Geospatial and Geophysical Monitoring of Coastal Wetland Dynamics in Texas Gulf Coast: Implications for Coastal Hazards Mitigation

Joshua Benford, Esayas Gebremichael
Department of Environmental and Geological Sciences, Texas Christian University, Fort Worth, Texas

ABSTRACT

Coastal wetlands are critical ecosystems located at the dynamic interface between terrestrial and marine environments, shaped by interactions among sediment transport and deposition, geomorphology, hydrodynamics, and biogeochemical processes. They provide essential ecosystem services, including protection against storm surge flooding and attenuation of cyclone-induced wind and wave energy. However, coastal freshwater wetlands are increasingly threatened by both natural and anthropogenic stressors, particularly sea level rise and land subsidence. Subsidence, together with saltwater intrusion largely driven by unsustainable groundwater extraction, contributes to soil salinization and a marked decline in the spatial extent of freshwater wetlands, thereby reducing their ecosystem functions. These challenges are especially pronounced along the Texas Gulf Coast, where frequent cyclone events result in significant environmental and socioeconomic impacts. This study adopts an integrated framework combining deep learning-based GeoAI approaches applied to remote sensing data, , and field-based geophysical methods to quantify spatiotemporal wetland dynamics, evaluate their driving factors, and assess implications for coastal hazard mitigation capacity.

