Using NDVI to Assess Plant Response after Storm Surges in Fresh Water Marshes on the Coast of Louisiana.

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Abstract

Effective management of natural resources in coastal areas requires an understanding of changes in salinity and water levels. In this master's thesis, I used the Normalized Difference Vegetation Index (NDVI), which allows one to infer plant health through remote sensing to analyze how plants respond to salinity and water levels in freshwater marshes after five major recent hurricanes. The NDVI was calculated for plots around Coastwide Reference Monitoring System (CRMS) monitoring stations in the path of the hurricanes before and after their landfall. I used the calculated values to assess the relationships between changes in NDVI and the following four variables calculated from data measured in the CRMS stations: peak water level, change in water level, peak salinity, and change in salinity. Results indicate that the change in NDVI is negatively correlated with the observed peak and the change in water levels of freshwater sites during the hurricanes. The direct relationships were not significant with salinity variables (i.e., peak salinity and change in salinity), which only became significant factors explaining the change in NDVI when combined with the water level variables, explaining up to 61% of the variability of the change in NDVI.

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List of Abbreviations

MRD	Mississippi River Delta
NDVI	Normalized Difference Vegetation Index
NIR	Near Infrared
CRMS	Coastwide Reference Monitoring System
PSU	Practical Salinity Unit
m	Meter
B3, B4, B5	Band 3,4,5 (range of frequency bands in satellite image)
BIC	Bayesian Information Criterion
R^2	Coefficient of Determination
Δ	Changes in Variables

1. Introduction

Strong winds during tropical storms may push saltwater into freshwater ecosystems upstream in estuary systems. This form of superficial saltwater intrusion is relatively common in coastal areas subject to tropical storms, which have recently experienced increased frequency and intensity(Allahdadi & Li, 2018). Not only coastal regions directly facing the ocean but also certain inland freshwater ecosystems such as wetlands, lakes, and ponds linked within the land-ocean interface are susceptible to such extreme occurrences. For instance, widespread flooding encompassed numerous inland water bodies, properties, and vital energy infrastructure during Hurricane Katrina, rendering it one of the most catastrophic hurricanes in U.S. history (Williams, 2010). The ecological impacts, particularly the loss of vegetation in freshwater wetlands and its replacement for salt-tolerant species or switch to open water areas, are still being felt throughout the region of the coast of Louisiana (Tully et al., 2019).

Saltwater intrusion is a major issue that has long been damaging the coastal region of Louisiana. For example, a study of vegetation species assessment on the Mississippi River Delta (MRD) showed the landscape experienced decreasing coverage and floristic quality during the flooding periods and low and nominally increasing vegetation cover and quality through the dieback and recovery periods (Suir et al., 2022). Plants are excellent indicators of wetland function and condition because of their rapid growth rates and direct response to environmental stressors and disturbances (Smith et al., 1996). Freshwater wetland plants can be affected when exposed to salinities outside the freshwater range (i.e., >0.5 PSU). The relationship between plants and salinity can be complex and depends on several factors, including the plant species, the degree of salinity, and the duration of exposure. Still, all species are typically more affected by increased salinity concentrations and exposure duration (Visser and Peterson 2015). Also, the tolerance of saline conditions in those plant roots is a matter to consider. There is a continuous spectrum of plant tolerance to saline ranging from very sensitive glycophytics, those showing conditions of dying and going yellow at salt concentrations of less than 1/10 sea water (50 mol m–3), to halophytes, that complete their life cycles at 500 mol m (Volkmar et al.1997). The effect of saltwater intrusion on plants can be detrimental, especially for plants that are not susceptible to high salinity levels (i.e., 10 PSU to 35 PSU). The most significant impacts include reduced water uptake, ion imbalance, toxicity, and reduced growth and yield (Husen et al., 2018).

The Normalized Difference Vegetation Index (NDVI) is a remote sensing matrix often used to interpret the overall functioning of different ecological systems, and multiple studies have linked it with plant health in upland and wetland ecosystems (Elliott et al., 2015; Xu et al., 2018). The NDVI is calculated from reflectance in the red and near-infrared wavelength bands in multispectral imagery, and high values are linked to low-stress levels, while low values are associated with high stress. However, other factors also can impact the NDVI value e.g. size of the plants, and seasonal changes. Variations in NDVI values have been used to evaluate plant conditions after a storm. For example, a study conducted over the coast of Louisiana by (Steyer et al., 2007) used NDVI values to compare greenness in vegetation over five years, including the landfall of Hurricane Katrina and Rita. The results indicated a decline in vegetation density and vigor across the east region of New Orleans from August 2005 to September 2005 after Hurricane Katrina. Also, the prevalence was seen across all areas from September 2005 to October 2005 after Hurricane Rita. The NDVI values suggest that over 4,714 km2 or 32.9% of the coastal wetland area of Louisiana experienced an immediate decline in vegetation density and vigor in October 2005 (Steyer et al. 2007). According to (Mo et al., 2020) the decrease in NDVI data during the middle of the years 2005-2008 indicates that impacts from Hurricane Katrina were magnified by Hurricane Rita, which was tracked just southwest of the study area before making landfall at the Louisiana/Texas.

