drying introduce sufficient oxygen in the system to remove ammonium though nitrification. Denitrification requires anaerobic conditions which are found in wetlands with long periods of inundation or soil saturation.

Factors specific to the Equation 2 (ammonium removal) are V_{dry} and V_{LU}. V_{dry} represents the tendency for a wetland to draw down and thus introduce oxygen needed to promote nitrification. V_{LU} is included due to field observations by Baylor University researchers that surface waters collected from a grazed site in Brazoria County have higher ammonia concentrations than waters collected from non-grazed sites. Both Equations 2 and 3 include the variables V_{buff} and V_{mac}. Wetlands that dry out periodically have been found to have greater rates of nitrification (Patrick and Mahapatra, 1968 and Ponnamperuma, 1972).

Wetlands that have a tendency to dry out, receive runoff undeveloped or natural lands, and have abundant vegetation will be thought to be effective at retaining/removing ammonia (Equation 2). Wetlands that have abundant vegetation will be thought to be effective at retaining/removing nitrates (Equation 3).

$$FCI_{NH3} = V_{dry} \times \left(\frac{V_{buff} + V_{mac} + V_{LU}}{3} \right) \tag{2}$$

$$FCI_{NO3} = \left(\frac{V_{buff} + V_{mac}}{2} \right) \tag{3}$$

Phosphorus Retention

The phosphorus retention model estimates the capacity of a wetland to both remove phosphorus from the water column and retain it within sediments, soils, plants, and other organisms. Phosphorus is introduced to wetland systems through wet and dry aerial deposition, and surface runoff. Phosphate has a strong affinity for clay and other mineral particles, thus phosphorus loading may be increased by an influx of sediment during large flooding events (McKee et al., 2000).

Primary mechanisms of wetland phosphorus retention are: (1) microbial uptake by plankton and other organisms; (2) plant uptake; (3) incorporation of organic phosphorus into soil peat; and (4) soil adsorption (Richardson, 1985). Phosphorus retained in organisms and plants is released back into the wetland system seasonally during senescence. More permanent retention occurs in sediments and soils. Greater than 95% of the phosphorus can be found in the sediment-litter compartment of a natural wetland (Faulkner and Richardson, 1989).

Wetlands that have slow standing water and high hydraulic roughness (slower water movement) typically have a high proportion of suspended sediment; this provides an environment for effective particulate phosphorus removal. In addition to direct uptake of phosphorus, macrophytes can provide hydraulic roughness to slow water velocity.

Equation 4 represents phosphorus retention. The five variables import to the retention of phosphorus include: V_{LU}, V_{catch}, V_{buff}, V_{mac}, and V_{clay}. Small wetlands with a small catchment that contain abundant vegetation and clay-rich soils are thought to be effective at retaining phosphorus.

$$FCI_P = \left(\frac{V_{LU} + V_{catch}}{2}\right) \times \left(\frac{V_{buff} + V_{mac} + V_{clay}}{3}\right) \tag{4}$$

Heavy Metal Retention

Similar to phosphorus retention, the heavy metal retention model measures the capacity of a wetland to remove heavy metals from the water column and retain heavy metals in sediments, soils, or plant material. Sources of heavy metals include fertilizer impurities, tire dust, cement production, wastewater, urban runoff, combustion products of fossil fuels, industrial sources, and other natural sources (Stumm and Morgan, 1996).

There are three main pathways for heavy metal sequestration in wetlands (Kadlec and Knight, 1996): (1) binding to particulates and soluble organics through cation exchange and chelation; (2) precipitation as insoluble salts; and (3) uptake by biota. Heavy metal retention studies have found that sediments are the primary storage components for metals (Lesage et al., 2007 and Zuidervaart et al., 1999).

Typically, well buffered, alkaline soils and the presence of organic matter of clay increase the ability for a wetland to retain heavy metals. Equation 5 includes vegetation variables (V_{buff} and V_{mac}) and soil variables (V_{clay} and V_{soilpH}). Well vegetated wetlands with alkaline and clay-rich soils are thought to be particularly effective at retaining heavy metals.

$$FCI_{Me} = \frac{\frac{V_{buff} + V_{mac}}{2} + V_{clay} + V_{soilpH}}{3} \tag{5}$$

Retention/Removal of Organic Compounds

The organic compound removal or retention model estimates the capacity of a wetland to remove or transform organic compounds in the water column. Organic compounds can be both natural and synthesized. Pesticides, petroleum, hydrocarbons and other industrial organics can lead to detrimental impacts in wetland systems. Five pathways for removal of hydrocarbons from wetlands are: (1) volatilization; (2) photochemical oxidation; (3) sedimentation; (4) sorption; and (5) biological degradation (Kadlec and Knight, 1996). In general, longer hydraulic retention times and shallow water depths are thought to result in greater degradation of organics via photochemical oxidation.

Equation 6 contains two variables, V_{mac} and $V_{catch,}$. V_{catch} can be correlated to relative hydraulic retention time. Wetlands with small catchments and significant vegetation should be effective at retaining and/or removing organic compounds.

$$FCI_{org} = \frac{V_{mac} + V_{catch}}{2} \tag{6}$$

GIS and Modeling

GIS is a powerful tool used by geographers and environmental scientists to map and analyze spatial data. Vector and raster data are two types of data used in GIS to represent features in the real world. Vector data is made up of points, lines, and polygons and are used to represent individual geographic features, such as a river, building, or road. Raster data exists as a grid of cells that represent a surface. Each square cell contains a value that represents a continuous phenomenon, such as elevation, across the surface. Common raster datasets include elevation, land cover/land use, and noise levels. Raster data provides the opportunity for grid based spatial modeling.

The universal soil loss equation (USLE) and DRASTIC are excellent examples of the potential power of modeling with GIS. The USLE estimates the amount of soil erosion per unit area per time by combining raster layers containing slope, soil quality, agricultural practices, and other variables (Wischmeier and Smith, 1978). The DRASTIC model maps the spatial distribution of vulnerability to groundwater contamination in an aquifer by combining several factors including aquifer medium, hydrologic conductivity, depth to water table, and topography, and other variables (Aller et al., 1987). Soil erosion and groundwater contamination are products of complex interactions. GIS technology allows researchers the ability to combine, analyze and map these interactions, resulting in estimates of erosion and contamination events over extensive areas of landscape. The model deployed in this study will follow the basic methodology of combining raster datasets, containing pertinent variable values, to estimate the functional capacity of wetlands to provide specific functions including as water storage and pollution mitigation.

STUDY AREA

Galveston Bay is located on the southeastern Texas coastline, south of Houston, Texas. This part of Texas has a subtropical climate and receives approximately 132.08 cm of rainfall a year. The topography of the area is very flat, sloping gently downward from Houston towards the coast. Thirty-two USGS 1:24,000 topographical quadrangles comprise the study area, lying within portions of Brazoria, Chambers, Galveston, and Harris Counties and covering a total of 5,376 km^2 (Figure 1). These topographical quadrangles were used to create a study area that was both representative of the coastal plains of Texas and encompass an area which surrounded the Galveston Bay.

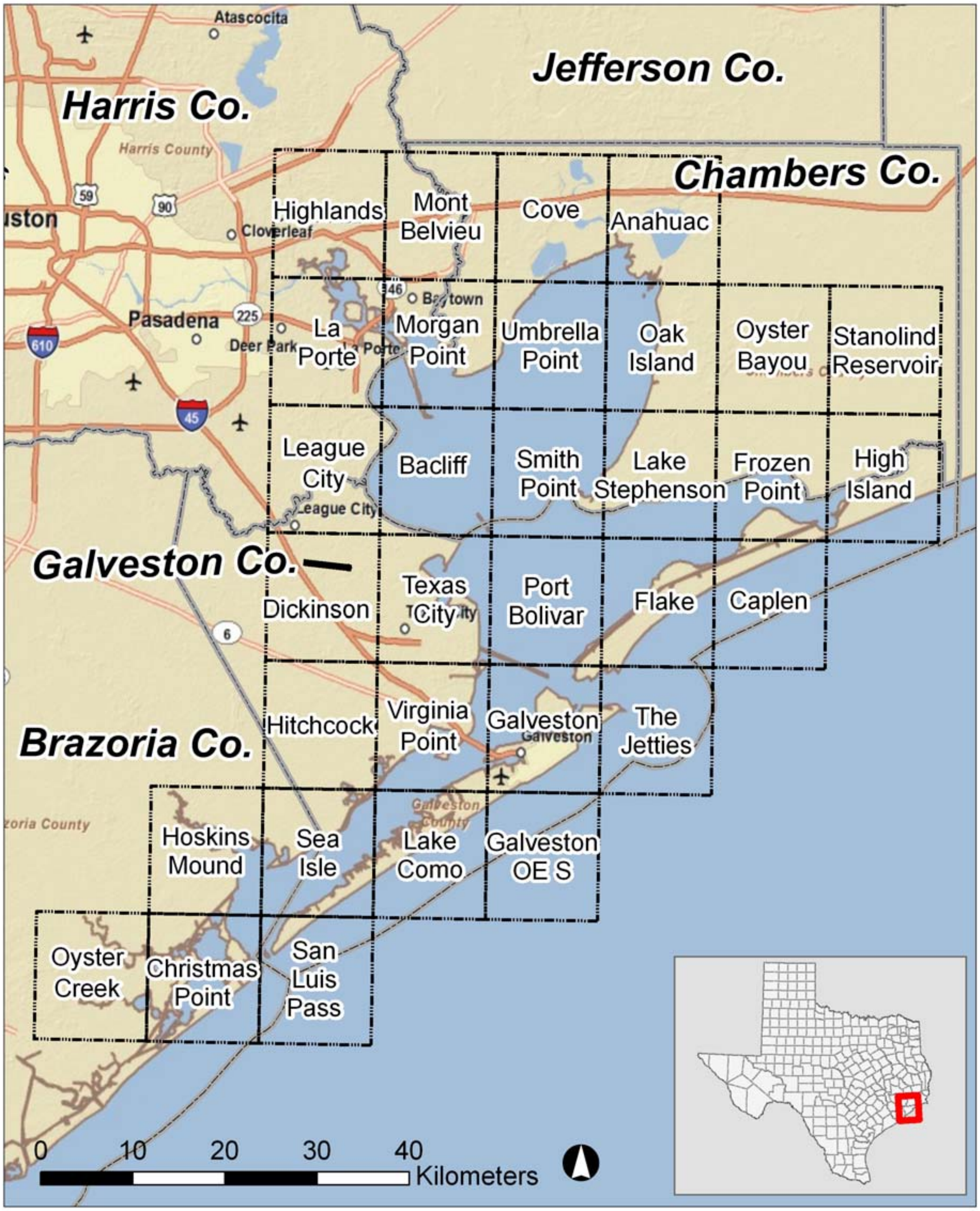


Figure 1. Study area.

METHODS

The primary datasets used in this study (Table 3) were either defined or reprojected to Universal Transverse Mercator Zone 15N coordinate system (North American Datum 1983). ESRI® ArcGIS 9.3.1 and ArcHydro Tools 1.3 (Environmental Systems Research Institute, Redlands, California) were used to prepare the variables, design and implement the model.

Table 3
Overview of GIS Datasets Used to Calculate Model Variables

Data	**Source**	**Resolution/Accuracy**
Wetlands	National Wetlands Inventory	1:24,000
Soils	County-Level Soil Survey Geographic Database (SSURGO)	1:24,000
Vegetation	2004 color-infared imagery from the National Agriculture Imagery Program (NAIP)	1 m
Land Use Land Cover	2001 USGS National Land Cover Dataset (NLCD)	30 m
Elevation	2008 Harris County Flood Control District LiDAR (Harris Co.)	1 m Horizontal: .67 m Vertical: .09 m
	2006 Texas Natural Resource Information Systems (TNRIS) LiDAR (Brazoria, Chambers, and Galveston Co.)	1.4 m Horizontal: .73 m Vertical: .37 m

National Wetlands Inventory

National Wetlands Inventory (NWI) shapefiles were downloaded for each of the 32 topographic quadrangles in the study area. Freshwater emergent, freshwater ponds, and freshwater forested wetlands were extracted from the NWI datasets. Most of the NWI data for the study area were recently updated in 2006, however a few quads were last updated in 1992.

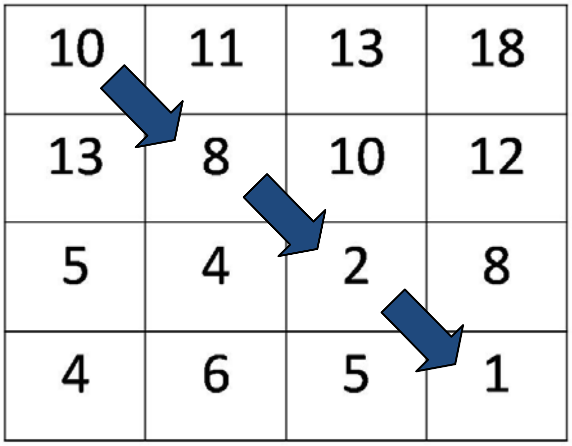
To avoid edge affects (cutting of portions of wetlands at the study area boundary), only wetlands located completely within 125 meters of the study area boundary were included in the study. This resulted in a total of 10,349 wetlands with a total area of 51,126 hectares. While the

NWI database contains inaccuracies and tends to underestimate the extent of wetland coverages, it was determined to be the best available dataset for such an extensive study area.

Watershed delineation

Delineating watersheds or “catchments” was one of the most challenging aspects of this study. The dataset used for this component was LiDAR (light detection and ranging); surface elevation data generated by firing a laser beam from an airplane-based instrument and recording the time increment required for the beam return. Elevations are calculated based on the time it takes for a laser beam to bounce from the surface and return to the aircraft, the position of which is recorded by highly accurate global positioning system (GPS). LiDAR data provides both horizontal positions in x,y geographic coordinates as well as vertical or elevation coordinates (z).

The *x*,*y*,*z* output tables were used to create a digital elevation model (DEM), a raster dataset in which grid cell or pixel values represent the elevation at the horizontal location of the cell. DEMs were then used to determine water flow direction across surfaces based on the principle that water flows from high to low elevations and takes the shortest route possible (Figure 2). Catchment delineation was determined computationally by identifying the breaklines, or watershed boundaries, between drainage systems.



10	11	13	18
13	8	10	12
5	4	2	8
4	6	5	1

Figure 2. Example of flow direction from cell to cell on a DEM (numbers represent elevation in meters).

DEMs used for this project were created from two LiDAR datasets. Harris County LiDAR was obtained from the Harris County Flood Control District and Brazoria, Galveston, and Chambers counties' LiDAR obtained from Texas Natural Resource Information Systems (TNRIS). Harris County data had a pixel resolution of 1 meter and the TNRIS data a resolution of 1.4 meters. The Harris County data were resampled to 1.4 meters to match the resolution of the data for the other counties. Both LiDAR datasets had been post-processed from the LIDAR raw data, thus they represented the surface of the earth, termed "bare earth", with vegetation, buildings, and other structures being removed.

Catchments for wetlands were delineated using a tiled approach. The DEM dataset was divided into tiles using natural breaklines, such as roads and rivers, to avoid edge effects. A smoothing process was used to minimize edge effects caused by tile boundaries. This process included buffering the tile boundaries by 0.5 kilometers and delineating catchments for wetlands falling inside these buffers. The catchments delineated in the buffers of the tiles were analyzed and merged with those delineated within the tiles. All of the catchments were combined to make a seamless catchment dataset for the study area.

A major issue within catchment delineation is how “sinks” are managed. A “sink” is defined as a location where surface water flow is interrupted (Figure 3). Sinks are often errors created during interpolation processes when creating a DEM; however sinks can also represent natural depressions. Delineating catchments for depressional wetlands requires non-traditional hydrological modeling methods. In traditional catchment delineation all sinks are filled, allowing flow to streams and rivers, and watersheds are delineated at locations, termed pour points, on the river. ArcHydro Tools 1.3 has tools that allow natural sinks, in this case wetlands, to be preserved while other sinks, such as errors in DEM, to be filled. The NWI dataset was used to determine which sinks were natural depressions.

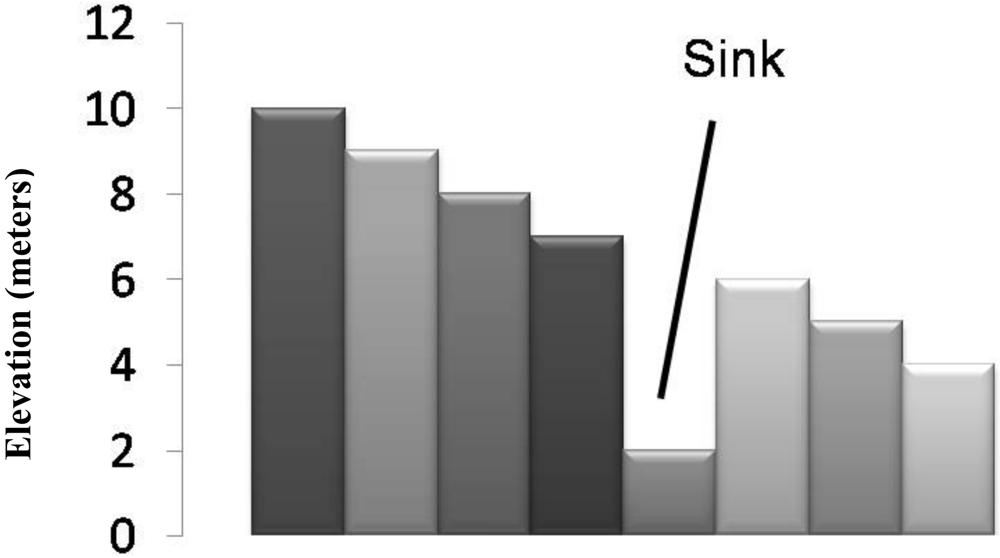


Figure 3. Profile view of a sink as identified on a DEM.

Individual wetlands may include gradients of elevation, soil type, or vegetation. During the NWI map construction process, wetland systems may have been divided into smaller conjoined wetlands based on observable characteristics of elevation, soil or vegetation. However, for catchment delineations and wetland volume calculations in this study, conjoined wetlands were treated as one wetland system. An example of a conjoined wetland system is shown in Figure 4.

Figure 4. Example of conjoined NWI; wetland system.