BACKGROUND

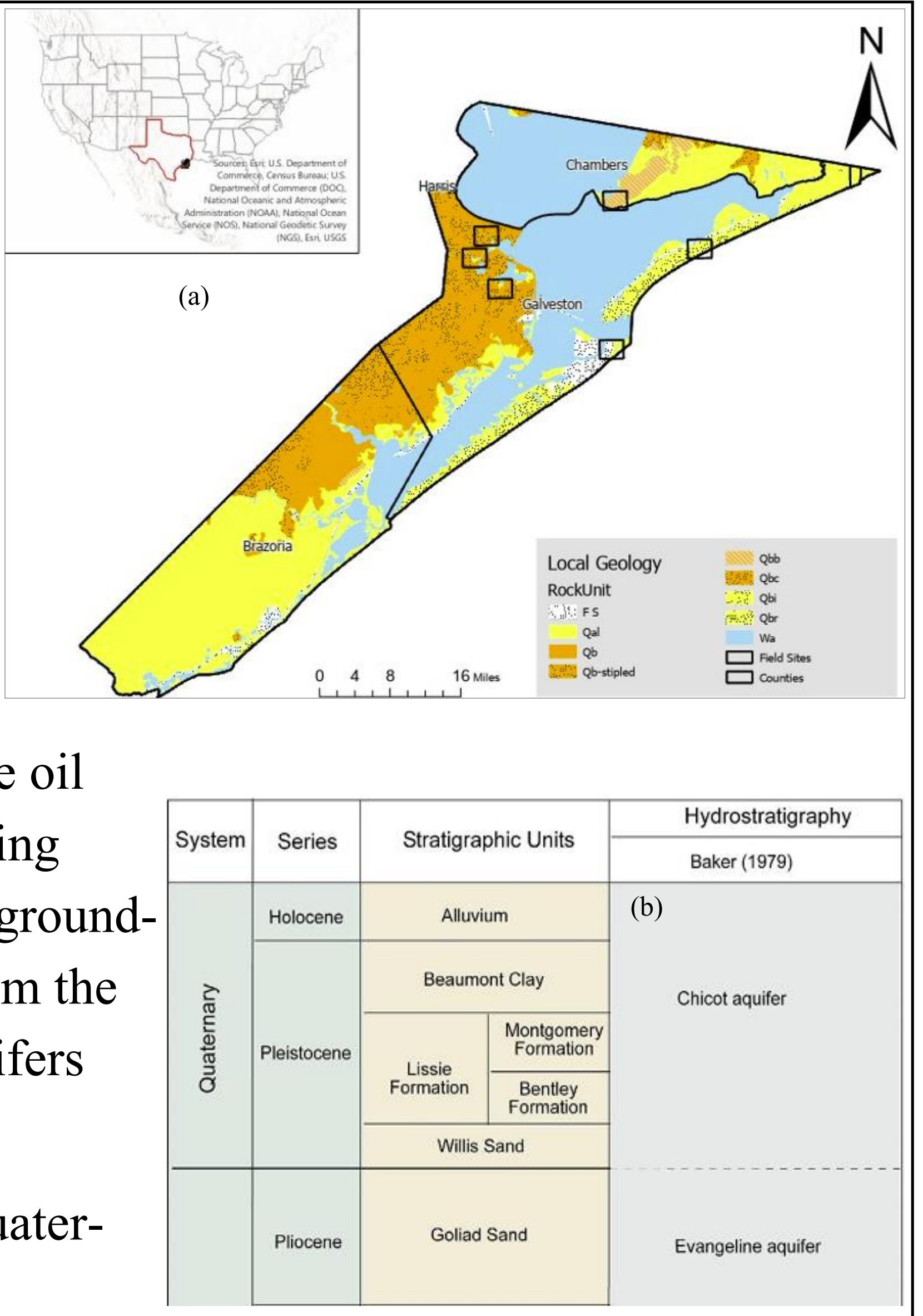

Fig. 1: The study area (with local geology) (a), and hydrostratigraphy (b)

- The study area (total area: 2,985.13 km²) is located along the Texas Gulf Coast (TGC) in southeast Texas (Fig. 1a), spanning Brazoria, Galveston, and Chambers counties.
- Early development in these areas was driven by the emergence of coastal lifestyles and later by extensive oil and gas exploration, including deep-water activities, with groundwater primarily sourced from the Chicot and Evangeline aquifers (Fig. 1b).
- The area is underlain by Quaternary barrier island deposits (alluvium) and Beaumont Formation (Qb) clays, with artificial fill and spoil (FS) present in some locations (Figs. 1a and 1b).
- The study area supports a diverse range of wetlands, primarily consisting of salt marshes, with limited mangrove coverage.

PROBLEM STATEMENT

- The TGC is among the most threatened coastlines in the United States, with a long history of flooding caused by storm surges dating back to the early 1900s.
- Previous studies have indicated that extensive groundwater withdrawal and hydrocarbon extraction have contributed to land subsidence and fault activation in the study area, which in turn have accelerated coastal erosion and wetland loss.
- Over time, prolonged storm surge flooding and soil oversaturation with mixed saline water (primarily seawater) have had detrimental effects on freshwater wetlands, potentially reducing their capacity to mitigate flooding and wind impacts during cyclone events.

OBJECTIVES

This study aims to evaluate the interplay between various stressors and coastal wetlands, as well as their ramifications on the coastal environment and community. Specifically, it investigates:

1) Spatial and temporal changes in coastal wetland extent and type from 2000 to 2025 in response to key stressors.
2) The hydrogeological conditions of the critical zone in areas experiencing declining wetland coverage, assessing the impacts of environmental stressors on the wetland critical zone.
3) Effects of wetland dynamism on ecosystem services, with a focus on changes in the capacity of wetlands to mitigate cyclone-induced hydrological hazards over time and space.

DATA AND METHODS

This study implemented a two-phased methodological approach to evaluate the spatiotemporal dynamics of wetlands along the Texas Gulf Coast and their response to environmental stressors.