This thesis focuses on the link between changes in NDVI of freshwater marshes on the coast of Louisiana and the water levels and salinity resulting from storm surges during hurricanes. To this end, I combined multispectral imagery from Sentinel-2 & Landsat-8 captured before and after five major hurricanes with water level and salinity concentrations measured in monitoring stations along the paths of the hurricanes.

2. Objective & Hypothesis

This thesis aims to evaluate the relationship between observed changes in NDVI and the magnitude of water levels and salinity during storm surges. Specifically, I evaluated the relationship with these four variables: peak water level during the surge (PkWL) and change in water level before and after the surge (ΔWL), peak salinity during the surge (PkSAL), and the change in salinity before and after the surge (ΔSAL). We tested the hypothesis that changes in NDVI are negatively correlated with these four variables.

3. Methodology

3.1 Study Area

This study was conducted in the freshwater marshes of Barataria Basin (south of New Orleans/23.8 miles from New Orleans) and the Lake Pontchartrain Basin (east of New Orleans/16.1 miles from New Orleans) (Figure 1). We selected this area for its combination of recent extreme hurricanes and coverage of CRMS stations. In this study, five major hurricanes of categories ranging from 2 to 4 were selected including Hurricane Ida, Harvey, Laura, Zeta, and Delta (Table 1). The marshes in the Barataria Basin are influenced by freshwater and sediment inputs from the Mississippi River, rainfall, and other environmental events that create freshwater conditions. Multiple Coastwide Reference Monitoring System (CRMS) sites located in freshwater areas along the hurricane paths were selected and then filtered according to the data availability (i.e., some did not have useful records within the period of analysis).

Table 1- Hurricanes used in this study, including their categories.

Hurricanes	Year	Category
Hurricane Ida	2021	4
Hurricane Laura	2020	3
Hurricane Zeta	2020	2
Hurricane Delta	2020	4
Hurricane Harvey	2017	4

