LAGOON LOGISTICS: FLOOD VULNERABILITY ASSESSMENT OF EASTERN NC INDUSTRIAL SWINE OPERATIONS

Highlights

- A new method for assessing flood-vulnerable, high-risk swine lagoons in Duplin and Sampson Counties was constructed and tested using spatial clustering and outlier analyses.
- The methodology proved to be effective at accurately identifying high-risk regions within the study area.
- The proposed method is unique in that it identifies high-risk lagoons *before* flooding occurs
- Methodologies for constructing vulnerability index can be applied to realms outside of lagoon flood risk analyses.

ABSTRACT. *NC represents the third largest pork-producing state and is home to one of the most concentrated industrial swine regions in the world. Across the state's more than 2,200 permitted hog operations, an estimated 10 billion gallons of waste is produced each year and managed via the lagoon-sprayfield system common to the eastern United States. This coastal portion of NC where the vast majority of swine concentrated animal feeding operations (CAFOs) reside is low-lying and highly susceptible to flooding from large precipitation events. Unfortunately, these high precipitation events are a well-documented mechanism by which significant amounts of hog waste can be released into the surrounding environment via inundated or breached waste lagoons. Major weather events in the southeast region are only increasing in frequency and intensity, raising major concerns regarding public and environmental health and the overall long-term sustainability of the NC hog industry. Few studies have been published on the continuing flood vulnerability of NC's hog industry, especially in terms of addressing and allocating resources toward reducing flood vulnerability of lagoons. This study poses a new and more robust method for identifying the most flood-vulnerable operations in Duplin and Sampson counties than what is currently used for state-funded swine farm easement programs via several GIS techniques. This research intends to be used as a tool for NC decision-makers who are responsible for allocating resources toward managing the most flood-vulnerable farms in the state.*

Keywords. *Eastern North Carolina, Flooding vulnerability, Lagoons, Risk management, Swine farms*

INTRODUCTION

Eastern North Carolina: a trampling ground for major flooding events… and hogs

North Carolina is a highly flood-prone state in the US and over the last few decades, record-setting storms have made landfall in eastern NC that left lasting impacts on populations and industries vital to the state (Shaffer-Smith et al., 2020). One such industry impacted by major flooding events is the NC swine industry. The flooding of hog farms and the potential impacts to human and environmental health by swine waste contamination has been and remains of great concern to residents across the eastern NC region and state environmental groups (Schmidt, 2000).

To fully recognize the scope of potential impacts from major swine operation flooding events, one must understand the scale and history of swine farming in NC. Eastern NC is home to one of the most densely-concentrated regions in terms of industrial hog production facilities in the western hemisphere (figure 1). Nestled side-by-side in the Lower Cape Fear River Basin, Sampson and Duplin counties represent a region where hogs outnumber humans by more than 35 to 1. Totaling over 4 million swine, operations in Duplin and Sampson counties house nearly half of the state's 9.2 million head (USDA-NASS, 2020).

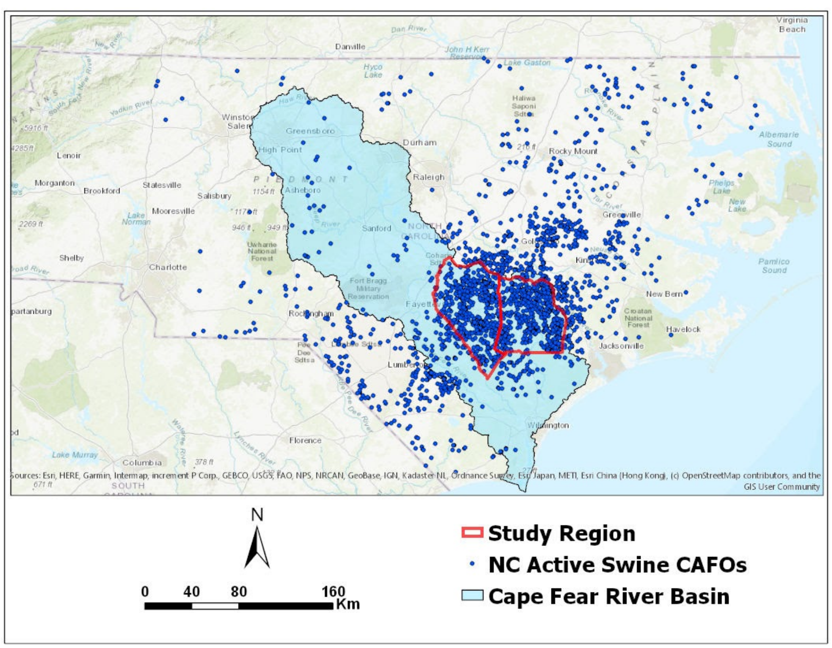

Figure 1. Spatial distribution of all swine CAFOs in NC. Duplin County and Sampson County are outlined.