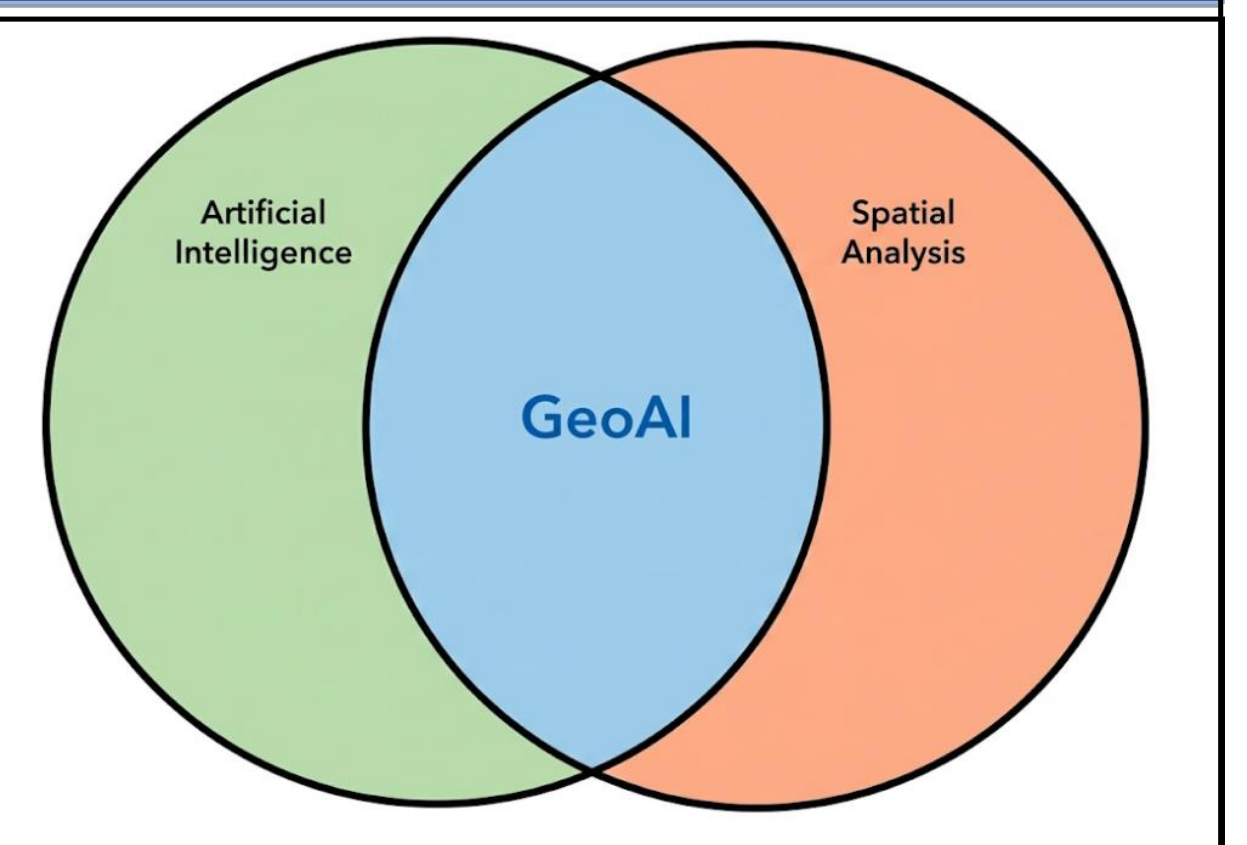

Fig. 2: GeoAI: an intersection of AI and spatial analysis

Fig. 3: DL workflow

a) First, to assess long-term changes in wetland extent, multispectral remote sensing datasets from Landsat missions (5, 7, 8, and 9) were acquired, and a Geospatial Artificial Intelligence (GeoAI)-based analysis was applied for change detection. Specifically, the study employed a Deep Learning (DL) approach, a subset of machine learning (Fig. 2), which utilizes multiple layers of algorithms in the form of neural networks. Input data are processed through successive layers of the network, with each layer learning and extracting specific features and patterns from the data .
   - For classification, a new schema was developed to categorize the study area into four land-cover classes: Estuarine and Marine Wetlands, Freshwater Emergent/Forested and Shrubland Wetlands, Urban, and Water. More than 3,000 training samples were delineated to train the model. Classification using DL (U-Net) in ArcGIS involves three key steps, facilitated through the ArcGIS Jupyter Notebook environment: (1) preparing the training data (exporting the data), (2) training the model (90% training and 10% validation), and (3) applying the trained model to classify the imagery (Fig. 3). Recall, which measures the model's ability to correctly identify all relevant features (true positives) out of the total actual instances present in the imagery, was used as the primary metric to assess model performance.

