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Land-use changes and community perspectives on the effects of sea water intrusion on riverine soils, vegetation, and cultivated areas in Tana River Delta, Kenya

Raburu F.A *, Kirui K.B, Githiri M.N and Tarus G.K

Department of Natural Resources, Faculty of Environment and Resources Development, Egerton University, Kenya. P.O. Box 536-20115. Egerton, Njoro.

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Abstract

Deltaic ecosystems are wetlands shaped by the interaction of freshwater and seawater dynamics. However, reduced river flow, especially during the dry season, allows seawater to intrude into river channels, disrupting deltaic vegetation and causing crop losses. Elevated salinity levels adversely affect riparian soils, freshwater-dependent vegetation, and agricultural productivity, with crops like rice being particularly vulnerable. This phenomenon is currently occurring in Kenya's Tana River Delta. This study investigated land-use changes resulting from seawater intrusion and its impacts on riparian soils, vegetation including mangroves, and on adjacent cultivated areas in the Kipini and Ozi regions of the Tana River Delta. Land cover changes were analyzed using satellite imagery from Landsat, Aster, and Sentinel, spanning the period from 1999 to 2021. Over this period, the area covered by mangroves increased by 10.8%, River area expanded by 2.7%, and human-occupied areas grew from 11 hectares to 20 hectares. Conversely, grasslands and non-vegetated areas decreased by 1.8% and 20%, respectively. The mean pH of mangrove soil was 7.028±0.127, while cultivated soils had a slightly lower mean pH of 6.608±0.133. The mean salinity of mangrove soils was 0.941±0.556‰. Water salinity decreased significantly with distance from the mouth of the delta, influenced by recent El Niño rains, which diluted saline levels. These conditions supported the growth of crops and the development of young mangroves.

Key words; Crop loss; Delta; Mangroves; Riverine vegetation; Sea water intrusion; Wetlands

1. Introduction

Deltas and estuaries are unique and highly productive wetland ecosystems, characterized by diverse habitats such as mangrove and riverine forests, floodplain grasslands, vegetated sand dunes, brackish water environments, and seasonal freshwater lakes [1]. These ecosystems are rich in natural resources and hold significant socio-economic value, providing food, freshwater, fuelwood, building materials, and more [2]. The ecological functions of most river deltas are shaped by the interplay between freshwater and seawater dynamics. As disturbance-driven systems, deltaic ecosystems experience frequent cycles of flooding and drought, with riparian vegetation adapting to these climate-related influences [3].

Seawater intrusion poses a significant threat to deltas worldwide [4]. This issue becomes particularly severe during dry seasons when reduced freshwater inflow from upstream allows seawater to encroach further inland [5]. Human activities, such as upstream land-use changes, the construction of hydroelectric infrastructure, and increased water abstraction, further exacerbate the problem [6]. The consequences are especially noticeable for freshwater-dependent riparian vegetation including mangrove forest and agricultural crops, such as rice, which are highly sensitive to increased salinity levels [7].

The Tana River Delta in Kenya is among the most significant and biodiverse wetland ecosystems in East Africa. Located along the Kenyan coast, where the Tana River—Kenya's largest river—flows into the Indian Ocean, the delta spans

* Corresponding author: Raburu FA

approximately 130,000 hectares [8]. It features a rich mixture of habitats, including mangrove forests, freshwater wetlands, floodplains, grasslands, lakes, and estuarine environments. The delta plays a vital role in supporting diverse ecological, social, and economic functions, making it a critical area for both conservation and human livelihoods. Key activities within the Tana River Delta include flood-recession farming of rice, horticulture of crops such as mangoes, coconuts, bananas, beans, and vegetables on sandy levees, maize cultivation in mixed soils, fishing in freshwater wetlands, the estuary, and near shore Ungwana Bay, livestock herding on communal rangelands, and small-scale businesses catering to local needs [6].

The Delta faces numerous interconnected pressures that threaten its ecological integrity, biodiversity, and the livelihoods of dependent communities. These threats stem from a combination of natural processes, human activities, and broader environmental changes. Some of the key challenges include seawater intrusion, driven by reduced freshwater flow during dry seasons and worsened by upstream water abstraction, dam construction, and climate change; the development of water management infrastructure along the Tana River, such as dams, hydropower projects, and irrigation schemes; and over-harvesting of riverine vegetation including mangroves for fuelwood, charcoal production, and construction poles [9].

