Mapping Marsh Marvels: A GIS Approach to Locating Least Bittern Habitat in Northwestern Pennsylvania

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Abstract

As the smallest member of the heron family, the Least Bittern is often overlooked and pushed aside as not as important as these other species. But that couldn't be further from the truth. Playing a direct role in their native ecosystems these birds provide the ever-important ecosystem functions of nutrient cycling and population control. Pushed out of their wetland nesting sights due to urban expansion and resource extraction, this species is losing the fight to human development throughout Pennsylvania. Utilizing GIS this study sought to identify wetlands within the PA Fish and Game Commission Wildlife Management Unit 1B. To do so aerial photography was leveraged to conduct manual delineations separating each wetland by its vegetation type. Utilizing the amount of each vegetation type within the wetlands an analysis was undertaken to produce the likely, possible, and unlikely habitable wetland categories. A resulting map was generated to highlight where and which wetlands were the best for least bittern habitat needs. The resulting data found that 83.7% of wetlands within the study region were unlikely habitable because they were forested wetlands. A recommendation was made for more in-depth research into the likely habitable wetlands to determine exact nest sites. As well as conservation improvements for the unlikely habitable wetlands. Utilizing the resulting data from this study the secretive least bittern habitat can be understood and by using the recommended wetlands can be better monitored to ensure the future of this species' health in Pennsylvania.

Introduction

Importance of wetlands

Wetlands are defined as areas of land where water is at or near the surface at all times or intermittently throughout the year. This presence of water creates a unique environment where plants and animals that have adapted to these conditions thrive (EPA, 2023). Wetlands serve an important role in the surrounding ecosystem and the economic system of the people who live there. These areas protect and improve water quality, provide wildlife habitat, and store water for drought and dry periods. One of the crucial aspects of wetlands is their wildlife. Wetlands can be described as a biological supermarket where the customers are the animals that live or hunt in these wetlands and the plants are the groceries. (EPA, 2023). Over one-third of the world's bird species nest or feed in wetlands. Combining this with wetlands being home to over 31% of plant species in the U.S., the ecological impact these seemingly small pieces of land can have is obvious (U.S. Fish & Wildlife Service, n.d.). Another important aspect is water quality. Wetlands are natural waste-water plants trapping pollutants such as phosphorus and heavy metals in their soils and breaking down nitrogen into natural plant fertilizers that help regulate the surrounding environments resulting in healthier ecosystems (World Wildlife Fund, n.d.). Water quality regulation and ecosystem suppliers are important, but to humans, wetlands also have another more obvious importance. Food supply and natural resources are abundant and easily gathered from wetlands. Fish, shellfish, produce such as cranberries, specialty timber, rice, and even ingredients for medicine are harvested from wetlands (EPA, 2023). This plethora of natural materials makes wetlands a necessity for economic growth in areas nearby.

Although wetlands played an important role in both economics and the environment in the past, not much was known about their importance in the ecosystem. As a result of this lack of knowledge, they were often looked upon as a wasteland whose only use was the extraction of natural resources and as flat land for building (Tiner, 1990). In the past 300 years, an estimated as much as 87% of the world's wetlands have been lost due to human activities (World Wildlife Fund, n.d.). This loss started happening rapidly in the early 1900s with people recognizing the nutrient-rich soil and draining the wetlands for agriculture. This was a trap of assigning value to wetlands based on short-term economics instead of researching all the effects the mass destruction of these unique areas would have on the future (Mitsch, 2000). As a result of research

and general awareness of wetlands growing around the 1960s, public push for better regulation and control began (Tiner, 1990). This push has led to multiple regulations all around the United States from both the federal and state levels such as the North American Wetlands Conservation Act of 1989 as well as countless new companies and nonprofits fighting wetland loss.

Pennsylvania is one example of the history of horrid wetland loss. From the 1780s to the 1980s an estimated more than half of all Pennsylvania's wetlands were lost (Tiner, 1990). In Pennsylvania, conversion to cropland, lakes, and ponds and urbanization destroy the wetlands. With only around 1.4 percent of Pennsylvania's land being covered by wetlands, this loss negatively impacted the surrounding ecosystem (National Water Summary, n.d).

Least Bitterns: Who are they

As a result of this loss of wetlands, plants and animals are becoming endangered with approximately half of all federally endangered listed species making wetlands their home or depending on them for survival (U.S. Fish & Wildlife, 2023). One such species is the Least Bittern. The Least Bittern (*Ixobrychus exilis)* is a bird that is often unknown or confused even by bird enthusiasts. As the smallest member of the heron family, this bird is only 11 to 14 inches in length with a wingspan of 16 to 18 inches (Haffner, 2014). Their main coloration is darker browns and blacks on the top with necks and sides that are light brown to orange. They are most readily recognized by the white stripes that occur heading down their necks (Massachusetts Division of Fisheries & Wildlife, 2015). Least Bitterns are carnivorous birds whose main diet consists of small fish, but they have been known to eat anything including mice, small snakes, and even small crustaceans (Cornell Lab of Ornithology, 2023). Their home range extends from southeastern Canada through the United States to the Atlantic coast. They migrate north in mid to late spring and south in the beginning of fall (National Audubon Society, 2023). They are found in freshwater and brackishwater wetland habitats and favor emergent vegetation such as cattails (Cornell Lab of Ornithology, 2023).