b) Secondly, the impact of wetland stressors on the critical zone was assessed to determine their influence on wetland dynamism.
   - Ground Penetrating Radar (GPR) was used to characterize the shallow subsurface (~10 ft). The resulting signatures were analyzed to assess saltwater intrusion within the critical zone supporting the wetlands. This assessment relied on interpreting electromagnetic wave propagation, specifically signal amplitude attenuation, as a function of subsurface dielectric properties and electrical conductivity. High dielectric permittivity and conductivity, characteristic of saline conditions, result in strong signal attenuation (Table 1).
   - Additionally, the combined effects of coastal subsidence and relative sea-level rise were assessed using displacement maps generated by the Alaska Satellite Facility based on Sentinel-1 Synthetic Aperture Radar (SAR) data (2017–2025).

Material	**Dielectric constant (ϵ_r)**
Air	1
Dry Sand	5
Granite	6
Dry Salt	6
Limestone	8
Shale	15
Saturated Sand	25
Silts	30
Clays	40
Distilled Water	80
Fresh/ Sea Water	**~80**
Metal	∞

Table 1: Dielectric properties of materials

RESULTS AND DISCUSSION

Class	Mean recall value
Marine wetland	0.70
Freshwater wetland/Forested	0.80
Urban	0.89
Water	0.98

Table 2: DL accuracy assessment

- The DL analysis shows high recall across all classes (mean = 0.84; Table 2), indicating strong detection of true positives and minimal false negatives, and supporting model reliability.
- Overall trends (Figs. 4a) indicate a decline in marine wetlands (slope: −0.014) and increases in freshwater wetlands/forests (0.02), urban areas (0.004), and open water (0.04), though these patterns vary locally.
- At Site 3 (red-filled polygon in Fig. 4a), DL results show a slight decrease in freshwater wetlands/forests (slope: −0.0001), coincident with a slight increase in urban areas (slope: 0.0001), and an almost complete loss of marine wetlands (Fig. 4b). Open water exhibits minimal change, with a slight increasing trend (slope: 0.0001). The site is underlain by clay- and mud-rich sediments of the Beaumont Formation (Fig. 1a), which likely limit saltwater intrusion and contribute to relative freshwater wetland stability. However, the loss of marine wetlands and subtle freshwater decline may reflect relative sea-level rise and increased saline influence. Notably, in several years (e.g., September 2022; Figs. 4a and 4b), an inverse relationship between marine and freshwater wetlands suggests episodic saltwater intrusion and partial conversion of freshwater systems to more saline conditions.
- To further evaluate potential saltwater influence, GPR data were analyzed using OneVision software to assess whether freshwater-to-marine wetland transitions are ongoing. The GPR profiles (Fig. 5) show strong reflections and horizontal layering in the upper ~5 ft, characteristic of clay-rich or compacted sediments (as Beaumont Formation (Fig. 5)), where signal attenuation produces diffuse returns. While such attenuation is expected in clay, saline intrusion would enhance signal loss due to increased electrical conductivity. This effect is observed below ~5 ft, particularly in localized zones (~300–450 ft and 500–550 ft; yellow-outlined boxes in Fig. 5), where increased attenuation and signal diffusion suggest higher-conductivity regions consistent with possible saline intrusion.
- In addition, increased urbanization and relative sea-level rise, supported by a mean subsidence rate of −6.2 mm/yr (Fig. 6) at the site, further highlight the influence of multiple stressors on wetland distribution.
- The implications of this wetland dynamism for flood mitigation were evaluated using results from a previous study (Gebremichael et al., 2020). A flood distribution map derived from SAR data illustrates inundation patterns following three extreme weather events (2015, 2017, and 2019). As shown in Fig. 7, Site 3 (yellow-outlined polygon) is among the areas experiencing recurrent cyclone-induced flooding. This observation reinforces the interpretation that wetland loss in this area has reduced its capacity to mitigate flood impacts.

