



Assessing the impact of land use and land cover change on the Densu Delta wetland using Markov chain modeling and artificial neural networks

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ABSTRACT

This study investigates the dynamics of land use and land cover (LULC) changes in the Densu Delta wetlands, a critical ecosystem in Ghana. Here, satellite images spanning from 1998 to 2023 were used to analyse the spatio-temporal patterns of LULC changes and their implications for water bodies, wetlands, vegetations, bare lands and urban areas in the Densu Delta wetland. Employing advanced techniques such as Markov chain modelling and artificial neural networks (ANNs), the research assesses and predicts LULC alterations. Significantly, the largest loss of LULC is observed in the Densu Delta wetland, where wetlands transition to waterbody cover type (14.02 km²). Model validation for 2023 attests to the accuracy of the model, boasting a correctness percentage of 70% and a kappa value of 0.74. In-depth analyses explore regional variations in the Densu Delta wetlands, revealing distinct patterns in the rates of LULC change before and after 2013. Notably, urbanization emerges as a prominent factor post-2013, with urban areas experiencing remarkable rates of change in the wetland. Transition matrices underscore the intricate interplay of different land cover classes over the years. Simulated LULC predictions for 2033 and 2043 highlight the urban land cover type as having the highest positive change, recording approximately 0.39% for the Densu Delta wetland. The wetland land cover in the Densu Delta wetland exhibit negative changes of about -0.52%. The synthesis of LULC data enhances our understanding of the complex interactions shaping these critical ecosystems. This research offers valuable insights for sustainable environmental conservation, emphasizing the pivotal role of informed urban planning policies. It also unveils potential challenges posed by climate change, advocating for a holistic approach to preserve these vital wetland ecosystems.

Introduction

Wetlands, characterized by their wetlands, bogs and peatlands, represent invaluable ecosystems that support diverse flora and fauna while providing essential ecosystem services. These dynamic habitats occupy approximately 6% of the Earth's surface and play a critical role in maintaining ecological balance and supporting human well-being (Gokce, 2019). Wetlands are known to be very sensitive to changes in land use which can have significant impacts on their wetlands and water bodies, which are essential to ecosystem functioning and human

well-being. Changes in land use such as deforestation and urbanization can alter the way water and nutrients are distributed and used within ecosystems. Land use can be defined as the actions of people on the land surface that alter the land cover and define how land is used, while land cover is defined as the physical characteristic that covers a land surface and describes an area. Research shows that human settlements and activities have impacted 83% of the Earth's land surface, with only 17% remaining in natural areas (Potapov et al., 2022). Over the past two decades, almost half of the total wetland area has been lost due to urbanization, agricultural use, industrial sites, and the development of the

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country's largest port (Nonterah et al., 2015). In most cases, human influence on biophysical factors in wetlands leads to land use and land cover changes (Addae et al., 2019).

The issue highlights the increasing threats to wetlands due to land use change in the Densu Delta wetland basin in Ghana. These wetlands are undergoing rapid changes in land use/land cover resulting in significant impacts on their water resources and ecosystems. Anthropogenic factors, including urbanization, construction of roads and buildings, removal of vegetation for cropland and firewood, water consumption, pollution, and introduction of invasive species, are the main threats to wetlands (Ekumah et al., 2020; Sun et al., 2020). Despite recognition of the importance of wetlands, the lack of comprehensive assessments hinders effective management strategies and exacerbates ecosystem degradation. Urban sprawl caused by population growth and migration further exacerbates the problem, with areas such as the greater Accra region of Ghana experiencing alarming levels of wetland collapse (Osei et al., 2013; Stemn et al., 2014). The urgent need for holistic studies that integrate land use and wetland dynamics is emphasized, as current conservation policies often ignore the broader landscape context (Braff, 2020). Addressing these knowledge gaps is critical to developing effective management strategies to protect wetland ecosystems and their valuable services.

By closing these knowledge gaps, we can develop more informed and effective management strategies for the conservation and sustainable management of wetlands, ensuring the continued provision of their valuable ecosystem services. The main objective of this study is to assess the impacts of land use/land cover changes in the Densu Delta wetland, predict future land use changes, and assess the environmental risks associated with these changes for 25 years. To achieve this, the study aims to (i) develop historical maps and conduct change detection analysis to identify trends in land use/land cover changes in the Densu Delta wetlands using geospatial and remote sensing tools and (ii) assess potential land use changes using the Cellular Automata Artificial Neural Networks (CA-ANN) approach and assess the associated environmental

risks associated with ongoing land use/land cover changes.

Materials and methods

Study area description

The Densu delta basin located in southeastern Ghana covers an extensive area of 2490 km² and encompasses the Densu River along with its tributaries. The geographical boundaries of the basin extend between longitudes 1°0'0"W and 0°0'0"W, as well as latitudes 6°30'00"N and 5°30'0"N. The basin hosts a population of more than 600,000 people, mostly engaged in agriculture. In the Densu wetland, subsistence farming is carried out in the neighbourhoods of Akplaku, Bortianor, and Tetegbu using crops such as cassava, maize, and vegetables. Through pollution, the use of herbicides, other agrochemicals, and chemical and organic fertilizers in these farming practices threatens the stability of the wetland ecosystem. The major forest vegetation of the Aplaku-Bortianor hills has been severely destroyed by farming activities on their slopes. This has caused the soils on the hill slopes to erode more quickly, increasing the amount of silt that is released into the Densu wetland.

The Densu wetland in Fig. 1 is ecologically significant and known for its rich biodiversity, which is home to a wide variety of flora and fauna. Salt production is also an important economic activity in the Densu Delta basin. This involves the extraction of salt from seawater through evaporation processes in salt pans. While salt production is not classified as an agricultural activity, it has notable environmental impacts on the wetland ecosystem. The construction and operation of salt pans can lead to the alteration of natural landscapes, loss of wetland habitats, and changes in the hydrological regime.

Methodology for assessing the impact of land use on wetland

Landsat images for the years 1998, 2003, 2008, 2013, 2018, and 2023 were collected. These images underwent atmospheric correction to

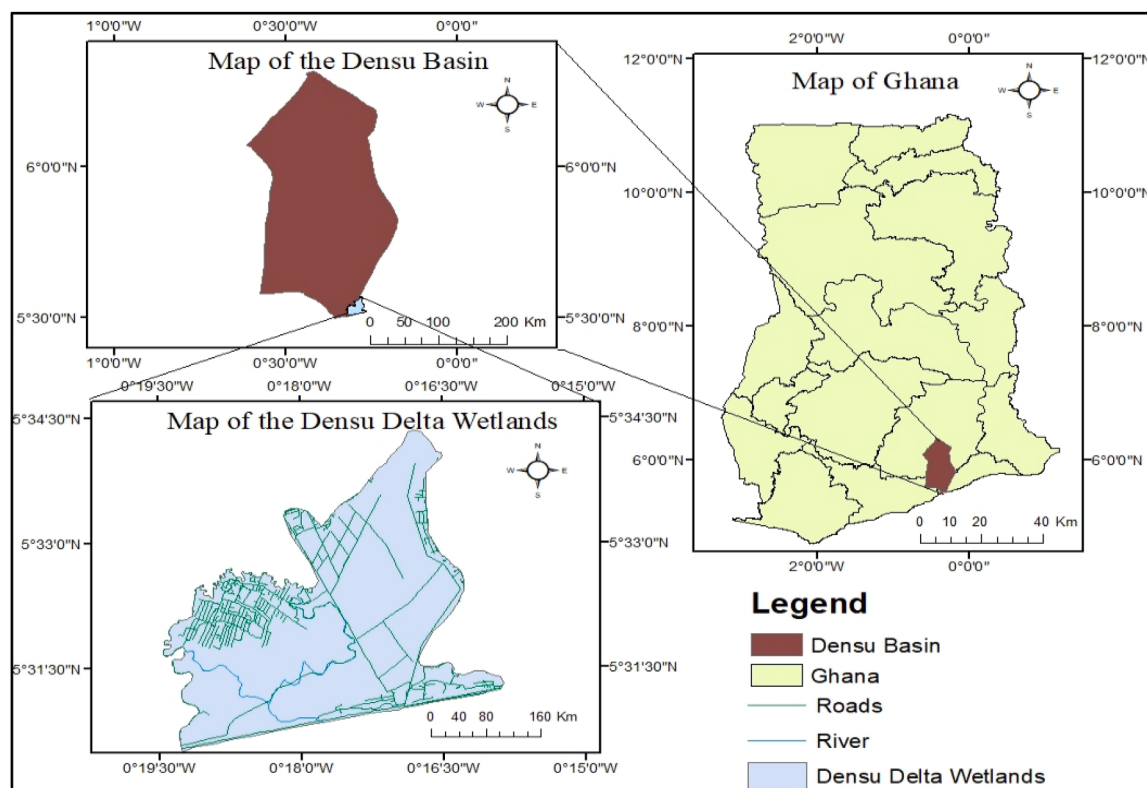


Fig. 1. Map showing the location of the Densu Delta basin in Ghana.

remove atmospheric effects, followed by the derivation of spectral indices such as the Normalized Difference Vegetation Index (NDVI), Normalized Difference Built-up Index (NDBI), and Modified Normalized Difference Water Index (MNDWI). The processed images were then subjected to supervised classification using a Support Vector Machine (SVM) to generate LULC maps for the respective years. The accuracy of these classifications was validated using training data. To analyse land use class attrition, the percentage of area for each land use class that transitioned to a different class between consecutive time periods was calculated. These attrition rates were then mapped to visualize the spatial distribution of change, providing insights into the locations most susceptible to land use conversion over time. A fragmentation analysis was conducted using Python software, with libraries such as rasterio, numpy, matplotlib, and scipy being utilized to calculate the number of patches and the mean patch size for each land use class throughout the various periods. Valuable insights into the degree of landscape fragmentation and the spatial configuration of various land use types over time were gained through these calculations. By examining these metrics, a better understanding of how the landscape is divided into smaller, isolated patches and how these patches change in size and distribution was achieved.