Least Bitterns play an important role in the habitats they live in by providing population control and nutrient cycling. Through consuming different prey, the Least Bittern helps keep the populations of small fish in check. If left unchecked, the populations could grow to an unmanageable size and have detrimental impacts on local wildlife. They also play an important role in nutrient cycling. By consuming food in one area of a wetland and excreting waste in

another area or a different wetland altogether, they help move nutrients from areas of high concentration to areas of lower concentration. This movement of nutrients is vital to a wetland's health and keeps the delicate balance required in wetland ecosystems.

Although not endangered at the federal level, the Least Bittern is considered endangered within many states including Pennsylvania (Haffner, 2014). This is due to the continual loss of wetlands. Although the rate of wetland loss has slowed, wetlands are still facing challenges from ongoing agriculture, urbanization, aquaculture, and industry (Ballut-Dajud, 2022). Another issue Least Bitterns are facing is a lack of knowledge. Due to their small stature and preference for dense vegetation, this bird is difficult to monitor and study. The current methods rely on a combination of utilizing vocalization and in-person spotting of the species to determine population density in a set area (Znidersic, 2020).

Utilizing GIS for habitat needs

Past research has been conducted both on geographic information systems (GIS) habitat modeling as well as on Least Bittern habitat needs. GIS is a collection of computer software that allows users to store and analyze data in a spatial setting. One large area where we can see GIS being used is within habitat modeling. Habitat models are often closely related to niche theory where an animal's presence is determined by its niche or specific conditions in which the animal can live. It is generally believed that there are three main limits in a species niche. First, the local environment allows the population to grow, meaning there is enough food, water, and shelter. Second, the interactions with other species allow species persistence, resulting in no over-predation and enough prey. Lastly, the location can be reached by the spread of the species, meaning that the species can migrate into this area allowing for wider distribution and resulting in a better chance for the species' survival (Hirzel & Le Lay, 2008). Habitat modeling takes one or more constraints such as these and boils them down into a resulting restrictive area where the species could exist within these constraints.

GIS habitat modeling has a plethora of past research. When compared to the amount of research existing regarding Least Bitterns, it is staggering how little is recorded on this bird species. With so few studies, many focus exclusively on site-specific locations. Locations such as Quebec (Jobin, 2011), Florida (Rodgers & Schwikert, 1999), Arkansas (Budd & Krementz, 2010), Vermont (Cherukuri, 2018), and more have had detection and monitoring studies done in

the past. When combined and supplemented with more general articles such as Breeding Biology of the Least Bittern by Milton W. Weller, they give a great overview of the type of wetlands, vegetation, and situations the Least Bitterns thrive in as well as where Least Bitterns avoid (Weller, 1960).

Research objectives

The goal of this study is to determine areas of wetland within Pennsylvania where Least Bitterns could live and nest in. By doing so land conservation can occur for future population growth and better monitoring. This study hopes to accomplish three main objectives; 1) identify the wetlands suited the best for Least Bittern habitat, 2) identify wetlands that can be improved to create suitable habitat, and 3) create an easily adapted GIS workflow to help determine wetland suitability in regions beyond the scope of this study. This study will provide comprehensive maps detailing habitat to focus on when looking for least bittern conservation areas. These maps and resulting statistics will be provided to outside researchers within the study region such as the Pennsylvania Fish and Game Commission and Erie Bird Observatory to help push for future research and monitoring of this small and widely unknown species.

Methods

Study region

The Pennsylvania Game Commission's Wildlife Management Unit (WMU) B1 consists of Erie County and parts of Crawford, Warren, Venango, and Mercer counties. Consisting of 2,117.69 acres of land, 82.7 acres of which are public or game lands. Of the total land, 3.5 percent of the land is wetlands (Pennsylvania Game Commission, n.d). Within these wetlands, a majority of land is located on private land with only 4% located on public or conservation lands.

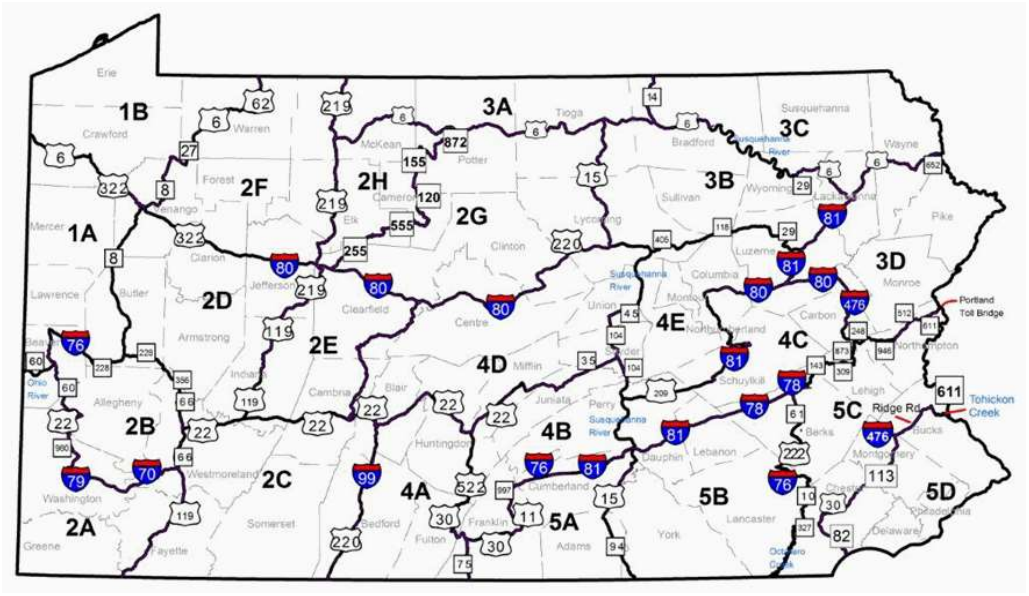

Figure 1. *Study region map of wildlife management unit 1B (*Alex, "*East meets West: Some notes", 2020).*