Catchments were not individually delineated for wetland systems within the 100-year floodplain due to their connectivity to nearby rivers or streams and their extensive catchment area. For example, attempts to delineate catchments along the Trinity River, which flows through the study area, using high resolution LiDAR data would produce a catchment that extends into numerous counties. Wetlands within the 100-year floodplain were considered to be part of a river and for this reason a 100 meter buffer around the perimeter of the wetland was used as the catchment rather than attempting to create one with DEM data.

Catchments were delineated for wetlands outside of the 100-year floodplain (~ 4,000). An example of a delineated catchment in Harris County is shown in Figure 5. Note that the catchment area includes the wetland surface area. For wetlands within the 100-year floodplain (~6,300), 100 meter wide buffer areas were used as catchments.

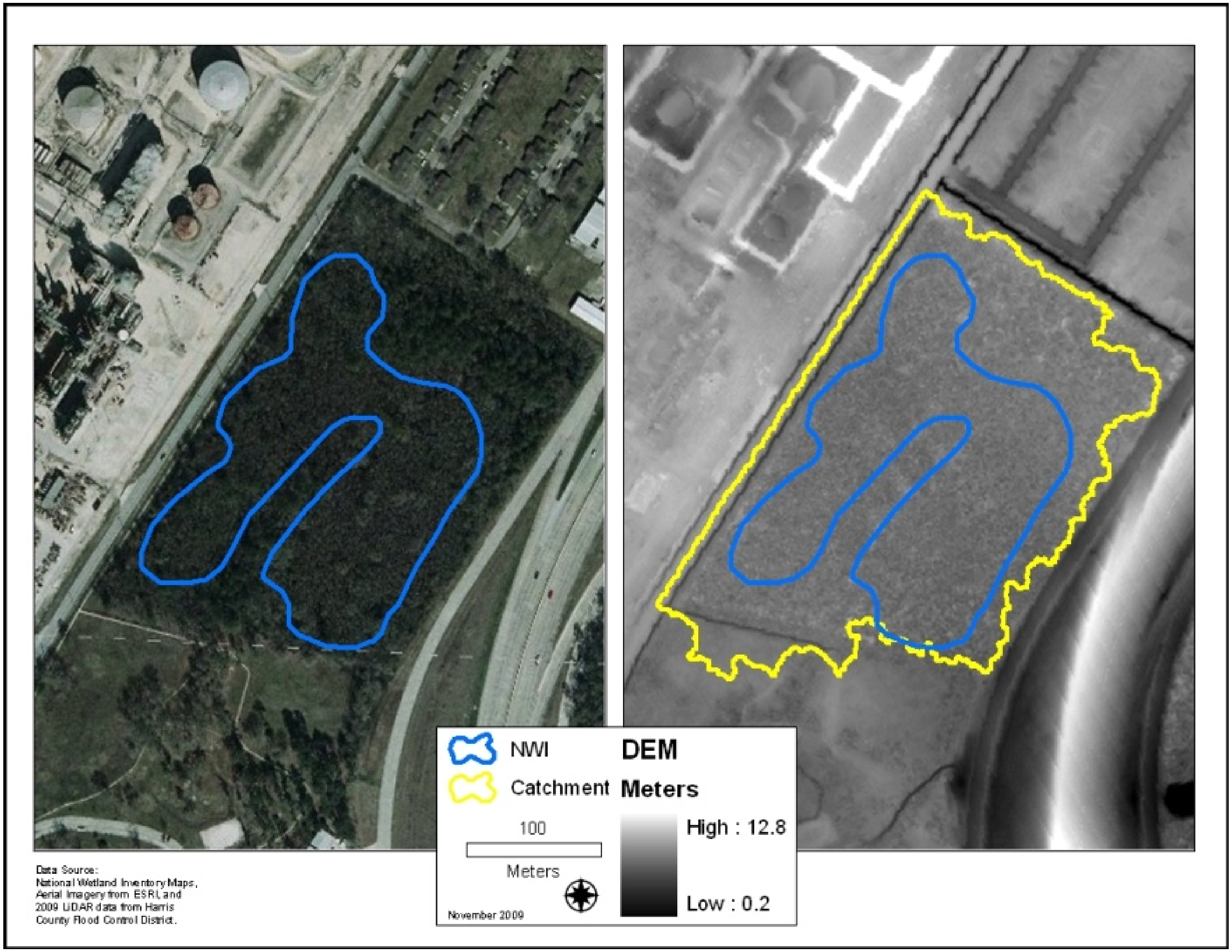


Figure 5. Example of catchment delineation in Harris County using ArcHydro “sink watershed delineation” method.

100 meter buffers were used for wetlands were no catchment was delineated. A catchment may not have been delineated for various reasons including: 1) vertical error in LiDAR data and 2) registration issues or errors with NWI, and/or 3) the wetlands have been drained and filled. Note wetlands (15.24 cm or less) may not be recognized as natural depressions using LiDAR datasets with a vertical accuracy of 0.37 meters (TNRIS data), as was used for much of the study area. Figure 6 shows two wetlands in the upper right quadrant of the highlighted catchment in were not detected by LiDAR. Additionally, V_{catch} was screened and 100 meter buffers were used for wetlands with erroneous values, which included wetlands with a $V_{catch} \leq 0.01$, which are small wetlands with extremely large catchments and wetlands with a $V_{catch} > 1$, meaning wetlands where the computed catchment was smaller than the wetland itself. For the reasons mentioned above, 170 wetlands were flagged as having uncertainty for V_{catch}.

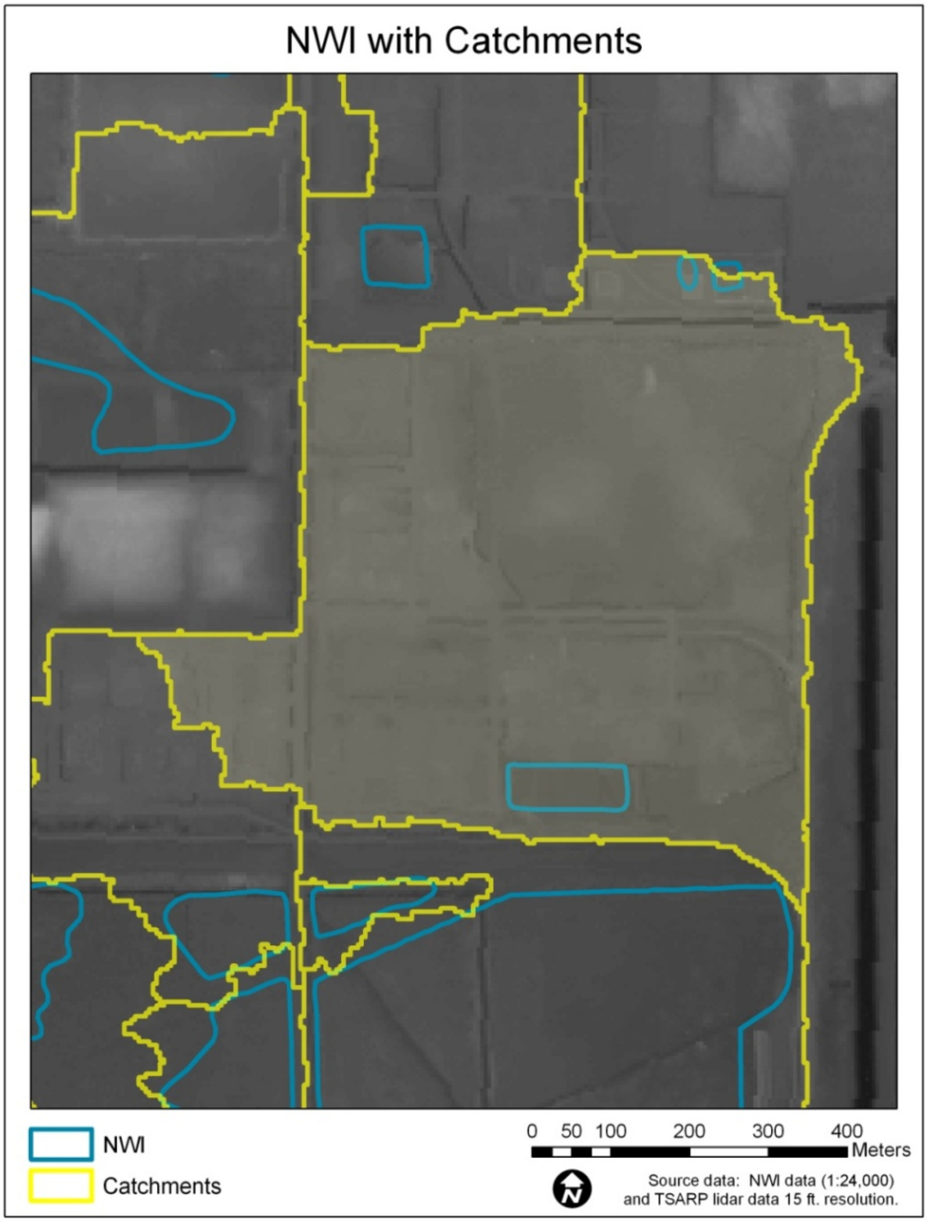


Figure 6. Two NWI wetlands in Harris County that have apparently been filled and thus no volume or catchment estimates can be made.

Raw V_{catch} ratios were reclassified by M. Forbes using the following procedure. For all catchments, a theoretical 2-yr rainfall event (5 cm in one hour) and a runoff coefficient of 0.15 was used to estimate the volume of runoff from 1 m^2 of catchment. The median wetland depth (4.9 cm) and an infiltration rate of 15% was used to estimate the available volume of a typical wetland. This estimate resulted in wetlands with a wetland area:catchment area ratio of between 0.04 and 0.18 able to store 25-100% of runoff and these wetlands were assigned a value of 1.0 (Table 4). Ratios smaller than this range (storage between 10-25%) were assigned a value of 0.6 and ratios associated with less than 10% storage were assigned a value of 0.4. Ratios greater than 0.18 represent wetlands that have more storage capacity than runoff and were assigned a V_{catch} value of 0.6.

Table 4
Wetland Area : Catchment Area Ranges, Approximate Runoff Storage, and V_{catch} Values

Wetland Area: Catchment Area	**Approximate Runoff Storage Capacity (%)**	**Vcatch**	**Number of wetlands**
0.005 – 0.017	< 10	0.4	779
0.018 – 0.044 0.181 – 0.999	10-<25 >100	0.6	3723
0.045 – 0.180	25-100	1.0	2861

Although catchment delineation at the landscape level can be calculated using the tools discussed above, there are assumptions and that need to be acknowledged. Wetlands often have “fuzzy” boundaries. For example, it may be difficult to identify an exact boundary where a wetland begins and ends. This is particularly true for NWI delineations, which are mapped primarily using aerial photography.

Wetland Volume Calculation

As mentioned previously, a single DEM for the entire study area was created by mosaicing the LiDAR derived data from the four counties. The sinks representing data errors were filled to build the catchment areas. The remaining “sinks” are the depressional wetlands. A method developed by Antonic et al. (2001) for estimating the volume of shallow water bodies using DEM and the “fill sinks” function was used to estimate the volume of the wetlands. The Fill Sink tool in ArcGIS was used to fill the depressions of the wetlands; Wetland volumes (V_{vol}) were estimated by comparing the difference in elevation between the newly filled DEM with the original DEM. Specifically, the elevation of each pixel in the original DEM was subtracted from the elevation value in the filled DEM. If there was no difference in elevation, the resulting output pixel value was 0. If the pixel was filled, the difference resulted in a positive elevation value representing potential depth of water at that point. Next, the depth per pixel was multiplied by the area of the pixel, in this case 1.96 m^2, to get the volume per pixel. Zonal statistics in ArcGIS is a function that summarizes pixels in a raster dataset using “zones”. NWI boundaries were used as “zones” to find the mean depth and total volume for each wetland.

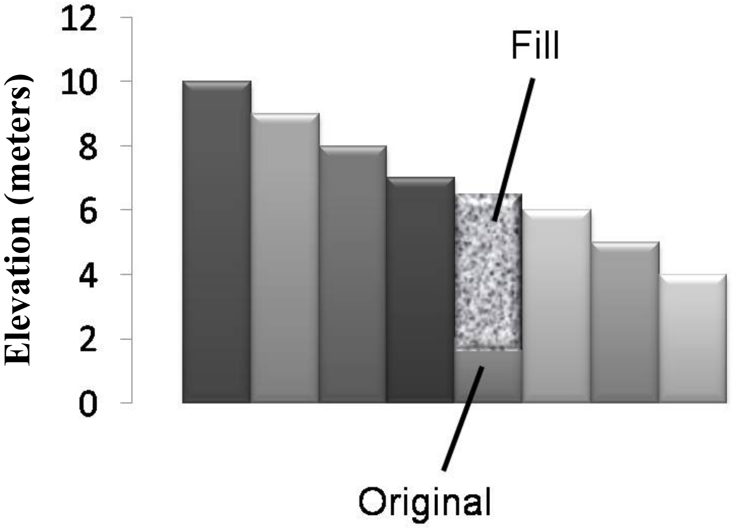


Figure 7. Conceptual profile of filling sinks using GIS “fill sinks” function.

A volume estimate could not be obtained for seven of the 10,349 wetlands identified in the study area. This was due to small “pockets” of no data in LiDAR values within the study area. These wetlands were coded as -9999 and were omitted from results for the water storage model. Additionally, a volume of zero was calculated for 22 wetlands (0.3%). This could be caused by a few issues including: (1) wetland that was drained or filled (possibly an error in NWI); (2) wetland was flooded; or (3) depression was too shallow to be detected by the LiDAR. Wetlands with a zero volume were assigned a value of 0.1 for volume.

The methodology used to calculate wetland volumes is best suited for natural systems. Wetlands with steep contour modifications, most likely constructed features, will typically contain exaggerated depths and volumes. These results occur because the contour modifications used to direct drainage to the water body are also included in the depth to volume calculation.

V_{vol} ratios were ranked and normalized by M. Forbes based on percentiles. For example wetlands from 0 - 15% were giving a value of 0.1; 15 - 25% a value of 0.2; and 25 – 35% a value of 0.3; to a total value of 1.0.

Evaluation of LiDAR datasets

To evaluate error associated with LiDAR elevations, topographical surveys were performed at two of the six field study sites. For each survey site, elevation differences between a control point and randomly selected individual survey points were compared to the elevation difference in LiDAR for the same locations. Survey points were collected using a Trimble GeoXM GPS unit. Differences in elevation between LiDAR and GPS points are partially attributable to differences in horizontal positional due to registration error between LiDAR and GPS; the LiDAR horizontal error is +0.73 m and the GPS horizontal error is approximately 1 m.

To minimize horizontal error, sample elevations from LiDAR were compared to GPS using both a “spot check approach” (Figure 8) and a “neighborhood approach” (Figure 9). The neighborhood approach involved calculating the mean elevation for a nine-pixel neighborhood and assigning that elevation to the point falling in the center pixel of the neighborhood. The root mean squared error (RMSE) in meters was calculated for both sites. Data was normally distributed for each study site, thus the RMSE can be multiplied by 1.96 to get a vertical accuracy estimate at the 95% confidence level (Blak, 2007). The RMSE for the LeConte site (Table 5) was 0.14 meters using the “spot check approach” and 0.1 meters using the “neighborhood approach” and vertical accuracy estimates (95% confidence level) of 0.27 meters and 0.19 meters, respectively. The RMSE for the Sedge Wren site (Table 6) was 0.13 meters using the “spot check approach” and 0.14 meters using the “neighborhood approach” and vertical accuracy estimates (95% confidence level) of 0.25 meters and 0.28 meters, respectively. The results of the LiDAR analysis confirmed that the vertical error was within the stated range (+/- 0.37 meters).

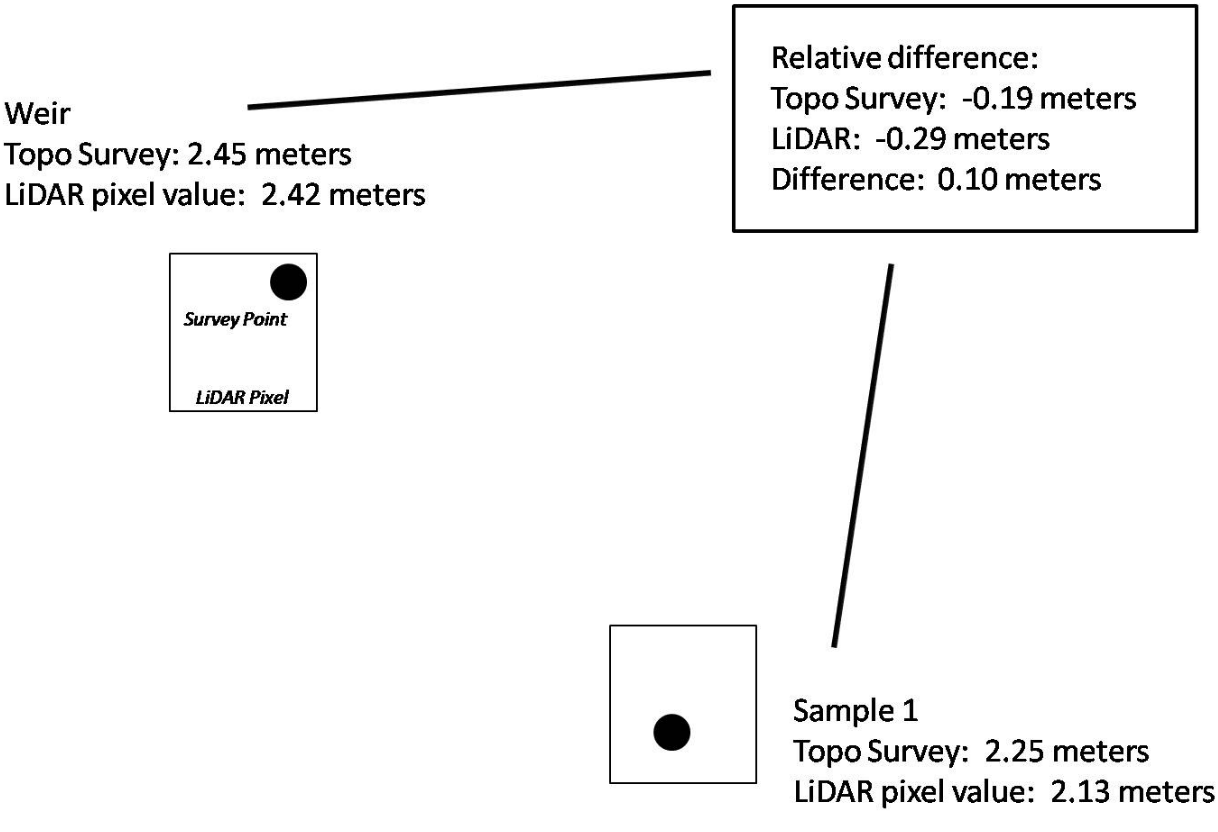


Figure 8. Comparison of topographic survey and LiDAR – “Spot Check Approach”.