A Cellular Automata - Artificial Neural Network (CA-ANN) model, specifically Molosce, was implemented to simulate future LULC changes. The model used the LULC data as input parameters to predict LULC maps for the years 2033 and 2043. The model's accuracy was validated using the 2023 LULC map. Following the simulation, the predicted LULC maps for 2033 and 2043 were generated.

Data source and types

Satellite images are a useful source of information for studying the Earth's surface and its changes over time. This study uses satellite images from Landsat, a series of satellites that have been collecting images of the Earth since 1972. Landsat satellites cover large geographical areas and enable analysis of wetlands at a regional scale (Guo et al., 2017). Landsat images also have a temporal resolution of 16 days, meaning every location on Earth is imaged by the same satellite every 16 days. For the wetlands of the Densu Delta, images are collected for the years 1998, 2003, 2008, 2013, 2018 and 2023. Initially, efforts to gather data for periods before 1998 were hampered by the scarcity of relevant datasets. Furthermore, the data that was available was frequently marred by significant cloud cover, rendering it unsuitable for accurate analysis. By focusing on the period from 1998 to 2023, we ensured that we had access to higher-quality satellite imagery and geospatial data, which are crucial for reliable land use/land cover change detection and climate impact assessment (Table 1).

Image classification

The selected downloaded Landsat images used for analysis had little to no cloud cover as cloud cover could lead to land use/cover misclassification. All datasets were assigned the World Geodetic System 1984 (WGS84), Zone 30 N, and Universal Transverse Mercator (UTM) projection system. QGIS was used to preprocess the photos for atmospheric correction. After pre-processing the photos, the Densu Delta Wetland or Area of Interest (AOI) was extracted from the photos using their shapefiles in QGIS. The recovered photos were stacked by the Landsat

satellite that captured the image. The stacked image was processed in ENVI to classify land use and land cover. In ENVI, classifications were performed both supervised and unsupervised. To facilitate supervised classification, unsupervised classification was first performed with the aim of locating regions with comparable classifications. Table 2. categorizes land use and cover types in the Densu Delta wetland and provides brief descriptions for each category. It helps to define and distinguish the main features of urban areas, bare areas, water bodies, wetlands and vegetation within the study area.

Table 3 provides a numerical classification system for different land use and land cover classes within the study area. Each class is assigned a unique number for convenient reference during data analysis and mapping.

Change detection

Following the classification results for each individual year, a post-classification change detection algorithm with multiple date comparisons was implemented to assess changes in land cover over five intervals: 1998 to 2003, 2003 to 2008, 2008 to 2013, 2013 to 2018, and 2018 by 2023. This widely used approach is critical for detecting land use change and has been proven effective in numerous studies (Potapov et al., 2022; Ekumah et al., 2020). The post-classification method provides valuable from-to change information and allows specific landscape transformations to be calculated and mapped. A change detection map containing detailed information about the changes from "to" was then prepared for each of the five classification maps corresponding to the years 1998, 2003, 2008, 2013, 2018 and 2023 in the Densu Delta wetland projects. This process enables a comprehensive understanding of land cover dynamics and transitions within the specified time intervals and across both wetlands.

Accuracy assessment

Assessing the accuracy of a map created from remote sensing data is important not only for validating its suitability for a particular application, but also for understanding the inherent errors and their potential impact. There are various methods for assessing map accuracy, with the confusion matrix often used for maps derived from different classification methods (Tana et al., 2013). In this study, the assessment of accuracy relied on two key metrics: overall accuracy and the kappa coefficient (Mui et al., 2015). The kappa coefficient, a measure of chance-corrected agreement, measures the agreement between actual land cover classes and those classified by remote sensing techniques.

The kappa coefficient (K) is computed using the formula in Eq. (1):

$$K = \frac{N \sum_{i=1}^r n_{ii} - \sum_{i=1}^r (n_{i+} \times n_{+i})}{N^2 - \sum_{i=1}^r (n_{i+} \times n_{+i})} \quad (1)$$

$$K = \frac{(\text{Total} \times \text{sum of correct}) - \text{sum of all the (row total} \times \text{column total)}}{\text{Total squared} - \text{sum of all the (row total} \times \text{column total)}}$$

In Eq. (1), 'r' denotes the number of rows in the matrix, 'n_{ii}' represents the observations in row i and column i, 'n_{i+}' and 'n_{+i}' are the marginal totals of row i and column i, respectively, and 'N' represents the total number of observations in the matrix. Interpretation of kappa values generally categorizes them as follows: values ≥ 0.75

Table 1
Landsat images and their date of acquisition for the Densu Delta basin.

Densu	Satellite	Date of imagery	Spatial Resolution (m)
1998	Landsat 4	24th January 1998	30
2003	Landsat 7 ETM+	12th February 2003	30
2008	Landsat 7 ETM+	24th November 2008	30
2013	Landsat 8	13th October 2013	30
2018	Landsat 8	12th January 2018	30
2023	Landsat 8	2nd January 2023	30

Table 2
Land use land cover types and description.

Land use/cover types	Description
Urban	Residential areas and associated driveway
Bare lands	Lands where there is no vegetation
Waterbody	Surface of land covered entirely with water
Wetlands	Surface of land saturated with water and water-dependent vegetation.
Vegetation	Land dominated by trees and grasses

Table 3
Land use land cover classes.

Class number	Land use/cover class
1	Waterbody
2	Wetlands
3	Vegetation
4	Urban
5	Bare lands

signify excellent agreement beyond chance, values ≥ 0.4 to < 0.75 indicate fair to good agreement beyond chance, and values < 0.4 denote poor agreement beyond chance (Tana et al., 2013). This approach provides a robust framework for rigorously assessing the accuracy of land-cover classifications derived from remote sensing data.

LULC gains, losses and transition probability analysis. The study of land use/land cover change (LULC) in wetlands involves a systematic analysis of both losses and gains within specific time intervals. This project uses satellite imagery and geospatial data to quantify changes in wetland landscapes, with a focus on identifying transitions between different LULC categories and understanding the driving factors behind these changes. Net area gains and losses are determined to capture the positive and negative changes in the wetland ecosystem, respectively. Transition probability analysis, embedded in transition matrices, serves as a key tool for comprehensively examining how different wetland states evolve over time. By analyzing these transition probabilities, the study aims to uncover nuanced patterns and trends that determine wetland transformation, thereby contributing to a deeper understanding of the underlying factors influencing wetland transformation. This quantitative methodology provides valuable insights into the complex processes that drive the temporal evolution of wetland landscapes, improving both the accuracy of wetland change predictions and the overall understanding of wetland dynamics.

LULC predictions

The Cellular Automaton (CA) combined with the Artificial Neural Network (ANN) framework serves as a spatiotemporal model to predict land use and land cover change (LULC) in the Densu wetland. Originally conceived by John Von Neumann and Stanislaw Ulam, cellular automata provide a discrete and spatially explicit representation of systems (Neumann, 1966). ANN models have been used to predict changes in LULC, and their combination with other methods such as Markov chain models and Cellular Automata (CA) have yielded encouraging results in assessing LULC dynamics and modeling future situations (Eshetie et al., 2023).

Predictive modeling for 2033 and 2043 used LULC data from 2013 to 2023 for the former and 2023 and 2033 for the latter. The CA-ANN model was calibrated using a learning rate of 0.100, 10 hidden layers, and a momentum of 0.050 in the learning process. A neighbourhood size of 3×3 pixels was optimized for model performance, as recommended by Verburg et al. (2004). While increasing neighbourhood size resulted in slight improvements in accuracy, the effects were not statistically significant. The model's validation was conducted using the Kappa technique, comparing actual and predicted LULC images. The validation process involved calculating the Kappa coefficient, which measures the agreement between the actual and predicted classifications, as well as the overall accuracy of the model. The accuracy percentages were 70% for the Densu wetland suggesting a reasonably accurate simulation. The Kappa values were 0.74 for the Densu indicating significant agreement but also highlighting areas for potential improvement in the model's performance.

Model assessment

A comprehensive assessment was conducted in the Densu Delta wetland to evaluate the accuracy of predictions generated by the

predictive model. Key metrics such as Overall Accuracy and the Kappa Coefficient were utilized to assess the model's performance. The Overall Accuracy metric measured the percentage of correctly classified pixels, while the Kappa Coefficient offered a chance-corrected assessment of predictive capabilities. Interpretation of Kappa values followed established criteria to categorize agreement levels. Correctness percentages were also calculated to measure the accuracy of predicted changes compared to actual observations. Through these rigorous assessments, the study ensured thorough validation of the predictive model, enhancing the credibility and reliability of simulated LULC changes for wetland ecosystems.