National Wetland Database

Created by the U.S. Fish and Wildlife Service (USFWS), the National Wetland Inventory (NWI) (U.S. Fish & Wildlife, 2023) is a collection of maps and data on wetlands throughout the United States. With the 1986 Emergency Wetland Resource Act, the start of wetland mapping and monitoring by the USFWS began (U.S. Fish & Wildlife, 2023). One of the main resources provided by the NWI is the maps of wetlands boundaries and associated habitat characteristics. Using aerial photography and in-person observations, researchers split wetlands into eight main categories; Freshwater, Forested and Shrub, Freshwater Emergent, Freshwater ponds, Estuarine and Marine wetlands, Riverine, Lakes, Estuarine and Marine Deepwater, and Other Freshwater (U.S. Fish & Wildlife, 2023). Each wetland is also assigned a code containing information on the type of bottom, tidal information, and type of vegetation. Special modifiers are added to the code for information on acidity, salinity/halinity, if it is farmland, how often flooding occurs, and special wildlife such as beavers (NWI, n.d.). Additional information such as water level is appended to the maps. This information is made available to the public via download on the NWI online mapper (U.S. Fish & Wildlife Service, n.d.) as well as for download in different formats to be used with GIS applications. This study took the plethora of information provided

by the NWI and used both the maps of all wetlands as well as the vegetation information provided in the code to conduct an analysis of the wetland's habitat.

Dataset Preparation

A map of WMU 1B was downloaded from Pennsylvania Spatial Data Access (PASDA) and uploaded into the GIS (commonwealth of Pennsylvania, n.d). Wetland data for the state of Pennsylvania was downloaded from the USFWS NWI viewer (U.S. Fish & Wildlife Service, n.d.) and overlaid digitally in GIS. All wetlands outside of WMU 1B were removed. Any wetlands overlapping the boundary were cut at the boundary. Riverine wetlands were removed due to Least Bitterns avoiding habitat with flowing water. Wetlands under 2 hectares were removed due to their size being under the ideal nesting size found by past research. This resulted in a map containing all initially suitable wetlands within the study region.

Maps were taken for PASDA for federal, state, non-profit, county, and easement lands. These maps were then combined to get one map containing all non-private lands. The combined map was then parsed down to match the extent of the study site. The map of public and conserved lands was overlaid with the map containing all the wetlands. Using this overlay the wetlands were separated into wetlands on public and conserved lands and wetlands on private lands, The wetlands on private land were then removed resulting in a map of all wetlands within public or conserved lands.