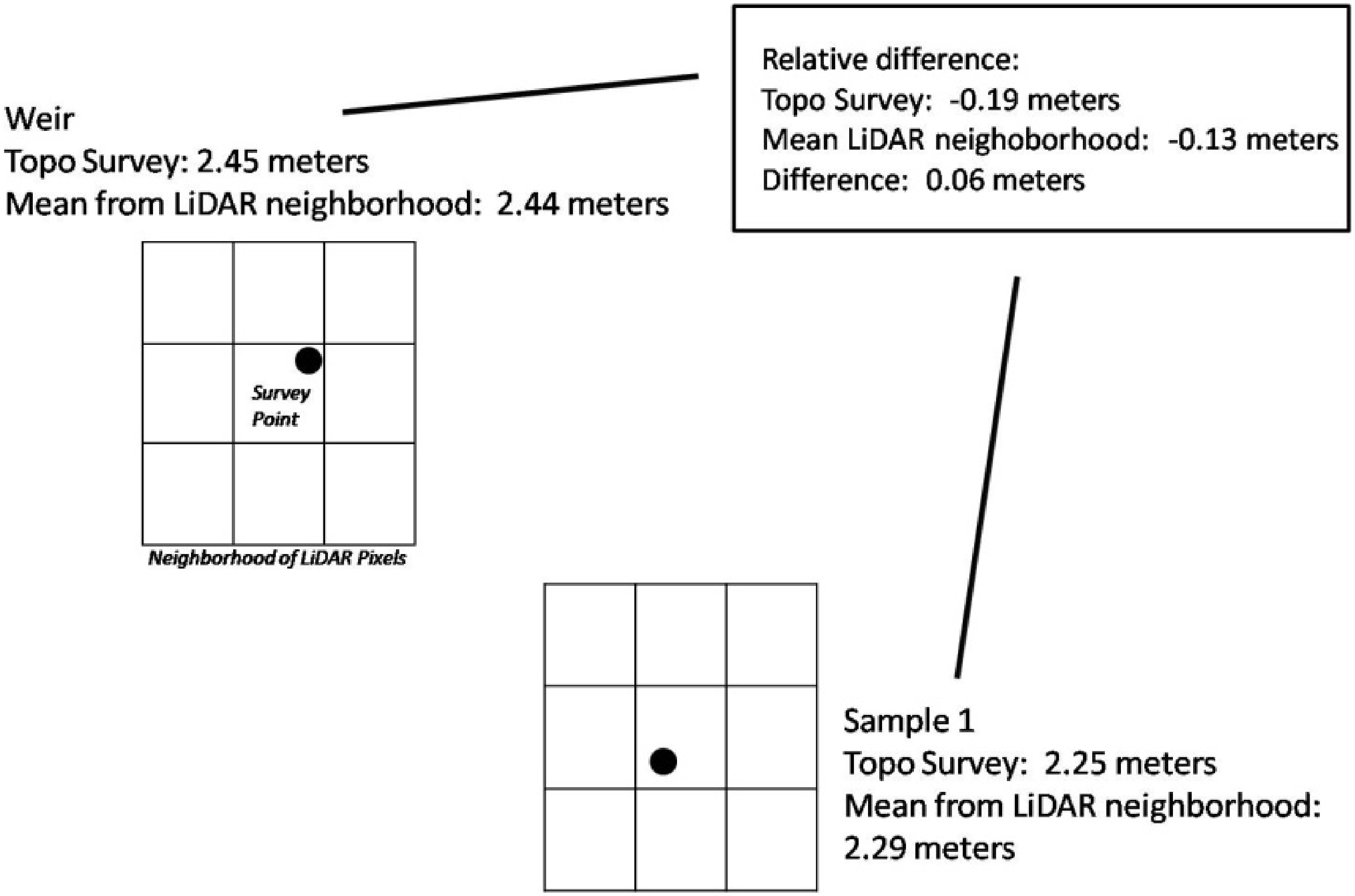


Figure 9. Comparison of Topographic Survey and LiDAR – “Neighborhood Approach”

Table 5

LiDAR Analysis for LeConte, Chambers County

	Field Data	Lidar Data			
		Spot Check Approach		Neighborhood Approach	
Survey Label	Relative Diff (M)	Relative Diff (M)	**Error(M)**	Relative Diff (M)	**Error (M)**
Weir	-----	-----	-----	-----	-----
1.3	-0.20	-0.29	0.09	-0.06	0.14
1.9	-0.16	-0.30	0.14	-0.29	0.14
2.1	-0.34	-0.10	0.24	-0.15	0.19
2.2	-0.13	-0.18	0.05	-0.14	0.02
2.9	-0.21	-0.14	0.07	-0.26	0.05
2.10	-0.12	-0.17	0.05	-0.08	0.04
3.1	-0.23	0.02	0.25	-0.17	0.06
3.7	-0.10	-0.26	0.16	-0.18	0.08
4.2	-0.17	-0.17	0.00	-0.36	0.19
4.5	-0.09	-0.16	0.07	-0.20	0.10
4.7	-0.18	0.01	0.19	-0.23	0.05
5.2	-0.21	-0.08	0.13	-0.19	0.02
5.3	-0.19	-0.11	0.08	-0.23	0.04
5.5	-0.23	-0.08	0.15	-0.20	0.03
5.7	-0.14	0.05	0.19	-0.14	0.00
5.8	-0.23	-0.36	0.13	-0.23	0.00
6.6	-0.16	-0.21	0.05	-0.37	0.21
4.3	-0.12	-0.27	0.15	-0.15	0.02
2.6	-0.06	-0.27	0.21	-0.01	0.06
2.7	-0.20	-0.16	0.04	-0.25	0.05
RMSE (M)			**0.14**		**0.10**
Vertical Accuracy (95%) - M			**0.27**		**0.19**
Difference +		**9**		**7**	
Difference -		**10**		**11**	

Table 6

LiDAR Analysis for Sedge Wren, Chambers County

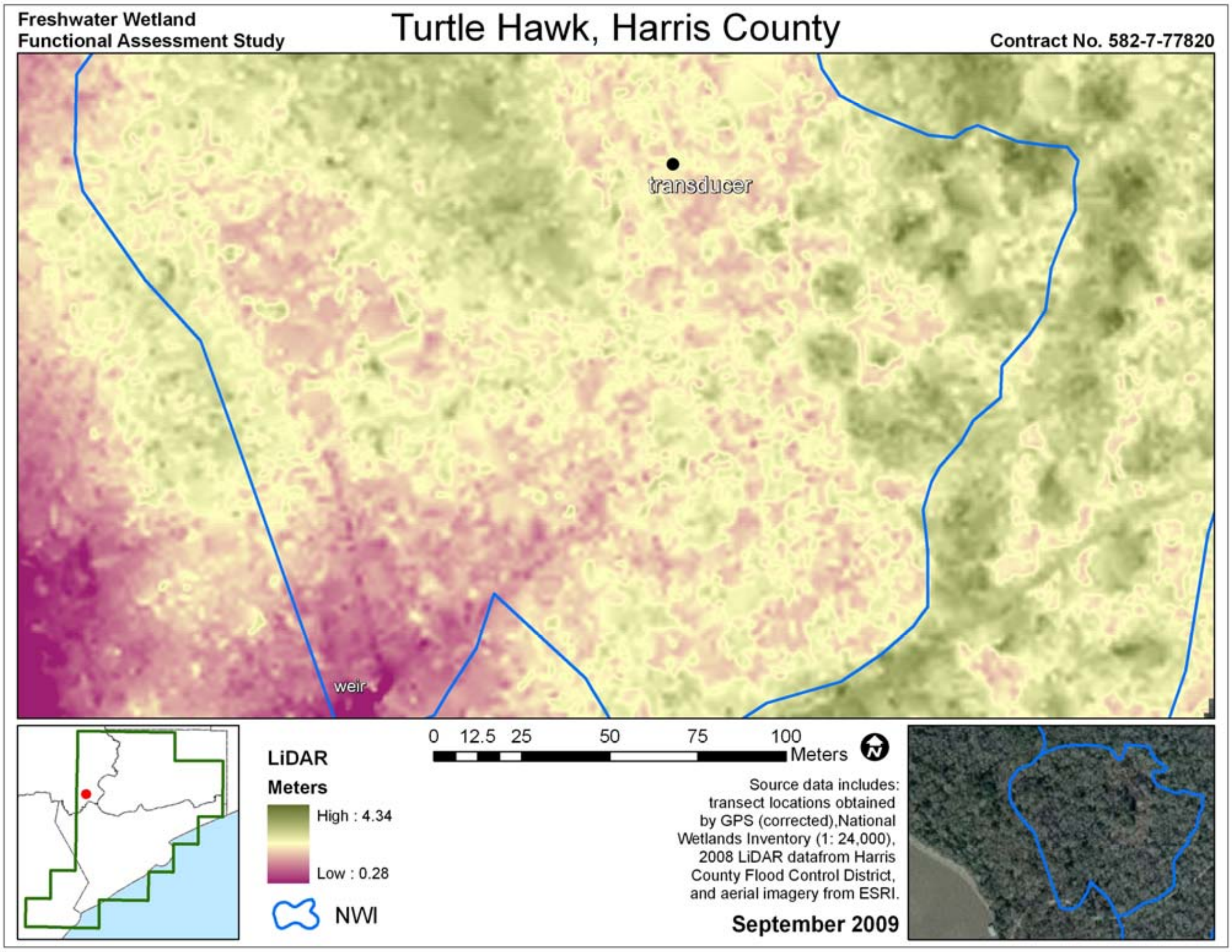
	Field Data	Lidar Data			
		Spot Check Approach		Neighborhood Approach	
Survey Label	Relative Diff (M)	Relative Diff (M)	**Error(M)**	Relative Diff (M)	**Error (M)**
1.1	-------	-------	-------	-------	-------
1.4	0.07	-0.06	0.13	-0.01	0.08
1.6	0.06	-0.07	0.13	-0.07	0.13
1.11	-------	-------	-------	-------	-------
1.12	-0.25	-0.03	0.22	0.02	0.27
1.13	0.04	0.04	0.00	0.01	0.03
1.17	-0.01	-0.11	0.10	-0.13	0.12
1.18	0.02	-0.13	0.15	-0.14	0.16
1.19	0.05	-0.11	0.16	-0.14	0.19
1.24	-0.22	-0.01	0.21	-0.04	0.18
1.26	0.03	0.10	0.07	0.04	0.01
1.27	-0.01	0.16	0.17	0.12	0.13
2.19	0.05	-0.12	0.17	-0.13	0.18
2.20	0.02	-0.11	0.13	-0.15	0.17
2.21	-0.01	-0.10	0.09	-0.12	0.11
2.23	-0.01	-0.14	0.13	-0.18	0.17
2.26	-0.07	-0.04	0.03	-0.06	0.01
3.24	0.04	-0.07	0.11	-0.13	0.17
4.19	0.02	-0.08	0.10	-0.13	0.15
4.20	0.01	0.01	0.00	-0.03	0.04
4.23	-0.07	-0.06	0.01	-0.11	0.04
4.24	0.04	-0.04	0.08	-0.10	0.14
RMSE (M)			**0.13**		**0.14**
Vertical Accuracy (M) (95%)			**0.25**		**0.28**
Difference +			**6**		**5**
Difference -			**13**		**15**

LiDAR and Water Bodies

An issue with the LiDAR dataset and volume analysis of wetlands concerns water levels at the time the LiDAR data were obtained. Terrestrial LiDAR systems, like the one utilized for this study, fire laser pulses that have a spectral resolution of near-infrared (0.75 – 1.4 µm). Near-infrared light is absorbed by water and therefore will not record elevations below the surface of the water. LiDAR systems for mapping bathymetry do exist; they use a laser with a spectral reference in the visible green and infrared bands. The return pulse of the infrared laser indicates the surface of the water and the return from the green laser records the bottom of the water body (Guenther, 2007). A custom LiDAR data collection mission is extremely costly and was not an option for this study. The LiDAR datasets used in this study were from missions flown to map floodplains in the vulnerable coastal counties, thus a terrestrial LiDAR was used. It is important to note that if a large depth of water was present in the wetlands during the time LiDAR data were being collected, volume and depth for the flooded wetlands were underestimated.

Dense canopy can also create issues with LiDAR data. When a laser pulse hits tree canopy, the receiver will register multiple returns. The first return is the canopy, and the last return is assumed to be the “ground” return. A general rule of thumb is if one is that if one is standing under dense tree canopy and cannot see the sky, then it is unlikely a laser pulse will strike the ground.

Post-processing of raw LiDAR data removes the canopy cover, when possible, takes the ground returns and “smoothes” the areas where anomalies exist (Fowler et al., 2007). For instance, areas in the forest where the last return is not the “ground” return, a tree top, for example, the anomaly can be smoothed using surrounding data. This can result in a loss of microtopography for some forested wetlands. Figure 10 shows the field site named Turtle Hawk, a forested wetland in Harris County. Note in the aerial photograph located in the lower right hand corner of the figure the densely forested land cover. Despite the dense canopy cover, ground surface microtopography was detectable in the LiDAR data for this site.



Source data includes: transect locations obtained by GPS (corrected),National Wetlands Inventory (1: 24,000), 2008 LiDAR datafrom Harris County Flood Control District, and aerial imagery from ESRI.

Figure 10. Turtle Hawk with LiDAR.

Hydroperiod Variables

Two variables were derived from the NWI hydroperiods based on the Cowardin wetland classification scheme found in the NWI dataset. In the water storage model, V_{wet}, refers to the duration of inundation in a wetland. Table 7 contains variable values for water regimes in the study site. V_{wet} ranges from a low value of 0.1 for permanently flooded wetlands to high of 1.0

for wetlands that are seasonally flooded. In the ammonium removal model, V_{dry}, refers to the tendency of wetlands to dry out. Table 8 contains variable values for wet-dry potential.

Table 7
V_{wet} Values Vased on Cowardin Classification of Water Regimes

Water Regime	**Weeks Flooded**	**Description of Surface Water**	**NWI symbol**	**V_{wet}**
Permanently and Artificially flooded	52	Present year round	H, V, K, h, x, hs	0.1
Intermittently exposed	41 – 51	Present except during extreme drought	G , f (if rice)	0.2
Semipermanently flooded	18 – 40	Present most of year, when absent, very shallow water table	F,T	0.3
Seasonally flooded	5 – 17	Wet during growing season, typically exposed during some period of each year	C,R, d, s, f (not rice)	1.0
Saturated	Seldom	Seldom present but soils saturated for extended periods	B	1.0
Temporarily flooded	1 – 4	Present for brief periods, lower water table, facultative vegetation	A,S	1.0
Intermittently flooded	Seldom	If present, no seasonal pattern, hydric soils unlikely	J	1.0

Table 8

V_{dry} *Values Based on Cowardin Classification of Water Regimes*

Water Regime	**Weeks Flooded**	**Description of Surface Water**	**NWI symbol**	$\mathbf{V_{dry}}$
Permanently and Artificially flooded	52	Present year round	H,V,K, h, hs, x	0.1
Intermittently exposed	41 – 51	Present except during extreme drought	G, f (if rice)	0.2
Semipermanently flooded	18 - 40	Present most of year, when absent, very shallow water table	F,T	0.4
Seasonally flooded	5 - 17	Wet during growing season, typically exposed during some period of each year	C,R, d, s, f (not rice)	0.5
Saturated	seldom	Seldom present but soils saturated for extended periods	B	0.6
Temporarily flooded	1 – 4	Present for brief periods, lower water table, facultative vegetation	A,S	0.8
Intermittently flooded	seldom	If present, no seasonal pattern, hydric soils unlikely	J	1.0

For this study tidal wetland hydroperiods were given the same variable values for non-tidal systems. For example, seasonally tidal (water regime code R) had the same value as seasonally flooded (water regime code C). Additionally, modified wetlands, specifically “diked/impounded (h/hs)” or “excavated (x)”, were grouped in the permanently/artificially flooded category (Tables 7 and 8). All of assumptions above were made based on an understanding of hydrology and field observations (M. Forbes, personal communication).

Farmed wetlands presented a problem. Pasture and rice crop represent the two most common types of farmed wetlands found in the study area. Wetlands farmed for rice are often heavily modified and are flooded for longer periods of time than pasture, which tends to be a more natural system. Using land use\land cover data, aerial photographs, and advice from local agriculture extension agents, the farmed wetlands were classified as either rice or pasture and given a hydroperiod of “intermittently exposed” and “seasonally flooded”, respectively. Any wetland containing an assumption for hydroperiod was “flagged”.

Land Use\Land Cover

Land cover\land use (LULC) for the study area was obtained from the 2001 USGS National Land Cover Dataset (NLCD). This raster dataset has a pixel resolution of 30 meters and was resampled to 1.4 meters to match the LIDAR resolution. The variable for land use (V_{LU}) was used in two water quality models: ammonium removal and phosphorus reduction. Phosphorus loading estimates associated with different land cover types were derived from a study conducted by Adamus and Bergman (1995) and converted to a relative scale from 0.0 to 1.0. Table 9 shows the variable values for V_{LU}. V_{LU} are high for land uses such as agriculture and intensely developed areas and low for natural areas including undeveloped forest and grassland. NLCD data does not distinguish between residential, commercial, and industrial land uses, but rather groups the land uses into a developed category; thus the mean loading rates found by Adamus and Bergman found for these three categories were used for various densities (low, medium, high). The variable was calculated as the mean weighted average for each catchment.