This study examined land-use changes resulting from seawater intrusion and its impacts on riparian soils, vegetation, and adjacent cultivated areas in the Kipini and Ozi regions of the Tana River. Understanding the extent and impacts of seawater intrusion is vital for effective land management and sustainable development. Investigating land-use changes in response to these intrusions provides essential insights into how the Tana delta's ecosystems and agricultural areas are being transformed. The findings of this study will addresses critical gaps in knowledge by assessing the spatial and temporal changes in land cover from 1999 to 2021 and quantifying the impacts on riparian soils, vegetation, and cultivated areas. The findings will also inform strategies for mitigating seawater intrusion, restoring degraded ecosystems, and enhancing the resilience of local communities in the Tana River Delta.

2. Materials and methods

2.1. Study Area

The study was conducted along the Tana River Delta, situated in Tana River County in the coastal region of Kenya (Figure 1). The Tana Delta and its associated ecosystems span an area of approximately 1,300 km^2 [10]. The delta has a roughly triangular shape, with its apex located at Lake Bilisa (north of Garsen) and its base extending along a 50 km stretch of coastline along Ungwana (or Formosa) Bay. This stretch runs from Kipini in the northeast to Mto Kilifi in the southwest.

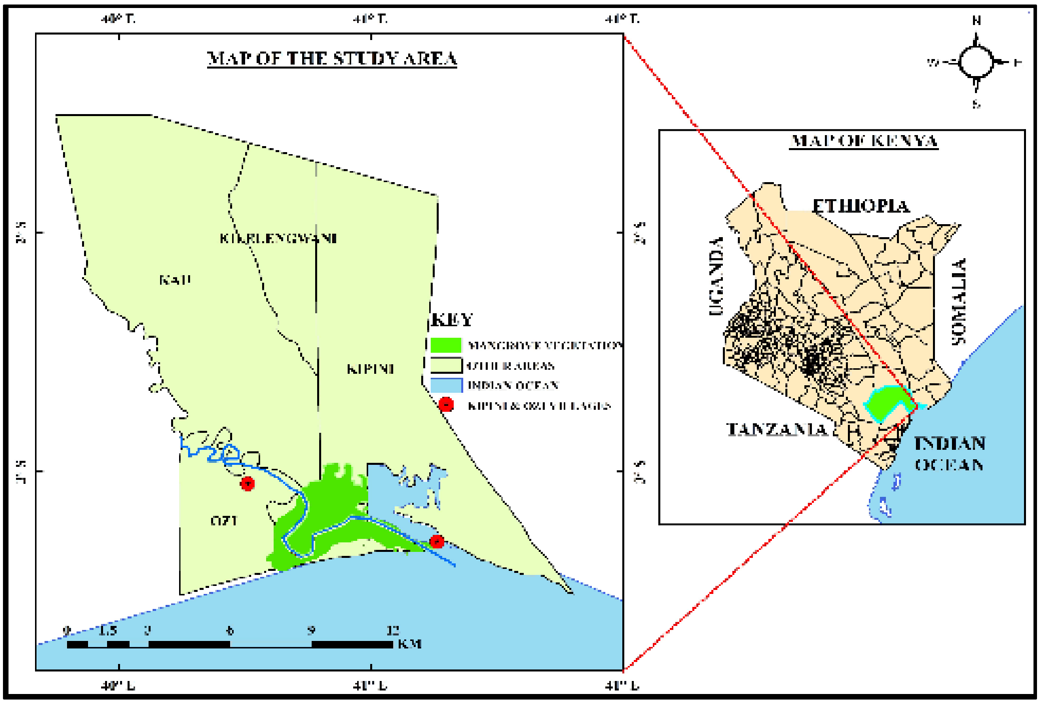


Figure 1 Map of Tana river delta

2.2. Data Collection and analysis

2.2.1. Land cover changes

Satellite data from 1999 to 2021, covering a 22-year period, was obtained, consisting of multi-temporal satellite images. The satellite imagery of Tana delta boundary used in the study included Landsat data from the Landsat Enhanced Thematic Mapper (ETM+) with a 30-meter resolution, Aster imagery with a 15-meter resolution, and Sentinel imagery with a 10-meter resolution. The Landsat imagery for 1999 was sourced from the United States Geological Survey (USGS) Glovis website (https://glovis.usgs.gov/). For the 2005 and 2010 images, Aster satellite data was obtained from the Terra NASA website (https://terra.nasa.gov/data/aster-data/), while Sentinel images for 2018 and 2021 were downloaded from the Copernicus website (https://dataspace.copernicus.eu/).