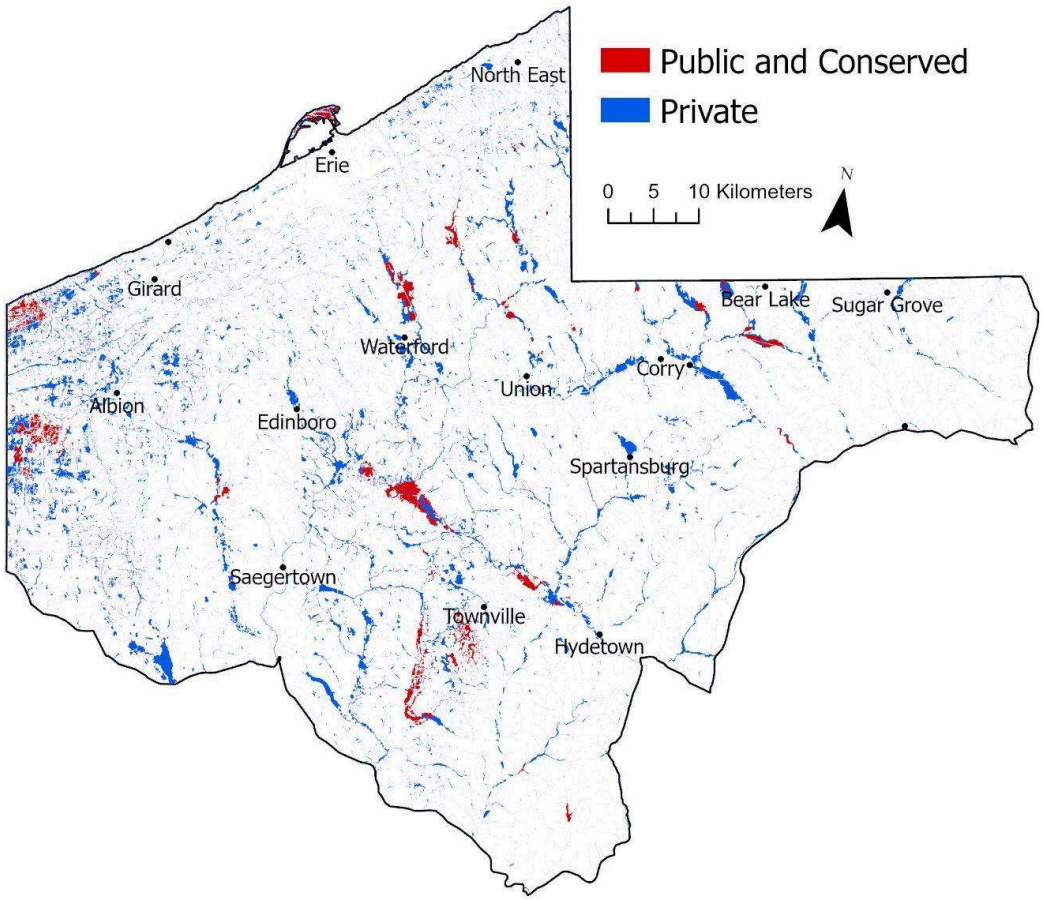

Figure 2. *Wetlands in the study region separated by land ownership.*

In order to delineate vegetation within these wetlands aerial photography was gathered. To gather the aerial photography, 1-meter aerial imagery was acquired from the U.S. Geological Survey (USGS) National Map Viewer (USGS, n.d). Due to the wetland categorization of the NWI, some river and stream wetlands remained. A visual approach using aerial photography for each wetland was used to sort out any of these remaining wetlands where Least Bitterns would be less likely to nest due to moving water. The remaining wetlands were given a 20-foot buffer in order to account for wetland water level fluctuations and prepare them for manual vegetation delineation. (Environmental Laboratory, 1987)

Vegetation Delineation

To conduct delineation of the vegetation each wetland was split up into polygons that were attributed with an ID that matched up to the ID of the wetland the polygon was located in

on the map of filtered NWI wetlands. Each of these polygons represented a vegetation type. For the vegetation type, five main categories were selected based on previous studies; open water consists of areas where only water was visible, densely vegetated wetland consisting of areas where no water could be seen through the vegetation, forested consisted of areas in which dense tree cover was present, lightly vegetated consisting of areas where vegetation was the predominantly cover but occasional small pockets of water could be seen, farmland or grassland consisting of recognizable tilled land or pastures, and human structures consisting of buildings and roads. A sixth category was included for unknown sites that were unrecognizable at the photography scale available. These categories were selected to contain all types of land being descriptive enough to calculate the best wetlands for the least bitterns. The delineations were completed manually based on the aerial photography at a scale of 1:1000. This scale allowed for easy recognition of vegetation borders as well as efficiency in the delineation process.

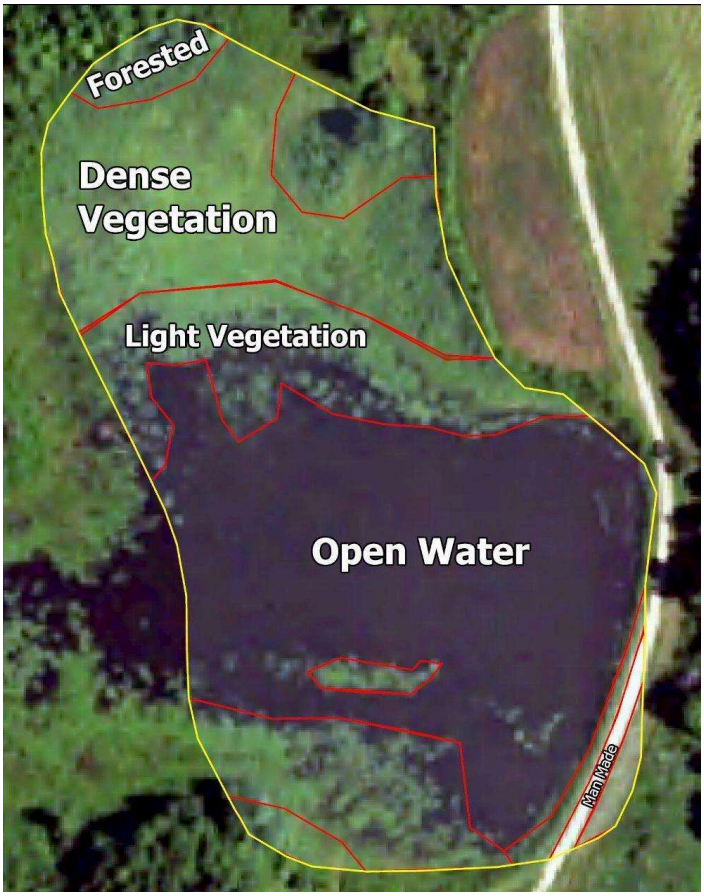

Figure 3. *Delineation of vegetation types in one representative wetland.*

Determining Ideal Wetlands

To determine the ideal wetlands, the data from the manually delineated vegetation types were combined to calculate statistics on each of the wetlands. This data included the wetland ID, size in acres, and vegetation type for each individual delineation. The information was separated into groups containing all delineations within a singular wetland ID. Utilizing the math functions, total acreage was calculated. Based on the total acreage, percentages of each type of vegetation within the wetlands were calculated. Statistical data on distance to the nearest wetland and average distances between wetlands were calculated. Wetlands were split up into three groups based on percentages of vegetation types. Utilizing a combination of recommendations based on past research, the "likely" habitable wetlands are characterized by having over 50% wetland vegetation between light and dense vegetation and over 2% of open water for least bittern hunting grounds. The "unlikely" habitable wetlands were categorized by over 95 % of one type of vegetation or over 70 % forested or 50 % farmland. To obtain "possibly" habitable wetlands that fell under neither category, a combined layer of both the likely and unlikely wetlands was created. This layer was then used to highlight the wetlands within the study region that were outside the two categories. These wetlands then were taken and placed into the possibly habitable category.