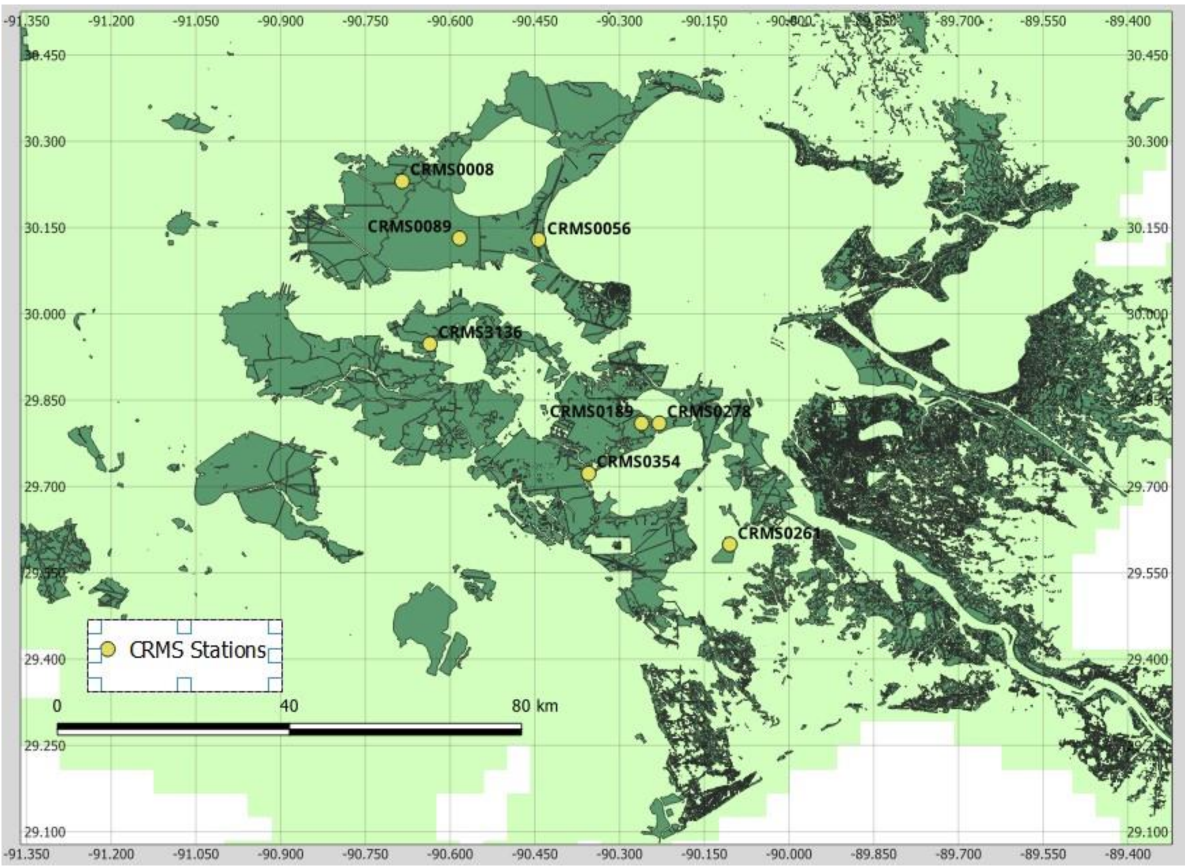

Figure 1: *Map with CRMS sites used in this study.*

3.2 Image Acquisition:

Multispectral imagery of the area of interest was collected from Landsat 8 & Sentinel-2 (Figure 2). These images consisted of red (R) and NIR (Near Infrared) bands (Landsat 8 'is B4 & B3 & Landsat 8 is B4 & B5). The aim was to get images approximately one month before or after the hurricanes, depending on the availability of imagery (Table 2). After downloading, images were processed, and the cloud cover was removed to adjust the noise (Fig 2). The images were downloaded with 5-10% cloud cover, and while working on ArcGis, I used the CON spatial analyst tool to remove the rest of the cloud cover to achieve better resolution. The resulting images covered the period between August and early November of any given year, encompassing the more active part of the hurricane season.

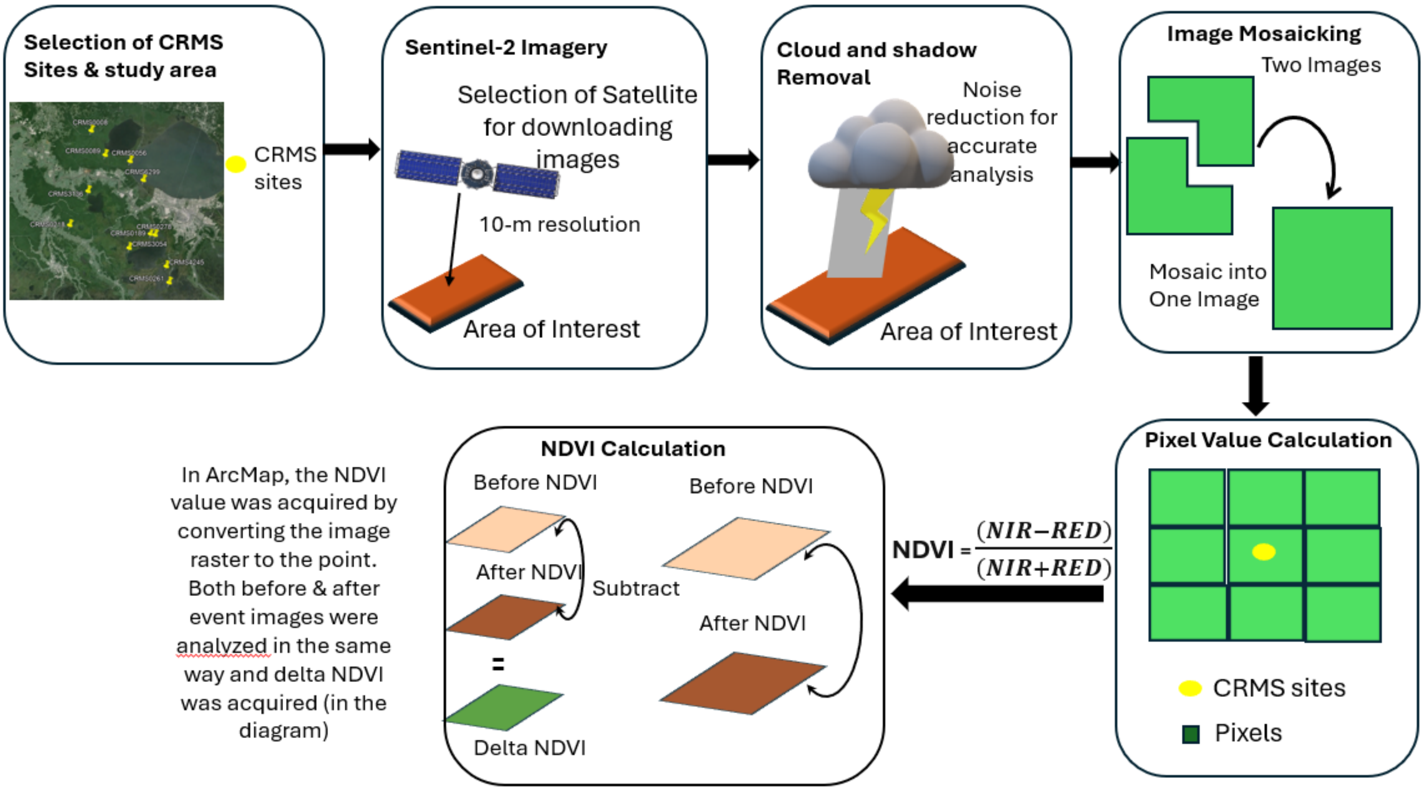

Figure. 2: *Explaining the process of multispectral and ground data acquisition.*

Table 2- Image acquisition data with satellite.