The NC Hog Farm Common Components and Configuration

The typical NC swine CAFO comprises three parts: the hogs and hog barns, anaerobic waste lagoon(s), and adjacent sprayfield. Lagoons and housing structures are typically built on the most highly elevated portion of the property to prevent flooding. Large amounts of waste is flushed from hog barns and stored onsite in open-air, earthen pits called lagoons. Manure then undergoes anaerobic digestion. Top water is periodically pumped from the top of lagoons and sprayed as fertilizer on adjacent fields at agronomic rates on a nitrogen basis, while undigested solid material settles to the lagoon bottom as sludge. In general, lagoons are considered the most environmentally dangerous structures on a given swine CAFO due to the amount of nutrient-, heavy metal-, and bacteria-laden material usually stored (Osterberg & Wallinga, 2004). Such intensive industrial swine production can come at a high environmental price; this is true for many commodities produced at scale. A significant amount of the risk of swine production environmental toll in NC, however, is tied to the flood-susceptible geographic features of the very location where much of the industry is located and the open-air design of lagoons.

Recognizing problems and searching for solutions: Swine floodplain buyout program

The problematic placement of NC's hog operations is a well-known issue at the legislative level (Osterberg & Wallinga, 2004). In efforts to alleviate some of the flood risks associated with vulnerable operations, the state of NC has offered a voluntary Swine Floodplain Buyout Program (referred to from here on as the "buyout program") in five different installments since its introduction in 1999. Prior to its fifth and most recent installment in 2018, the buyout program had received a total of 138 applications and successfully closed 43 operations, amounting to 106 lagoons closed via buyout (Cox, 2018).

Though well-intentioned, the buyout program is underfunded and eligibility requirements are somewhat stringent. Available descriptions of buyout eligibility clearly state that to be considered, at least 20 acres of the proposed closure tract must reside in FEMA's estimated 100-year floodplain among other stipulations (Cox, 2018). Typically if an operation meets the first set of buyout consideration stipulations, buyout selection is then based on a point system assigned to six different water quality criteria and weighed against an applicant's desired bid price for operation buyout (Baumgardner & Williams, 2017). More about the buyout program is included in sections below.

QUANTIFYING FLOOD RISK: CURRENT PRACTICES AND PREVIOUS WORK

Flood Risk Assessment Methods

A wealth of research has been published surrounding quantification of "flood risk." Naisiri and Shahmohammadi-Kalalagh (2013) did a comprehensive review of current knowledge on flood vulnerability assessment approaches, narrowing risk assessment approaches into four distinct groups: vulnerability indicators methods, which measures the exposure of an area to flood hazard via indexed and weighted parameters composited into a risk formula; vulnerability curve methods, where flood risk and elements at risk are studied by empirical damage or fragility curves founded on data from well-documented case studies in a specific area; disaster loss data methods, constructed from data of real flooding events and average annual damages from flooding hazards; and finally computer modeling methods capable of evaluating depth, elevation, and flood velocity using frequency, magnitude, and shape of calculated hydrographs over a given topographic area. Policy makers and regulatory bodies tend to prefer vulnerability indicator approaches due to a clear assessment of flood vulnerability over a given region and the ability to incorporate a number of factors with adjustable weights (Nasiri & Shahmohammadi-Kalalagh, 2013).

NCDA&CS Buyout Program Flood Risk Approach

NCDA currently uses a vulnerability indicators-type flood risk assessment when reviewing applications for swine floodplain buyout. This index was constructed by an advisory panel consisting of members from the Clean Water Management Trust Fund, NCDA&CS, the NC Pork Council, the Conservation Council of NC, and the NC Cooperative Extension Service based on six selected water quality criteria to weigh against the applicant's bid price (Baumgardner & Williams, 2017). These criteria include:

- Structural condition of the facility's waste storage lagoons relative to current standards (0-20 pts),
- Elevation of the top of the lagoon dike relative to the 100-year flood elevation (0-45 pts),
- Elevation of the production houses relative to the 100-year flood elevation (0-20 pts),
- Elevation of the production houses relative to the 100-year flood elevation (0-20 pts),
- Distance to a water body that is classified as either water supply or high-quality waters (0-10 pts),
- Applicant's willingness to install a 100 ft buffer (instead of the minimum 50 ft buffer) adjacent to all United States Geological Survey (USGS) blue line streams in the easement area (0-5 pts).

Once criteria data are collected for a particular site, the water quality criteria are divided by the bid price, normalized on a dollar per pound of steady state live weight from which the final rankings are determined. Details about how points are assigned within each parameter are not publicly available.

NC Swine Farm Flooding Assessment Studies

Only two studies were found that directly address the issues surrounding the geospatial flood vulnerability of NC's hog operations, Harmin (2015) and Wing et al. (2002). Only the latter is published in a peer-reviewed journal. Neither of these studies suggest refining the considerations and eligibility criteria for buyout program consideration, however some analytical approaches for this study draw upon their work as well as the ranking system already used by NCDA&CS during buyout application review.