Land use land cover classification in the Densu Delta wetland. Fig. 2 illustrate the trend of land use and land cover changes in the Densu delta wetlands Urban land use area increased significantly between 1998 and 2023, from about 18.6% to about 41.4%, with a rapid increase observed between 2013 and 2018. In contrast, waterbodies and vegetation experienced significant declines, with the number of waterbodies declining from about 41.5% to almost 25.6% over the same period. The total area of wetlands also decreased from about 35% to about 29% but showed fluctuations and peaked at about 37% in 2003 and fell to about 16% in 2013. The proportion of undeveloped areas remained relatively stable until 2013, recorded a significant increase until 2018 and fell slightly until 2023. Fig. 2 visually presents these changes, highlighting declines in water bodies and wetlands, significant urban expansion, variations in vegetation cover, and differences in bare areas. The derived land use and land cover maps for the Densu Delta wetlands were produced by SVM for the years (a) 1998, (b) 2003, (c) 2008, (d) 2013, (e) 2018 and (f) 2023, as shown in Fig. 3.

Trends in land use land cover types. The urban land cover area in both Densu Delta wetlands experienced continuous growth from 1998 to 2023, with a significant increase observed between 2008 and 2013. Table 4 shows the trends in different land use and cover types for the wetland during the indicated time periods. The highest average annual increase in urban settlement change occurred between 2008 and 2013, while the lowest rates occurred between 2003 and 2008 in the wetlands of the Densu Delta. The wetland land cover class experienced significant fluctuations in both wetlands, with the highest average percent change per year occurring in the Densu wetlands between 2013 and 2018. In contrast, the lowest change per year between 2003 and 2008 was recorded in the Densu wetlands. Notably, between 2008 and 2013, the wetland land cover class decreased by about 4.21% per year in the Densu wetlands. The area occupied by the aquatic land cover class recorded the highest change in the Densu wetlands as it lost about 1.27% of its area per year between 2018 and 2023. The aquatic land cover class showed a decline in most years and recorded only an increase of about 0.3% in 2003 and 2008.

Average percent area. Table 5 shows the average percent area change per year for the Densu Delta wetlands. The Bare Land land cover class had the lowest average annual percentage change in wetlands. Notably, the wetland bare land cover class experienced the largest change, decreasing by approximately 0.38% between 1998 and 2003. Between 2008 and 2013, the uncovered land area class recorded the highest rate of change for the Densu Delta wetlands, the vegetation land cover class in the Densu Delta wetlands recorded its highest rate of change as it increased by about 1.29% per year increased. In contrast, the lowest rate of change occurred when it decreased by about 0.17% per year from 2018 to 2023. The most significant changes in land use and land cover were observed in the Densu Delta wetlands between 2008 and 2013, and after 2013, land use and land cover changes in the wetland gradually decreased. The urban settlement and vegetation land cover class in the wetlands of the Densu Delta almost doubled its area change between 2008 and 2013 compared to the changes between 2003 and 2008.

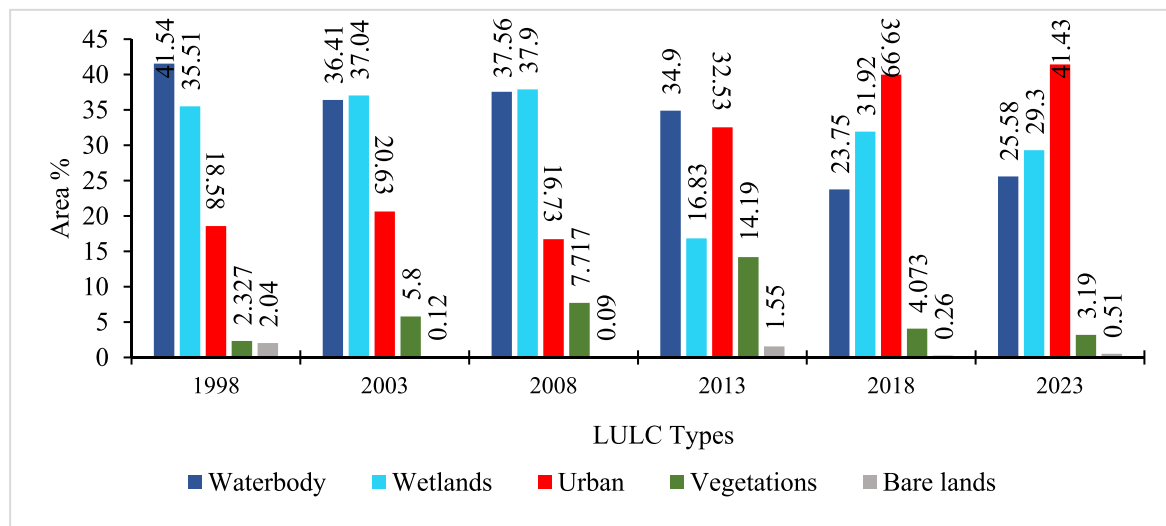


Fig. 2. Trend of land use/ land cover in the Densu Delta wetland, from 1998 to 2023.

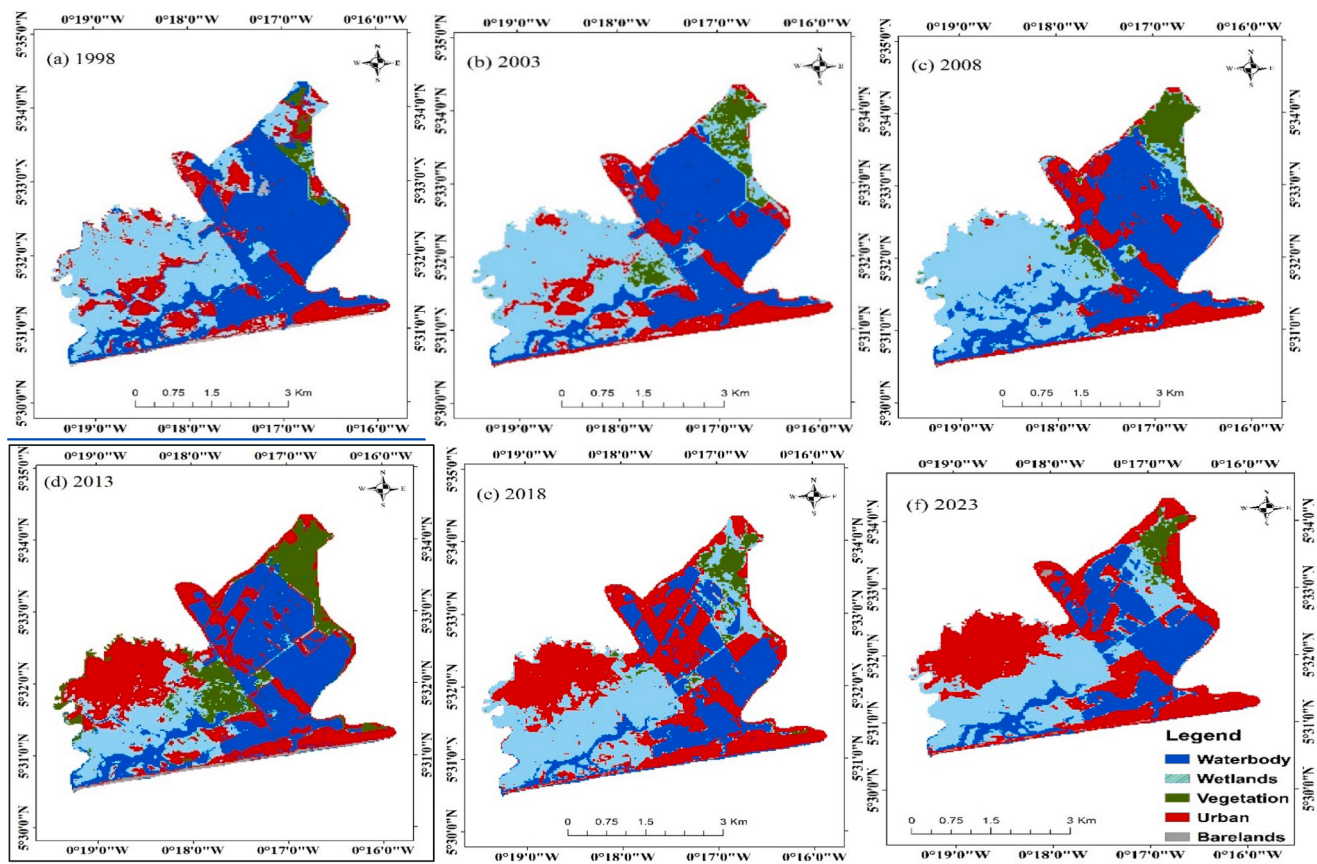


Fig. 3. LULC maps for Densu Delta wetlands (a) 1998 (b) 2003, (c) 2008, (d) 2013, (e) 2018, (f) 2023.

Likewise, the land use and land cover class of wetlands in the Densu Delta wetlands increased to more than twice the area change between 2013 and 2018 compared to the change between 2008 and 2013. There were also significant changes in land cover classes in the wetland water bodies and undeveloped land, with significant increases observed between certain periods.