Hurricane	Hurricane Date	Image captured date (before)	Image capture date (after)	Satellite
Ida	08/26/2021	08/16/2021	09/12/2021	Sentinel-2
		08/21/2021	09/12/2021	
Laura	08/27/2020	07/08/2020	09/10/2020	Sentinel-2
		07/04/2020	09/10/2020	
Zeta	10/28/2020	10/17/2020	11/02/2020	Sentinel-2

		10/17/2020	11/28/2020	
Delta	10/09/2020	08/24/2020	10/17/2020	Sentinel-2
		08/16/2020	10/17/2020	
Harvey	08/17/2017	05/10/2017	09/08/2017	Landsat-8

For more detail, Sentinel-2 images were preferred for their 10 m spatial resolution and the availability of multiple images compared to the Landsat image (30 m spatial resolution) collection. Sentinel-2 images were used for all hurricanes, except Harvey which took place in 2017 and was analysed through Landsat-8 imagery since Sentinel-2 does not have images prior to 2018. ArcMap 10.8.2 was used to create the NDVI index using a raster calculator. Every pixel within the raster image was assigned a digital number corresponding to each band collected from satellite imagery. This digital number quantifies the light reflection within the specified area of the vegetation represented by the pixel in that specific band. The calculation of NDVI, derived from the red and near-infrared bands in multispectral data, was executed for every pixel in each image as follows:

$$\text{NDVI} = \frac{(\boldsymbol{NIR}-\boldsymbol{RED})}{(\boldsymbol{NIR}+\boldsymbol{RED})} \qquad \text{equation [1]}$$

To get a more approximated value for the area around the CRMS stations, the NDVI of the eight neighbouring pixels was also calculated and averaged per station. Then, the change in NDVI (ΔNDVI) was calculated by subtracting the average values after and before the hurricane.

3.3 Water and salinity levels

Hourly water levels and salinity concentrations ten days before and ten days after the hurricanes were used to determine four water level and salinity variables: peak water level

(PkWL), change in water level (ΔWL), peak salinity (PkSAL) and change in salinity concentration (ΔSAL). PkWL (m) and PkSAL (PSU), were determined as the maximum value in the 20-day hourly record, while ΔWL and ΔSAL, were calculated as the difference between the mean of the values 48 hours after the hurricane's landfall and the mean of the values 48 hours before it (Figure 3).

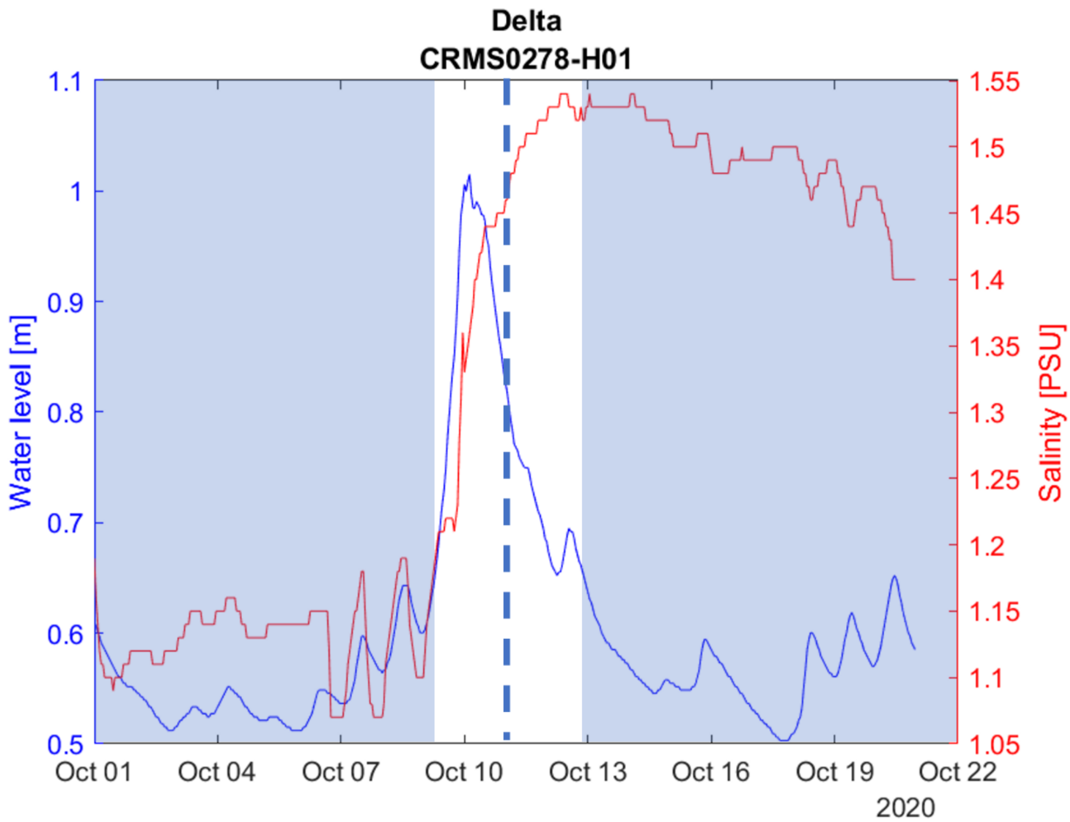

Figure 3: *Sample storm surge showing the landfall (dashed line) and periods used to calculate mean water levels and salinity before and after the hurricane (grey highlights).*

The water level and salinity data used were downloaded from the CRPA (Coastal Protection and Restoration Authority) Lacoast.gov website.