Table 9

Estimated Phosphorus Concentrations in Runoff and FCI Values for V_{LU} for NLCD Land Use Categories

NLCD Code	**Definition**	**Land Use Category (Adamus and Bergman 1995)**	**Total Phosphorus Conc. in Runoff (mgL^{-1})**	**FCI**
11	Open Water	Natural Areas	0	1.0
21	Developed Open Space	Recreation, Open Space, Range[a]	0.05	0.53
22	Developed, Low Intensity	Low Density Residential, Commercial and Industrial[a]	0.21	0.41
23	Developed, Medium Intensity	Medium Density Residential, Commercial and Industrial[a]	0.30	0.24
24	Developed, High Intensity	High Density Residential, Commercial and Industrial[a]	0.40	0.15
31	Barren land	Mining and Natural Areas[a]	0.075	0.78
41	Deciduous Forest	Natural Areas	0	1.0
42	Evergreen Forest	Natural Areas	0	1.0
43	Mixed Forest	Natural Areas	0	1.0
52	Shrub/Scrub	Natural Areas	0	1.0
71	Grassland/ Herbaceous	Natural Areas	0	1.0
81	Pasture/Hay	Agriculture - Pasture	0.48	0.07
82	Cultivated Crops	Agriculture – Crop	0.68	0.0
90	Woody Wetlands	Natural Areas	0	1.0
95	Emergent Herbaceous Wetlands	Natural Areas	0	1.0

a. Phosphorus concentrations for these land use categories were averaged to obtain corresponding NLDC value

Vegetation Parameters

One-meter resolution color infrared imagery from National Agriculture Imagery Program (NAIP) collected in 2004 was used to calculate a Normalized Difference Vegetation Index (NDVI). NDVI is a standard vegetation index used by remote sensors to identify general vegetative cover types. The index is obtained using the following equation:

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{RED})}{(\mathrm{NIR} + \mathrm{RED})}$$

where NIR is the brightness values recorded in near infrared band and RED is the brightness values recorded in the visible red band in the imagery. The equation is based on plant chlorophyll absorption of red visible light and reflection of near-infrared light. Application of the equation produces a raster dataset with pixel values ranging from -1.0 to 1.0. Negative values and near zero values represent open water features and bare soil; generally, values of 0.1 – 1.0 represent vegetated areas. Using 2005 true-color NAIP imagery, transitions from bare soil areas to vegetated areas were sampled and a value of 0.1 was assigned as the lowest detectable value (threshold) for the presence of vegetation. Values below this threshold were considered unvegetated pixels (Figure 11), allowing the calculation of percent vegetated cover of the wetland (V_{mac}) or its 30 meter buffer (V_{buff}).

It should be noted that bi-directional reflectance can be an issue related to NDVI using mosaicked aerial photography. This effect can lead to the threshold value for NDVI varying slightly from scene to scene in mosaicked aerial imagery. However, this issue was not expected to have seriously affected the results.

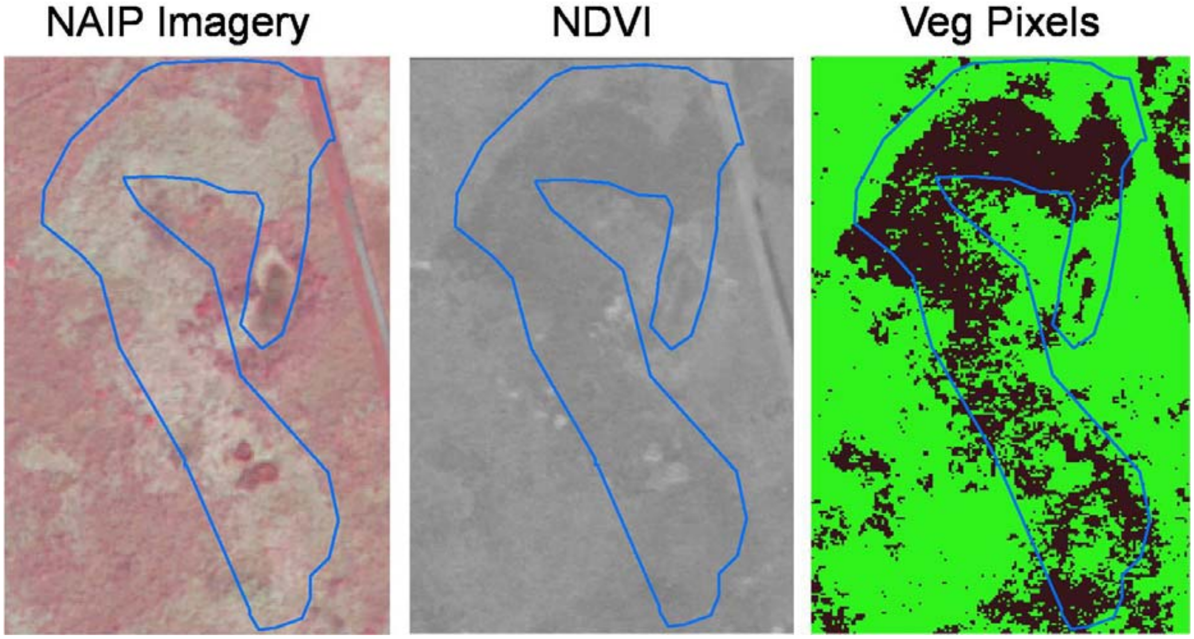


Figure 11. NAIP to NDVI to vegetated pixels (note: green represents vegetation in veg pixels).

Soils

Soil Survey Geographic Database (SSURGO) soils data were obtained for each county at a scale of 1:24,000. SSURGO soils data for the study area are identified by soil map units and are dominated by one to three types of soil. Soil characteristics provide such parameters as soil clay content (V_{clay}) and soil pH (V_{soilpH}). Datasets with values for these parameters were obtained in GIS format using the Soil Data Viewer tool (United States Department of Agriculture, Natural Resources Conservation Service). These datasets were overlaid with the NWI dataset to determine the value for each soil parameter at each wetland.

Variable values for soil clay content V_{clay} correspond directly to the clay proportion found in SSURGO data. For example a SSURGO clay content of 32 percent will result in a V_{clay} value of 0.32. Table 10 shows how soil pH (V_{soilpH}) was attributed. In general, the variable value increases as a soil becomes more alkaline. If numerous soil map unit polygons were located below a wetland, a mean weighted average parameter value was calculated and assigned to that wetland.

Table 10
Soil pH Classes, Associated pH Values, and Indices Values for V_{soilpH}

Soil pH Class	**Soil pH Range**[a]	**FCI Value**
Ultra acid	< 3.5	0.0
Extremely acid	3.5 – 4.4	0.1
Very strongly acid	4.5 – 5.0	0.2
Strongly acid	5.1 – 5.5	0.3
Moderately acid	5.6 – 6.0	0.4
Slightly acid	6.1 – 6.5	0.5
Neutral	6.6 – 7.3	0.6
Slightly alkaline	7.4 – 7.8	0.7
Moderately alkaline	7.9 – 8.4	0.8
Strongly alkaline	8.5 – 9.0	0.9
Very strongly alkaline	> 9.0	1.0

a. National Soil Survey Handbook (USDA 1993).

Initially, this study included a variable for soil organic matter, however, comparison of field soil sample results with that of SSURGO found the field data to be more variable and the SSURGO data to be more homogeneous (Table 11). Due to this inconsistency, the soil organic matter variable was removed from the model.

Table 11
Comparison of Field Soils Data with SSURGO Soils Data for Study Sites

	Soil Organic Matter (%)			**pH**			**Clay (%)**		
Site	Field	GIS	Δ	Field	GIS	Δ	Field	GIS	Δ
Chicken Road	5.2	2.0	-3.2	4.6	6.2	1.6	42.0	17.5	-24.5
Kite Site	6.4	2.5	-3.9	4.8	5.4	0.6	52.5	32.0	-20.5
LeConte	9.6	2.0	-7.6	4.8	5.1	0.3	36.0	34.7	-1.3
Sedge Wren	4.0	2.2	-1.9	4.7	4.9	0.2	52.2	39.2	-13.0
Turtle Hawk	4.9	2.5	-2.4	4.4	5.3	0.9	32.9	34.0	1.1
Wounded Dove	7.0	1.3	-5.7	5.2	7.2	2.0	49.4	42.0	-7.4
Median Δ			**-3.6**			**0.8**			**-10.2**

Another modification to GIS application of SSURGO data addresses the zero value that SSURGO assigns to some map units, such as the “water” class. Where permanent water bodies exist in the SSURGO soils data, soil scientists had assigned a value of zero for soil parameters. In these cases, the value of the dominant adjacent soil map unit, determined within a specific buffer distance of 15 m, was assigned to the areas in question. Wetlands with these modified soil parameters were also “flagged” in the database.

Zonal Statistics and Attributing Overlapping Polygons

The zonal statistics tool in ESRI® ArcMap was used to calculate the mean weighted average values for soil parameters and vegetation within wetlands (V_{mac}). Overlap was common in the 30 meter buffers used to calculate wetland buffer vegetation (V_{buff}) and the 100 meter buffers used for wetlands within the 100-year floodplain to calculate land use (V_{LU}). The zonal statistics tool in ESRI® ArcMap cannot process data with overlapping polygons (zones); therefore the zonal statistics in Hawth’s Tools version 3.27 was used.

Editing NWI based on study sites

In some cases, the area sampled in the field represents only a small portion of a very large NWI polygon. This is true for the sites Chicken Road, Turtle Hawk, and Wounded Dove. For a more valid comparison with specific field site results, the NWI data was split into smaller sections to better represent the area studied in the field (Figure 12).

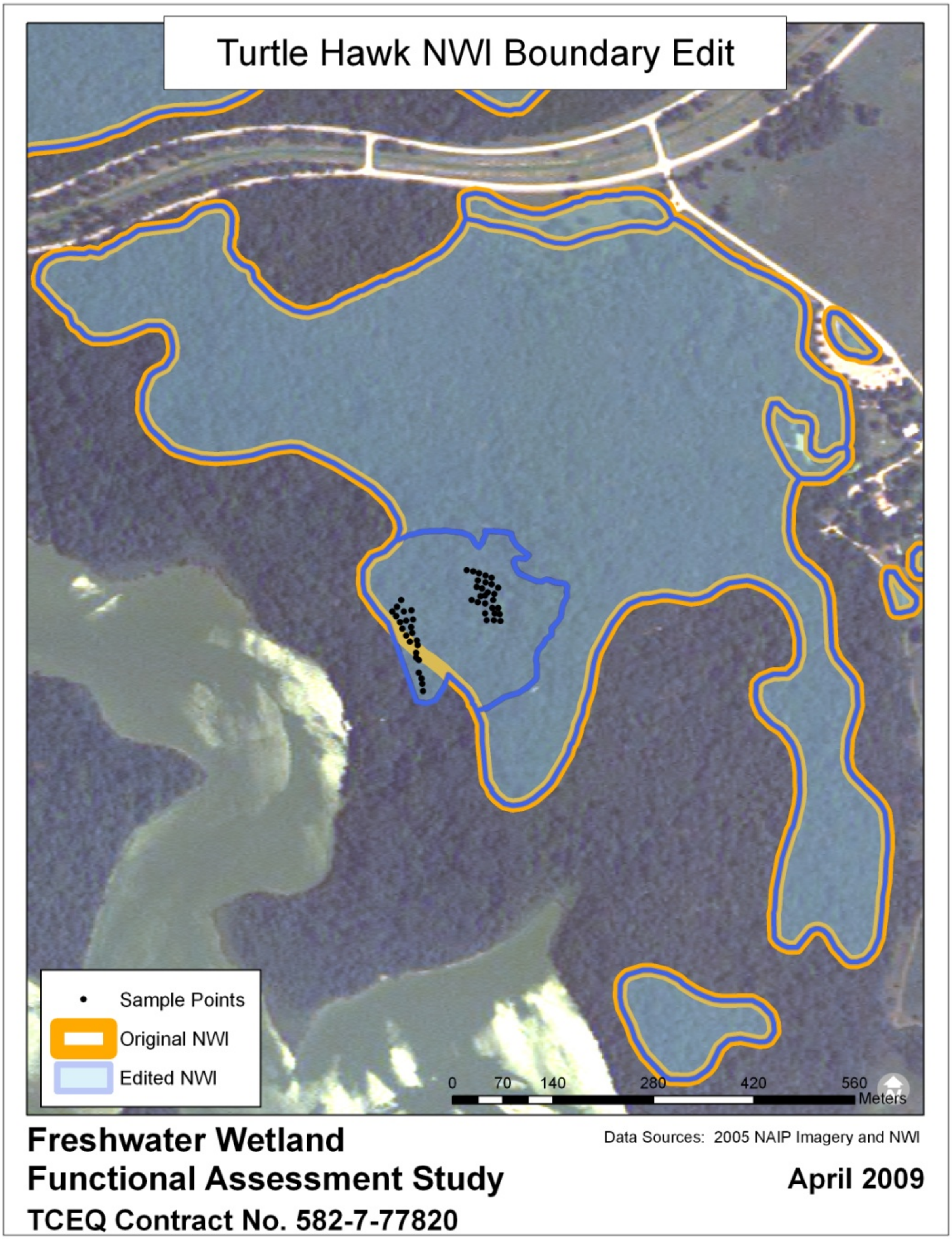


Figure 12. Turtle hawk NWI boundary edit.

RESULTS

Before discussing the results, it should be noted that this project contains two separate components. The study outlined in this thesis covers the process of deploying the models developed by M. Forbes using geographic information systems (GIS) and geospatial datasets. The other study involves calculating the models at various study sites located throughout the study area by the research team at Baylor University. At the time of the writing this report, research to calculate the models for study sites was still ongoing. Validation of results from the GIS derived variables are planned to be completed in the future by M. Forbes of Baylor University. However, validation of variables V_{catch} and V_{Vol} were addressed with the analysis LiDAR (light detection and ranging) dataset using a topographic survey is previously discussed in the Evaluation of LiDAR datasets section found in the methods chapter. Additionally, soil variables (V_{clay} and V_{soilpH}) were compared with field data collection (Table 12). Note, in some cases Soil Survey Geographic Database (SSURGO) data was similar to that of soils found in the field. For example, SSURGO values for percent clay were in agreement to those determined in the field for LeConte, Turtle Hawk, and Wounded Dove. Likewise, SSURGO soil pH values at LeConte and Sedge Wren were similar to those identified on-site.

Datasets used in this study include high resolution data (LiDAR datasets and NAIP color-infrared imagery), however also lower resolution landscape data (SSURGO data and National Land Cover Dataset [NLCD]). For this reason results for the GIS model should be viewed as a survey tool; thus conclusions should not be made about individual wetlands without a field visit.

Catchment Delineation (V_{catch})

Figure 13 shows a histogram for the raw ratios of variable V_{catch}. Note, both V_{catch} and V_{vol} were measured for wetland systems. In general, coastal prairie freshwater wetlands (CPFW) are small in area and have small catchment area. The V_{catch} ratios ranged from 0.005 to 1.0 and had a mean of 0.165, standard deviation of 0.186, and a median of 0.09 (N = 7,370).

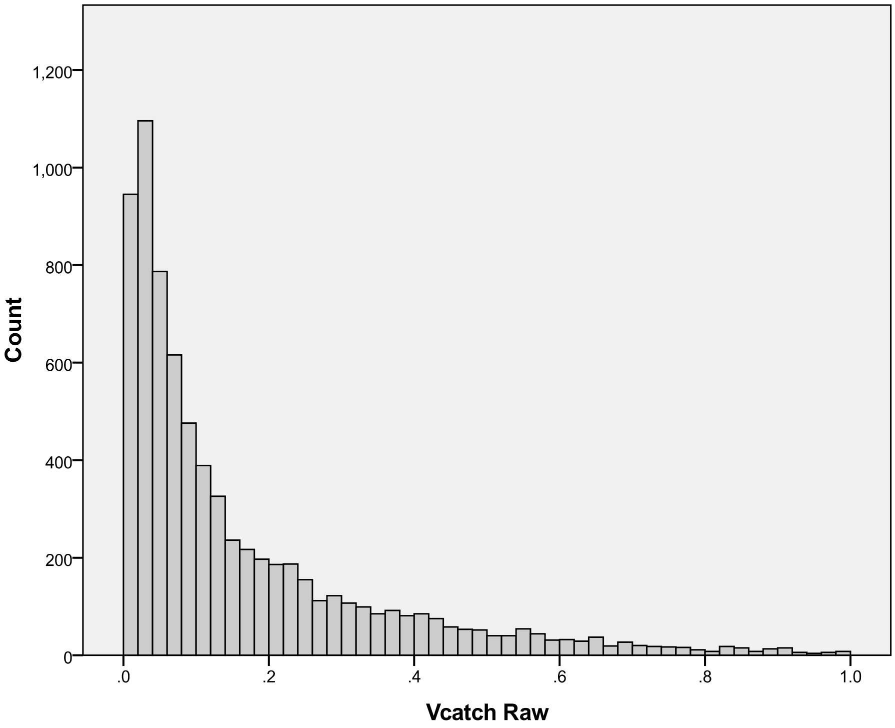


Figure 13. Histogram for raw wetland area to catchment area ratios (V_{catch}) (n = 7,370).

Figure 14 shows a histogram for the reclassified values of V_{catch}. The reclassified V_{catch} values used in the conceptual models ranged from 0.4 to 1.0 and had a mean of 0.7 with a standard deviation of 0.2, and a median value of 0.6. This distribution of values better represents the reality of CPFW.

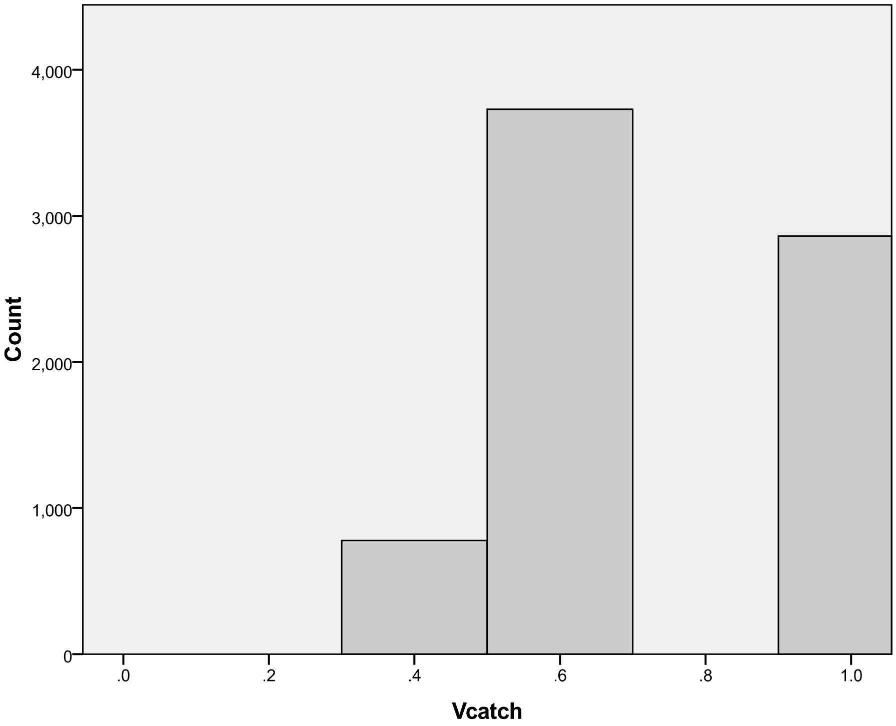


Figure 14. Histogram for reclassified wetland area to catchment area ratios (V_{catch}) (n = 7,370).