Transition probability statistics for LULC 1998–2023. The transition matrix provided for the Densu Delta wetland from 1998 to 2023

(Tables 6–10) represents the probabilities of transition from one land use/cover class to another in the specified period.

Rate of change of land use and land cover type before 2013 and after 2013. The analysis provides insights into land use changes in the Densu wetlands (Fig. 4) and compares the growth rates of different land use and cover types before and after 2013. Before 2013, the water area in the Densu wetlands increased significantly by 115.51%, a significant growth of 110.45% in the wetlands. However, after 2013, the expansion slowed

Table 4

Rate of change for different land use classes between 1998 and 2023 in the Densu wetlands.

Land use/cover types	1998–2003 (km ²)		2003–2008 (km ²)		2008–2013 (km ²)		2013–2018 (km ²)		2018–2023 (km ²)	
	Δ Area	Δ %	Δ Area	Δ %	Δ Area	Δ %	Δ Area	Δ %	Δ Area	Δ %
Waterbody	−1.16	−5.12	0.34	1.48	−4.77	−2.66	−0.68	−2.98	−1.49	−6.33
Wetlands	0.35	1.53	0.12	0.53	−0.6	−21.07	1.57	6.92	1.26	5.55
Urban	0.46	2.04	−0.88	−1.92	3.57	15.80	1.69	7.46	0.32	1.43
Vegetations	0.79	3.47	0.44	−3.89	1.46	6.47	−2.29	−2.97	−0.20	−0.88
Bare lands	−0.43	−1.92	−0.01	−0.02	0.33	1.45	0.29	−1.29	0.05	0.24

Table 5

Average percent change in area/year for the Densu Delta wetlands.

Land use/cover types	1998–2003	2003–2008	2008–2013	2013–2018	2018–2023
Waterbody	−1.02	0.30	−0.53	−0.60	−1.27
Wetlands	0.31	0.12	−4.21	1.38	1.11
Urban	0.41	−0.38	3.10	1.49	0.29
Vegetations	0.69	−0.78	1.29	−0.59	−0.17
Bare lands	−0.38	0.00	0.29	−0.26	0.05

Table 6

Densu Delta wetlands transition matrix between 1998–2003.

	Waterbody	Wetlands	Urban	Vegetation	Bare lands
Waterbody	0.784	0.092	0.113	0.011	0.000
Wetlands	0.044	0.816	0.058	0.082	0.000
Urban	0.089	0.188	0.672	0.050	0.001
Vegetation	0.007	0.326	0.024	0.643	0.000
Bare lands	0.290	0.008	0.659	0.002	0.041

Table 7

Densu Delta wetlands transition matrix between 2003–2008.

	Waterbody	Vegetation	Urban	Wetlands	Bare lands
Waterbody	0.022	0.001	0.103	0.873	0.000
Wetlands	0.794	0.105	0.023	0.078	0.000
Vegetation	0.370	0.618	0.005	0.007	0.000
Urban	0.268	0.009	0.581	0.138	0.004
Bare lands	0.000	0.000	0.900	0.033	0.067

Table 8

Densu Delta wetlands transition matrix between 2008–2013.

	Wetlands	Vegetation	Waterbody	Urban	Bare lands
Wetlands	0.365	0.169	0.033	0.433	0.000
Vegetation	0.014	0.882	0.003	0.102	0.000
Urban	0.009	0.011	0.240	0.659	0.081
Wetlands	0.073	0.021	0.788	0.115	0.003
Bare lands	0.000	0.000	0.000	0.000	1.000

Table 9

Densu Delta wetlands transition matrix between 2013–2018.

	Wetlands	Waterbody	Vegetation	Urban	Bare lands
Wetlands	0.037	0.817	0.006	0.140	0.000
Vegetation	0.004	0.632	0.237	0.127	0.000
Waterbody	0.612	0.138	0.016	0.233	0.000
Urban	0.034	0.134	0.002	0.828	0.002
Bare lands	0.383	0.000	0.000	0.501	0.116

to 84.23% and 78.05%, respectively. Urban areas recorded a remarkable increase of 113.95% after 2013 compared to 55.94% before 2013, indicating accelerated urbanization. The vegetation cover experienced modest growth (15.84%) before 2013 but increased to 21.45% after 2013. The rate of change for bare land accelerated slightly from 2.25%

Table 10

Densu Delta wetlands transition matrix between 2018–2023.

	Waterbody	Wetlands	Vegetation	Urban	Bareland
Waterbody	0.781	0.088	0.005	0.125	0.001
Wetlands	0.055	0.736	0.038	0.171	0.000
Bare lands	0.000	0.222	0.438	0.341	0.000
Vegetation	0.132	0.071	0.002	0.786	0.009
Urban	0.030	0.000	0.000	0.576	0.394

before 2013 to 2.32% after 2013. Overall, there was significant growth in waterbodies, wetlands, and urban areas before 2013, with growth in waterbodies and wetlands slowing after 2013 slowed while urban areas expanded rapidly.

Losses and gains. Analysis of land use and cover loss in the Densu wetlands from 1998 to 2023 shows significant transitions between land cover classes. [Table 11](#) shows that the water bodies suffered a net area loss of 10.11 km², mainly due to transitions into urban areas, indicating encroachment of urban expansion into water regions. Wetlands suffered a notable net area loss of 22.61 km, mainly through transitions to water bodies and urban areas, highlighting their vulnerability to urbanization. Vegetation recorded a net area loss of 10.14 km², mainly due to the transition to urban areas, illustrating the impact of urban development on vegetated regions. Urban areas experienced significant net area losses, particularly at transitions to wetlands, highlighting conversion to wetlands and aquatic areas. Bare areas experienced minimal net area loss, primarily through transitions to water bodies, wetlands, and vegetation. The analysis also shows net gains in aquatic area at the expense of wetlands, vegetation and urban areas, indicating shifts in landscape dynamics within the Densu wetlands.

[Table 12](#) provides insights into the net increases in land use and land cover classes in the Densu wetland and highlights specific transitions that contribute to the expansion of particular land cover types. The transitions in [Table 12](#) indicate changes in landscape dynamics, such as: E.g., the conversion of wetlands to water bodies, vegetation to water bodies, and city to water bodies, indicating changes in water body extent within the Densu wetlands. There is a net gain of 10.8 km², indicating an increase in water area at the expense of wetlands. There is also a net gain of 2.16 km² and a net gain of 4.67 km², indicating an increase in water area at the expense.

Land use land cover validation. The model's assessment of land cover change is done by comparing observed and simulated data for the year

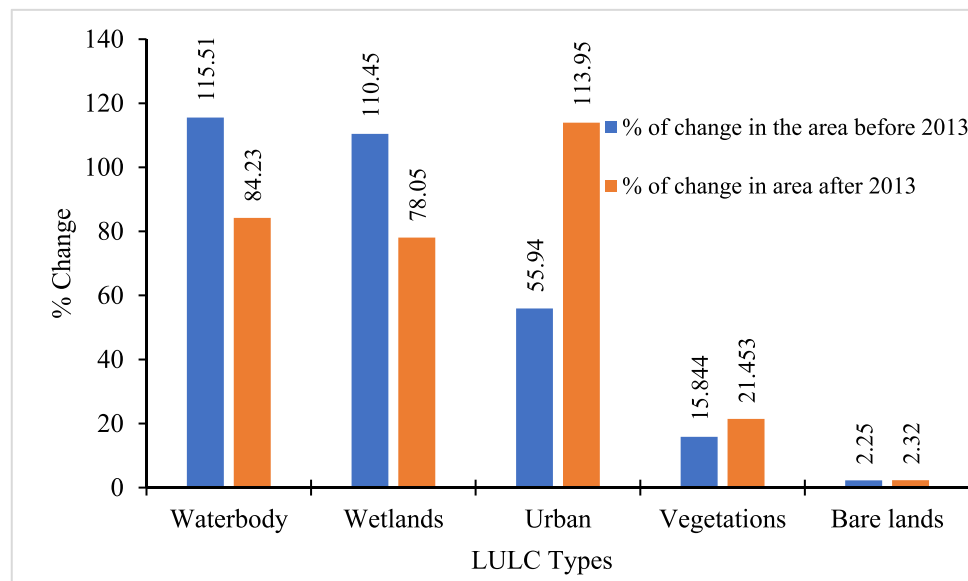


Fig. 4. Rate of change in the Densu wetlands.

Table 11
Land use land cover loss in the Densu Wetlands.

Land use and land cover change			
From	To	Area (km ²)	Net area loss (km ²)
Waterbody	Wetlands	3.22	10.11
Waterbody	Vegetation	0.45	
Waterbody	Urban	5.4	
Waterbody	Bare lands	1.04	22.61
Wetlands	Waterbody	14.02	
Wetlands	Vegetation	2.4	
Wetlands	Urban	5.49	10.14
Wetlands	Bare lands	0.7	
Vegetation	Waterbody	2.61	
Vegetation	Wetlands	2.08	19.04
Vegetation	Urban	2.7	
Vegetation	Bare lands	2.75	
Urban	Waterbody	10.07	0.36
Urban	Wetlands	6.24	
Urban	Vegetation	2.51	
Urban	Bare lands	0.22	0
Bare lands	Waterbody	0.04	
Bare lands	Wetlands	0.3	
Bare lands	Vegetation	0.02	
Bare lands	Urban	0	

Table 12
Land use land cover gains in the Densu Delta wetland.