3.4 Data analysis

Linear regressions were used to evaluate the direct relationships between ΔNDVI and ΔWL, PkWL, ΔSAL, and PkSAL. Then, a forward stepwise regression model was run to assess the combined effects of the water level and salinity variables on the observed ΔNDVI. All statistical regression analyses were conducted in JMP Pro 16. The ΔWL, PkWL, ΔSAL, PkSAL, and ΔNDVI variation between hurricanes was evaluated with a non-parametric comparison of each pair using the Wilcoxson method. The regressions and comparison by hurricanes were conducted with a significance level (α) of 0.05

4. Results

Out of the 43 storm surges analysed, 8 were discarded because the salinity decreased, indicating that the surge may have brought freshwater instead of saltwater. The peak water levels observed in the different CRMS stations ranged from 0.5 m at CRMS 0089 during Hurricane Ida to 2.4 m at CRMS 0056 (Figure 4a). These peaks led to ΔWL that ranged from 0.1 m in the further inland stations (e.g., CRMS 0354) to up to 2.2 m in those fringe stations more exposed to the storm surge (e.g., CRMS 0056) (Figure 4b). Salinity ranges were also highly variable, with peak levels as low as 0.06 PSU at CRMS 3136 during Hurricane Harvey and as high as 2.16 PSU in CRMS 4245 during Hurricane Harvey (Fig. 4c). Salinity change was also associated with the exposure to the surge and was the highest in stations more exposed and ranged from 19.2 PSU at CRMS 0354 during Laura, to 0.21 PSU at CRMS 0089 (Figure 4d). ΔNDVI ranged from -0.44 during Laura to 2.35 during Zeta. Interestingly, these extremes were observed at the same station, CRMS 4245.