Results

Out of 874 wetlands, 8.9% were found likely to have nest sites, 7.4% were possible for nesting habitat and 83.7% were found unlikely to be habitable by least bitterns. The majority of wetlands were located in small clusters. The clusters were spread out evenly over the study region. The average distance between all wetlands was 0.06 kilometers with the average distance between recognized likely nesting wetlands being 1.33 kilometers.

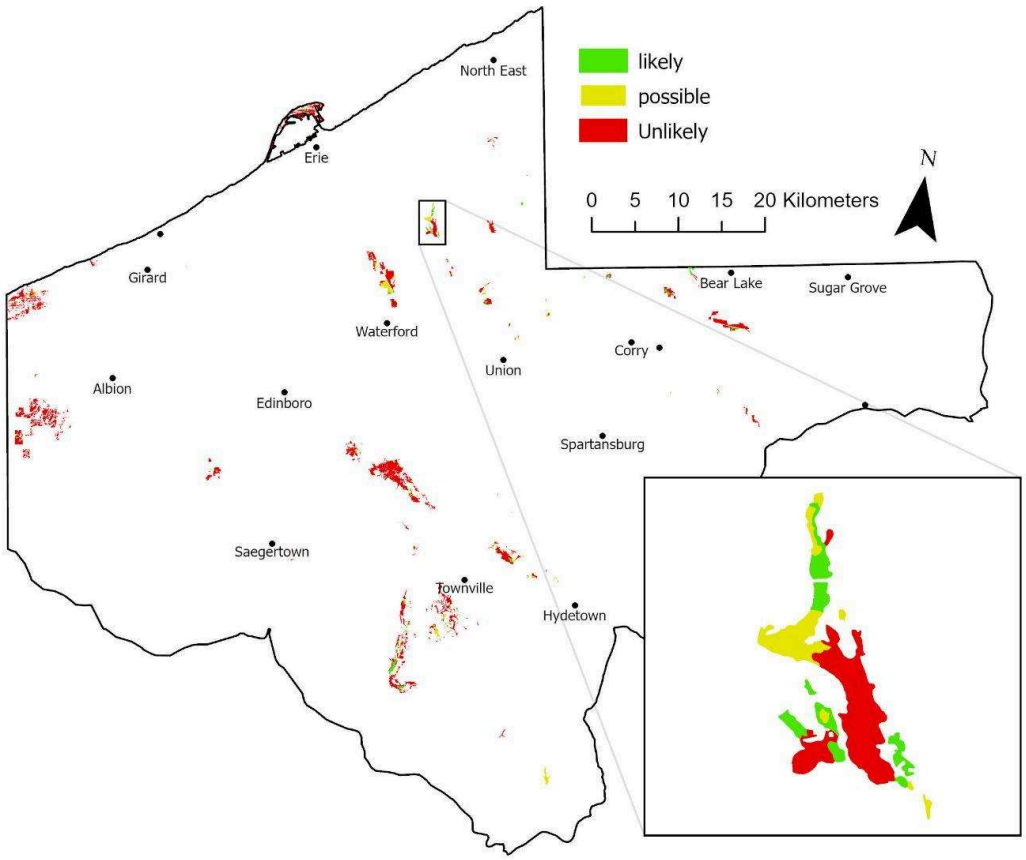

Figure 4. *Likely, possible, and unlikely habitable wetlands.*

Although no discernible trend in the distribution of wetlands throughout the study region was recognized, the possible and likely habitable sites tended to come in groups of two or more neighboring wetlands. In total, all wetlands covered 13,614 acres. Out of this, unlikely habitable had the most acreage with possible habitable being second and the likely habitable wetlands having the least.

Table 1. *Number of wetlands and total acreage of the three categories of wetlands.*

Habitability -	Likely	Possibly	Unlikely
Total # of Wetlands	78	63	733
Total acreage	988.4	1,086.4	11,539.2

On average, the wetland size was 15.58 acres. Man-made structures had the lowest amount of land followed by field and pasture, open water, light vegetation, dense vegetation, and forested land respectively. Wetlands on average consisted of 59.9% of forested land with the second largest contributor of land, dense vegetation, being 21.7%. A majority of wetlands were found to have one vegetation type.

Discussion

This study aimed to determine the ideal wetlands within conserved and public land in Pennsylvania Wildlife Management Unit 1B. Through identifying nesting habitats, the study sought to point future conservation efforts and research in the direction of this small, elusive bird. Resulting from the Least Bittern's status as endangered within Pennsylvania, it is important to understand their needs to prevent the loss of this ecosystem's regulator species.

This study found a majority of wetlands within the study region were likely unusable for Least Bitterns. This was a result of the majority of wetlands being swamp-type wetlands filled with trees. The Least bitterns require dense or semi-dense vegetation in which to make their nests resulting in forested wetlands being unusable. The wetlands that were identified as “likely” were due to the mixture of majority emergent vegetation and some open water. The emergent vegetation is required for the nesting needs and the open water is a major benefit as it acts as a hunting ground.