Land use and land cover change		
From	To	Net Gain Area (km ²)
Wetlands	Waterbody	10.8
Vegetation	Waterbody	2.16
Urban	Waterbody	4.67
Urban	Wetlands	0.78
Wetlands	Vegetation	0.32
Vegetation	Urban	0.19

2023. A slightly underestimated water area with a $\Delta\%$ of -4.41% , and an overestimated wetland area with a $\Delta\%$ of 7.34% was observed in the wetland in 2023. The vegetation area in 2023 was also underestimated in the simulation with a $\Delta\%$ of -3.00% . This is a notable deviation and improvements in capturing vegetation dynamics could increase the accuracy of the model. The simulation produced a very small

overestimation of urban area in 2023, with a $\Delta\%$ of 0.31% . This suggests that the model is generally accurate in predicting urban land cover changes. With a $\Delta\%$ of -0.25% , the area of undeveloped land in 2023, as slightly underestimated. The comparison between the observed and simulated data can be visualized in Fig. 5. for the Densu Delta wetlands.

Spatial distribution of attrition

Our analysis of land use class attrition from 1998 to 2023 shows dynamic spatial and temporal patterns of change in the Densu Delta wetland (Fig. 6). Waterbody attrition exhibited significant fluctuations, peaking at 99.86% and 99.74% in the 2003–2008 and 2008–2013 periods respectively, before declining to 21.86% in 2018–2023. This suggests intense pressure on water resources during the middle of our study period, with some recovery in recent years.

Wetlands have consistently high attrition rates, exceeding 90% between 2003 and 2013. This alarming trend indicates substantial loss or conversion of wetland habitats, particularly in the central and southern portions of the study area. The attrition rate decreased to 26.42% during 2018–2023 which may be due to conservation efforts or changes in land use policies. Vegetation attrition showed an increase from 32.81% in 1998–2003 to 98.88% in 2008–2013, remaining high at 87.27% in 2013–2018. This trend aligns with our earlier observations of significant vegetation loss, likely due to urban expansion and agricultural intensification. Urban areas showed an interesting pattern, with attrition rates increased over time reaching a peak of 99.83% between 2013 and 2018. This could indicate rapid urban turnover or redevelopment, particularly in the eastern sectors of the delta. Bare lands exhibited consistently high attrition rates throughout the study period, with a notable exception of 0% in 2008–2013. This anomaly suggests a period of stability or complete conversion of the remaining bare lands to other uses.

Fragmentation analysis of land use classes

The fragmentation analysis reveals dynamic changes in landscape structure across different land use classes in the Densu Delta wetland from 1998 to 2023 (Fig. 7). Waterbodies exhibited fluctuating fragmentation patterns. The number of patches decreased from 303 in 1998 to 62 in 2008, indicating consolidation, but then increased to 214 in 2013 before declining again to 91 in 2023. Mean patch size showed an inverse relationship, peaking at 82.47 in 2003 and reaching 70.67 in 2023, suggesting overall larger, more contiguous water bodies by the end of the study period.

Wetlands demonstrated a complex fragmentation trend (Fig. 8). The

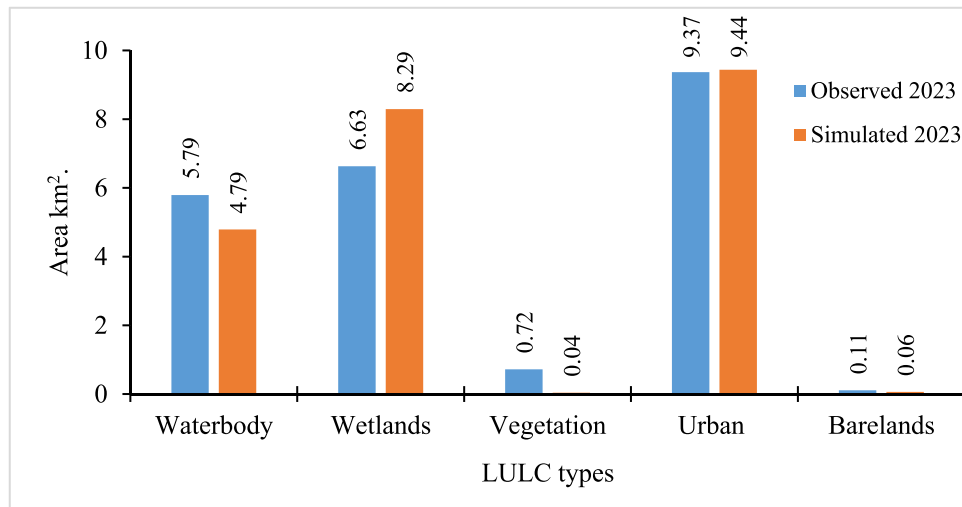


Fig. 5. Statistical comparisons between simulated and observed Densu LULC map for 2023.

number of patches initially increased from 227 in 1998 to 342 in 2013, indicating increased fragmentation. However, this was followed by a decrease to 252 patches in 2023, suggesting some wetland consolidation in recent years. Mean patch size fluctuated significantly, dropping from 39.33 in 1998 to a low of 12.37 in 2013, before recovering to 29.23 in 2023. This pattern indicates a period of severe wetland fragmentation followed by partial recovery. Urban areas showed a clear trend of consolidation and expansion. The number of patches decreased from 282 in 1998 to 97 in 2023, while mean patch size increased dramatically from 16.57 to 107.36 over the same period. This indicates the formation of larger, more contiguous urban areas, consistent with our observations of rapid urbanization. Vegetation experienced significant changes in fragmentation patterns. Patch numbers increased from 35 in 1998 to a peak of 235 in 2013, before declining to 23 in 2023. Mean patch size fluctuated, reaching a maximum of 46.94 in 2008 before decreasing to 34.87 in 2023. This suggests a period of vegetation fragmentation followed by loss of smaller patches. Bare lands showed relatively low and stable patch numbers throughout the study period, with a slight increase from 12 patches in 2003 to 38 in 2023. Mean patch size fluctuated, with a notable peak of 24.31 in 2013.

Cubic linear trends of the land use classes (1998 to 2023)

To better understand the long-term dynamics of land use change in the Densu Delta wetland, a cubic linear trend analysis for each land use class was conducted from 1998 to 2023 (Fig. 9; Table 13).

Waterbody trends ($R^2 = 0.4126$) show a complex pattern, represented by Eq. (2):

$$y = -3.51 \times 10^{-3}X^3 + 2.12 \times 10^1X^2 - 4.26 \times 10^4X + 2.86 \times 10^7 \quad (2)$$

The graph in Fig. 9 indicates a sharp initial decline followed by a slight recovery and stabilization, suggesting multiple phases of change in water bodies. Wetlands exhibit a trend ($R^2 = 0.4082$) characterized by Eq. (3):

$$y = 3.08 \times 10^{-3}X^3 - 1.85 \times 10^1X^2 + 3.73 \times 10^4X - 2.50 \times 10^7 \quad (3)$$

The curve shows an initial increase, followed by a decline and a slight recovery towards the end of the study period.

Vegetation displays a strong trend ($R^2 = 0.7731$) represented by Eq. (4):

$$y = -3.92 \times 10^{-4}X^3 + 2.41X^2 - 4.91 \times 10^3X + 3.35 \times 10^6 \quad (4)$$

The graph shows a consistent upward trajectory, particularly accelerating in the latter half of the study period.

Urban areas show a pronounced curved trend ($R^2 = 0.6289$) with Eq. (5):

$$y = 1.33 \times 10^{-3}X^3 - 8.11X^2 + 1.65 \times 10^4X - 1.12 \times 10^7 \quad (5)$$

The curve indicates an initial increase followed by a sharp decline, suggesting significant changes in urban land use over time. Bare lands show a relatively stable trend ($R^2 = 0.5969$) represented by Eq. (6):

$$y = -5.09 \times 10^{-4}X^3 + 3.07X^2 - 6.18 \times 10^3X + 4.14 \times 10^6 \quad (6)$$

with the graph showing slight fluctuations but remaining a minor component of the landscape.

Land use and land cover prediction. Figs. 10 and 11 shows the simulated land use and land cover forecast (LULC) for 2033 and 2043 in the Densu Delta wetlands. In 2033, the simulated area of water bodies is 5.54 km² and increases slightly to 5.57 km² in 2043. The share of water bodies in the total area is 24.50% in 2033 and increases slightly to 24.62% per year 2043. This means that the observed area in 2023 is higher than the two simulated values for 2033 and 2043. In 2033, the wetland area decreased slightly to 6.21 km² in 2043, but in 2023 the wetlands recorded an area of 6.63 km², which was higher than both simulated values. The proportion of wetlands in the total area is 27.98% in 2033 and decreases to 27.46% in 2043. The urban area is expected to increase from 9.84 km² in 2033 to 9.92 km² in 2043, which is exactly corresponds to the trend that it showed in previous years. The proportion of urban areas in the total area increases from 43.47% in 2033 to 43.86% in 2043. Both vegetation and bare land showed minor changes in area in the simulated years.

