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Land formation driven by sediment accumulation and vegetation dynamics in the marsh: A case study in the Kitchen Pond area in the modern Mississippi River Delta.

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Abstract

A study was conducted to analyze how sediment accumulation affects land formation and marsh development in river deltaic ecosystems. It examined the temporal variations in turbidity levels and chlorophyll content driven by sediment input, and their long-term impacts on land formation processes in the Kitchen Pond area of the modern Mississippi River Delta. Using multi-temporal Landsat imagery (2006–2021) and spectral indices such as NDWI (Normalized Difference Water Index), NDTI (Normalized Difference Turbidity Index), and NDCI (Normalized Difference Chlorophyll Index), the current analysis demonstrated the evolution of a new bird-foot deltaic pattern within ecosystems with similar morphology. Nearly a 15-year period was needed to form a permanent landmass by the sedimentation process under the conditions. A mathematical model was also developed to predict actual turbidity levels in waterbodies using remote sensing data. This study shows the interconnected relationship between sediment deposition, vegetation growth, and their combined influence on the emergence of new land. These findings offer valuable insights to the restoration agencies for developing effective strategies and adaptive management approaches for similar environments.

Key words: Land formation, Marsh development, Mississippi River Delta, Remote sensing

1. Introduction

Sediment accumulation is an important mechanism of land formation and marsh development in river deltaic ecosystems. This phenomenon is especially pronounced in the Mississippi River Delta (MRD), where the deposition of organic and mineral sediments influences the reshaping of the delta's morphology (Sanks et al., 2022). The typical "bird-foot" morphology of the modern/lower Mississippi River Delta is primarily a result of sediment delivery by river flow. It is often emphasized that this process outweighs the effects of waves and tidal reworking. As a result, narrow distributary channels are extended into the Gulf of Mexico. Due to this, finger-like landforms develop, creating the distinctive delta shape (Edmonds and Slingerland, 2007; Syvitski and Saito, 2007). Such land formations often occur when high sediment loads are delivered to relatively flatter areas, allowing sediment to accumulate at low laying areas of the river and form distributary channels independently.

During the seasons with high floods, a large amount of essential nutrients is delivered to the marsh through sediment carried by the river, supporting the growth of algae and aquatic plants (Amer et al., 2017). Elevated chlorophyll levels in water bodies reflect this process, indicating nutrient richness and increased biomass within the ecosystem (Xu et al., 2022). However, investigating these dynamics has certain challenges, as the identification of the precise starting point or triggering point of ecosystem changes under natural conditions is often difficult. In such cases, man-made structures can serve as reference points for ecosystem alterations. For example, in 2006-2007, a diversion canal was constructed in the Kitchen Pond area of the modern MRD (bird-foot delta). This incident can be considered an ideal case study for examining how sediment deposition affects aquatic chlorophyll levels, turbidity, and land formation processes within a similar water body. Satellite imagery serves as an invaluable tool in this type of analysis, enabling long-term monitoring of environmental changes and their impacts (USGS, 2006; Barras, 2006).

Sediment-vegetation feedback mechanisms and their implications for sustainability and restoration of deltaic ecosystems have been demonstrated by recent research. For instance, Schile et al. (2014), Kirwan and Megonigal,(2013) showed that the vegetation grows in response to sediment deposition and promotes further sediment capture, thereby creating a self-reinforcing cycle that is crucial for both

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formation and stability of marsh. However, the persistence of these landforms is not guaranteed, as external pressures such as accelerated sea-level rise, subsidence, reduced sediment loads in future etc., can threaten newly formed marshes and even reverse land gains (Kearney et al., 2002). The application of remote sensing, particularly with multi-temporal satellite imagery and advanced indices, has become indispensable for tracking these complex processes over time and at landscape scales (Kuenzer et al., 2011). Multi-temporal satellite imagery, combined with spectral indices such as NDWI, NDTI, and NDCI, enables researchers to monitor changes in the extent of water, sediment deposition, and vegetation dynamics with high temporal and spatial resolution (Kuenzer et al., 2011; McFeeters, 1996). This imagery is crucial for understanding the physical processes that drive the changes of the geomorphology of the modern MRD (bird-foot region), whereby long-term sustainability of this wetland system of enormous ecological and economic significance. Thus, the objective of this study was to analyze temporal variations in turbidity levels and chlorophyll content driven by sediment load, and to characterize long-term land formation processes that resemble the "bird-foot" pattern in the MRD ecosystem.