The classified raster and vector data were imported into Geographic Information System (GIS) software, ArcGIS 10x, for analysis and map creation. To enhance classification accuracy, post-classification refinement was applied using a multi-date post-classification comparison change detection algorithm. This involved comparing maps from 1999 to 2005, 2005 to 2010, 2010 to 2018, and finally 2018 to 2021, identifying variations across the different land cover classes.

To evaluate land use changes caused by the seawater intrusion, seven land use categories were defined and utilized for classifying and assigning land cover and land use in the mapping exercise. These categories included dense mangroves, scattered mangroves, reeds, grasslands, bare areas, built-up areas, and water bodies.

Table 1 Description of classes for Land-use characterization

Class type	**Description**
Dense mangrove	Mangrove of over 70% canopy cover
Scattered mangrove	Canopy cover of 20-50%
Reeds	Tall, green aquatic plant mostly found in tidal areas like marshes and along rivers
Uncultivated/bare area	Uncultivated farmlands with bare soil and rock outcrops that lack vegetation cover.
Human occupied	Residential, commercial as well as the transit infrastructure and settlements
Grassland	Land naturally dominated by grasses and forbs
Water body	A body of water that serves as a physiographic feature

2.2.2. Water Analysis

Water samples were collected from eight locations along the river, starting from the mouth and moving inland. At each sampling location, water samples were gathered in 250 ml transparent PC bottles from three distinct points. In-situ measurements of water pH, temperature, and salinity were also taken at these points. pH and salinity were measured using a calibrated multi-probe meter, while temperature was recorded using a thermometer.

2.2.3. Soil Analysis

Soil samples were collected from ten locations along the river, starting from the mouth and moving inland. These included five mangrove zones located 15 meters from the stream and five cultivated areas situated 40 meters from the stream. The sampling points were selected in areas with mangrove vegetation, terrestrial vegetation, and cultivated land. At each site, soil was collected from two points within the 2-25 cm depth range and mixed to create a composite sample. The samples were then transported to the KEFRI – Gede laboratory in Malindi in a cooler box within 24 hours for pH and salinity analysis.

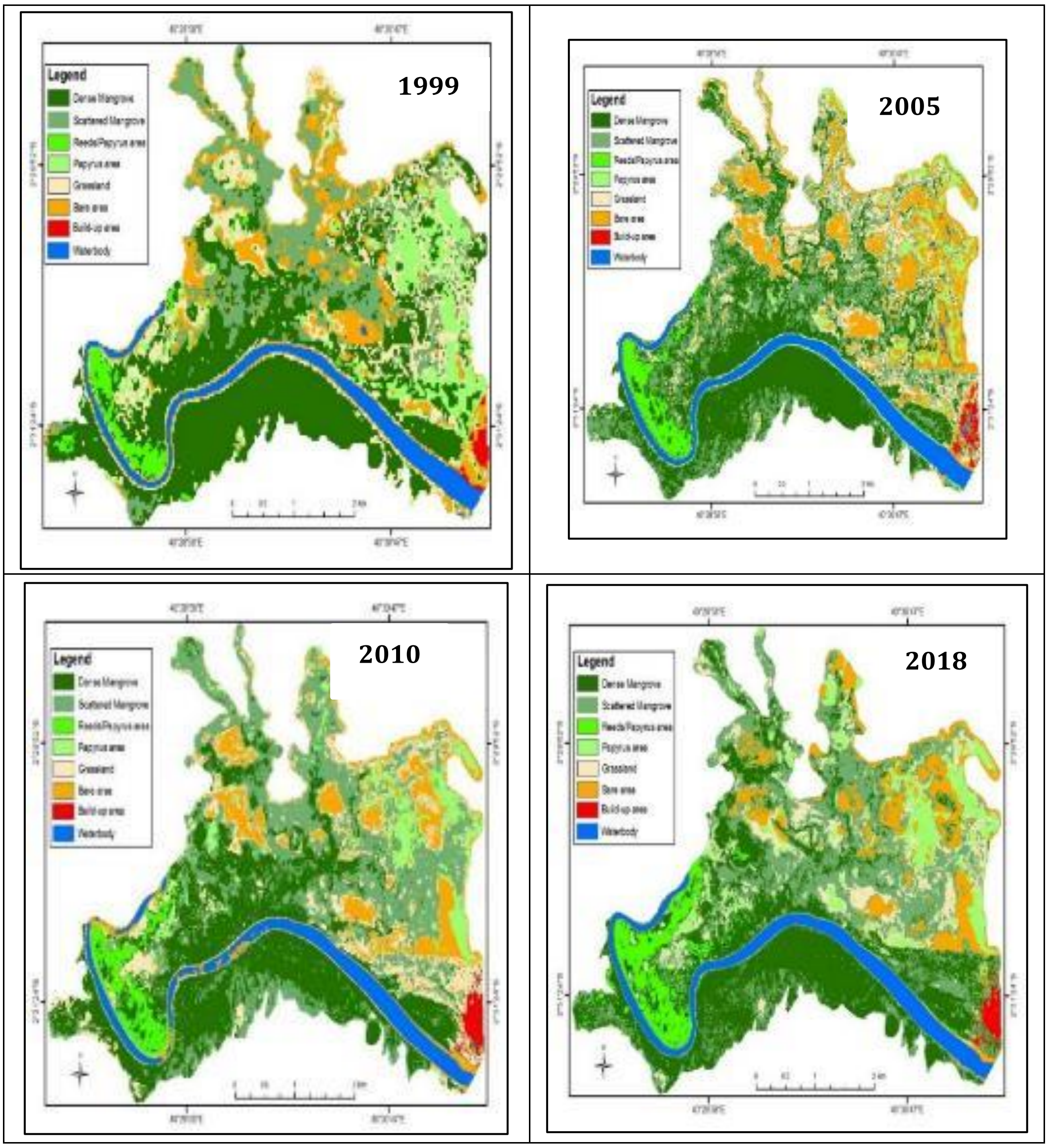
In the laboratory, 200 ml of distilled water was added to 100g of the composite soil sample. The mixture was stirred for 30 seconds, then left to sit for 15 minutes. The water was filtered into a clean beaker, stirred again, and a calibrated probe meter was placed in the solution for 1 minute before recording the final salinity reading.