The results of this study show that there are very few suitable wetlands within the study region. For conservation purposes, a recommendation of continued or increased habitat conservation in these wetlands is encouraged. This includes the introduction or addition of emergent vegetation as well as the removal of invasive species and harmful chemical and plastic waste. The development of more studies into possible land outside of conserved areas in order to find more likely nesting sites and conserve them is also recommended.

GIS as a tool in habitat conservation and recognition has widely been used. An example of this is *Habitat-Suitability Models for Cavity-Nesting Birds in a Postfire Landscape* by Robin E. Russell, Victoria A. Saab, and Jonathon G. Dudley (2007). In this study, they compare two methods to determine nesting areas for six different bird species. This study helps the reader understand not only how data can be gathered and combined into an understanding of habitat, but also how the use of different constraints can cause different outcomes (Russell, 2007).

Integrating GIS and remote sensing for vegetation analysis and modeling: methodological issues by Michael F. Goodchild talks about many of the methods utilized in this study (Goodchild, 1994). It identifies how GIS can be combined with remote sensing to understand vegetation in a region. Another example is *Testing a GIS Model of Habitat Suitability for a Declining Grassland Bird* by Chris L. Lauver, William H. Busby, and Jerry L. Whistler. This study follows a similar framework that utilizes remote sensing aerial photography combined with GIS delineations to produce a vegetation map that is then used to predict low, moderate, and high areas fitting the habitat needs of a bird species (Lauver, 2002).

Within this study, many limitations arose. The first main limitation of the methods was the connection between wetlands and how this study viewed them. The study's wetlands were often grouped with two or more being connected through a shared border. This shared border could theoretically mean that the connected wetlands, although different in some attributes, can be considered as one larger wetland. The limitation in this case is that if the connected wetlands were viewed as together the composition of vegetation would change. The results relied on the percent of vegetation within a wetland if one wetland consisted entirely of forest, but was connected through a shared border to a wetland consisting entirely of dense vegetation if considered together then the percentage for forested and dense vegetation would be 50/50. In this study, without connecting the wetlands each would be given 100% of the type of vegetation. This would affect results dramatically, leading to a different view on what wetlands were considered to be habitable or not. To combat this an approach where wetlands that shared borders were combined could be utilized. This method would result in fewer individual wetlands being recognized but could have a possibility to increase the likelihood of wetlands being recognized as better nesting sites.

The second main limitation of the methods was the selection process. This process utilized percentages selected based on past research to parse out data that represented the most likely and least likely habitats to contain Least Bitterns. By tweaking the percentages used the results could have changed. If the limit of forest percent was lowered by another 10% it might result in fewer wetlands being listed as unlikely to be inhabited. This study utilized strict percentages, one method that could be utilized is a fuzzy selection in which the percentages are a range. This would allow for slight variation and the variation would allow for wetlands that are on the border of the used percentages to switch to a different category. In the case of this study,

more in-depth research into number selection for the wetland categories and selection type could improve the accuracy and reliability of the results.

The main limitation facing this study's results is the usefulness of the data. Although this research can help make informed decisions on where to focus future research, it does not do a good job of helping conservation efforts. This is a result of the land being selected for this study already being conserved. By taking the public and conservation land and only looking at those wetlands, this study is examining the areas that would likely not have drastic changes occur such as home development. This limits the study in its effort to enact conservation as it will not help identify sites that likely could be destroyed in the near future.

This study also faces a limitation in accuracy due to wetlands' ever-changing nature. Wetlands are one of the fastest-changing habitats in nature. They are often affected by erosion, droughts, sea level changes, storms, human interaction, and more. This quick-changing effect of wetlands acts as a limitation in the regard that the data used for conducting this study could have already been inaccurate and as more time passes, there is an increased chance for this study's results to be invalid.

Looking towards the future of Least Bitterns, this study can be expanded on in various ways. One example is the incorporation of private land. thus, eliminating some of the limitations of this study. By incorporating private land better and more specific recommendations could be made for conservation efforts, such as what land the government could buy to act as a conservation site. Another large area that can build upon this research is incorporating an observational aspect into the study. in-person examinations of the recognized wetlands could be conducted. This could result in a better knowledge of the accuracy of data as well as help identify which actual sites are home to Least Bittern nests by allowing for more accurate information on the vegetation types present in specific wetlands.

Overall, this study can be used to help drive the decision-making process as it relates to conservation efforts regarding the Least Bittern species in the future. This study found that few wetlands are ideal or even compatible with Least Bittern nesting needs. This necessitates the need for better conservation of the recognized sites and future research into possible other habitable sites in order to stop the endangerment of this key species of bird.

References

Alex. (2020, March 8). *East meets West: Some notes*. APT Outdoors. https://aptoutdoors.com/east-meets-west-some-notes/

Ballut-Dajud, G. A., Sandoval Herazo, L. C., Fernández-Lambert, G., Marín-Muñiz, J. L., López Méndez, M. C., & Betanzo-Torres, E. A. (2022). Factors Affecting Wetland Loss: A Review. *Land*, *11*(3), 434. https://doi.org/10.3390/land11030434

Bartok, N. D. (n.d.). *RELATIVE ABUNDANCE AND HABITAT ASSOCIATIONS OF LEAST BITTERNS (Ixobrychus Exilis) AT LONG POINT, LAKE ERIE, ONTARIO*. https://ir.lib.uwo.ca/digitizedtheses/3487/

commonwealth of Pennsylvania. (n.d.). *Open GIS data access for the commonwealth of Pennsylvania*. Pennsylvania Spatial Data Access. https://www.pasda.psu.edu/

Cornell Lab of Ornithology. (2023). *Least bittern life history, all about birds*. All About Birds. https://www.allaboutbirds.org/guide/Least_Bittern/lifehistory#:~:text=Least%20Bitterns%20eat%20mainly%20small,young%20of%20Yellow%2Dheaded%20Blackbirds.