Wing et al. (2002) explored the geographic point coordinates of more than 2,000 permitted swine CAFOs in relation to flooding estimates derived from digital satellite images of the coastal NC region taken a week after Hurricane Floyd (1999), and compared results to NC Department of Water Quality (NCDWQ)-confirmed lagoons that inundated or breached during or directly after the historic storm. This was a first attempt at quantifying the flood vulnerability of eastern NC CAFOs using GIS methods and study findings pointed toward disparities in flood zone estimate accuracy and true flood regions observed. Though important insight into the flood vulnerability of eastern NC CAFOs was gained, Wing et al.'s study made use of swine CAFO permit point locations, which do not offer a detailed analysis of flood vulnerability due to the large, sometimes noncontiguous regions occupied by swine farms and the error often associated with the placement of CAFO and lagoon points in publicly available data.

Harmin (2015) delineated hog lagoons and housing structures using polygon features to represent each structure and constructed a point system to assess vulnerability in a manner similar to NCDA&CS, relating housing and lagoon structures to nearby flood zones using three parameters. This approach is certainly more accurate in assessing flood vulnerability of hog farm structures compared to point features. Parameters explored in Harmin's study are important indicators of flood vulnerability for a given CAFO structure, however do not take into account environmental and human concerns. Harmin's study region is the northern portion of NC where CAFOs are less densely concentrated compared to Duplin and Sampson Counties but shares the same issue of repeated lagoon inundations during flood events.

STUDY CONSIDERATIONS AND GOALS

Proposed Flood Assessment Approach

Although previous work has provided strong background in the overall flooding risk of coastal hog operations, a better way of pinpointing individual operations most likely to flood and pose the most human and environmental risk in the event of inundation or breach is needed. The flood risk indexing method currently used by NCDA&CS is thorough, however important parameters such as impact on communities and the spatial relationship between neighboring high flood risk operations go unconsidered. The buyout program also works on a reactive basis versus a proactive basis; additional buyout funding is usually only offered in the wake of drastic flooding events that caused lagoon inundation or breaches. This study offers a new approach for identifying high-risk flood-vulnerable operations using seven spatial criteria, incorporating relationships between lagoons and important or nutrient-sensitive surface waters, nearby flood zones, human populations, and neighboring lagoons.

The proposed approach places emphasis on assessing the current state of the industry, the associated flood, health, and environmental risks of individual lagoons, and opens the door for proactive mitigation efforts at target operations before flooding events occur. Increased management efforts of target lagoons that are deemed high-risk might include more frequent inspections to ensure structural integrity, stricter sludge removal regulations or schedules, or risk-mitigating technologies such as lagoon coverings.

METHODS

GIS analyses employed in this study were used to concretely quantify the flooding vulnerability and environmental risk of swine operations in Sampson and Duplin counties via a multi-component ranking system. As mentioned, some spatial methods draw on those used by NCDA and Harmin (2015), however also incorporate additional geospatial considerations including geographic relationships between neighboring lagoons and human populations. Spatial relationships between delineated lagoon polygons and other processed data layers representing local topography, FEMA-approved estimated flood zones, surface water quality, and human populations were used as inputs for determining the most flood-vulnerable operations, serving as a simple but more holistic approach comprised of environmental and social components.

STUDY REGION

For demonstration purposes, only Sampson and Duplin counties were chosen for analysis. These regions were chosen because of the significant density of CAFOs per unit area compared to other NC hog-producing counties and the large percentage of all NC swine CAFOs that reside here.

DATA AND DATA SOURCES

All data used for swine CAFO flood vulnerability analyses were publicly available from NC government websites and geospatial streaming services. NC OneMap (NCOneMap.gov) hosts a wealth of public datasets that were particularly useful for this study, including county boundary shapefiles and swine waste lagoon points published in 2003. The NC Flood Mapping Program's (NCFMP) Flood Risk Information System (FRIS) website (www.fris.nc.gov/fris) offered all FEMA-approved flood zone tile data used in this study, with publication dates between 2006 and 2018. A dataset updated each year by NC Department of Environmental Quality (NCDEQ) containing all permitted active CAFO locations was downloaded and used as farm point locations. High resolution 1/3 arc-second digital elevation model

(DEM) raster tiles published in 2014 were downloaded from the USGS National Map and used for elevation data. Population and census block 2019 data were downloaded from the US Census Bureau website (www.census.gov). Basemap imagery was streamed via the ArcGIS interface, with imagery flight dates between 2019 and 2020 (Esri Inc., Redlands, CA).

GIS METHODS

Delineation of Active and Buyout Swine Lagoons

Delineation of active permitted swine lagoons was primarily guided by the NCDEQ Permitted CAFO spreadsheet containing point coordinates of all CAFOs in the state. Placement of these coordinates were sometimes erroneous, located hundreds of yards away from any lagoons or housing structures. Despite some misplacement, important information about each permitted CAFO was included in this dataset such as operation name, permit number, owner, address, allowable number of animals, and number of lagoons. Information contained in this spreadsheet was crucial for accurately associating which lagoons belonged to specific operations; the number of lagoons and addresses were especially helpful in tracking down corresponding lagoons and farm points. Addresses provided in the spreadsheet were frequently cross-checked in Google Earth Pro (Google, n.d.) to verify corresponding permit numbers.