Wetland Volume

The volumes for 7,363 wetland systems were calculated. Calculated volumes ranged from 0 to 10,353,582 cubic meters. The mean volume was 6,378.1 cubic meters. These results are highly variable with a mean volume of 6,378.1 cubic meters, a standard deviation of 129,694.8 cubic meters, and a median value of 235.5 cubic meters. Figure 15 shows a histogram for calculated volumes. In this case, due to numerous outliers, the median value is more representative for the volumes of CPFW. Additionally, the average depth was explored. The average mean depth was 0.19 meters; however the results were somewhat variable with a standard deviation of 0.4 m. Again due to variability in the results, median depth is a better descriptive statistic. The median depth of the wetlands was 0.05 m. This may seem low; however, many wetlands in the study area are simply moist soil and many of the CPFW consist of hummocky depressions that are six inches or less. Table 12 shows the wetland volume and mean depth calculations for the six study sites. Figure 16 shows a histogram for the variable V_{vol}. Ranging from 0.1 to 1.0, the V_{vol} had a mean value of 0.5, a standard deviation of 0.29, and a median of 0.5. As expected, these values were well distributed due to the fact that volume was normalized using percentiles.

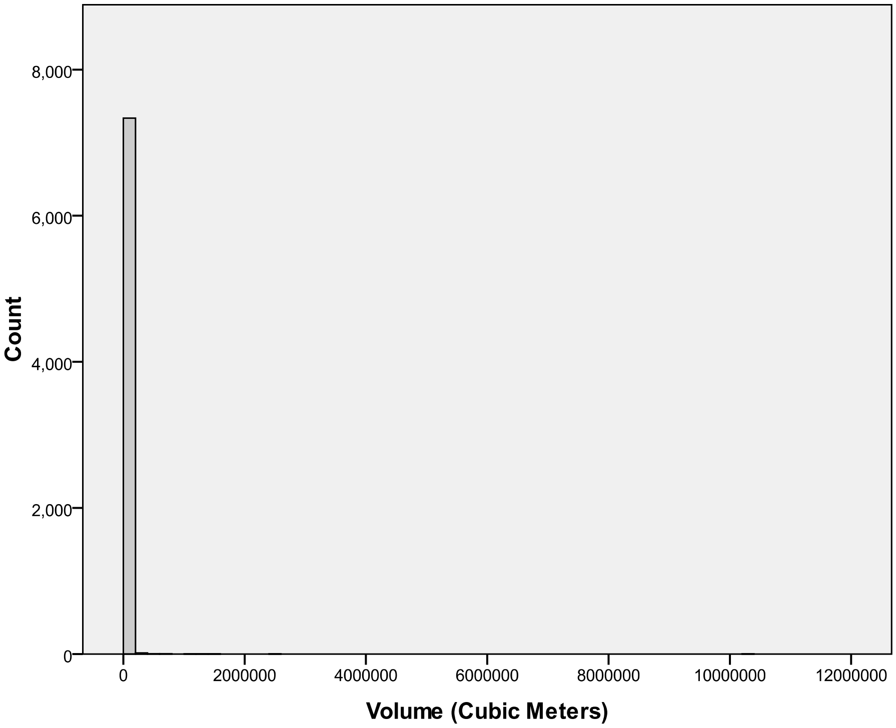


Figure 15. Histogram for volume (cubic meters) (n = 7,363; omitted 7 wetlands with no data for volume).

Table 12

Statistics of Wetland Volume Calculations of Study Site Wetlands

Site	Area (m^2)	Total Volume (m^3)	Mean Depth (m)
Chicken Road	5,434.4	540.0	0.099
Kite	34,213.4	880.6	0.026
LeConte	10,374.8	537.7	0.052
Sedge Wren	23,982.1	5196.1	0.217
Turtle Hawk	482,295.7	997.7	0.002
Wounded Dove	15,506.4	496.1	0.032

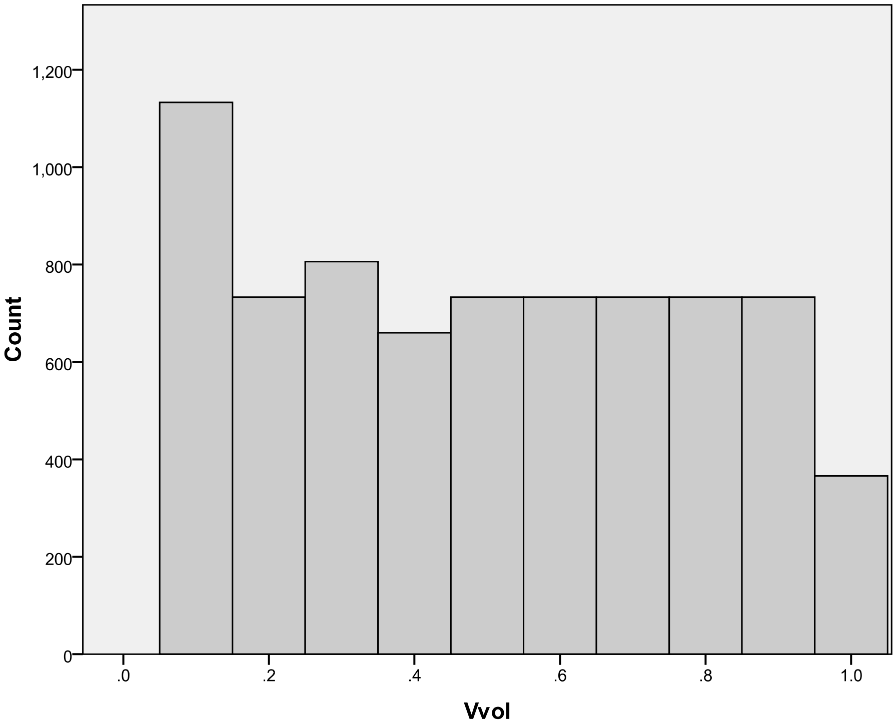


Figure 16. Histogram for volume (V_{vol}) (n = 7,363; omitted 7 wetlands with no data for volume).

Hydroperiod Variables

V_{wet} ranges from 0.1 to 1.0, with the majority of the wetlands having a value of 0.1 (permanently flooded) or 1.0 (seasonally/temporarily/intermittently flooded) (Figure 17). The mean value was 0.7, the standard deviation was 0.4, and the median was 1.0. As expected with CPFW, 7,211 of the wetlands were classified as seasonally/temporarily/intermittently flooded. V_{dry} ranged from 0.1 to 0.8, had a mean of 0.5, a standard deviation of 0.3, and a median value of 0.5 (Figure18). The majority of the wetlands were either 0.1 (permanently/artificially flooded) or 0.5 and 0.8 (seasonally and temporarily flooded, respectively).

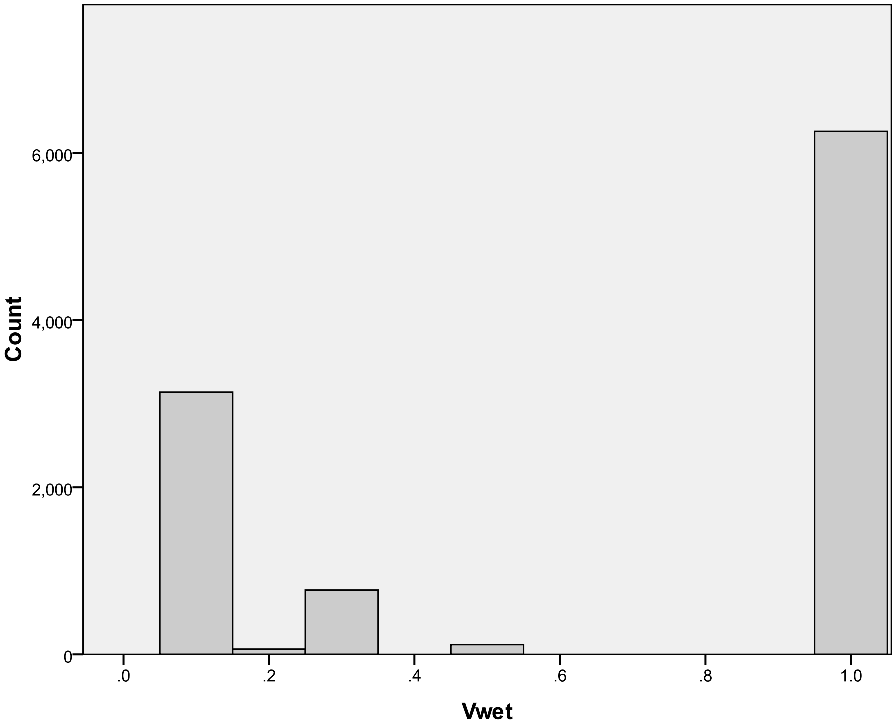


Figure 17. Histogram for water regime (V_{wet}) (n = 10,349).

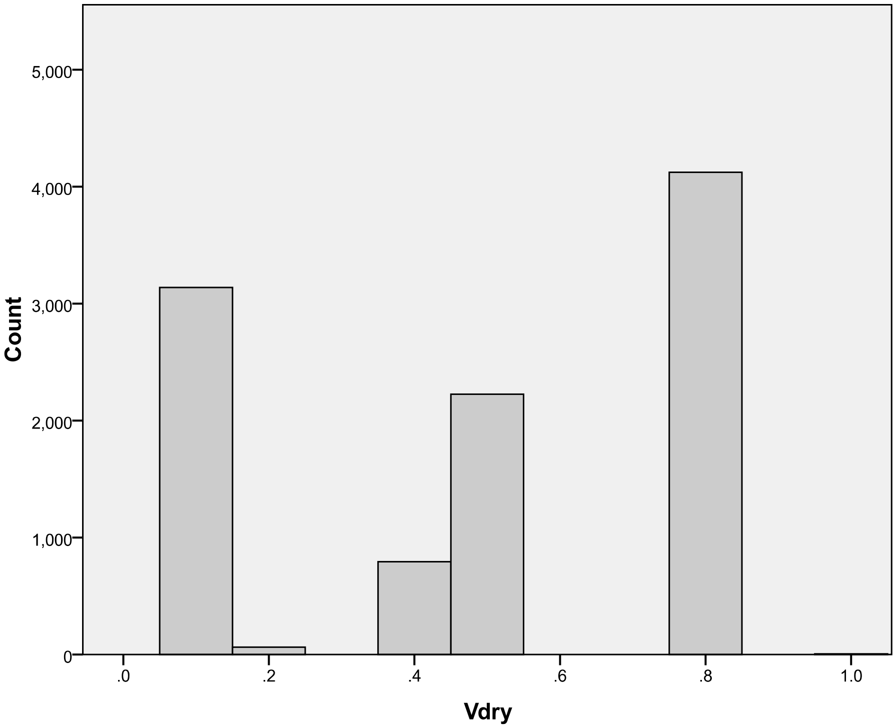


Figure 18. Histogram for wet-dry potential (V_{dry}) (n = 10,349).

Land Use

Values for land use ranged from 0 to 1.0 had a mean of 0.7, a standard deviation of 0.3, and a median value of 0.8 (Figure 19). The distribution is skewed to the left with the majority of wetlands having values of 0.9 and 1.0. Higher values indicated more natural land uses such as forests, shrub/scrub, and grasslands.

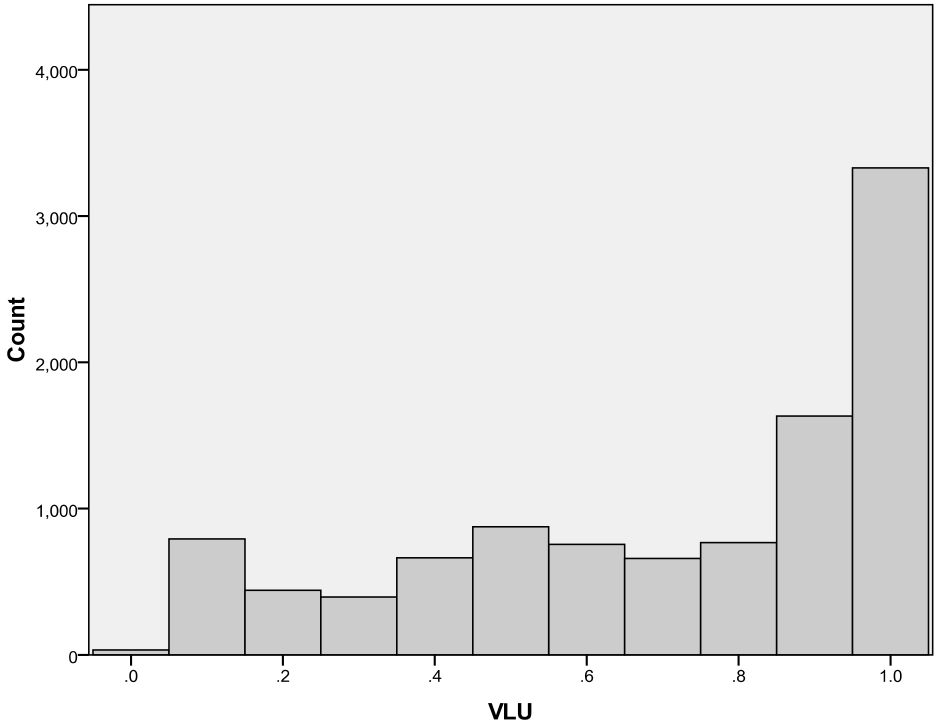


Figure 19. Histogram for land use (V_{LU}) (n = 10,349).

Vegetation

Both V_{mac} (Figure 20) and V_{buff} (Figure 21) are skewed to the left. This is expected as it was noted in the previous section that the majority of the land use in the study area was natural land cover areas. Both variables range from 0 to 1.0, have a mean of 0.7, a standard deviation of 0.3, and a median 0.8.

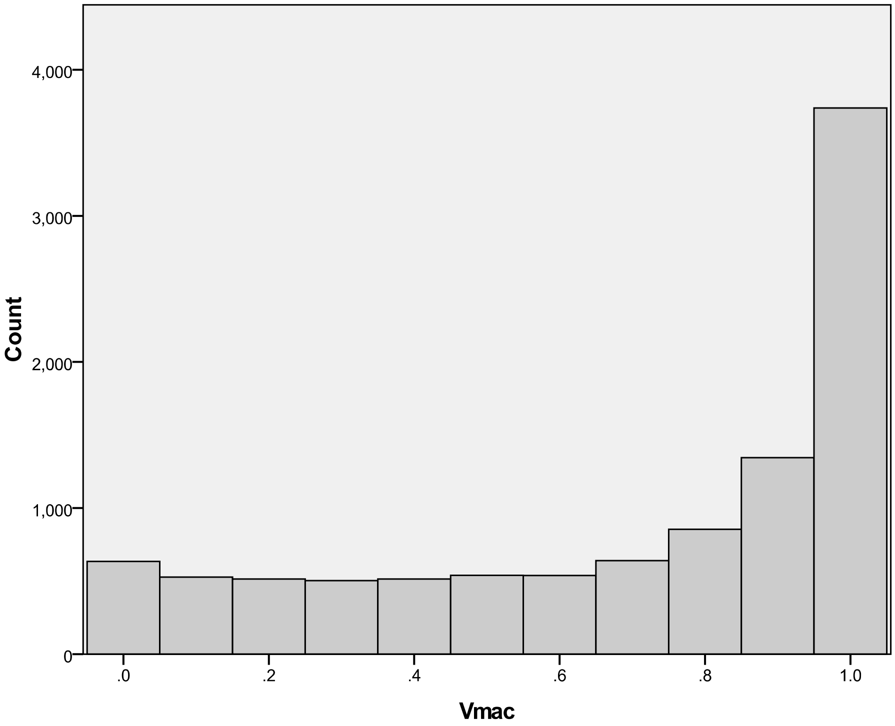


Figure 20. Histogram for macrophyte density (V_{mac}) (n = 10,349).

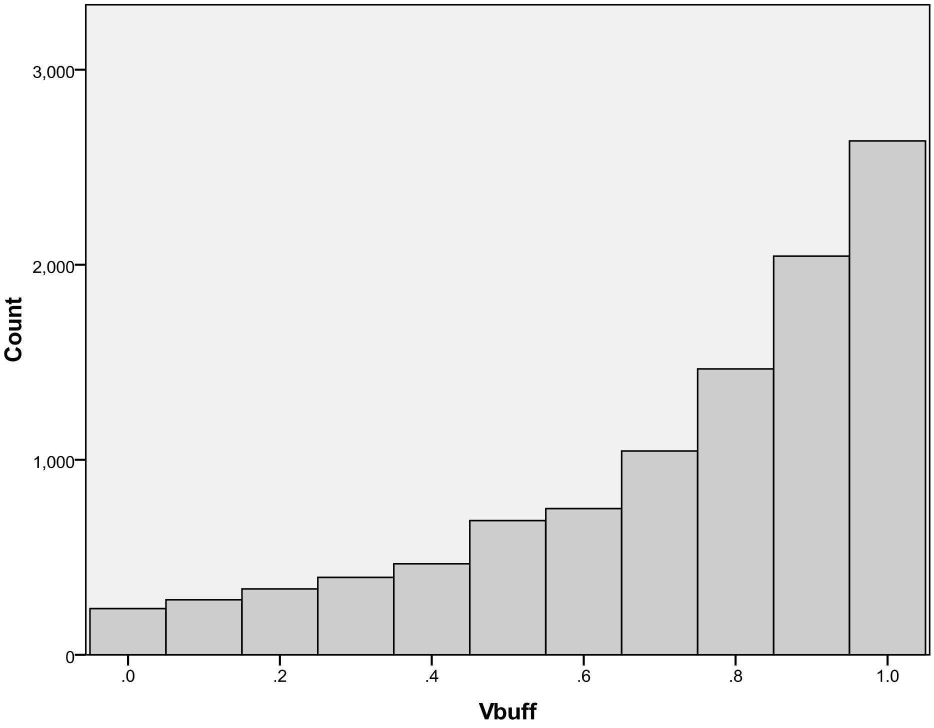


Figure 21. Histogram for wetland buffer (V_{buff}) (n = 10,349).