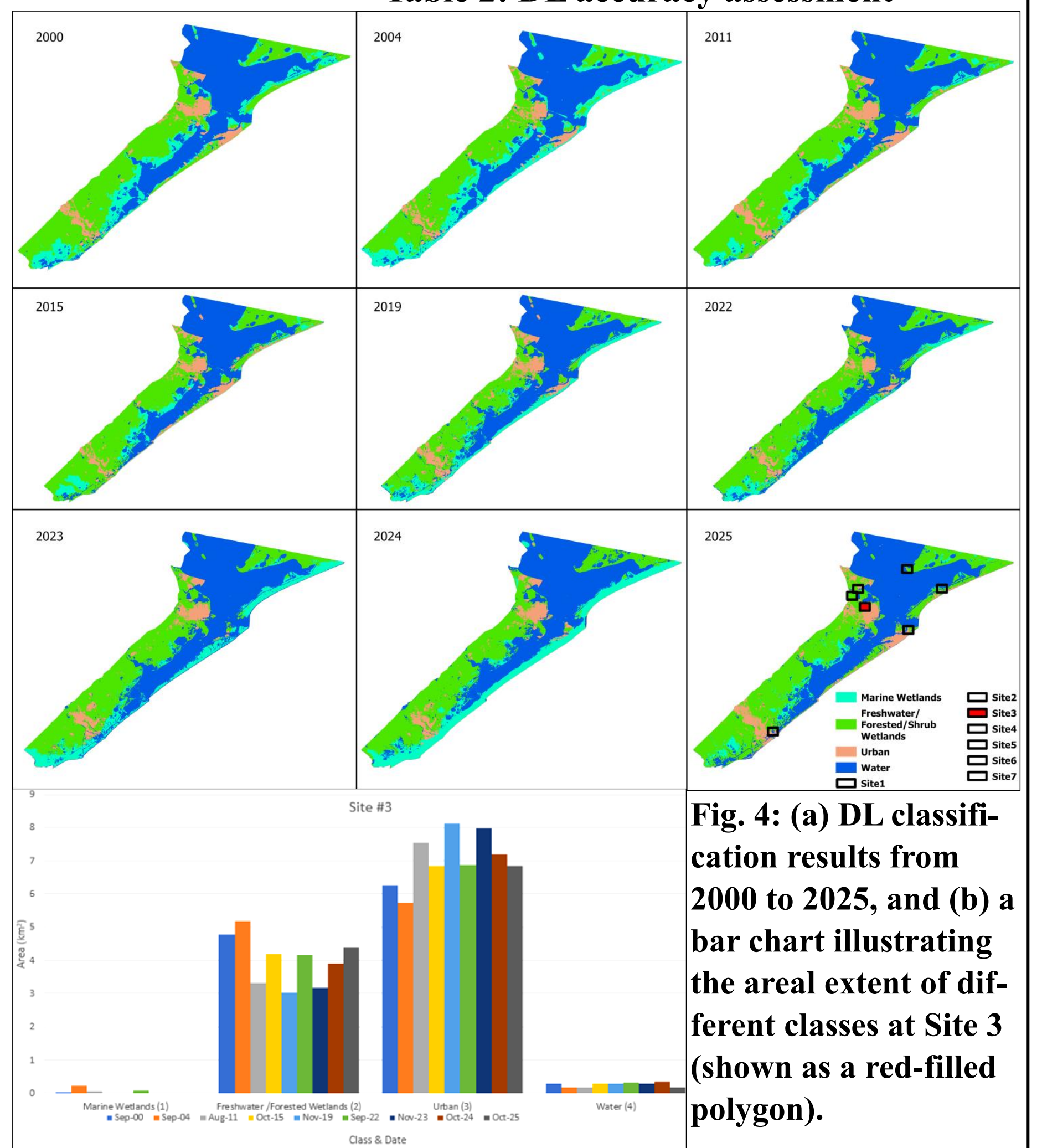

Fig. 4: (a) DL classification results from 2000 to 2025, and (b) a bar chart illustrating the areal extent of different classes at Site 3 (shown as a red-filled polygon).