Discussion

The aim of this study is to explore and summarize existing knowledge on key topics central to the comprehensive analysis of wetlands, with particular emphasis on the Densu Delta wetland in Ghana. This study emphasizes a multidisciplinary approach and covers various areas including ecology, land use and land cover change, geographic information systems (GIS) and remote sensing (RS). Wetlands, which make up approximately 6% of the Earth's surface and perform a variety of useful functions, including flood control and water filtration, are an integral part of our ecology. Wetlands are important to society due to a combination of these functions and products, as well as the importance attached to biodiversity and cultural and heritage characteristics. Wetlands play an important role in maintaining the water cycle, maintaining the diversity of the world's ecosystems, controlling the climate system,

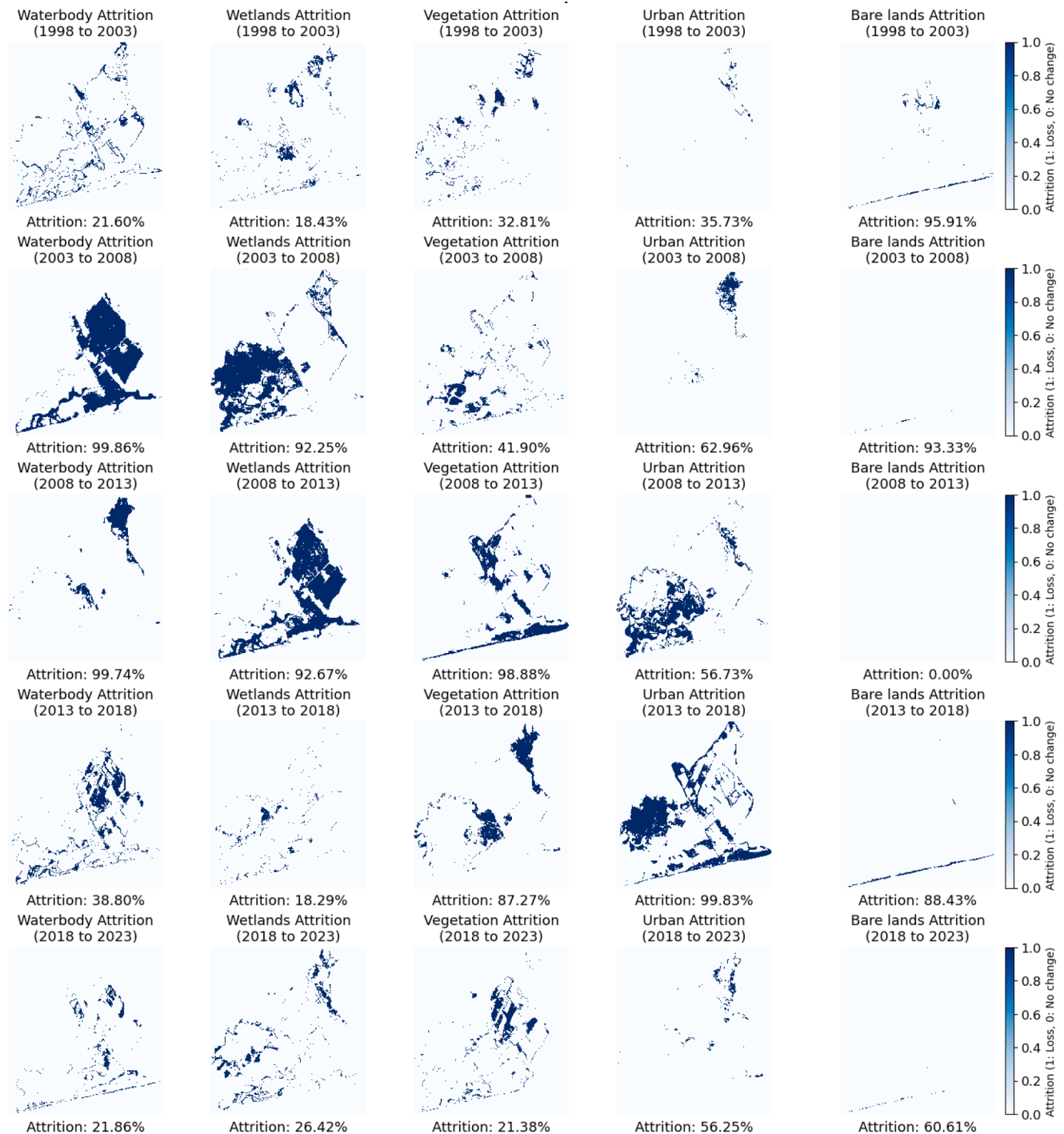


Fig. 6. Land use attrition maps in the Densu Delta basin (1998 to 2023).

and promoting human well-being (Dinsa and Gemed, 2019). Land use and land cover change (LULCC) is urgently needed as it is an environmental problem with profound implications for sustainable development and environmental well-being worldwide. In developing countries such as Ethiopia, human activities play an important role in promoting LULC (Moisa et al., 2022). To address these challenges, several new global land use and land cover (LULC) datasets have been developed to meet growing needs, such as Esri 2020 Land Cover and European Space Agency World Cover 2020 (Potapov et al., 2022). The Densu Delta Wetland is a prime example of the complex interplay between human activities, changes in land use and the delicate balance within ecosystems. This wetland ecosystem, known for its biodiversity and significant

essential ecological contributions, is facing major challenges due to rapid increases in urbanization and changing land use patterns (Ekumah et al., 2020).

The analysis of land use and land cover changes in the wetlands of the Densu Delta shows a significant change in the distribution of different land cover classes during the period from 1998 to 2023. The urban land use/land cover recorded a remarkable increase, increasing from about 18.6% increased to around 41.4% during this period. This increase was particularly pronounced between 2013 and 2018, indicating a rapid pace of urbanization in the wetland. In contrast, there were significant declines in water bodies and vegetation, with the proportion of water bodies falling from around 41.5% to almost 25.6% over



Fig. 7. Spatial distribution of segmentation in the Densu Delta basin (1998 to 2023).

the same period. The reduction in water bodies highlights the encroachment of urban areas into previously aquatic regions and reflects the pressure that urban expansion places on natural ecosystems. The total area of wetlands has declined from about 35% to about 29% between 1998 and 2023, indicating a loss of wetland habitat in the Densu Delta wetlands. Although there are fluctuations, with a peak of about 37% in 2003, followed by a decline to about 16% in 2013, the downward trend indicates a worrying decline in wetland cover. This decline can have negative impacts on biodiversity and ecosystem services provided by wetlands, such as: B. Water filtration and flood protection. Overall vegetation cover experienced a moderate increase from about 2% to 3%, reaching a peak of about 14% in 2023. However, there was a significant decline in vegetation cover between 2013 and 2018, indicating possible disturbance to vegetation areas in the wetlands. This decline in vegetation cover may be due to various factors, including land conversion for urban development or changes in land management practices. Barelands area share remained relatively stable through 2013, but experienced a significant increase through 2018, followed by a slight decline through 2023. This fluctuation in undeveloped land reflects changing land use patterns and management practices within the wetland area. It highlights the dynamics of land cover change and the importance of monitoring and managing undeveloped areas to maintain ecological integrity and biodiversity in wetlands. The results indicate continuous growth of urban land cover area in the Densu Delta wetlands throughout the study period. Significant increases were observed particularly between 2008 and 2013, attributed to urbanization in certain areas such as Weija, Bortianor and Mpoase. This expansion highlights rapid urban growth and its impact on surrounding wetland ecosystems. The complex interplay between urbanization and wetland dynamics in the wetlands of the Densu Delta. Rapid urban expansion

poses significant challenges to wetland ecosystems, including habitat loss, water quality degradation, and altered hydrological systems. The observed variations in wetland land cover highlight the vulnerability of these ecosystems to external stresses and require effective management strategies to ensure that these areas are protected from further degradation, promote sustainable land use practices, and maintain the ecological balance necessary for the health of wetland ecosystems.

The Densu Delta wetland transition matrices from 1998 to 2023 show the probabilities of land use/cover class transitions over specific time periods. Between 1998 and 2003 there was a significant likelihood of wetland to aquatic transition, indicating significant conversion during this period. The expansion of the city into water areas was also noticeable. From 2008 to 2013, in addition to the transition from water bodies to wetlands, urban interventions in wetlands also occurred. The period between 2018 and 2023 saw further conversion of wetlands to bodies of water, with urban expansion into barren areas becoming apparent. Over the years, there have been significant transitions from water bodies and wetlands to other land use/cover classes, highlighting the changes in these areas. Urbanization remained a consistent trend, with high transition probabilities to urban areas observed in various land use/cover classes. These matrices provide valuable insights into the dynamics of land use change and help identify important transition patterns and problem areas in the wetlands of the Densu Delta. The years from 2018 to 2023 continue to reflect ongoing changes in the wetlands of the Densu Delta, with wetland to water conversion observed. Furthermore, urban expansion into previously barren areas represents a notable trend that illustrates the relentless pressure of urbanization on the wetland ecosystem. These observations highlight the dynamics of land use change in the wetlands of the Densu Delta and highlight the importance of proactive conservation efforts to mitigate the negative impacts of