(2020). *Design Metrics for Assessing Unmanned Aerial Vehicle Mission Suitability*. https://doi.org/10.2514/6.2021-1062.vid

Eilers, H. P., Taylor, A., & Sanville, W. (1983). Vegetative delineation of coastal salt marsh boundaries. *Environmental Management*, *7*(5), 443–452. https://doi.org/10.1007/bf01867124

EPA. (2021). EPA - Threats to Wetlands. https://www.epa.gov/sites/default/files/2021-01/documents/threats_to_wetlands.pdf

Fortin, M.-J., & Edwards, G. (2001). Delineation and analysis of vegetation boundaries. *Spatial Uncertainty in Ecology*, 158–174. https://doi.org/10.1007/978-1-4613-0209-4_8

Gage, E., & Cooper, D. J. (2010). *Vegetation Sampling for Wetland Delineation: A Review and Synthesis of Methods and Sampling Issues*. https://doi.org/10.21236/ada524401

Goodchild, M. F. (1994). Integrating GIS and remote sensing for vegetation analysis and modeling: Methodological issues. *Journal of Vegetation Science*, *5*(5), 615–626. https://doi.org/10.2307/3235878

Haffner, C., & Gross, D. (2014, August 19). *Least bittern Species Profile*. Pennsylvania Game Commission Least bittern Species Profile. https://www.pgc.pa.gov/Wildlife/EndangeredandThreatened/Pages/LeastBittern.aspx#:~:text=The%20least%20bittern%20arrives%20in,(17%2D20%20days)

Harms, T. M., & Dinsmore, S. J. (2013). Habitat associations of secretive marsh birds in Iowa. *Wetlands*, *33*(3), 561–571. https://doi.org/10.1007/s13157-013-0414-0

Hirzel, A. H., & Le Lay, G. (2008). Habitat suitability modelling and niche theory. *Journal of Applied Ecology*, *45*(5), 1372–1381. https://doi.org/10.1111/j.1365-2664.2008.01524.x

Hirzel, A. H., Le Lay, G., Helfer, V., Randin, C., & Guisan, A. (2006). Evaluating the ability of habitat suitability models to predict species presences. *Ecological Modelling*, *199*(2), 142–152. https://doi.org/10.1016/j.ecolmodel.2006.05.017

Jobin, B., Bazin, R., Maynard, L., McConnell, A., & Stewart, J. (2011). Least bittern (*ixobrychus exilis*) survey protocol. *Waterbirds*, *34*(2), 225–233. https://doi.org/10.1675/063.034.0212

Jobin, B., Robillard, L., & Latendresse, C. (2009). Response of a least bittern*(ixobrychus exilis)*population to interannual water level fluctuations. *Waterbirds*, *32*(1), 73–80. https://doi.org/10.1675/063.032.0108

Jobin, B., Fradette, P., & Labrecque, S. (2011). Habitat use by least bitterns (*ixobrychus exilis*) in Québec. *Waterbirds*, *34*(2), 143–150. https://doi.org/10.1675/063.034.0202

Langley, C. H. (1983a). Biology of the little bittern in the southwestern Cape. *Ostrich*, *54*(2), 83–94. https://doi.org/10.1080/00306525.1983.9634451

Langley, C. H. (1983b). Biology of the little bittern in the southwestern Cape. *Ostrich*, *54*(2), 83–94. https://doi.org/10.1080/00306525.1983.9634451

Langley, C. H. (1983c). Biology of the little bittern in the southwestern Cape. *Ostrich*, *54*(2), 83–94. https://doi.org/10.1080/00306525.1983.9634451

LAUVER, C. L., BUSBY, W. H., & WHISTLER, J. L. (2002). Testing a GIS model of habitat suitability for a declining grassland bird. *Environmental Management*, *30*(1), 88–97. https://doi.org/10.1007/s00267-001-2609-z

Massachusetts Division of Fisheries & Wildlife. (2015). Natural heritage least bittern & endangered species Program. https://www.mass.gov/doc/least-bittern/download

Moore, S., Nawrot, J. R., & Severson, J. P. (2009). Wetland-scale habitat determinants influencing least bittern use of created wetlands. *Waterbirds*, *32*(1), 16–24. https://doi.org/10.1675/063.032.0102

Minnesota Department of Natural Resources. (2021, February 10). *National Wetland Inventory Frequently asked questions*. Minnesota Department of Natural Resources. https://www.dnr.state.mn.us/eco/wetlands/nwi_faq.html#:~:text=This%20means%20that%2095%25%20of,boundaries%20for%20wetland%20permitting%20purposes

Mitsch, W. J., & Gosselink, J. G. (2000). The value of wetlands: Importance of scale and landscape setting. *Ecological Economics*, *35*(1), 25–33. https://doi.org/10.1016/s0921-8009(00)00165-8