2. Results and discussion

Figure 1 demonstrates the actual turbidity levels measured at USGS station 07374525 and the corresponding NDTI values at the gauge location during 2013-2016 (The relevant data is given in the supplementary data file). The fitted model demonstrates a strong linear relationship between NDTI and turbidity levels. These results confirm that Landsat 8-derived NDTI values are accurate for predicting water turbidity and sediment levels in the non-gauged Kitchen Pond area. The present analysis confirms the accuracy of the developed remote sensing model for estimating water turbidity (R^2>0.7). This regression model (Actual turbidity, FNU=(1664.5*NDTI) +53.245) can effectively predict actual turbidity levels based on remotely sensed turbidity data (NDTI).

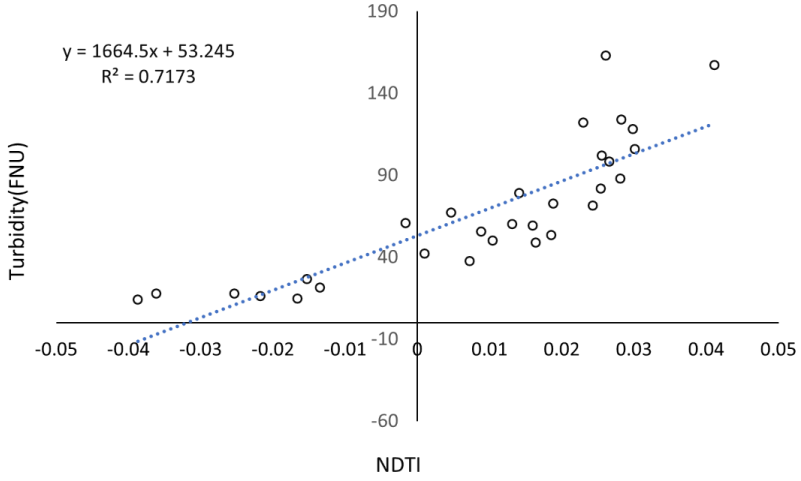

Figure 1. Relationship between actual water turbidity and the NDTI values.

Figure 2 illustrates the changes in sedimentation behavior in the Kitchen Pond area based on historical imagery of Google Earth, after construction of the diversion canal in 2006-2007. Satellite images taken in 2007 (2007.07.22), 2009/2010 (2009.12.31), and 2012 (2012.10.29) clearly showed initial sediment accumulation from the mouth of canal toward the Kitchen Pond. As observed from the image in 2012, a

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sediment deposition pattern resembling a “bird's foot” pattern is clearly visible, representing a typical deltaic morphologic structure of the area. This pattern forms because the inlet water carries a large amount of sediment which then accumulates at lower elevations, forming clogs forcing the flow to spread out like fingers. Each of these fingers transports water and sediment outward to the low-lying water bodies, in this case, the Kitchen Pond. The “bird’s foot” pattern is especially prominent when waves and tides are too weak to erode or smooth out the new deposits, allowing each finger to continue expanding outward independently (Edmonds and Slingerland, 2007). The conditions in the Kitchen Pond area are highly favorable for this process to occur.