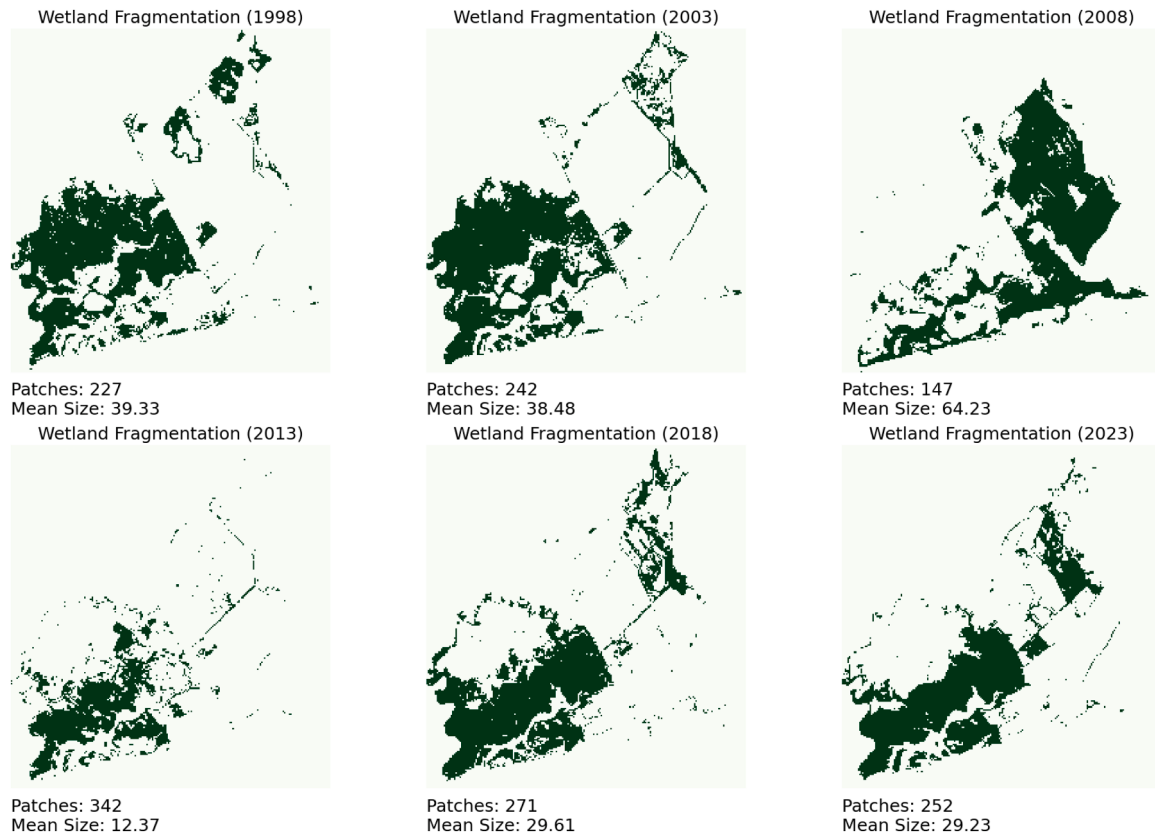


Fig. 8. Spatial distribution of wetland segmentation (1998 to 2023).

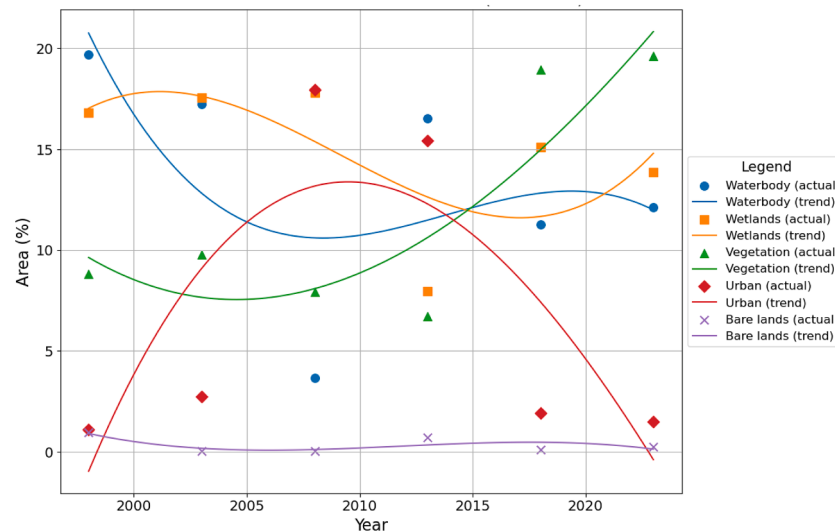


Fig. 9. Cubic Linear Trends of Land Use Classes (1998–2023).

urban interventions and land use conversions. Throughout the analyzed period, transitions from water bodies and wetlands to other land use/cover classes remain significant, indicating fluid land use dynamics within the wetland ecosystem. The persistence of urbanization as a dominant trend with high probabilities of transition to urban areas in different land use/cover classes highlights the need for comprehensive conservation strategies that address the diverse challenges of urban expansion.

The significant growth of aquatic, wetland and urban areas observed prior to 2013 highlights the importance of these ecosystems and the

challenges they face in the face of rapid urbanization and environmental change. The slowdown in stream and wetland growth after 2013, coupled with accelerated urban expansion, highlights the need for proactive management strategies to ensure the long-term sustainability of the wetland ecosystem. This requires integrated approaches that balance conservation efforts with the socioeconomic needs of surrounding communities and emphasize the importance of informed decision-making and sustainable development practices in maintaining the ecological integrity of the Densu wetlands. The observed net aquatic area loss totaling 10.11 km, mainly due to transitions into urban areas,

Table 13

Land use class change dynamics in the Densu Delta wetland.

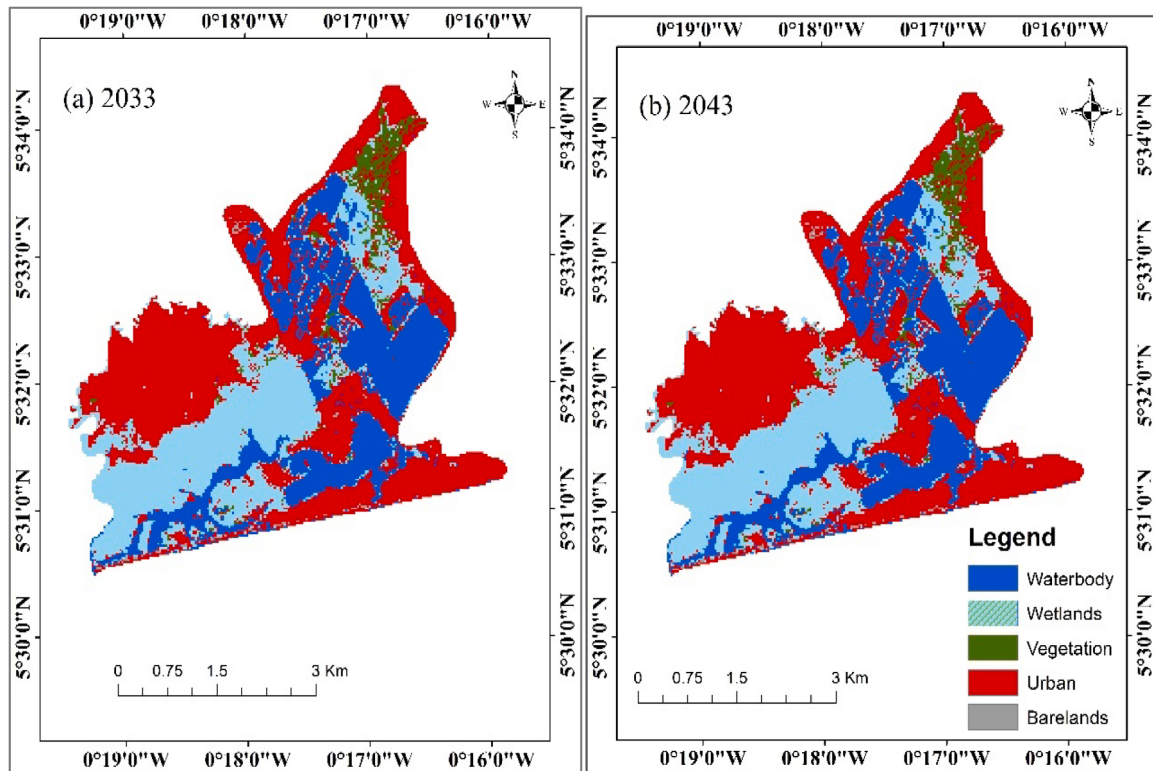
Land Use Class	Cubic Equation	R-squared
Waterbody	$y = -3.51e-03x^3 + 2.12e+01x^2 + -4.26e+04x + 2.86e+07$	0.4126
Wetlands	$y = 3.08e-03x^3 + -1.85e+01x^2 + 3.73e+04x + -2.50e+07$	0.4082
Vegetation	$y = -3.92e-04x^3 + 2.41e+00x^2 + -4.91e+03x + 3.35e+06$	0.7731
Urban	$y = 1.33e-03x^3 + -8.11e+00x^2 + 1.65e+04x + -1.12e+07$	0.6289
Bare lands	$y = -5.09e-04x^3 + 3.07e+00x^2 + -6.18e+03x + 4.14e+06$	0.5969

indicates a worrying trend of urban encroachment into aquatic regions. This encroachment not only reduces the extent of the water body, but also poses a threat to aquatic habitats and biodiversity, highlighting the urgent need for integrated urban planning strategies that prioritize environmental protection alongside development goals. The significant net area loss of 22.61 km in wetlands, primarily through transitions to water bodies and urban areas, highlights the vulnerability of wetland ecosystems to the pressures of urbanization. Wetlands play a critical role in regulating flooding, water filtration and providing habitat, and their degradation or loss can have far-reaching consequences for both local ecosystems and human communities that rely on wetland services.