The salinity test involved mixing 100g of a homogenized soil sample with deionized water until saturation was reached. The mixture was allowed to sit for 15 minutes, after which the water was filtered out. The filtered water was then stirred, and a calibrated probe meter was placed in the water for 1 minute to obtain salinity readings, which were subsequently recorded.

3. Results and discussion

3.1. Land Cover Changes 1999-2021

The seven land use/cover categories were used to run a change detection procedure on the various satellite images to produce 5 map overlays presented in Figure 2 below.



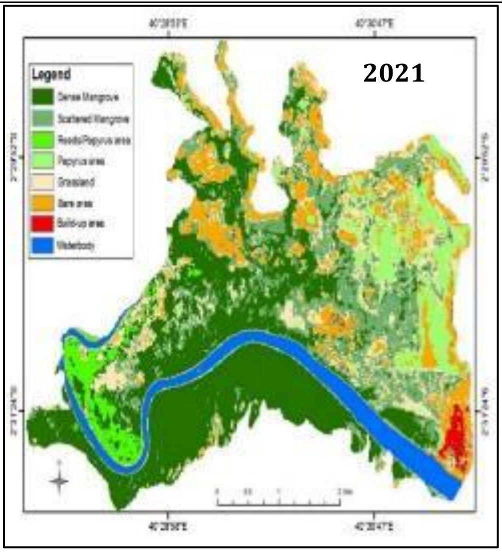


Figure 2 Imagery showing LULC variations from1999 to 2021

Each land use/cover category was quantified in each time-step and as shown in Table 2 below. The area of interest covered a total of 2014 ha. In 1999, the dominant vegetation cover was mangrove (dense and scattered) with a coverage of 1077 ha (53.47%). Over time this land cover domination has exhibited an increasing trend to 1193 ha (59.23%) by the year 2021. The area under reeds along the river has also increased from 60 ha (2.9% of the total area) in 1999 to 90 ha (4.47%) in 2019 and slightly reducing to 84 ha (4.17%) 3 years later thereby exhibiting a 68% increase over the 22-year period. The coverage of area under grassland did not change much with cover being 279 ha in 1999 but reducing to 277 ha in 2021 registering 0.7% decrease. The area covered by uncultivated area also decreased from 13.4% to 10.7% of the total area in the same timeline whereas area under water body and human occupied/ area increased from 5.5% and 0.55% in 1999 to 5.6% and 1% in 2021 respectively.