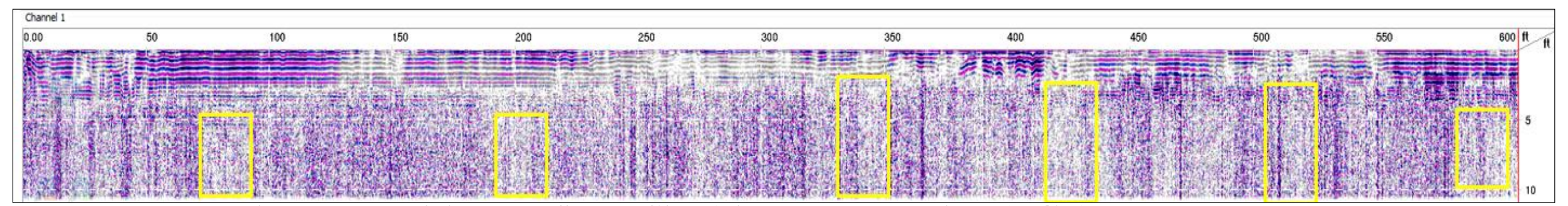

Fig. 5: OneVision profile at Site 3 in blue-grey-pink (BGP) channel palette.

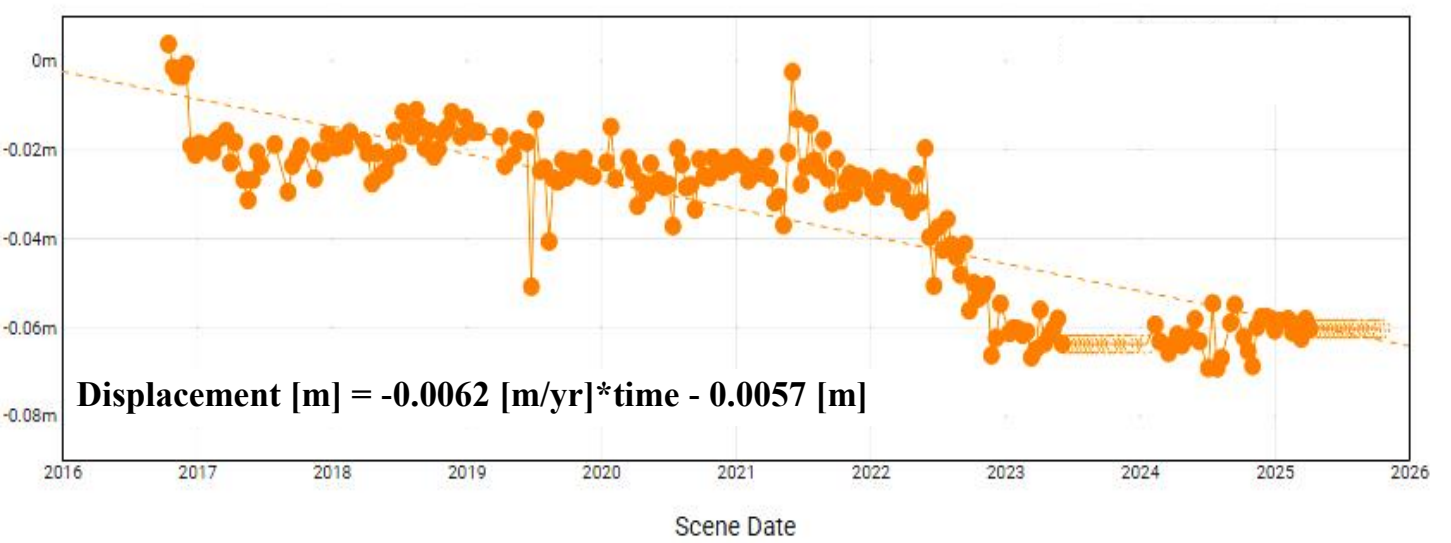

Fig. 6: Mean displacement (2017–2025) at Site 3.