Soils

Soil clay content (V_{clay}) was somewhat skewed to the right (Figure 22). The value ranged from 0 to 0.7 and had a mean of 0.3, a standard deviation of 0.2, and a median of 0.2. The majority of wetlands have soils with either 10%, 20% and 50% clay.

The distribution for soil pH (Figure 23) was more normally distributed than that of soil clay content. Values ranged from 0.1 to 0.8, with a mean of 0.5, a standard deviation of 0.2, and a median value of 0.6.

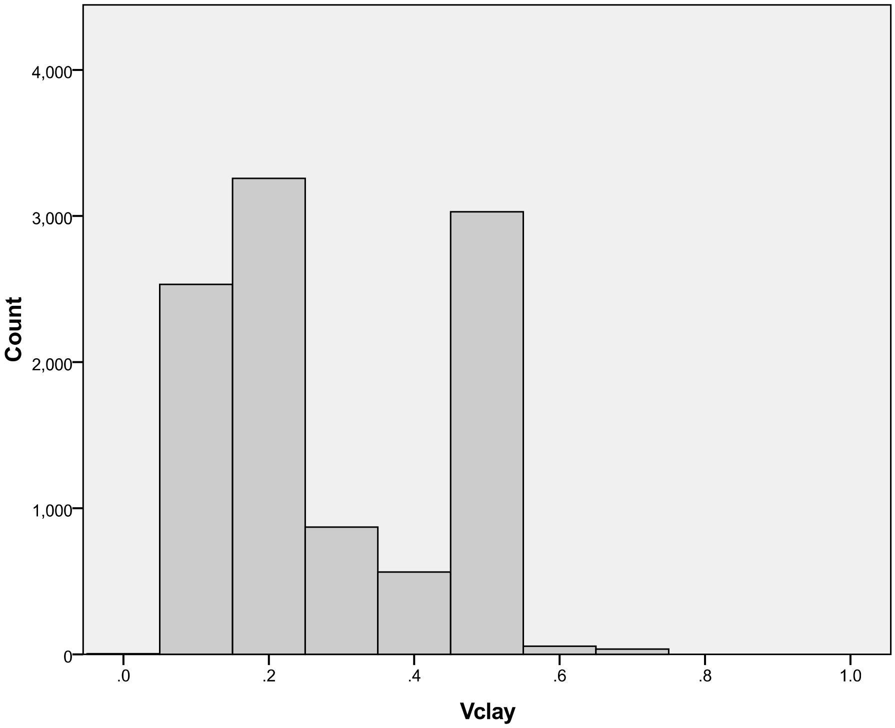


Figure 22. Histogram for soil clay content (V_{clay}) (n = 10,349).

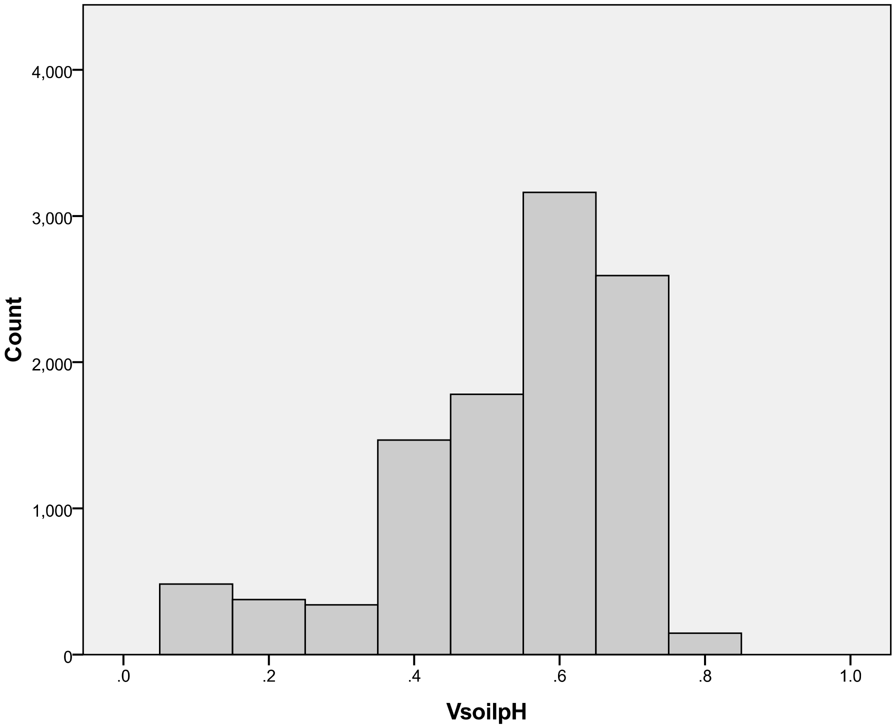


Figure 23. Histogram for soil pH (V_{soilpH}) (n = 10,349).

Water Storage Model (FCI_{ws}) Results and the Concept of Two Systems

Figure 24 shows the histogram for the results of the water storage model (FCI_{ws}). Ranging from 0 to 1.0, the mean water storage value was 0.3, the standard deviation was 0.3 and the median was 0.2. Note the distribution is skewed to the right. Based on the water storage model equation (Equation 1), the variables capable of driving the distribution of FCI_{ws} are most likely V_{vol} or V_{wet}. While V_{vol} may account for some of the skewness, the distribution of V_{wet} (Figure 17) appears to be the main factor influencing the distribution of FCI_{ws}. 3,138 wetlands have a V_{wet} value of 0.1, which represent wetlands that are permanently or artificially flooded. Permanently flooded and/or artificially flooded (PFAF) wetlands (Figure 25) are largely modified and are not similar to natural CPFW. Often PFAF wetlands are non-natural wetlands that are deep, excavated systems and lack vegetation due to anthropogenic disturbance. Based on this understanding, all model results were analyzed, both for all wetlands and with PFAF wetlands excluded. Figure 26 shows the distribution of the water storage model results with PFAF wetlands excluded. Note that exclusion of these wetlands led to a more normal distribution.

As expected, excluding PFAF led to an increase in potential for water storage. The mean water storage model results increased from 0.3 to 0.4 and the median water storage model results increased from 0.2 to 0.4. The standard deviation was 0.25. Based on the model results, CPFW tend to have moderate potential to store surface water during precipitation events.

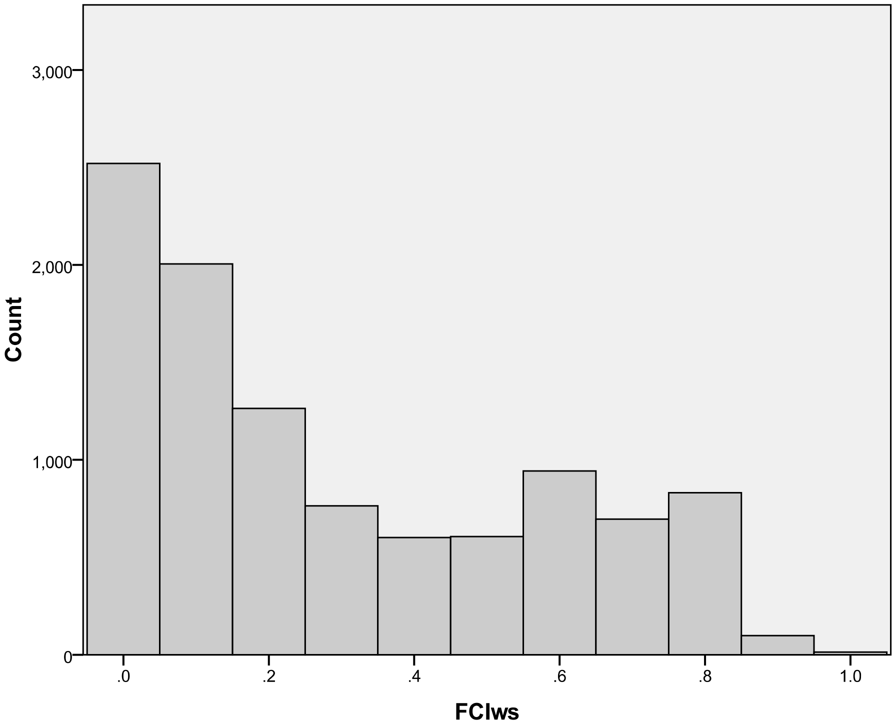


Figure 24. Histogram for water storage model (FCI_{ws}) results (n = 10,342; omitted 7 wetlands with no data for volume).

Figure 25. Example of PFAF wetlands (V_{wet} = 0.1).

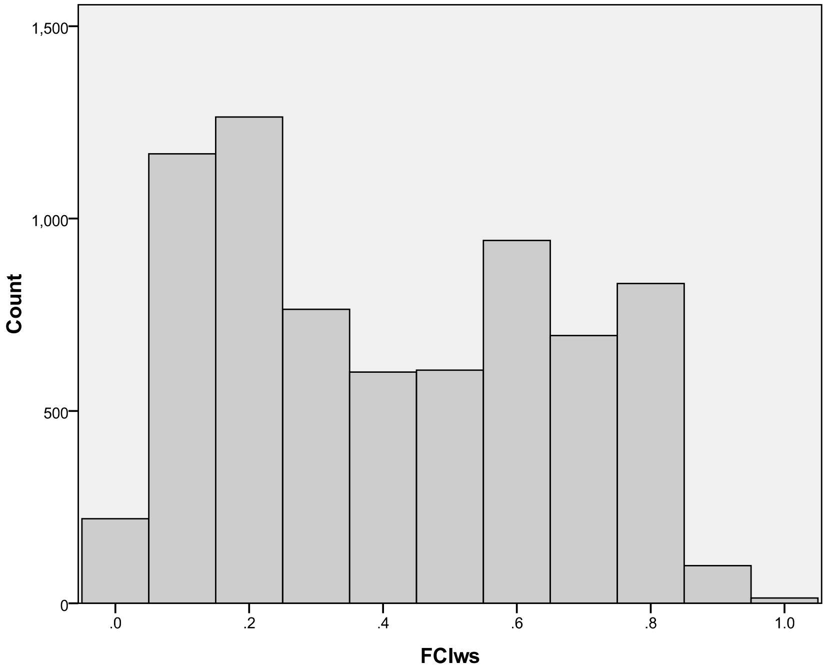


Figure 26. *Histogram for water storage model (FCI$_{ws}$) results with PFAF wetlands excluded (n = 7,204).*

Ammonium Removal Model (FCI$_{nh3}$) Results

Figure 27 shows the histogram for the ammonium removal model results with all of the wetlands included. Note that similar to the water storage, the distribution for ammonium removal is also somewhat skewed to the right. This is due to the influence of the variable V_{dry}. Like V_{wet}, V_{dry} has low values (0.1) for PFAF wetlands (Figure 28). Values for ammonia removal range from 0 to 1.0. Both the mean and the median for ammonium removal, with all wetlands included, are 0.4 with a standard deviation of 0.3. Figure C19 shows the histogram of the ammonium removal model results with PFAF wetlands removed. Also, similar to the distribution of the water storage results, removal of PFAF led to a more normal distribution of the results. Exclusion of the PFAF wetlands from the analysis led to an increase in the mean and median values and a decrease in variability. Both the mean and the median for ammonium removal with

PFAF wetlands excluded are 0.5 with a standard deviation of 0.2. Based on the results CPFW wetlands tend to have a moderate capacity to remove ammonium.

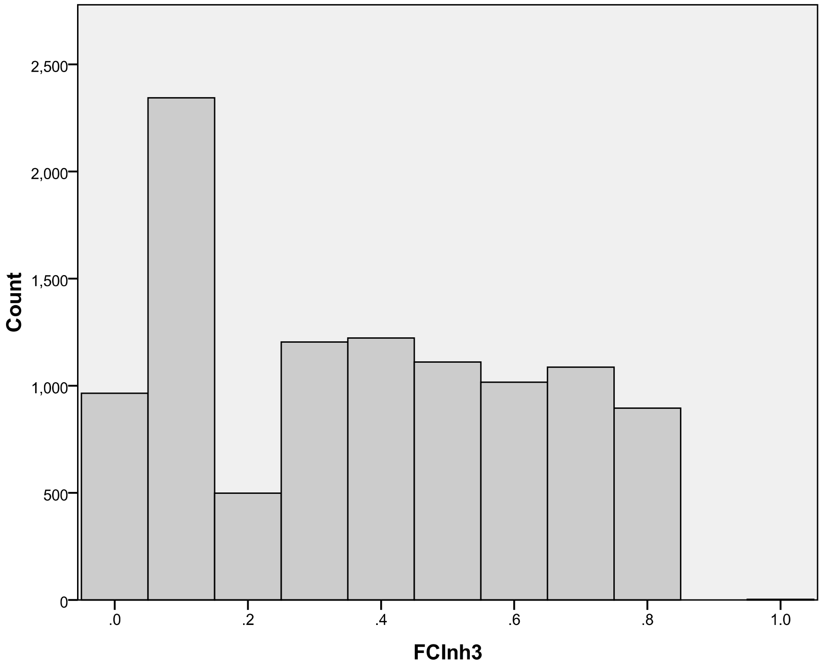


Figure 27. Histogram for ammonium removal model (FCI_{nh3}) results (n = 10,349).

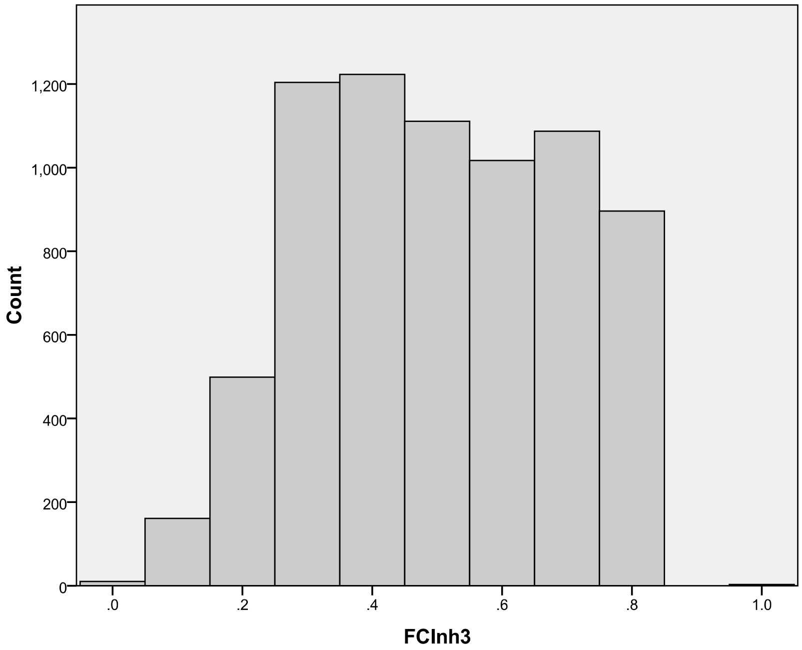


Figure 28. Histogram for ammonium removal model (FCI_{nh3}) results with PFAF wetlands excluded (n = 7,211).

Nitrate Removal Model Results

The histogram for nitrate removal for all wetlands is skewed to the left (Figure 29). This is mainly due to the variables associated with nitrate removal, V_{buff} and V_{mac}. Most CPFW, as natural systems, contain abundant vegetation both within the wetland itself and within a 30 meter buffer of the wetland. Ranging from 0 to 1.0, model results with all wetlands included suggest the CPFW to be highly capable of removing nitrate with a mean of 0.7, median of 0.8, and a standard deviation of 0.3. While excluding the PFAF wetlands does not particularly effect the distribution of results (Figure 30), the mean and median are slightly higher at 0.8 and 0.9 respectively. Consistent with field studies, overall model results suggest CPFW tend to highly capable of removing nitrate.

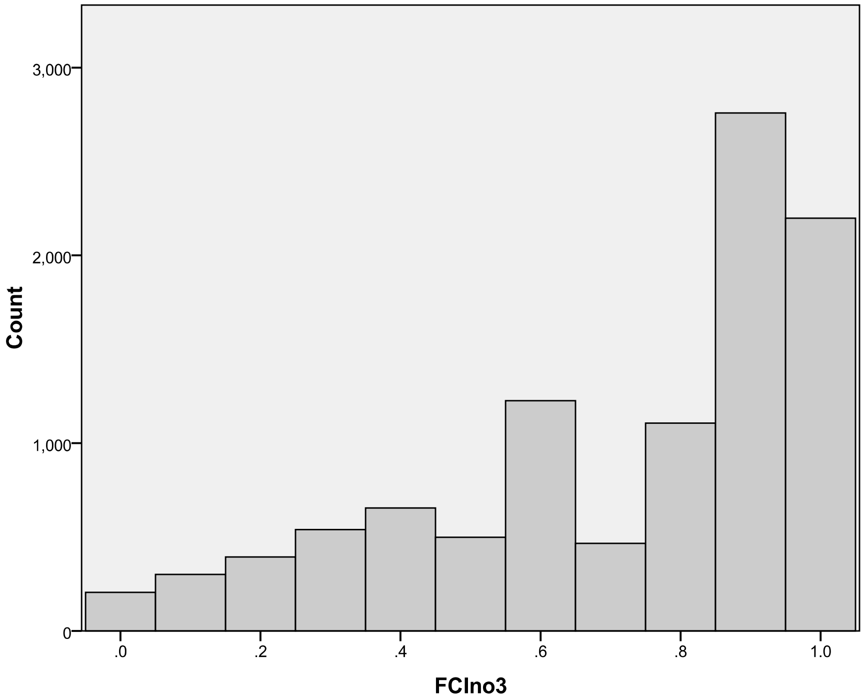


Figure 29. Histogram for nitrate removal model (FCI_{no3}) results (n = 10,349).