Lagoon point data collected and published in 2003 by NC Division of Water Quality (DWQ) were imperative to identifying all active swine lagoons. These points were generally well-placed at the centroid of lagoons. Though the shapefile has some inaccuracies (many bodies of water that were not waste lagoons were labeled as such, for example), some lagoons would not have been successfully delineated without these points. Polygons were carefully drawn around each lagoon, taking care to delineate along the inside of the top of lagoon berms instead of along the water line. Each polygon was assigned a unique Permit ID, consisting of the associated CAFO permit number provided in the DEQ CAFO spreadsheet and a corresponding number lagoon for that particular site.

The DEQ permitted CAFO spreadsheet contained some operations that had an allowable animal count of zero meaning no animals resided onsite but the facility's permit remained current. These operations were delineated but ultimately not included in lagoon flood vulnerability analyses.

The proposed method eventually needed to be verified for effectiveness in identifying flood-vulnerable lagoons. To do so, decommissioned lagoons awarded buyout by NCDA&CS in the past within the study region were delineated, processed, and ranked. The CREPS easement website contains a map with delineated buyout land tracts. Some of the lagoon structures on these sites were no longer visible on the streamed aerial imagery having been completely excavated and filled in with topsoil. Aerial images of these sites dating to when lagoon structures were still intact were examined on Google Earth and used for delineation. This verification of the proposed approach's effectiveness is important because the proposed method cannot be compared to the vulnerability assessment approach currently used by NCDA&CS for buyout; the two approaches are fundamentally different. The proposed method is a proactive approach for risk mitigation compared to the reactive buyout application process, although the two glean vulnerability scores from some of the same parameters.

Constructing Flood Vulnerability Indicators

Several geospatial tools were utilized in feature layer processing and refinement to identify high-risk, flood-vulnerable lagoons including extracting, clipping, joining, merging, and intersecting. Analyses also required multiple table-to-excel conversions and vice versa.

Distance to the nearest 100-year or 500-year flood zone from each delineated lagoon polygon was calculated using the near analysis tool. Information about the nearest flood zone including its type and other relevant attributes were spatially joined to each lagoon polygon. Uncertainties associated with FEMA flood zone estimates are considerable (Wing et al., 2002) and are a crude metric for gauging risk of lagoon inundation. Incorporating this information as one of the flood vulnerability indicators, however, contributes important insight. Even inundation of outer lagoon berms or surrounding areas can lead to decline in lagoon wall structural integrity, increasing the risk of eventual failure.

LiDAR elevation (Z) data were acquired and spatially joined to delineated lagoon polygons to find the difference in average lagoon berm elevation and nearest flood zone elevation. Considering anomalously high or low elevation points often found along lagoon berms, each lagoon polygon was converted to line features and buffered 6 meters inward and outward from which the mean elevation and standard deviation of Z values intersecting buffered regions were extracted. The mean elevation of each lagoon berm buffer plus one standard deviation was used as average lagoon berm heights for nearest flood zone Z comparison to avoid any irregularly high Z values surrounding the berm while still incorporating enough raster cells with high Z values to be representative of the berm lip.

Cost-distance analyses make use of calculated accumulative "impedance" or level of resistance across a given grid raster surface and assign unitless impedance "cost" values to grid cells. Cost distance results essentially give the distance to the nearest "source" for each cell in the raster based on the least-accumulative cost over a cost surface. A cost-distance analysis was performed to calculate a cost-distance raster for water to travel from floodplain boundaries (source location) toward lagoon berms feature class in three dimensions (figure 2).

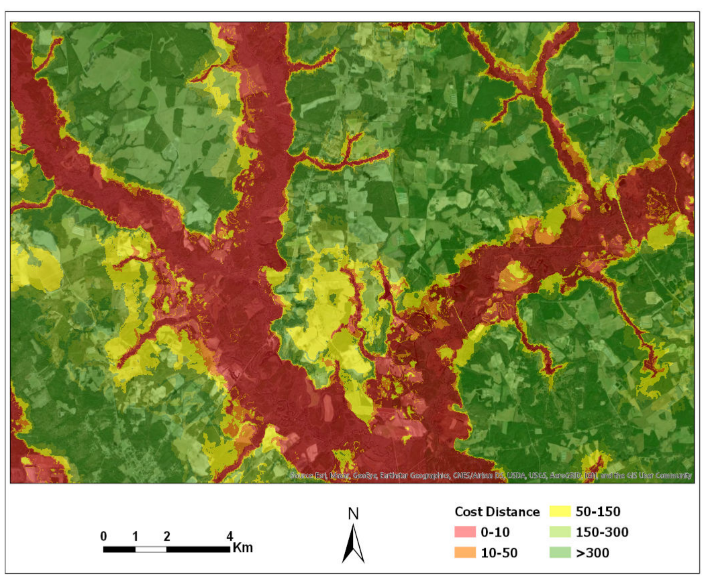

Figure 2. Cost-distance analysis of a flood zone in Duplin County. The cost distance at the source of floodwaters (i.e. rivers and streams) is minimal, growing more difficult for waters to travel upland with increased elevation impedance.