National Water Summary. (n.d.). Pennsylvania Wetland Resources. https://www.fws.gov/wetlands/data/Water-Summary-Reports/National-Water-Summary-Wetland-Resources-Pennsylvania.pdf

Newling, C. J., & Smith, H. K. (1982). The Corps of Engineers Wetlands Research Program. *Wetlands*, *2*(1), 280–285. https://doi.org/10.1007/bf03160561

NWI. (n.d.). *Nwi Wetlands and deepwater map code diagram*. WETLANDS AND DEEPWATER HABITATS CLASSIFICATION. https://www.fws.gov/wetlands/Documents/NWI_Wetlands_and_Deepwater_Map_Code_Diagram.pdf

Patel, M. R., Vashi, M. P., & Bhatt, B. V. (2017). SMART-Multi-criteria decision-making technique for use in planning activities. *New Horizons in Civil Engineering (NHCE 2017)*, 1-6.

Pennsylvania Game Commission. (n.d.). *WMU 1B*. Pennsylvania Game Commission. https://www.pgc.pa.gov/Wildlife/HabitatManagement/WildlifeManagementUnits/Pages/WMU-1B.aspx

RUSSELL, R. E., SAAB, V. A., & DUDLEY, J. G. (2007). Habitat-suitability models for cavity-nesting birds in a postfire landscape. *Journal of Wildlife Management*, *71*(8), 2600–2611. https://doi.org/10.2193/2007-034

Tiner , R. W. (1990). *Pennsylvania's wetlands: Current status and recent trends - U.S. .* ,Pennsylvania's wetlands: Current status and recent trends. https://www.fws.gov/wetlands/Documents%5CPennsylvanias-Wetlands-Current-Status-and-Recent-Trends.pdf

U.S. Fish & Wildlife Service. (n.d.). National Wetlands Inventory. https://fwsprimary.wim.usgs.gov/wetlands/apps/wetlands-mapper/

USGS. (n.d.). *USGS National Map Accesses*. The national map - advanced viewer. https://apps.nationalmap.gov/viewer/

U.S. Fish & Wildlife Service. (2023, April 26). *Why healthy wetlands are vital to protecting endangered species: U.S. Fish & Wildlife Service*. FWS.gov. https://www.fws.gov/story/2023-04/why-healthy-wetlands-are-vital-protecting-endangered-species

U.S. Fish & Wildlife Service. (2023b, October 12). *National Wetlands Inventory: U.S. Fish & Wildlife Service*. FWS.gov. https://www.fws.gov/program/national-wetlands-inventory

U.S. Fish & Wildlife Servicve. (n.d.). *Essential habitats: U.S. fish & wildlife service*. FWS.gov. https://www.fws.gov/wetlands-month/essential-habitats

United States Environmental Protection Agency. (2023, March 22). *Why are wetlands important? | US EPA - U.S. Environmental Protection Agency*. EPA. https://www.epa.gov/wetlands/why-are-wetlands-important

United States Environmental Protection Agency. (2023, May 4). *What is a wetland? | US EPA*. EPA. https://www.epa.gov/wetlands/what-wetland

Weller, M. W. (1960). Breeding Biology of the Least Bittern. *The Wilson Bulletin*, *73*(1), 11–35. https://sora.unm.edu/sites/default/files/journals/wilson/v073n01/p0011-p0035.pdf

Wilen, B. O., & Frayer, W. E. (1990). Status and trends of U.S. wetlands and deepwater habitats. *Forest Ecology and Management*, *33–34*, 181–192. https://doi.org/10.1016/0378-1127(90)90192-e

Willard, D. E. (1977). The feeding ecology and behavior of five species of Herons in southeastern New Jersey. *The Condor*, *79*(4), 462–470. https://doi.org/10.2307/1367726

Wilson, E. D., Jensen, W. E., & Schultheis, R. (2018). Habitat use by secretive marsh birds during spring and fall migration in moist-soil wetlands in Kansas. *The Wilson Journal of Ornithology*, *130*(2), 385–396. https://doi.org/10.1676/16-215.1

Wilson, P. U., & Longcore, J. R. (2011). Least bittern nesting record in Maine. *Northeastern Naturalist*, *18*(3), 382–385. https://doi.org/10.1656/045.018.0311

World Wildlife Fund. (n.d.). *What is a wetland? and 8 other wetland facts*. WWF. https://www.worldwildlife.org/stories/what-is-a-wetland-and-8-other-wetland-facts#:~:text=A%20wetland%20is%20a%20place,has%20adapted%20to%20wet%20soil

Yang, X. (2007). Integrated use of Remote Sensing and geographic information systems in riparian vegetation delineation and mapping. *International Journal of Remote Sensing*, *28*(2), 353–370. https://doi.org/10.1080/01431160600726763

Zedler, J. B., & Kercher, S. (2005). Wetland Resources: Status, trends, ecosystem services, and restorability. *Annual Review of Environment and Resources*, *30*(1), 39–74. https://doi.org/10.1146/annurev.energy.30.050504.144248

Znidersic, E., Towsey, M., Roy, W. K., Darling, S. E., Truskinger, A., Roe, P., & Watson, D. M. (2020). Using visualization and machine learning methods to monitor low detectability species—the least bittern as a case study. *Ecological Informatics*, *55*, 101014. https://doi.org/10.1016/j.ecoinf.2019.10101