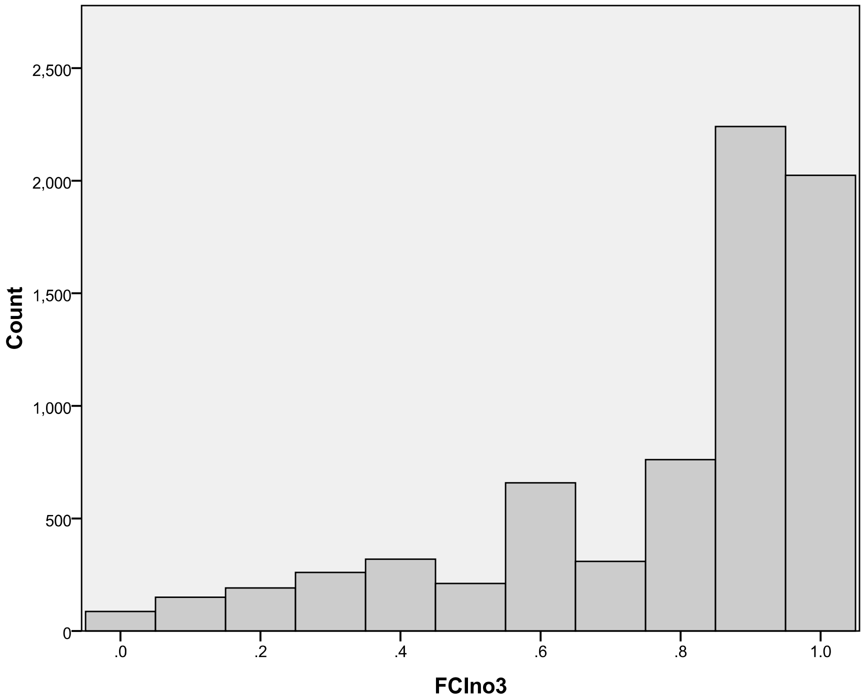


Figure 30. Histogram for nitrate removal model (FCI_{no3}) results with PFAF wetlands excluded (n = 7,211).

Phosphorus Retention Model Results

The results for phosphorus retention, including all wetlands, had a somewhat normal distribution with a range from 0 to 0.9, a mean of 0.4, standard deviation of 0.2, and median of 0.4 (Figure 31). Again, excluding the PFAF wetlands did not change the distribution of the results considerably, however it did increase the median value to 0.5 (Figure 32). The model results suggest CPFW tend to have a moderate capacity for phosphorus retention.

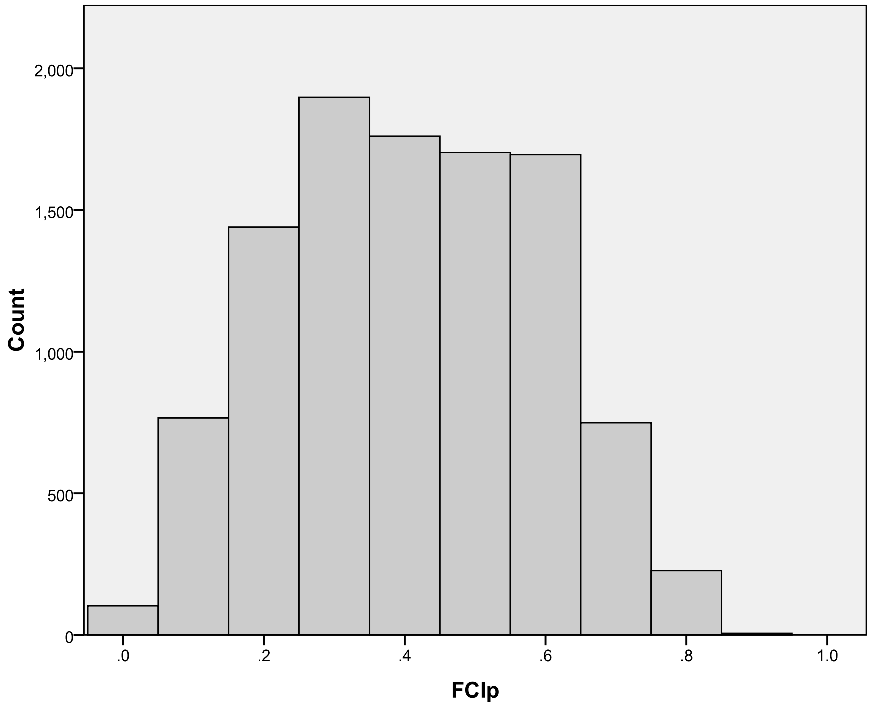


Figure 31. Histogram for phosphorus retention model (FCI_p) results (n = 10,349).

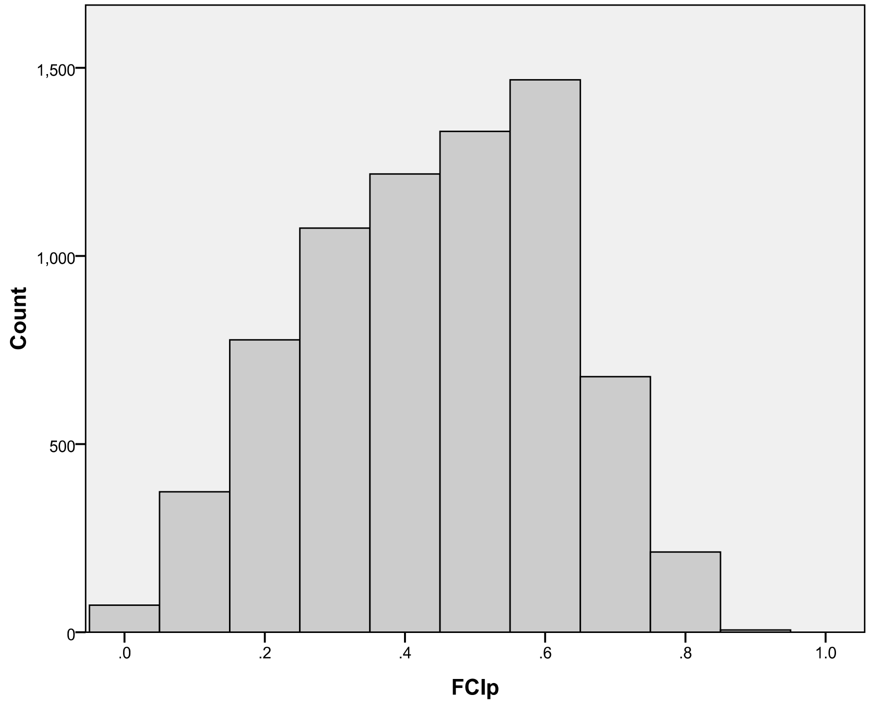


Figure 32. Histogram for phosphorus model (FCI_p) results with PFAF wetlands excluded (n = 7,211).

Heavy Metal Retention Model Results

Somewhat normal distributions were found for the results of the heavy metal retention when all wetlands were included and when PFAF wetlands were excluded (Figure 33 and Figure 34). Additionally for both cases, the results ranged from 0.2 to 0.8 and had a mean of 0.5, median of 0.5 and standard deviation of 0.1. A standard deviation of 0.1 makes the results for heavy metal retention the least variable of all models. The models suggest CPFW tend to have a moderate capacity to retain heavy metals.

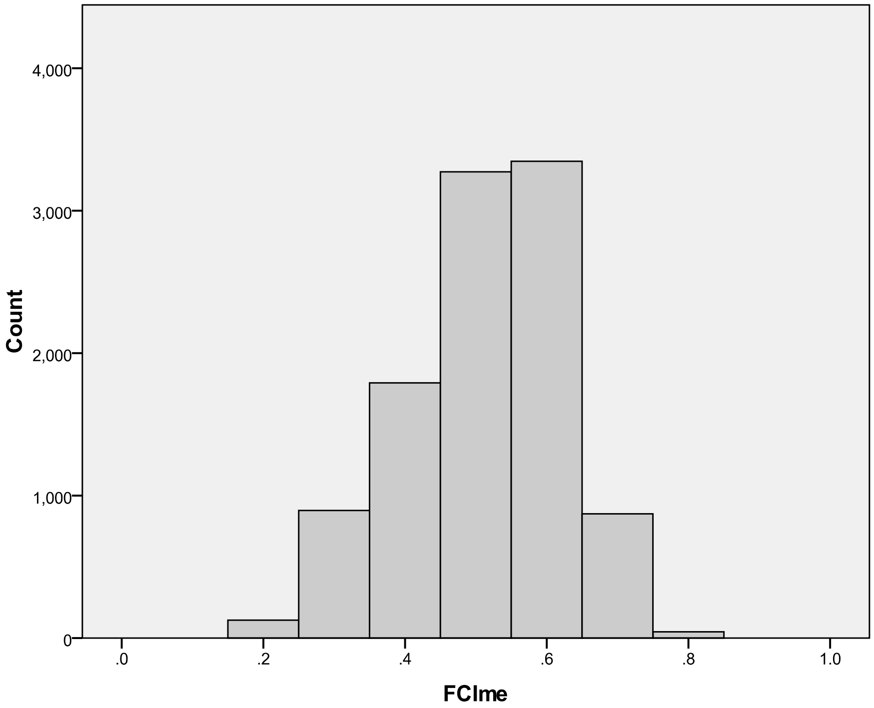


Figure 33. Histogram for heavy metal retention model (FCI_{me}) results (n = 10,349).

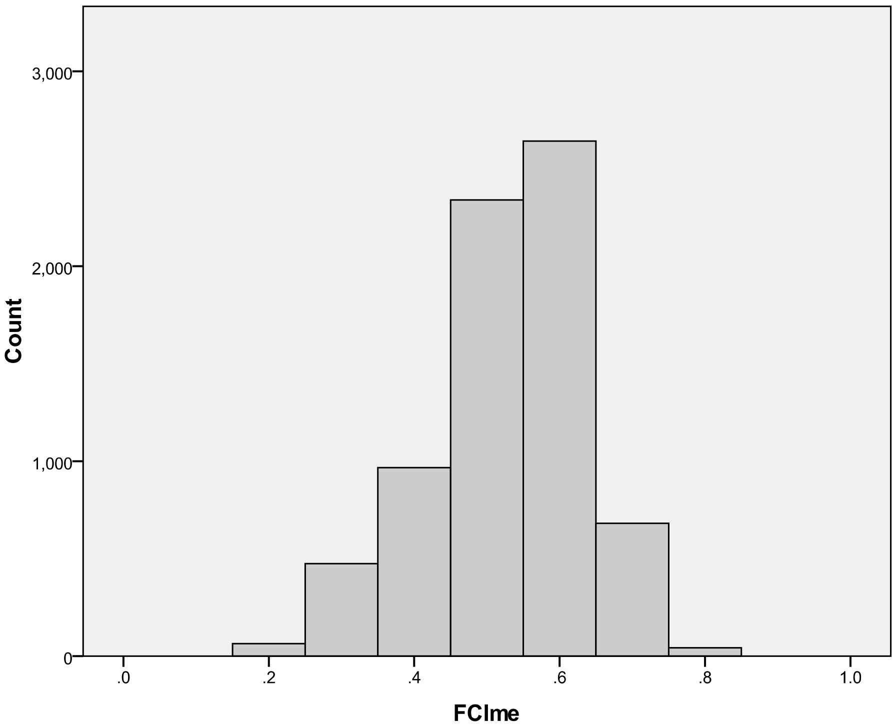


Figure 34. Histogram for heavy metal retention model (FCI_{me}) results with PFAF wetlands excluded (n = 7,211).

Organic Retention/Removal Model Results

Figure 35 and Figure 36 show the distribution of the results for organic retention/removal for all wetlands and for exclusion of PFAF, respectively. Both distributions are slightly skewed to the left and had values ranging from 0.2 to 1.0. When including all wetlands, the mean was 0.7, the median 0.8, and the standard deviation was 0.2. When PFAF were excluded, the mean increased to 0.8, while both the median and standard deviation remained unchanged. The model results suggest the CPFW tend to have a high capacity to retain/remove organic material.

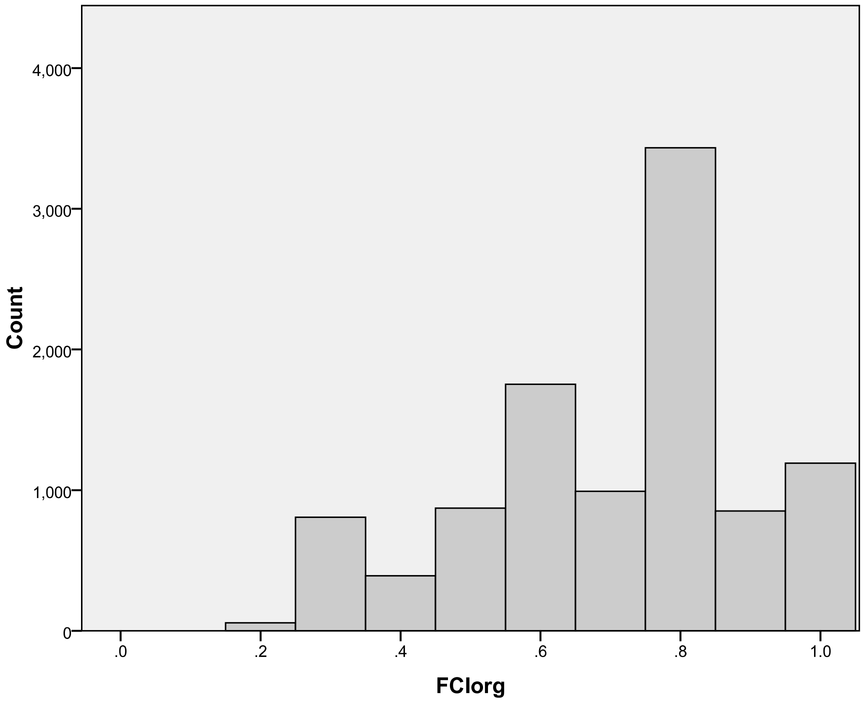


Figure 35. Histogram for organic retention/removal model (FCI_{org}) results (n = 10,349).

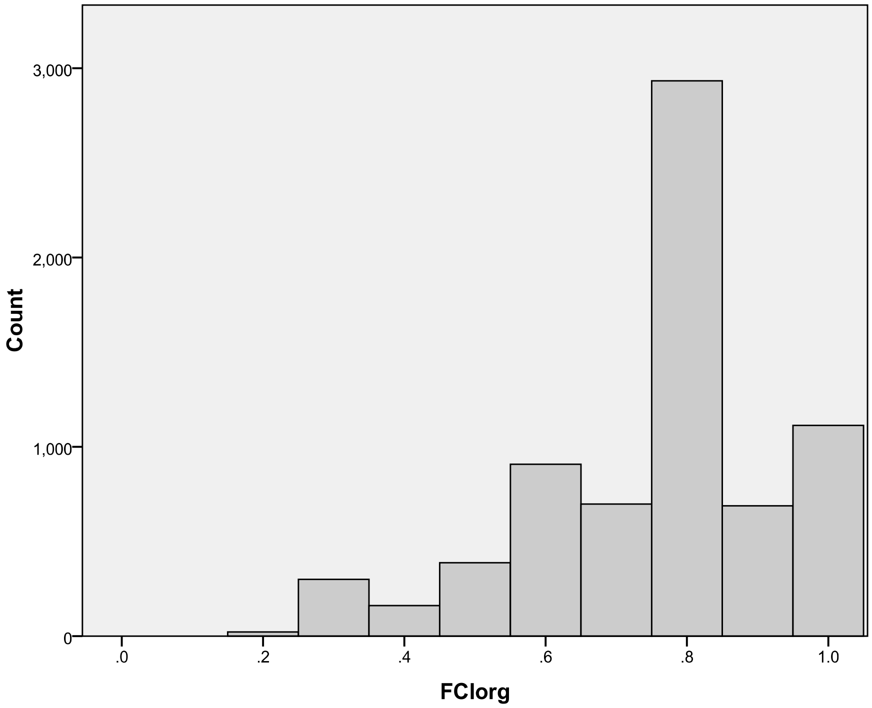


Figure 36. Histogram for organic retention/removal model (FCI_{org}) results with PFAF wetlands excluded (n = 7,211).

Overview of All Results

Table 13 shows an overview of descriptive statistics for all the model results for both all wetlands and exclusion of PFAF wetlands. Exclusion of PFAF wetlands had a positive effect for all models by increasing either the mean or median values or both, except for the heavy metal retention model. Results were least variable for the heavy metal retention. The results suggest that CPFW tend to have high capacity to remove nitrate and retain/remove organic compounds, a moderate capacity to retain heavy metals, phosphorus, remove ammonium and store flood waters.

Table 13
Overview of Descriptive Statistics for all Models

	All Wetlands			Excluding PFAF		
Model	Mean	Std. Dev.	Median	Mean	Std. Dev.	Median
Water Storage	0.3	0.3	0.2	0.4	0.3	0.4
Ammonium Removal	0.4	0.3	0.4	0.5	0.2	0.5
Nitrate Removal	0.7	0.3	0.8	0.8	0.3	0.9
Phosphorus Retention	0.4	0.2	0.4	0.4	0.2	0.5
Heavy Metal Retention	0.5	0.1	0.5	0.5	0.1	0.5
Organic Retention/Removal	0.7	0.2	0.8	0.8	0.2	0.8

Limitations for other Variables

Because this study required use of readily available datasets, resolution of some of the datasets, specifically NLCD LULC and SSURGO soils data, was problematic. Landsat TM data, which has a spatial resolution of 30 meters, used to produce the NLCD dataset. SSURGO data are typically derived from aerial photographs and topographic maps, and the parameters are not extensively sampled at the resolution of a detailed, local environmental study. As previously discussed, one soil parameter model, organics, was eliminated due to poor agreement between field and SSURGO data.

For vegetation variables, the imagery used to calculate the NDVI contained minimal cloud cover. Additionally, if sufficient water depth was present in the imagery, submerged vegetation may not have been recognized. Forested wetlands may have also lead to uncertainty in the emergent macrophytic vegetation variable (V_{mac}). Tree canopies are typically identified in the NDVI process, creating the appearance of high percentage of vegetative cover for a wetland when, in fact, the wetland may have little surface level vegetation. However, understory vegetation may be more important to the removal of pollutants.

GIS Deliverables

The deliverables of the GIS component were a series of paper and electronic maps showing wetland FCI values for each conceptual model and a GIS geodatabase containing all raw and output data layers.

Adobe® Acrobat® Professional was used to create .pdf mapbooks for each model. This was accomplished using the Adobe® Link Tool to draw links to quadrangle maps on map indexes for each model. Figure 37 shows the map index for water storage. Clicking on a quadrangle causes a map showing water storage model results to open for that quadrangle. For example, clicking on the northeastern most quadrangle, Anahuac, displays the results for the Anahuac quad (Figure 38). Wetlands were labeled with a “Wetland ID”, a unique identification number, which can be used to reference the wetland in an accompanying database.