A parameter that addressed lagoon flood risk to surrounding communities was needed to account for human population vulnerability. Census block boundaries and corresponding census block populations were spatially joined to lagoon polygons such that each lagoon had a corresponding population count in the shared census block. Though somewhat crude estimates of nearby populations, census blocks still provide useful insight into the impact lagoon inundation might have on surrounding human populations. Other entities also make use of census tracts as a base unit for assessing impacts of flooding disaster on local communities including the Centers for Disease Control Vulnerability Index and the Nature Conservancy (Shaffer-Smithet al., 2020).

When hog operations were still being constructed in the early- to mid-1990s, CAFOs were considered their own entity. Permit considerations neglected account for the density of nearby CAFOs already established (thus the high concentration of CAFOs we see today in eastern NC). To assess this relationship, the total distance from each lagoon to the nearest neighboring lagoon was calculated. This parameter was chosen as an important flood risk indicator due to the need to consider each lagoon as part of a larger picture; in the event that a given lagoon overflows, the potential for closely neighboring lagoon structures also experiencing inundation ought to be considered, as environmental detriments might compound.

A near analysis was also performed to determine the closest surface water source classified as either nutrient sensitive (coded as NSW) or considered high-quality waters (coded HQW) to each delineated lagoon structure. This consideration is important because environmental and economic repercussions of lagoon inundation or breach in the vicinity of important surface waters are considered greater (NCDA&CS, 2017).

Constructing Index of Flood Vulnerability

Each flood vulnerability parameter was indexed into five levels of overall vulnerability (table 1), ranging from 0 (least flood-vulnerable) to 4 (most flood-vulnerable). Index ranges were gleaned from consideration of data distributions of each parameter for delineated lagoons (i.e. examining quantiles, natural jenks breaks, and normal distributions of all delineated study lagoons) and appropriately refined. More on the method of indexing is included in discussion sections.

Table 1. Vulnerability and risk parameter indexes used to rank lagoons. A rank of "0" is considered least vulnerable.

Index Rank	Census block population (C_{Pop})	Elevation difference between FZ and lagoon berm (Z_{Diff})	Distance to nearest FZ (F_{Dist})	Cost distance from nearest FZ (C_{Dist})	Distance to nearest NSW (S_{Dist})	Distance to nearest HQW (Q_{Dist})	Distance to nearest neighboring lagoon (N_{Dist})
	people	m	m	unitless	m	m	m
0	0 to 75	> 5	> 105	> 300	> 1000	> 1000	> 950
1	75 to 150	3 to 5	75 to 105	150 to 300	500 to 1000	500 to 1000	450 to 950
2	150 to 225	2 to 3	45 to 75	50 to 150	300 to 500	300 to 500	170 to 450
3	225 to 300	1 to 2	15 to 45	10 to 50	100 to 300	100 to 300	20 to 170
4	> 300	0 to 1	0 to 15	0 to 10	0 to 100	0 to 100	0 to 20

Calculating Risk and Vulnerability of Lagoons

For demonstration purposes, the formula used to calculate overall lagoon vulnerability rank assigned an equal weight to each parameter. The formula used is as follows:

$$V_{Farm} = C_{Pop} + Z_{Diff} + F_{Dist} + C_{Dist} + S_{Dist} + Q_{Dist} + N_{Dist} \quad (1)$$

Where

V_{Farm} = Overall farm vulnerability

C_{Pop} = Total population in census tract where lagoon resides

Z_{Diff} = Elevation difference between nearest FEMA flood zone and lagoon berm elevation

F_{Dist} = Distance to nearest flood zone boundary from lagoon edge

C_{Dist} = Cost distance of flood source across slope raster

S_{Dist} = Distance to nearest nutrient sensitive water from lagoon edge

Q_{Dist} = Distance to nearest high quality water from lagoon edge

N_{Dist} = Distance to nearest neighboring lagoon from lagoon edge

The highest flood vulnerability score a given lagoon could therefore receive is 28 and the lowest 0. Results of the spatial distribution of high-risk and low-risk lagoons identified via the proposed methodology were then examined via two spatial analysis tools, detailed in section 3.2.

RESULTS

OVERALL RISK AND VULNERABILITY OF ACTIVE LAGOONS

A total of 1,497 lagoons belonging to 882 different farm sites were delineated within the study region, representing 41.5% of all permitted swine CAFOs in the state. An additional 39 lagoons were identified and deemed either inactive (a total of 34 lagoons) or belonging to an operation with a specified allowable count of zero in the NCDEQ spreadsheet (five lagoons). These operations were ultimately excluded from analyses. The decision to exclude these operations from consideration was based on the assumption that these lagoon structures were unlikely to contain fresh hog waste and therefore posed less of an environmental and human health risk during flooding events compared to active sites.

The vast majority of operations were ranked as having a flood vulnerability risk of 10 or below (94.3%) (table 2). The highest score any lagoon received was a 17 and both the average and median vulnerability rank of all delineated lagoons was 5.

Table 2. Number of operations falling within each vulnerability level. The majority of operations are considered low-to medium-risk.