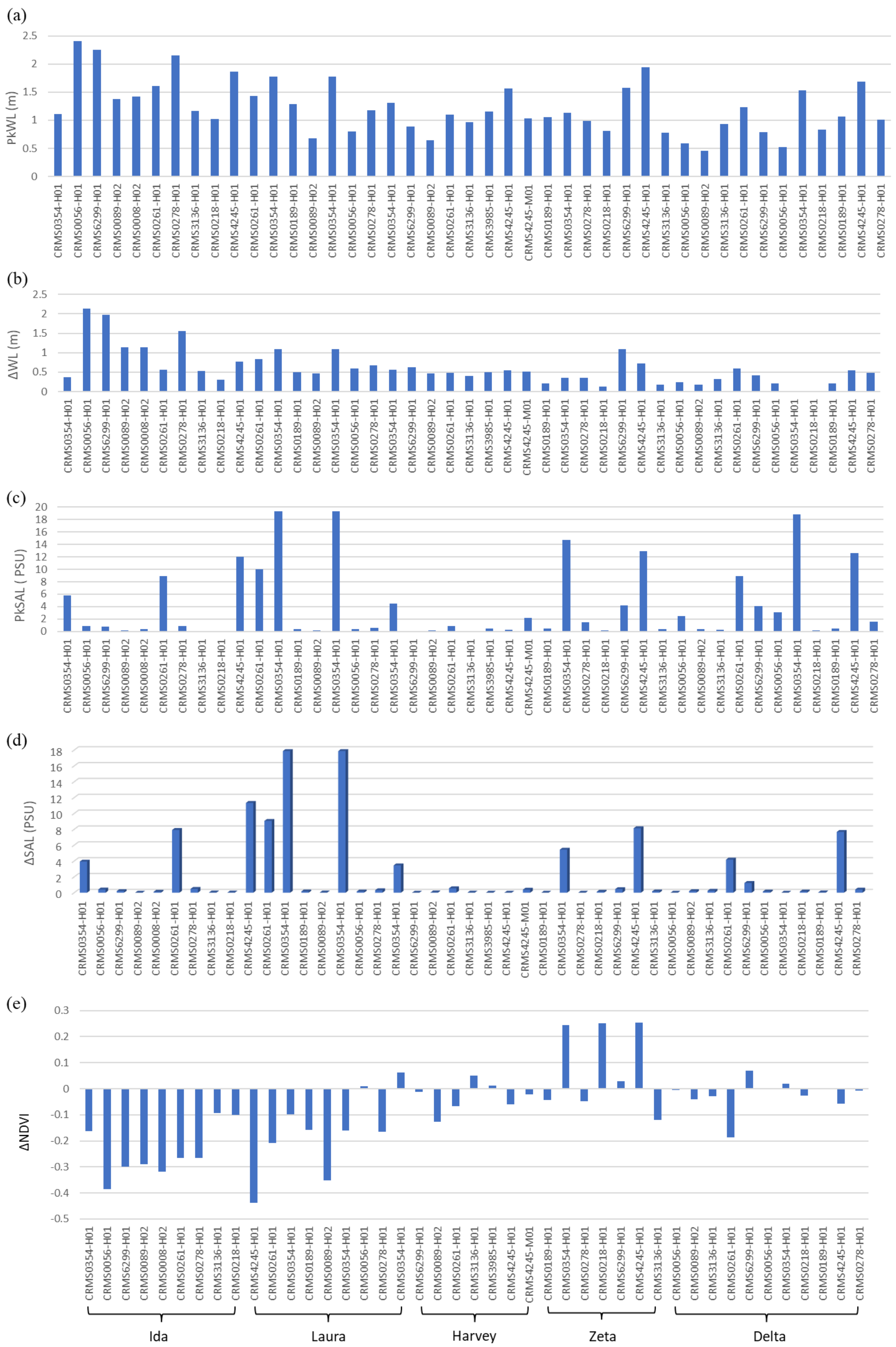

Figure 4: *(a) Peak water level (PkWL), (b) change in water level (ΔWL), (c) Peak salinity (PkSAL), and (d) change in salinity (ΔSAL). CRMS sites during hurricanes Ida (Ida (CMRS0354-H01, CMRS0056-H01, CMRS6299-H01, CMRS0089-H02, CMRS0008-H02, CMRS0261-H01, CMRS0278-H01, CMRS3136-H01, CMRS0281-H01), Laura (CMRS4245-H01, CMRS0261-H01, CMRS0354-H01, CMRS0189-H01, CMRS0089-*

H02, CMRS0354-H01, CMRS0056-H01, CMRS0278-H01), Harvey (CMRS0354-H01, CMRS6299-H01, CMRS0089-H02, CMRS0261-H01, CMRS3136-H01, CMRS3985-H01, CMRS4245-H01), Zeta (CMRS4245-H01, CMRS0189-H01, CMRS0354-H01, CMRS0278-H01, CMRS0218-H01, CMRS6299-H01, CMRS4245-H01, CMRS3136-H01, CMRS0056-H01), Delta (CMRS0089-H01, CMRS3136-H01, CMRS0261-H01, CMRS6299-H01, CMRS0056-H01, CMRS0354-H01, CMRS0218-H01, CMRS0189-H01, CMRS4245-H01, CMRS0278-H01).

The water level peaks and changes observed during hurricanes Delta and Harvey were generally lower than those during Ida (Fig. 5 a,b). Peak salinity tended to be lower during Hurricane Ida, but other patterns with peak and change in salinity were unclear as there was much variability within each hurricane (Fig. 5 c,b).