As shown in Figure 2, in 2021, a permanent landmass formed within the pond. providing potential for above-ground vegetation to establish and persist. Thus, it can be established that 15 years after the construction of the diversion canal, a permanent land mass occurred inside the pond as a result of sediment deposition. This decadal timescale for stable land formation is consistent with observations from other engineered sediment diversions in deltaic systems, such as those reported by (Kim et al., 2009), who found that significant land emergence in the MRD often requires 10–20 years, depending on sediment supply, hydrodynamics, and local basin conditions. This shows the effectiveness of sediment diversions in deltaic land formation under favorable conditions. As shown by (Cahoon et al., 1995; Morris et al., 2002), land formation proceeds through an initial rapid sedimentation phase followed by stabilization and biomass increases. However, it is important to recognize that such positive outcomes are not always possible. Day et al. (2009) and Kirwan et al. (2013) noted that land mass formation rates can be much slower, or even negative, in areas with insufficient sediment supply, rapid sea level rise, strong erosional forces etc. As evident by the present study, the 15-year development of a permanent landmass in Kitchen Pond provides a valuable benchmark for restoration planning.

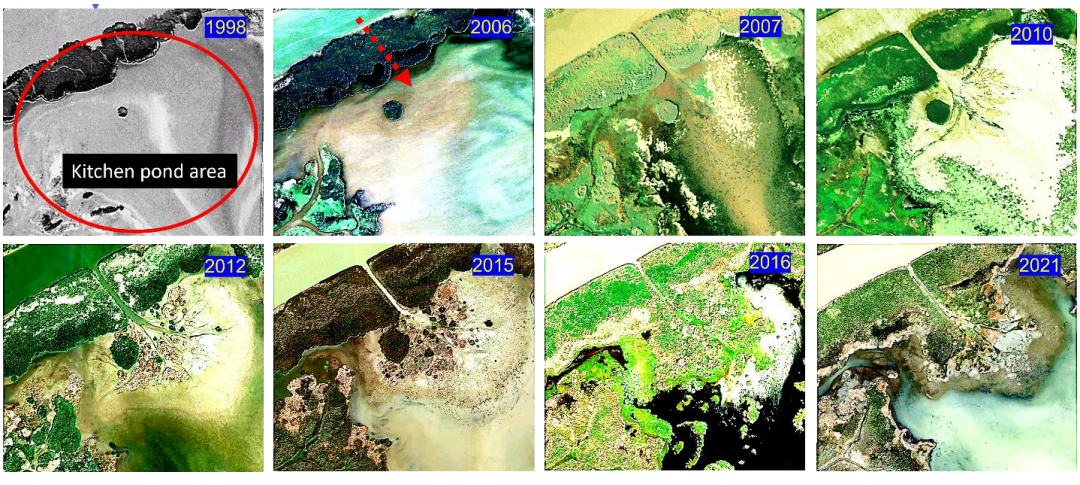

Figure 2. Sediment deposition pattern and land formation in the kitchen pond area after the construction of the diversion canal. The arrow in red indicates the newly constructed diversion canal in 2006-2007: Map data © 1998, 2006, 2007, 2010, 2012, 2015, 2016, 2021 Google.

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The google earth satellite images taken from year 2009/2010 (2009.12.31) and 2016 (2016.11.20) clearly demonstrated the presence of floating vegetation on the water surface in the pond. Additionally, high water turbidity was noted in the images from 2006 to 2012 (2006.3.14, 2007.7.22, 2009.12.31, 2012.10.29). This increase in turbidity could supply nutrients from the diversion canal for the growth of newly arisen vegetation. This pattern is further evident by NDTI values variations during the study period.

Figure 3 depicts the temporal variations in turbidity levels in Kitchen Pond from 2006 to 2021 based on the Landsat multitemporal imagery data (The relevant data is given in the supplementary data file). According to the fitted polynomial trend line for NDTI, the turbidity levels in the pond were high in the initial period (2007 to 2010) and then gradually declined. The minimum turbidity level was in 2019. From 2017 onwards, the turbidity trend reached approximately a constant level. The data gap from the 2012-2013 period was due to the non-availability of satellite images for the study area. The annual decline of NDTI was maximum in 2013 (1st order polynomial derivative).