Vulnerability /Risk Index	Level of Risk	Number of Lagoons Active Lagoons	Percent of all Delineated Lagoons in Study Area
0 - 4	Low	739	49.4 %
5 - 9	Low-Medium	634	42.3 %
10 - 14	Medium-High	114	7.6 %
≥ 15	High	10	0.07 %

It is important to note that the surface water parameters (S_{Dist} and Q_{Dist}) had very few lagoons that scored above 0. Only two lagoons were ranked as having "1" level of vulnerability in relation to nutrient sensitive waters (at a distance of between 500 and 1000 meters from the nearest nutrient-sensitive water body); the remaining 1,495 lagoons were ranked 0 for this parameter. Only 32 lagoons were ranked above a score of zero for distance from the nearest high quality water body. These parameters were certainly important to examine, however assessing the vulnerability and risks associated with specific lagoons with these criteria included slightly skewed the concept of a high-risk, flood-vulnerable lagoon when given the same amount of weight as all other parameters. Any score above a value of 15 was therefore considered "high risk."

Spatial Distribution of Identified High-Risk Lagoons

Two statistical analyses were performed on the total ranking scores of active lagoons to visually examine the spatial distribution of lagoons categorized as high- and low-risk using the new methodology: a hotspot analysis using Getis-Ord Gi* method and a cluster and outlier analysis using Anselin Local Moran's I method (figure 3). Hotspot, cluster, and outlier analyses were utilized to identify regions within the study area considered high-risk as well as identifying specific lagoons that might have a significantly high overall risk score in an otherwise statistically low-risk area (and vice versa).

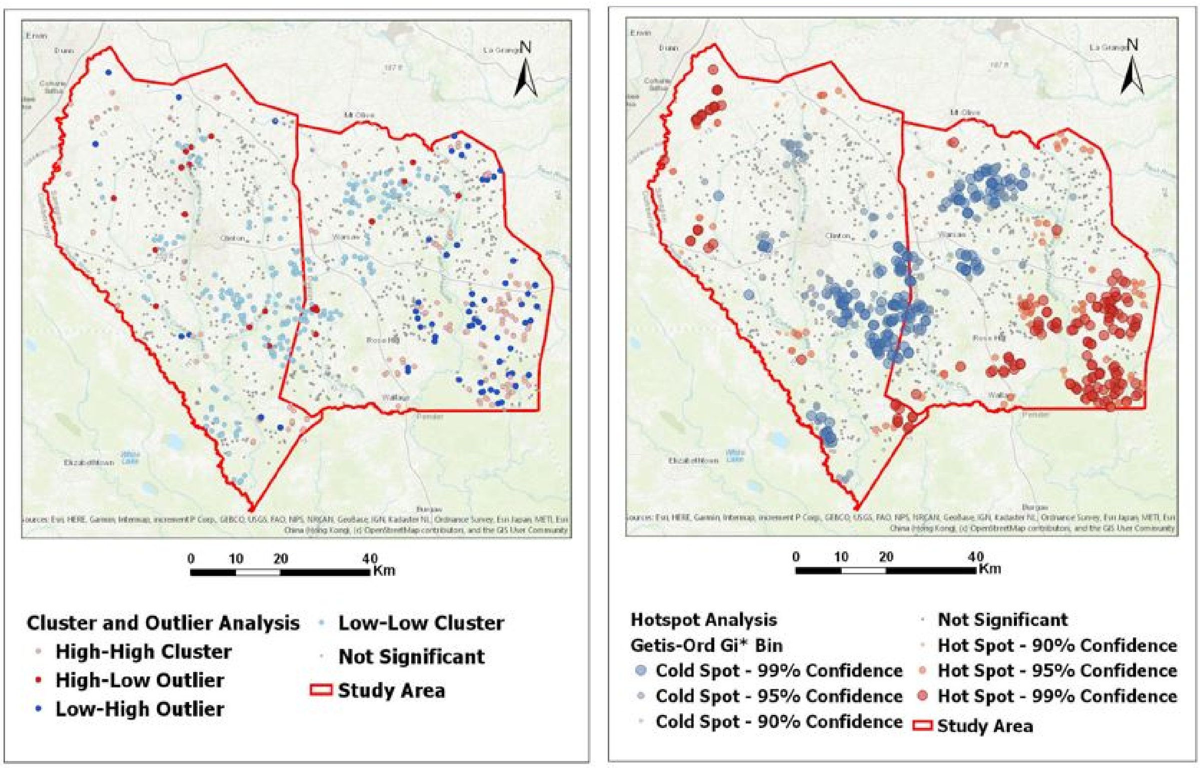

Figure 3. (Left) Hotspot analysis using the Getis-Ord Gi* statistic. Hotspots appear to occur in the southeast and northwest corners of the study region. (Right) Cluster and outlier analyses indicate where clusters of high and low risk occur (high-high and low-low) and regions where a low risk lagoon resides in a high-risk region (low-high) and vice versa.