Table 2 Changes in land use and land cover (in hectares) in the Tana Delta from 1999 to 2021 (% cover change in successive intervals)

Land Use Type	1999	2005	2010	2018	2021	Overall % Change
Dense Mangrove	723	623 (-13%)	682 (9%)	594 (12%)	581 (2%)	-19.6%
Scattered Mangrove	354	499 (41%)	421(-15%)	642 (52%)	612 (-5%)	72%
Area under reeds along the stream	50	60 (20%)	63 (5%)	90 (42%)	84 (-7%)	68%
Reeds outside the stream	216	266 (23%)	140 (-47%)	163 (16%)	110 (-32%)	-49%
Grassland	279	282 (1%)	276 (-2%)	187 (-32%)	277 (48%)	-0.7%
Uncultivated area	270	143 (-47%)	266 (86%)	191 (-28%)	216 (13%)	20%
Human occupied	11	13 (18%)	15 (13%)	16 (6.7%)	20 (25%)	81%
Area under waterbody	111	128 (15%)	151 (18%)	131 (-13%)	114 (-13%)	2.7%

Analysis of imagery for the 1999-2021 period, indicates a gain of 258 ha (72%) in area covered by scattered mangroves. There was however a loss of 142 ha (19.6%) in area under dense mangrove which is attributed to sediment settlement in these areas resulting from upstream riverine erosion from reported land use changes as reported in previous studies within the delta [10,11]. The findings from this study and other contemporary studies are further corroborated by findings from this study's interview schedule on community perspectives where it was reported that historically, massive deforestation of mangrove trees was prevalent in the Tana delta to a point that an area in the delta was named "Zoroteka", a Swahili name for 'degraded'.

The increasing trend of mangrove cover since 1999 is an indication that mangrove cover in the Tana delta is likely to expand in future. This is due to reduction in the volume of upstream freshwater in Tana river as result of saltwater intrusion further upstream. Climate change scenario models envisage increased periods and lengths of drought in the area and this coupled with increased abstraction of water, will lead to reduction of volumes reaching the delta and may lead to frequent sea-water moving upstream. Mangrove distribution can provide important insight into saltwater intrusion, as the progress of salinity further inland favours the establishment of new mangrove [12]. Mangrove forests can be easily identified from satellite imagery [13,14], as they have distinct textures, colours, shapes, and positions in the landscape [15]. For this reason, mangrove distributional changes determined from time-series satellite imagery have been used to infer on saltwater intrusion [16]. The mangrove area gained (312ha) and lost (142ha) over the 22-year period monitored has been systematic (in the inland direction), suggesting a link to sea level water movement upstream.

The coverage of area under grassland did not change much with cover being 279 ha in 1999 but reducing to 277 ha in 2021. The brief loss of area under grasslands can be attributed to overgrazing and climate change. Livestock production is the most extensive system in the grasslands [17] and is found in several ASAL counties in Kenya, Tana river county being one of them. Excessive removal of vegetation cover through overgrazing has led to grassland degradation [18] and according to [19], grassland ecosystems are of great benefit to human beings and even to animals in equal measure, but the benefits can easily diminish due to degradation of grasslands. However, even with knowledge of the importance of grasslands, there has been a continued decline in production capability of the grasslands due to human activities and climate change.

The area covered by uncultivated area decreased from 13.4% in 1999 to 10.7% in 2021 as Human occupied area increased from 11ha to 20 ha within the same period as a result of increased population. Population increase has been identified as LULC driver which exerts pressure on vegetation cover [20]. The increased population within Tana delta coupled with their economic activities like farming has contributed to the reduction of the available land for cultivation. Some of the uncultivated area currently available are agriculturally and economically unproductive due to presence of rocks and unsuitable soils.

The increased population mostly attributed to immigration of fisher folk and pastoralists due to all around availability of water and pasture along the river has also contributed to more sea water intrusion as reported by the 2014 Tana river delta strategic assessment report [21]. The most important human-induced mechanism that increases intrusion of seawater in coastal areas is overexploitation of the upstream water resource as a result of water demand during dry periods and other unprecedented human and climate induced stresses.

Agricultural practices, extensive land development and inefficient water management systems are among the human activities that can contribute to the salinization of marine aquifers [22]. According to previous studies in upper Tana delta [10, 23, 24] there's evidence of current and future human stresses such as expansion and intensification of agriculture, inter-basin water transfer at the upper catchment as well as existing and already planned hydro-electric dams (at the middle catchment and large irrigation schemes at the lower sub-basin Seven-Forks Dams). These anthropogenic developments creates 'space' which is filled by saline-water from the Indian Ocean causing the saline-water and freshwater interface to move further upstream and inlands.