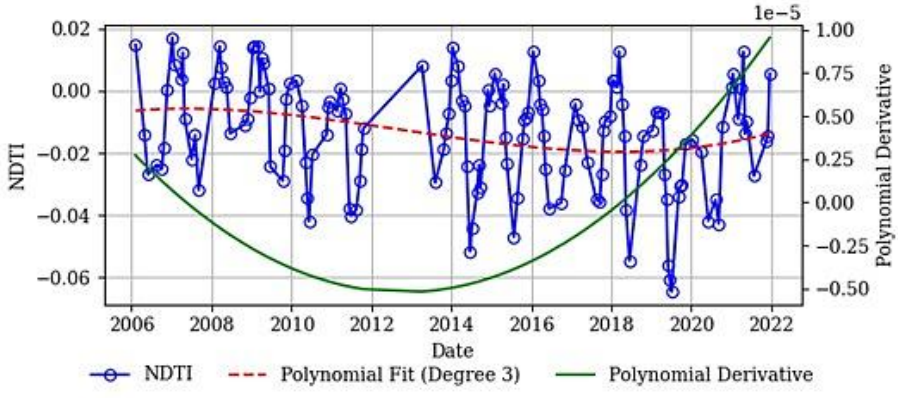

Figure 3. Temporal variation of NDTI in the water body in the Kitchen Pond.

Figure 4 depicts the temporal variation of NDCI in the Kitchen Pond area. In contrast to NDTI, the NDCI associated with the chlorophyll content in the pond showed a steady increase starting around 2009, approximately 2-3 years after the construction of the diversion canal and continued the increasing trend until 2018 (Figure 4). This increasing trend happened after the high turbidity event between 2007 to 2010. The nutrient input associated with turbid water could create a favorable condition for the proliferation of algae and floating vegetation. This increased vegetation biomass may have helped resist water flow across the pond and enhance the sedimentation processes further.

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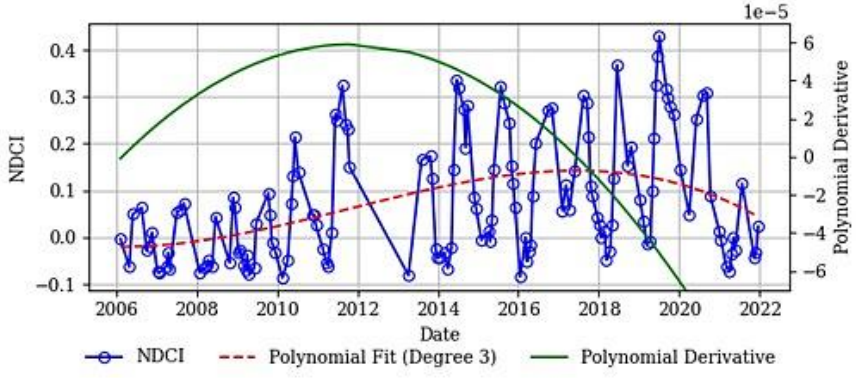

156 **Figure 4. Temporal variation of NDCI in the water body in the kitchen pond.**

157 Debris of dead vegetation can be trapped efficiently during this phase and slow down the water flow
158 through the submerged stems and roots, which concurrently could facilitate further sediment entrapment
159 (Schile et al., 2014; Kirwan and Megonigal , 2013). This interaction is characterized by a positive feedback
160 mechanism whereby the proliferation of vegetation is supported by increased sediment and nutrient
161 availability, while the vegetation itself further accelerates and stabilizes land formation processes. As
162 such, the newly emerged vegetation can be recognized as dependent on sediment and nutrient inputs but
163 also actively involved in promoting further land accretion, positive feedback that strengthens both
164 processes. As a result, the maximum rate of chlorophyll increase was observed as indicated by the
165 polynomial derivative line constructed for NDCI in 2012 (Figure 4).