The Getis-Ord Gi* hotspot analysis tool was used with a Euclidean distance band of 4500 meters. The Getis-Ord Gi* statistic examines z-scores and p-scores of the total sample and indicates where features with either high or low values cluster spatially by examining each feature within the context of neighboring features. Results from the hotspot analysis indicate that spatial clustering of high-risk operations occurs most prominently in the southeast portion of the study area and in the upper northwest corner. Clustering of high-risk operations in the eastern-most portion of the study area makes sense, as elevation tends to gradually slope toward the east in this region. Cluster and outlier analyses were performed using the Anselin Local Moran's I statistic. Output from this analysis locates hotspots (regions with clusters of high-risk lagoons), cold spots (regions where there are several lagoons with low risk value), and outliers within hot and cold spots, indicating a lagoon with a high risk value in a region of low-risk lagoons or vice versa. This tool is useful for identifying specific lagoons that might benefit from increased maintenance or inspection efforts in regions where the majority of lagoons are considered low risk.

Most tracts of land where easements were awarded are located directly within the floodplain and reside in regions identified as hotspot clusters in spatial analyses of active lagoons (figure 4), verifying the model's effectiveness in identifying presumably high-risk regions.

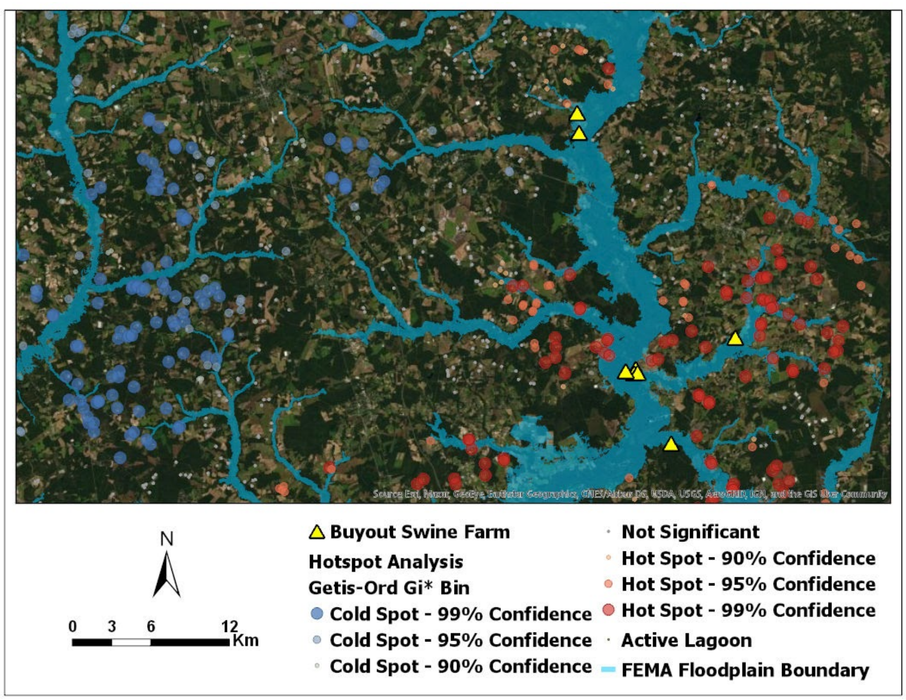

Figure 4. Locations of seven out of nine buyout sites within the study region reside in hotspot areas.

DISCUSSION

COMPARING STUDY VULNERABILITY AND NCDA&CS BUYOUT APPROACHES AND LIMITATIONS

The proposed method appears to be effective, however in need of refinement. The average vulnerability score of buyout lagoons nearly reached the defined threshold of "highly vulnerable" at a score of 15 but not quite. Adjustment of parameter weights (such as increasing the weights of strictly flood vulnerability parameters) might be an appropriate modification to equation 1 to assess highly flood-likely lagoons.

Some operations located outside the 100-year floodplain have been selected for buyout and closure by NCDA&CS in the past, likely due to repeated flooding events despite residing well outside of FEMA flood zone boundaries. In general, however, the buyout program eligibility requirements clearly state that an operation cannot be considered for buyout unless a large tract of land (20 acres or more) lies within the 100-year floodplain. Using solely the 100-year floodplain boundary stipulation for identification of eligible buyout operations, only eleven operations within the study area would technically be considered for buyout.

The proposed method strictly draws from publicly available data. Operations under consideration for NCDA&CS buyout are subject to site assessments where information such as flooding history can be obtained and CAFO property, housing, and equipment evaluations can be performed (NCDA&CS, 2017). Flooding history of each lagoon, berm inspection reports, and CAFO property, housing, and equipment condition or value estimates were not available for each farm site, and therefore could not be used for analysis though these factors would be useful in judging the most flood-prone, economically-relevant operations for potential closure or increased risk-mitigation efforts.

DATA UNCERTAINTIES AND POTENTIAL ERROR

Several uncertainties in data and methods exist that might contribute to inaccuracies in flood vulnerability analyses. The DEM from which all elevation information was of 1/3 arc-second resolution, or roughly 10-meter tiles. The USGS National Map contains 1/9 arc-second resolution DEMs for nearly the entire state of NC, save two roughly one-square mile areas in Duplin County. The reason for these two missing areas in the 1/9 arc-second DEM layer, specifically only in Duplin County, is not clear. Upon inspection of the missing areas, several lagoons fell within the region; the 1/3 arc-second DEMs were the next-highest available resolution that contained the entire study region and used for analysis.