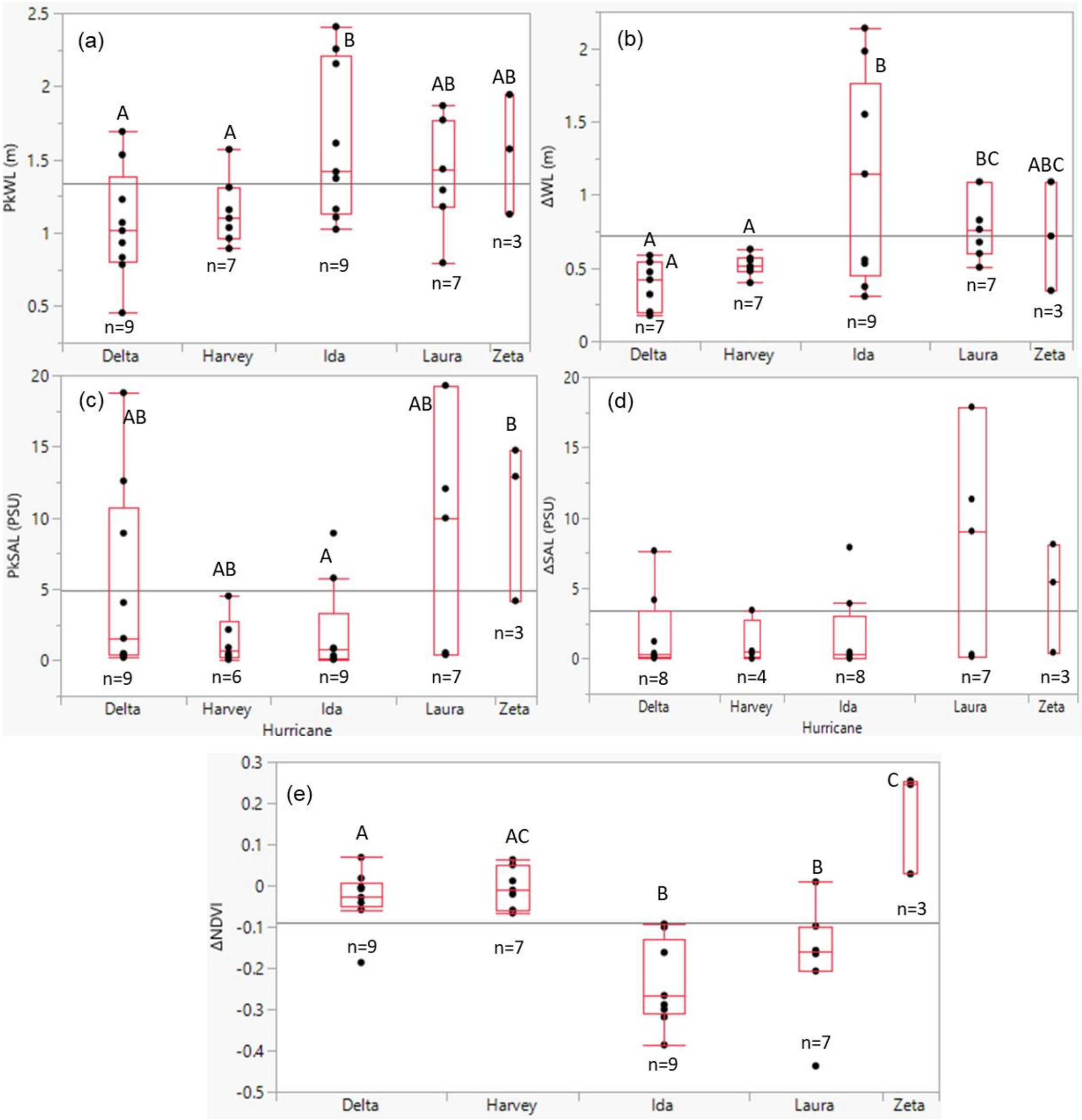

Figure 5: *(a) Pk WL, (b) ΔWL, (c) Peak Salinity, (d) Δ Salinity, and (d) changes in NDVI (ΔNDVI) by hurricanes. Different letters represent the statistical difference (α=0.05) for non-parametric comparisons calculated with the Wilcoxson Method, each pair comparison. The horizontal line shows the overall mean value.*

When analyzed independently, ΔNDVI were negatively correlated with the peak and ΔWL before and after the hurricanes and their corresponding storm surges (p<0,05, Fig. 6 a,b). No significant linear relationships existed between ΔNDVI and ΔSAL or PkSAL ΔSAL (p>0.05, Fig. 6 c, d).

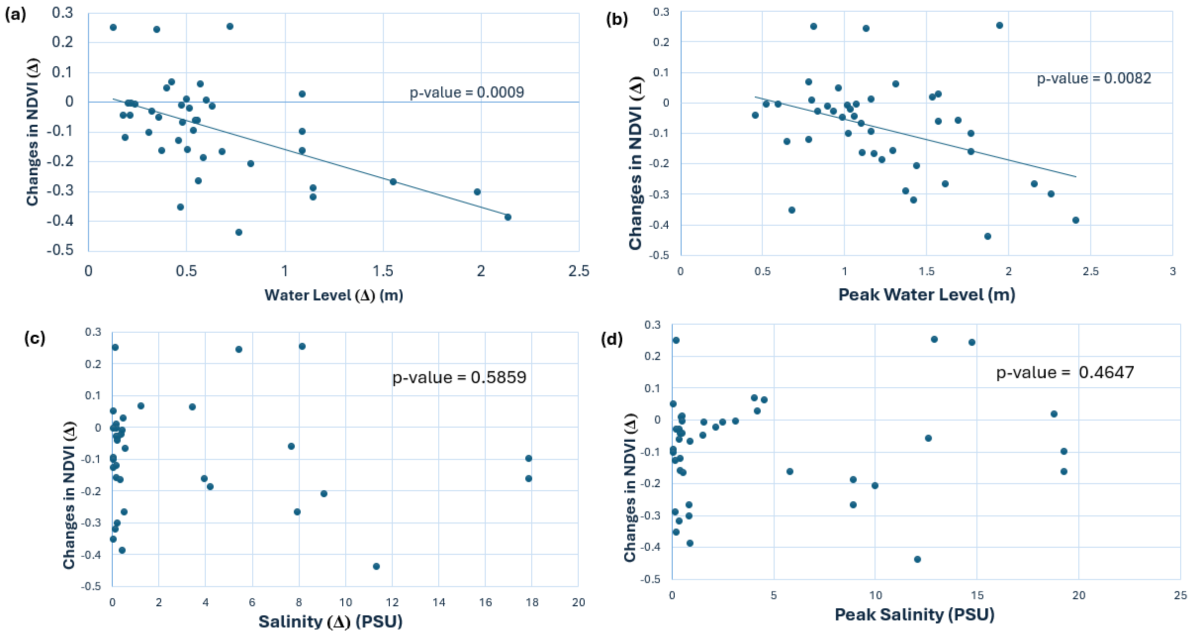

Figure 6: *Fit line plot for NDVI & Δ water level (a), peak water level (b), Δsalinity (c), and peak salinity (d).*

However, the stepwise regression model revealed that the effect of salinity is only apparent when combined with the water levels. In our analysis, ΔWL, the interaction between PkSAL and ΔSAL, and ΔWL and PkSAL accounted for as much as 61% of the variability of the NDVI changes before and after the hurricane (Table 3). The effect of the ΔWL was negative, as expected from our linear regressions (Figure 7), while the effects of the interactions were negative.

Table 3- Stepwise regression model. The sign on the independent variable column indicates the direction of the relationship between the change in NDVI and the variable.

Model Adjusted R^2	0.61	
Partial R^2	BIC (Bayesian Information Criterion)	Independent Variables
0.31	-24.09	- Delta water level
0.32	-32.41	Peak salinity × Delta salinity
0.05	-32.99	Delta water level × Peak salinity

5. Discussion

The purpose of this thesis was to evaluate the relationship between observed changes in NDVI and the magnitude of water levels and salinity during selected storm surges. The findings of significant negative relationships between ΔNDVI and PkWL, ΔWL partially confirm our initial hypothesis because we did not find significant relationships with the salinity variables (i.e., PkSAL, and ΔSAL) when considered separately (Figure 6c and d). However, the effects of salinity were unmasked when analyzing the salinity variables combined or with ΔWL (Table 2). For instance, the combined effect of PkSAL × ΔSAL and ΔWL × PkSAL were able to explain up to 37% out of the 61% of the variability of the ΔNDVI, or in other words, salinity-related effects can account for around half of the variability in ΔNDVI.