166 The current analysis indicates that the development of "bird-foot" like land formation is closely associated
167 with sedimentation, nutrient input and emergence of vegetation in the low-lying water bodies. This
168 highlights a dynamic interaction between hydrological and ecological processes, where changes in
169 landform and vegetation influence each other, contributing to the ongoing evolution of the marsh
170 ecosystem in the modern delta of the Mississippi River. However, recent studies have highlighted both
171 the potential and the limitations of sediment-driven land formation in deltaic environments. For example,
172 (Nienhuis et al., 2022) reported that man-made sediment diversions can lead to net land gain in certain
173 deltas, which supports the observations made in this study in Kitchen Pond area following the construction
174 of the diversion canal. However, it is important to note that the global trend is not always positive, as
175 many deltas continue to experience land loss due to human activities and specific natural events. As
176 indicated by (Morris et al., 2002), the ability of the vegetation to trap sediments and promote land
177 formation is strongly influenced by the rate of sea-level rise or water level of the river during the flood
178 season. In some cases, rapid sea-level rise can disturb sediment accumulation, resulting in marsh
179 submergence rather than expansion. Kearney et al. (2002) also demonstrated that significant marsh loss
180 can occur in regions where sediment supply or hydrological connectivity is disrupted.

181 The present analysis ensured a high level of accuracy and reliability in the results with the use of
182 multitemporal Landsat imagery which is widely recognized for long-term environmental monitoring in
183 wetland and deltaic systems, owing to its consistent revisit frequency. This makes it particularly effective
184 for detecting gradual changes in water, sediment, and vegetation dynamics (Kearney et al., 2002; Kuenzer
185 et al., 2011). Since the image database in GEE has already undergone standard preprocessing steps, such

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as radiometric calibration, geometric correction, and atmospheric correction (Gorelick et al., 2017), the analysis of turbidity and chlorophyll variations in this study is reliable.

3. Conclusion

This study successfully characterized the formation of landmass within a water body resulting from sediment accumulation in the Kitchen Pond area in the modern delta of the Mississippi River using satellite image analysis. The interaction between water turbidity driven by sediment supply, and the development of vegetation on the emerging land mass was described. It was worth noting that nearly a 15-year period was needed to form a permanent landmass by the sedimentation process under the conditions in the Kitchen Pond area. The findings of this study provide valuable insights toward understanding how sedimentation and natural succession of vegetation are involved in reshaping the landscape in the deltaic ecosystem by providing real-world examples usable by coastal restoration agencies worldwide.

Appendix: Materials and Methods

The study was conducted in Kitchen Pond, located within the Modern delta of the Mississippi river, with coordinates ranging from Latitude 29.203° to 29.210° and Longitude from -89.222° to -89.212° (Figure 5).

Landsat imagery from 2005 to 2021 was employed to analyze the water and land characteristics within the study area. Images from 2022 onwards were excluded from the analysis due to the construction of another diversion canal in the same area. All available Landsat images were visually inspected to identify and exclude the ones affected by cloud contamination (The used Landsat image list is given in the supplementary file "Supplementary_cloud free image list"). NDWI (Normalized Difference Water Index), NDTI (Normalized Difference Turbidity Index), and NDCI (Normalized Difference Chlorophyll Index) were estimated as defined by equations 1, 2, and 3. Cloud free 184 Landsat images were used. The computed timeseries dataset of NDTI, NDCI and NDWI are given in the supplementary file "Supplementary_NDTI.NDCI.NDWI".

$$NDWI = \frac{G-NIR}{G+NIR} \quad \text{..... Eq 01 (McFeeters, 1999).}$$

$$NDTI = \frac{R-G}{R+G} \quad \text{..... Eq 02 (Garg et al., 2017).}$$

$$NDCI = \frac{NIR-R}{NIR+R} \quad \text{..... Eq 03 (Mishra and Mishra, 2012).}$$

Where, G =green band, R = Red band, NIR = Near infrared band.

The NDWI, NDTI, and NDCI indices have been validated in numerous studies for delineating water bodies (McFeeters, 1996), mapping turbidity (Garg et al., 2017), and estimating chlorophyll concentrations in turbid waters (Mishra and Mishra, 2012), respectively. As the shape of the water body of Kitchen Pond changed over the study period, precautions were taken to exclude ground pixels from water pixels in the raster images by utilizing NDWI (Ortiz et al., 2017). The adoption of NDWI to separate water from land pixels is consistent with best practices in remote sensing and helps minimize classification errors due to seasonal or event-driven changes in pond morphology (Ji et al., 2009).