Flood zone estimates have documented errors and uncertainties but are used extensively for research, real estate, insurance, and city planning purposes (Nasiri et al., 2015). As a way to bypass FEMA flood zone uncertainties, flood extent estimates of Hurricanes Matthew (2016) and Florence (2018) were investigated as alternative indicators of major flood extent in the region (NCOneMap.com). Unfortunately, hurricane flood extent estimates ultimately could not be used as the flood estimate raster recognized all bodies of water (including lagoons) as part of the flood extent. Visual inspection of the estimated flood extents of Hurricanes Matthew and Florence in comparison to established 100- and 500-year flood zones was interesting, however, and supported the known fact that flood zone estimates are imperfect (figure 5).

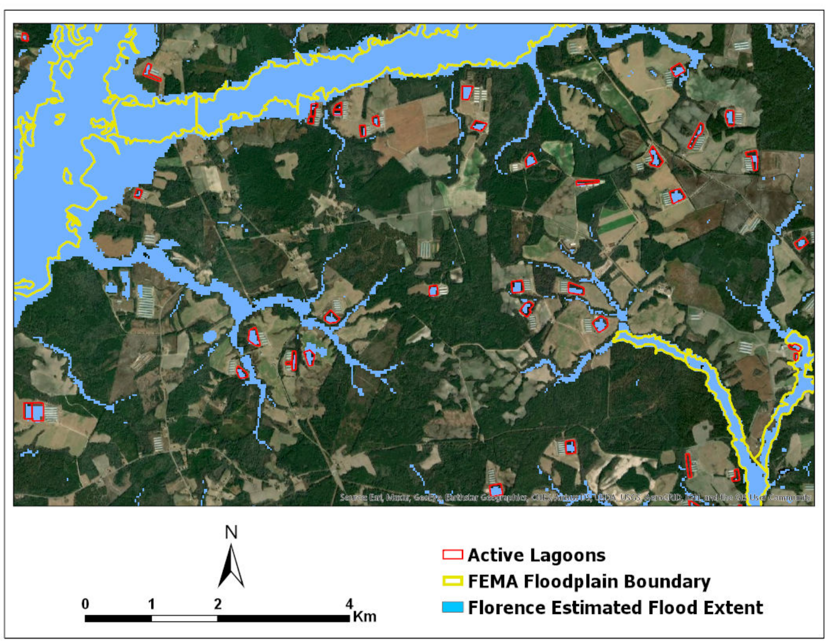

Figure 5. FEMA flood zone estimates superimposed over Hurricane Florence flood extent. The estimated hurricane flood extent classifies lagoons as part of the flood extent, and therefore could not be used unless each lagoon was examined manually.

Use of census block data in tracts where lagoons reside to serve as population estimates has limitations.

In the event of lagoon inundation or breach, lagoon material will most likely travel down the least cost-distance pathway--generally toward nearby surface waters and subsequently toward the east in this region. A lagoon located in the eastern-most portion of a given census tract or in an area of lower average elevation in relation to the rest of the census tract therefore likely would not have much effect on upper populations of the tract but would instead impact the adjacent tract in the direction of the least-cost pathway.

Some average elevation values used for assessing flood vulnerability might not serve as the most representative elevation value in some instances. Both the average nearest flood zone elevation and the average cost-distance value for each lagoon were used or extracted for analysis. Mean elevation values were used to curb the risk of anomalously high or low elevations and should therefore be considered estimates of true elevation differences.

Indexing of each parameter was done carefully but not the same across all parameters. The distribution of the seven parameter values for all 1,497 lagoons were first examined in considering appropriate index ranges. Though it was useful to see the distribution of values across parameters, indexing by natural breaks or by quantiles was not proportionately related to vulnerability ranking. For example, differences between average berm elevation and nearest flood zone elevation for considered lagoons ranged from 0 to nearly 10 meters, with an average berm elevation of roughly 3.5 meters. The historic storm surge of Hurricane Florence--the highest storm surge ever recorded in NC--reached between roughly 2.7 and 4 meters (Steward & Berg, 2019). Lagoon berm elevation and nearest flood zone elevation index ranking values were therefore selected to best reflect realistic levels of flood risk. Similar reasoning was used to select cost-distance, distance to nearest flood zone, distance to nearest important surface water, population, and distance to nearest neighboring lagoon vulnerability index values, taking into consideration the statistical spread of the data while also drawing on experience and real world logic. Assigning index values in this manner does leave room for speculation, as ranking values are subjective however can easily be adjusted.

CONCLUSIONS

The proposed vulnerability ranking method serves as a more holistic approach of managing flood risks of hog lagoons. This method is unique in that it proposes a way to mitigate flood impacts preemptively.

An outcome of this study is the indication that the vast majority of active swine CAFO lagoons in eastern NC are at very little imminent risk of experiencing floods and causing serious environmental or community damage as a result. This does not mean that CAFOs are not harmful to humans and the environment in other aspects, but that the model suggests most well-managed operations are geographically safe from serious flooding impacts. The approach adopted in this study is flexible and can be applied to realms outside of just hog lagoon management.

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