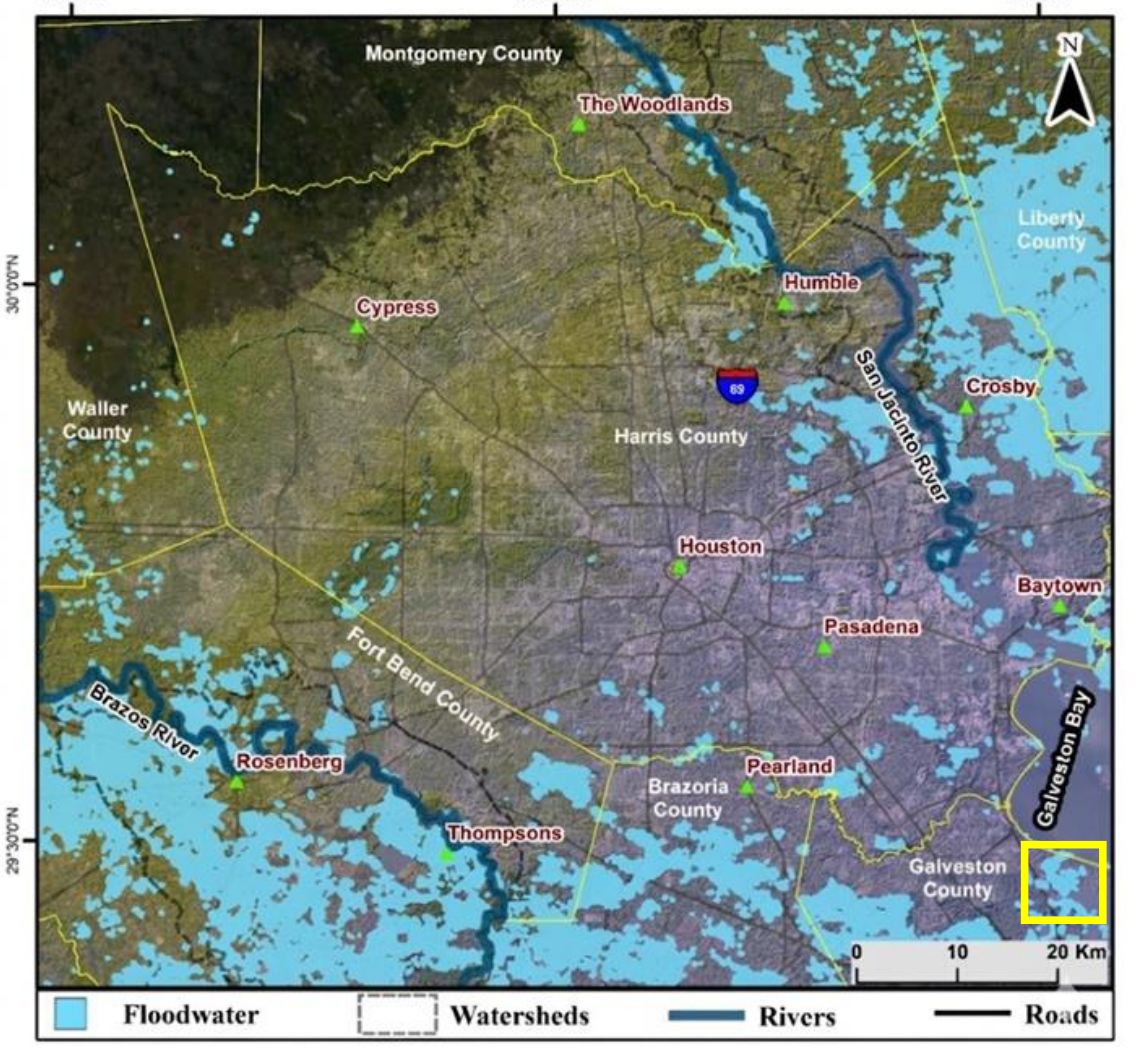

Fig. 7: Mean flood distribution map derived from three severe weather events.

CONCLUSION

- Regional trends show declining marine wetlands and increasing freshwater wetlands/forests, urban areas, and open water, reflecting broad-scale environmental and anthropogenic change.
- Local dynamics, such as at Site 3, diverge from regional patterns, with near loss of marine wetlands and episodic changes in freshwater wetlands, likely controlled by the interaction of geomorphology, sediment properties, salinization of the critical zone supporting freshwater wetlands, and urban development patterns.
- Coastal hazard implications include reduced wetland buffering capacity, which increases vulnerability to cyclone-driven flooding and long-term coastal inundation.