Image processing and data extraction were performed using Google Earth Engine (GEE) (Gorelick et al., 2017). Google Earth Engine offers significant advantages in computational power and scalability allowing for rapid processing of multiple satellite images without the need for local storage or high-end hardware.

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By its default, the GEE imagery database has already undergone standard preprocessing steps, including radiometric calibration, geometric correction, and atmospheric correction (Gorelick et al., 2017). Both Landsat 5 and Landsat 8 images were used. Landsat 5 (8-bit radiometry) covers the period from 2005 to 2012, while Landsat 8 (12-bit radiometry) provides data from 2013 onwards. The spatial resolution of both dataset is 30 meters. The code is available as a supplementary file (named "GEE code").

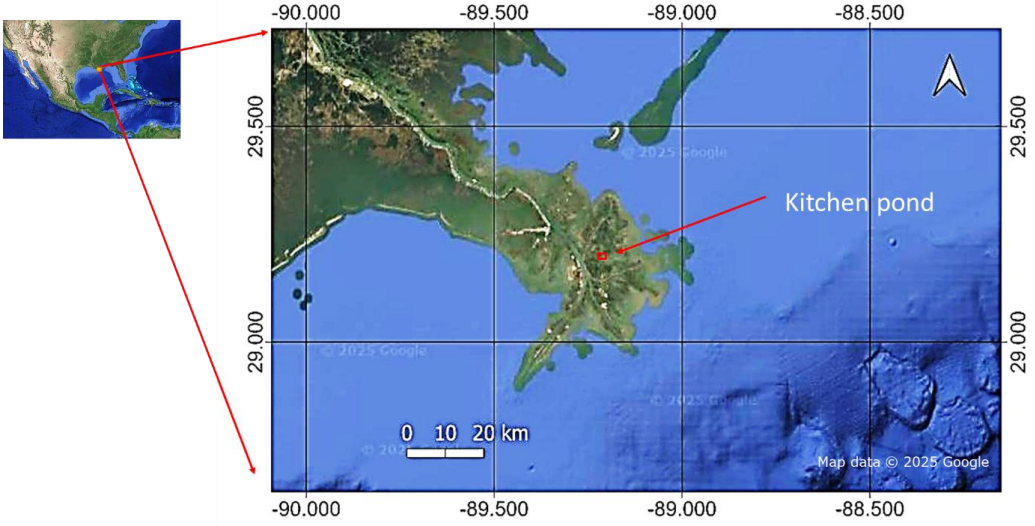

Figure 5. Study area in the Modern delta (bird-foot) of the Mississippi river: Map data © 2025 Google

The NDTI, calculated from Landsat data, was validated using water turbidity measurements from the Mississippi River at USGS station 07374525 (Mississippi River at Belle Chasse, LA). This station is the closest to the study area, located approximately 101 km away on the Mississippi River at Belle Chasse, LA, with coordinates 29.85715084°N, -89.97784700°W. USGS-07374525 turbidity data are available from September 30, 2012 to June 20, 2016, total 2,587 daily data points. Based on satellite image availability, 30 data points where both turbidity measurements and satellite images were available were used for the analysis. The dataset is given as a supplementary file "Suplimentory_turbidity data".

Data availability statement

The data utilized in this study are available as suplimentory fielss in this paper and also publicly accessible and can be downloaded online from "Mendeley data" web site. (Wijayawardhana, Janaka; Ratnayaka, Harish (2026), "NDTI, NDCI, and NDWI data for the Kitchen Pond area in the Mississippi River Bird Foot Delta.", Mendeley Data, V2, doi: 10.17632/kcztf6f37p.2)

Author contributions

L.M.J.R. Wijayawardhana contributed to research conceptualization, methodology development, coding, data analysis, and manuscript writing. C.M. James and A.C. Jordan conducted satellite image analysis and verification. H.H. Ratnayaka contributed to funding acquisition, method development, manuscript improvements, and overall supervision.

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Competing interests. Authors declare that none of the authors has any competing interests.

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Ethical declaration

The authors declare that no ethical clearance was required for the publication of the content of this manuscript.

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