NDVI of vegetation in a specific wetland is related to its water level, and it can serve as a metric for assessing water availability (Aguilar et al., 2012; Wang et al., 2014). Vegetation productivity is closely related to water level to the extent that flooding for prolonged periods can stop plant growth or even lead to plant dead (Aguilar et al., 2012). This effect of flooding was reported during Hurricane Katrina in 2005, when flooding from the Magnolia River caused water clogging in the coast of Alabama, which led to alteration of vegetation, as evident through changes in the NDVI over time series (Rodgers et al., 2009).

The area selected for this study has been impacted by multiple major hurricanes in recent decades. In this area, marshes are surrounded by freshwater lakes and other water bodies that can help propagate the effects during storm surges and further acting reservoirs for saltwater, creating longer than usual periods of elevated water levels and salinity concentrations (Bay et al., 2011).

Salinity is considered the primary environmental factor affecting community patterns in coastal ecosystems (Naumann et al., 2009). The sudden increase in water level and salinity resulting from storm surges, represented by an increase in saline level, alters plant growth and becomes toxic for plants (Goto et al., 2015). That results in less production and plant growth and eventually may lead to plant death. Through this process, multispectral sensors cannot detect the reflection of enough chlorophyll, rendering cues of unhealthy vegetation (Naumann et al., 2009 et al. 2009). In particular, NDVI is a very reactive index based on water levels and salinity (Omute et al., 2012).

One of the limitations of this study was that it did not include data on the structure of the vegetation community. Variables like density, size or life stage, and species could help understand better the variability in our observations as different plant species have different traits and tolerance (Yellen et al., 2021), thus influencing their response to storm surges. For example, the wide range of NDVI response observed at station CRMS 4245, which includes two separate surge conditions, may be explained by species-specific traits of the dominant vegetation or timing of hurricane strike to the growth stage.

The plant community structure and distribution are tied to the dynamic interactions between freshwater and saltwater, and it is influenced by factors such as river flow, sediment deposition, and human activities like levee construction and channelization (Yellen et al., 2021). Understanding these interactions and how they respond to extreme weather events is crucial for managing coastal wetlands, estuaries, and fisheries and addressing issues like land loss, saltwater intrusion, and ecosystem degradation exacerbated by climate change and sea level rise. Additionally, freshwater studies can inform restoration efforts and adaptation strategies to safeguard the ecological and economic resilience of the Louisiana coast.

Assessing the impact of hurricanes across a broad coastal area can be challenging due to the difficulty in finding suitable reference sites for comparison. However, in future studies, one potential method to overcome this challenge is to evaluate the NDVI and the condition of plants along a spectrum of water level changes. This approach allows for examining vegetation health and response to flooding, providing valuable insights into the effects of hurricanes on coastal ecosystems. Also, considering coastal resilience by having diversity in plant species is necessary since the long-term impact of hurricanes takes longer to recover (Yellen et al., 2021). For example, in brackish and saline systems of Louisiana, mangrove trees (*Avicennia germinans*), and salt marsh grass (*Spartina alterniflora*) were compared based on their potential to withstand major storms. Mangroves grew more slowly and limited the possibility of swift restoration, while salt marsh grass grew quickly, making it perfect for establishing vegetation cover in coastal areas (Yando et al., 2019). So, future studies may also consider long-term changes in vegetation due to alteration by wind and diverse plant species in different wetlands, which may help with more post-disaster management practices.

6. Conclusions

This thesis addressed the relationship between changes in NDVI and associated peak water and salinity levels and their changes before and after the hurricanes. Changes in NDVI were negatively correlated with the peak and the changes in water levels. The relationship of changes in NDVI with salinity was only evident when peak and changes in salinity were combined or when peak salinity was combined with changes in water level.

Some methodological challenges were identified during the development of this project that should be considered in future studies aiming to use a similar approach to combine remote sensing information and field observations of hydrological data during storms. A main issue that arose when this work was designed and undertaken was the match between hurricane landfall trajectories and CRMS station locations, which cannot be predicted, but it was a factor determinant of what hurricanes and stations to use. Related to this is the availability of satellite products for the hurricane and paths identified, and lastly, the availability of hydrological data in the stations, which typically get severely hit during the storm surges, and it was not uncommon to find stations with data gaps around the time the hurricanes made landfall.

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Biographical Sketch

Sadia Islam was born on January 2^{nd}, 1998 in Dhaka, Bangladesh. She is the daughter of Nasima Islam and Sirazul Islam. She graduated from the University of Dhaka with a bachelor of science degree in geography & environment in 2021. In Fall 2022, she entered the master's program in environmental resource science at the University of Louisiana at Lafayette. She joined the wetland ecosystem science lab in the geosciences department in 2022. Her research in that program involved using NDVI to assess plant response after storm surges in freshwater marshes on the coast of Louisiana. She graduated in the spring of 2024 with a master of science degree in environmental resource science.