The spatial patterns of land use class attrition provide crucial insights into the dynamics of landscape change in the Densu Delta wetland. The high attrition rates observed for waterbodies and wetlands, particularly between 2003 and 2013, coincide with the period of rapid urban expansion. This suggests that urbanization was a major factor in the loss of natural habitats in the delta. The extreme vegetation attrition rates after 2008 are consistent with our previous findings of significant decline in vegetation cover. This trend is particularly concerning because vegetation plays an important role in maintaining ecosystem

services such as carbon sequestration and soil stabilization. Increasing urban attrition rates over time, culminating in near-total attrition between 2013 and 2018, indicate a period of intense urban transformation. This could reflect both the expansion of urban areas into previously natural landscapes and the redevelopment of existing urban spaces. These attrition patterns highlight the need for targeted conservation efforts. Areas with persistently high attrition rates for natural land cover types (waterbodies, wetlands, and vegetation) should be prioritized for protection and restoration initiatives. The recent moderation in attrition rates for some classes (e.g., wetlands over 2018–2023) may be indicative of the initial success of conservation measures, but sustained efforts are clearly needed.

Fragmentation analysis provides crucial insights into the changing landscape structure of the Densu Delta wetland. The fluctuating fragmentation patterns of waterbodies, characterized by periods of consolidation and fragmentation, may reflect the complex interplay of natural hydrological processes and human interventions such as dam construction or water diversion. Of particular concern are wetland fragmentation trends. The sharp increase in patch numbers and decrease in mean patch size between 1998 and 2013 suggests a period of severe fragmentation, likely due to urban encroachment and land conversion. The partial recovery observed in recent years, with fewer but larger patches, may be attributed to conservation efforts or natural wetland expansion. However, overall reduction in wetland area and continued fragmentation highlights the ongoing threats to these critical ecosystems. The urban fragmentation pattern clearly illustrates the process of urban growth and consolidation. The formation of larger, contiguous urban patches suggests not only expansion but also infilling of previously undeveloped areas within the urban matrix. This pattern of urbanization can have significant implications for ecosystem connectivity and the provision of urban green spaces. The complex dynamics of vegetation fragmentation, with an initial increase in patch numbers followed by a dramatic decline, may indicate a process of initial disturbance and fragmentation followed by wholesale loss of vegetated areas. This trend is particularly worrying from a biodiversity and

**Fig. 10.** Simulated Densu Delta LULC Maps for years (a) 2033, (b)2043.

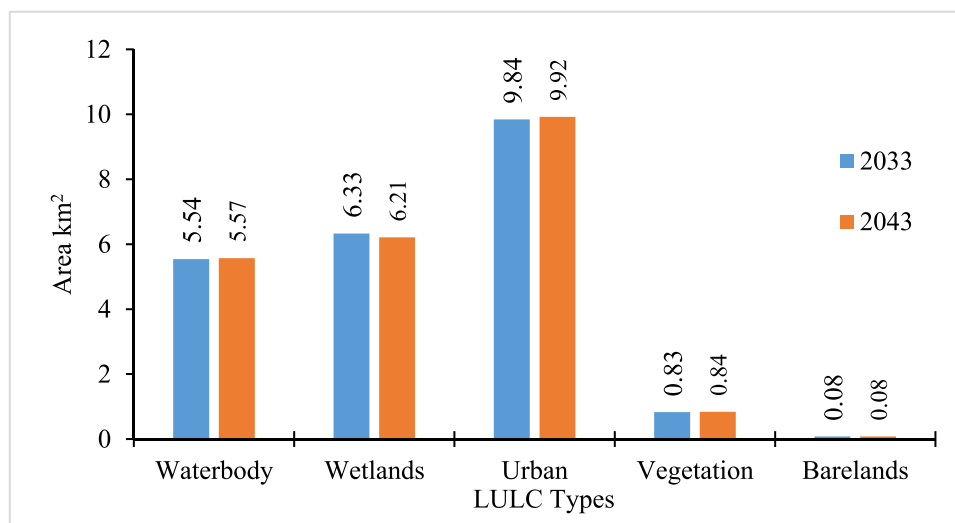


Fig. 11. Observed and simulated changes for 2033 and 2043 in the Densu wetland.

ecosystem services perspective. These fragmentation patterns, combined with analysis of land use changes and attrition rates, provide a more comprehensive understanding of the landscape transformation in the Densu Delta wetland. They highlight the need for conservation strategies that not only preserve total area but also maintain landscape connectivity and reduce fragmentation, particularly for critical habitats like wetlands and vegetation patches.

The cubic linear trend analysis provides valuable insights into the complex dynamics of land use change in the Densu Delta wetland over the 25-year study period. The non-linear trends observed for all land use classes highlight the dynamic nature of this ecosystem and the multiple factors influencing landscape change. The waterbody trend, characterized by an initial sharp decline followed by partial recovery, may reflect the impacts of climate variability, water management practices, and conservation efforts over time. This pattern underscores the need for long-term monitoring and adaptive management of water resources in the delta. The wetland trend, showing fluctuations over time, aligns with our earlier findings of wetland vulnerability and partial recovery. The cubic nature of the trend suggests periods of expansion and contraction, possibly influenced by both natural processes and human interventions. The vegetation trend shows the highest R-squared value (0.7731), indicating a strong fit to the cubic model. The consistent upward trajectory, particularly in recent years, suggests a significant increase in vegetation cover. This could be due to reforestation efforts, natural regeneration, or changes in land management practices. The urban trend, with the second-highest R-squared value (0.6289), shows an unexpected pattern of initial growth followed by decline. This contradicts our earlier observations of sustained urbanization and warrants further investigation. It may indicate a shift in urban development patterns or classification methods over the study period. The bare lands trend, while showing a moderate R-squared value (0.5969), indicates relatively stable conditions with minor fluctuations. This suggests that areas of bare land in the delta have remained consistent, possibly representing areas resistant to vegetation growth or subject to ongoing disturbance.

These cubic linear trends, when considered alongside our earlier analyses of land use change, attrition, and fragmentation, provide a comprehensive picture of the complex and dynamic nature of landscape change in the Densu Delta wetland. They underscore the need for nuanced, adaptive management strategies that can respond to non-linear changes and address the multiple drivers of landscape transformation.

Conclusions

Research conducted in the Densu Delta Wetland has provided important insights into the impacts of land use/land cover (LULC) and climate change. The study examined in detail LULC changes in both wetlands and explained transitions between waterbodies, wetlands, urban areas, vegetation, and bare areas over multiple time periods. Urbanization was found to be an important influencing factor for land use changes in both wetlands, particularly affecting water bodies, wetlands and vegetation. The study thoroughly validated the prediction model used and compared simulated changes with observed data. The model had a correctness percentage of 70% and a kappa value of 0.74, with different levels of accuracy in different land cover classes. Simulated forecasts for 2033 and 2043 were compared with observed changes in 2023, providing a comprehensive understanding of land use changes. This analysis included assessment of changes in land classes and provided valuable insights into the dynamic nature of land cover in the wetlands. Integrated urban planning initiatives are urgently needed to address the significant impacts of urban expansion on both wetland ecosystems. Authorities should prioritize the implementation of zoning regulations, green infrastructure initiatives and sustainable urban planning principles to balance development goals and environmental protection. By integrating these measures, the negative impacts of urbanization on wetlands can be effectively mitigated. Establishing a robust and continuous monitoring system is essential for conducting regular assessments of land use and land cover change (LULC) associated with climate change impacts.

Such a system enables early detection of trends and potential stressors and facilitates immediate conservation actions and adaptive management strategies to maintain the ecological balance of wetlands. Regular monitoring will provide critical insights into ongoing changes and enable informed decision making.

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Data statement

The data used in this study will be made available upon request from authors.

Data code availability statement

The data codes used in this paper will be made available upon reasonable request to the authors.

Ethical statement for solid state ionics

- 1) This material is the authors' own original work, which has not been previously published elsewhere.
- 2) The paper is not currently being considered for publication elsewhere.
- 3) The paper reflects the authors' own research and analysis in a truthful and complete manner.
- 4) The paper properly credits the meaningful contributions of co-authors and co-researchers.
- 5) The results are appropriately placed in the context of prior and existing research.
- 6) All sources used are properly disclosed (correct citation).

CRedit authorship contribution statement

Cynthia Laar: Writing – review & editing, Visualization, Validation, Supervision, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Kevin Buah Kofi Annan:** Methodology, Software, Data curation, Writing – original draft, Visualization. **Abass Gibrilla:** Formal analysis, Visualization, Supervision. **Zenobia Kusi-Afrakoma:** Investigation, Data curation. **Owusu Korkor-Asante:** Data curation, Formal analysis. **Michael Saah-Hayford:** Data curation, Formal analysis. **Courage Egbi:** Writing – review & editing. **Dickson Abdul-Wahab:** Writing – review & editing. **Julliet Attah:** Writing – review & editing. **Geophrey Anornu:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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