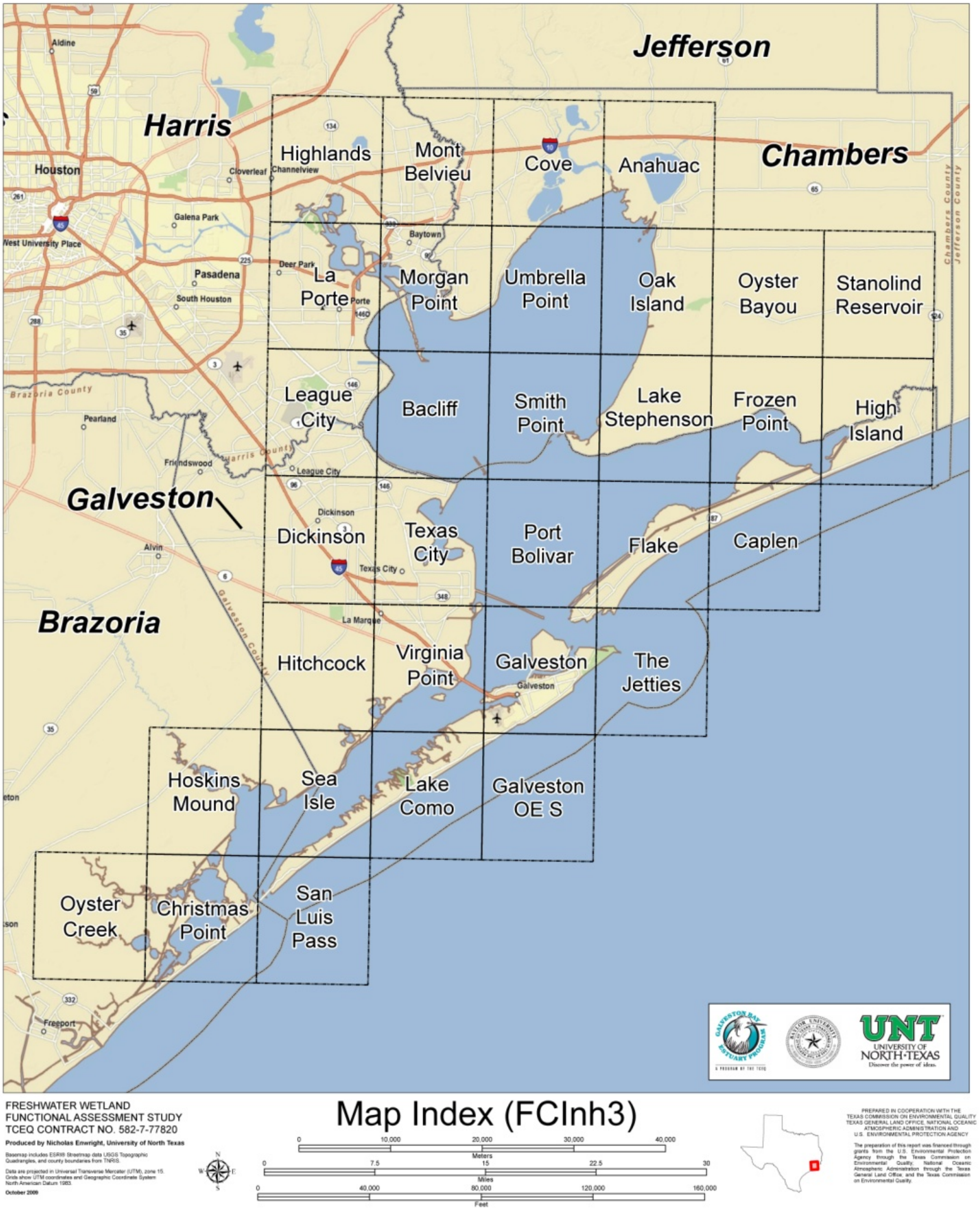


Figure 37. Map index for the ammonium removal model results (FCI_{nh3}).

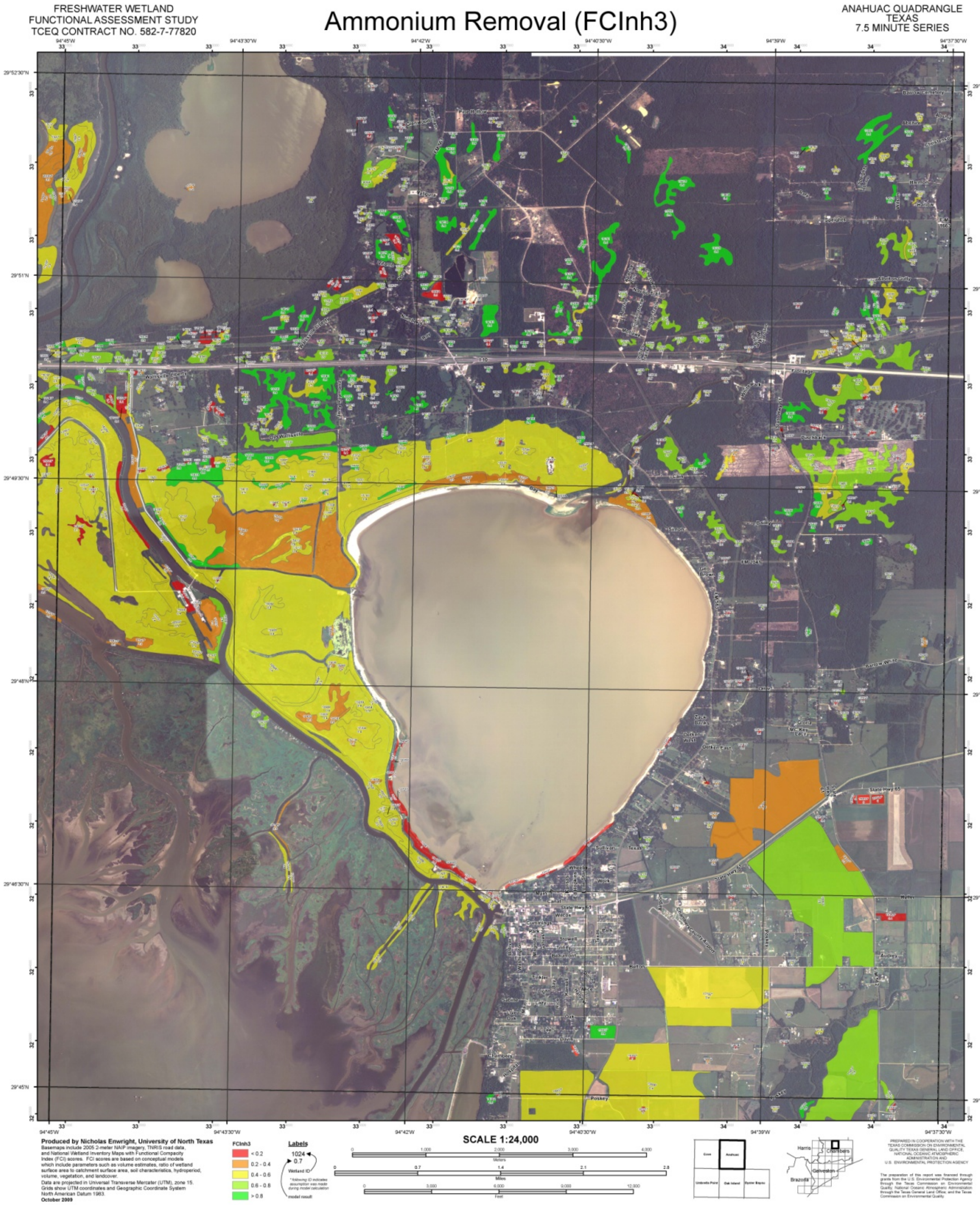


Figure 38. Anahuac quadrangle map displaying ammonium removal model results (FCI_{nh3}).

An advantage of using a .pdf mapbook is that users may use the zoom and pan tools to navigate within the maps and examine specific wetland sites in detail. Additionally, the Adobe® interface offers easy print options including printing in large format (native format) or letter size. The mapbooks were burned to a DVD and contain data dictionary documentation.

Maps for each model result were published for ESRI ArcReader, a free GIS viewer. The ArcReader maps content and symbology is similar to the quadrangle maps (Figure 38), however, they offer more advanced functionality including easy zoom and pan functions within the study area, querying a wetland to view model variables and other information, and printing custom maps.

Additional maps were created for the six original study sites. This maps series includes overviews of the sites, using aerial photographs, and maps that show local topography using LiDAR data (Figure 39 and Figure 40).

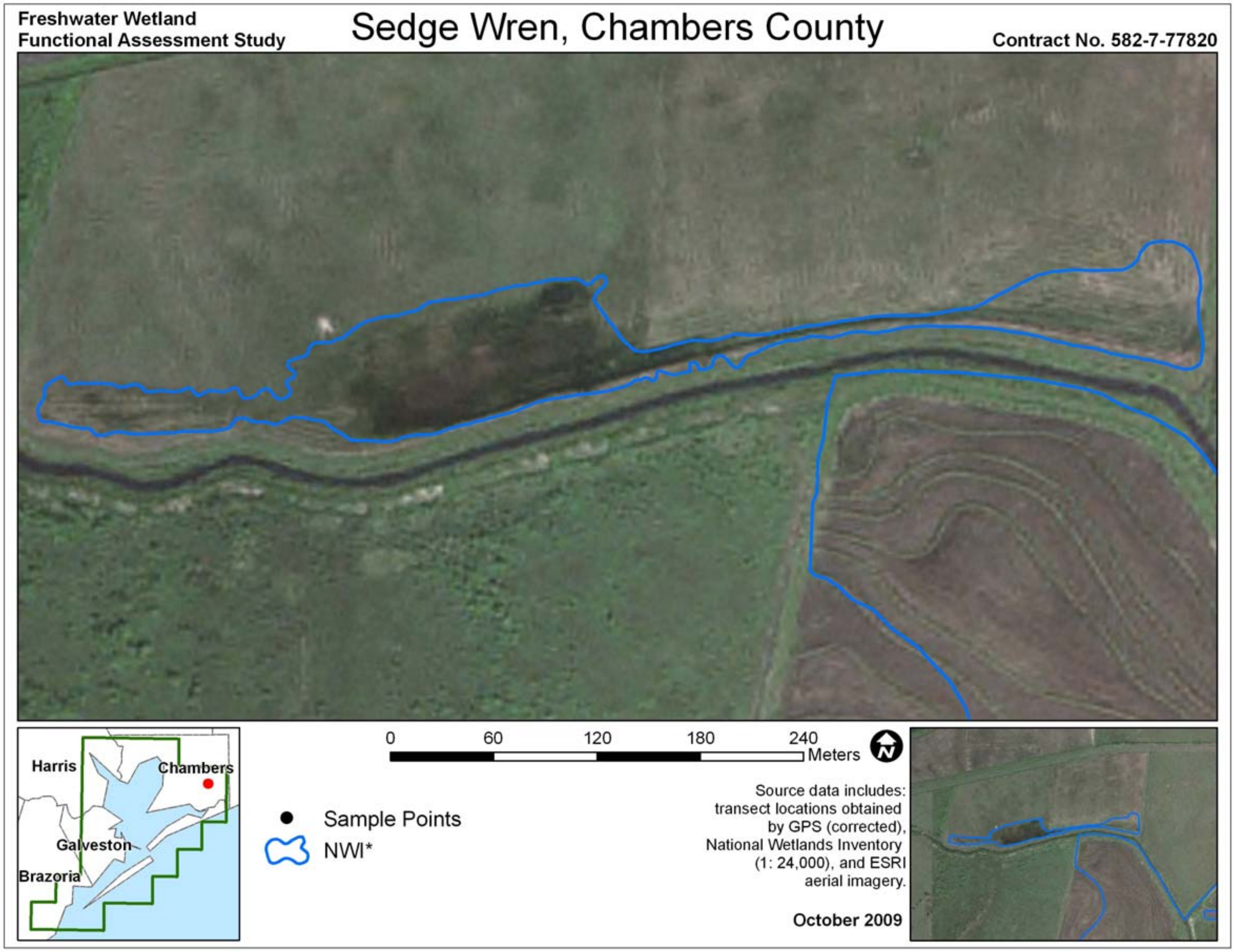


Figure 39. Map of sedge wren study site.

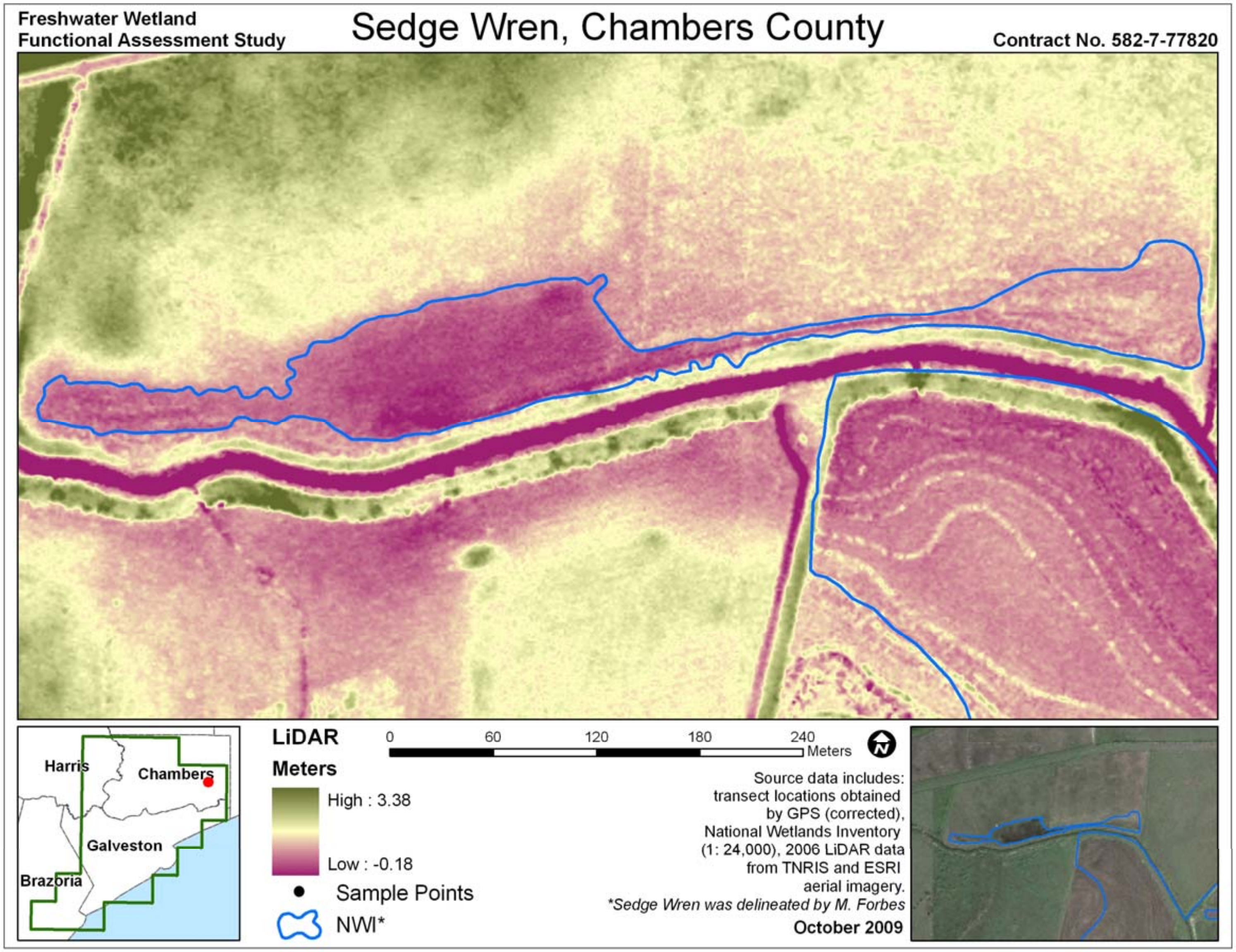


Figure 40. Map of sedge wren study site with LiDAR data.

CONCLUSION AND FUTURE DIRECTION

Analysis of the results of the models, particularly the water storage and ammonium removal models, suggests that two systems may be found in the wetlands included in the study area: permanently/artificially flooded (PFAF) wetlands which tend to be non-natural excavated wetlands which tend to be altered and non-natural and coastal prairie freshwater wetlands (CPFW) which are natural depressional wetlands. Results of the models for all wetlands and with PFAF wetlands excluded were presented.

Overall, results from this study found CPFW have the capability to perform numerous functions. CPFW typically have moderate capacity to store surface water from precipitation events, remove ammonium, and retain phosphorus and heavy metals. CPFW also tend to have a high capacity to remove nitrate and retain\remove organic compounds.

The results were not overly surprising. As discussed earlier, it is generally accepted that wetlands have the potential to perform a range of functions. CPFW were expected to be no different. What is important is to have a clear picture of the functionality. It is one thing to state wetlands perform functions, but the quantification of the capacity for a wetland to perform a function, which is possible with the results of this study, is valuable information.

It is understood that the primary purpose of datasets such as Soil Survey Geographic Database (SSURGO), National Wetlands Inventory (NW), and National Land Cover Dataset (NLCD) is as a regional screening tool. One of the objectives of this study was to construct a geographic information systems (GIS) model for large study areas, a model that can be replicated with readily obtained data. A lesson learned during the planning stages of this study was the extensive size of the study area limits the level of detail which the model can attain. For example, any variable that required detailed input from a specific site, such as drainage outlet modifications, was not plausible for a study area of this magnitude. While the models employed are not flawless, they are based on reviewed literature, field expertise, and professional judgment. Results from this study are useful in analyzing the general capacity of wetlands to perform specific functions. For this reason, conclusions should not be made about individual wetlands without a field visit.

A key contribution this study offers to wetland functional assessments is the use of high resolution LiDAR (light detection and ranging) datasets to delineate wetland catchments and volume estimation. An estimation of the total volume for CPFW in the study area is an intriguing statistic. Additionally, having a volume estimates for CPFW is useful as it adds a third dimension to discussions about wetlands allowing for clear distinction to be made in relation to wetland depth for individual wetlands. For instance, two wetlands maybe have the same area only one may be a saturated soil wetland and the other may be a true depressional wetland. As previously mentioned, delineated catchments can be used in other studies. Additionally, when the GIS model results are validated, this study can serve as a framework for functional assessments using readily available geospatial data in other regions.

Future direction includes comparison of model results to those of the original six study sites and seven recently added study sites. Samples obtained at those sites can be used to test the validity of both GIS input variables for the sites and functional assessment model results. Future studies could analyze the geography of wetland functionality using spatial autocorrelation to find “hot spots” or clusters of wetlands that have a high capacity to perform specific functions. Additionally, remote sensing technology could be used to map and classify wetlands not included in the NWI. The models could then be run on the newly identified wetlands.

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