3.2. Measurements of water and riverine physico-chemical parameters

In the meeting point of sea and river water, salinity values decreased from the mouth of the delta to the furthest point measured (H) at approximately 9.7km away. At the initial point A, the mouth of the delta at Kipini, the salinity value was 8.029 ‰ which decreased to 0.202 ‰ at the furthest point at Ozi (Figure 3). The general reduction in salinity can be attributed to gradual interaction of seawater with the freshwater input from river Tana at varying distances.

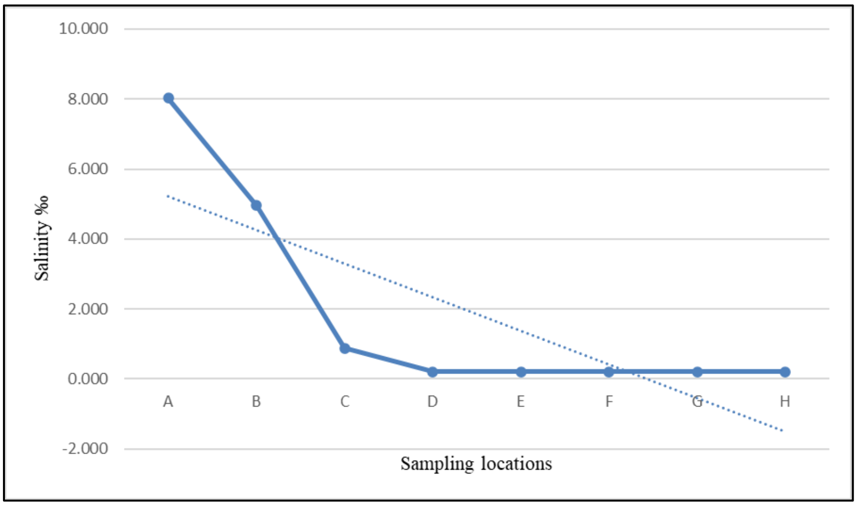


Figure 3 Salinity values (in ‰) along the river from the river mouth at Kipini

In the soil samples as shown in Figure 4 below, salinity followed a similar trend. Salinity decreased in mangrove soils as one moved further from the mouth of the delta with the highest value recorded at Point A (1.918 ‰) and the lowest EC value recorded at point E (0.481‰), beyond which there are no mangrove trees. Salinity of soils drawn from cultivated areas also decreased as well as one moved further from the mouth of the delta from point D1 to H1. The mean value was 0.491 ± 0.071 ‰ with the highest salinity value recorded at point D1 (0.574 ‰) and the least value recorded at point H1, 0.361 ‰.

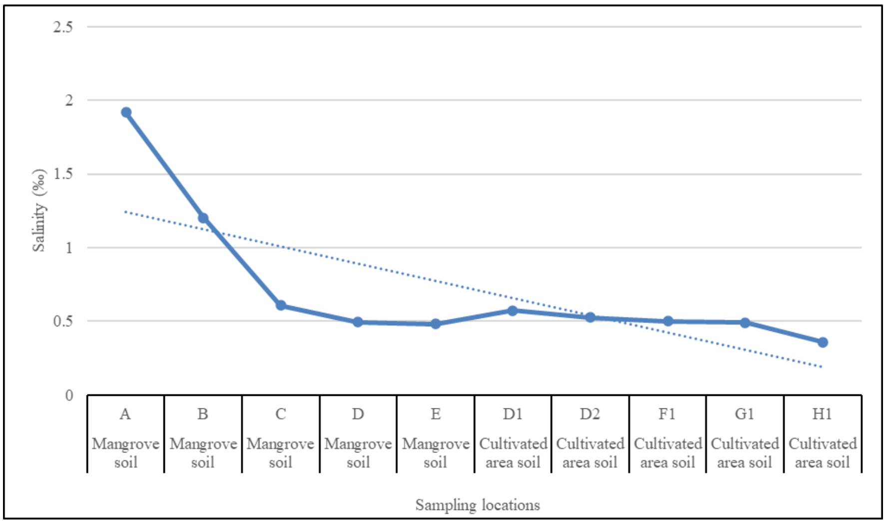


Figure 4 Salinity values of the mangrove and cultivated areas' soil samples**.**

The range of salinity values of mangrove soils observed in this particular study (0.481 – 1.918 ‰) are low compared to the optimum salinity values for mangrove growth which is 5–20 ‰ salinity range [25, 26, 27]. The lower than optimum salinity values observed in this study are attributed to the heavy rainfall experienced in the area since last quarter of last year 2023 that caused dilution of the saline water in the river. Similarly, assessment of water quality parameters in Upper Okavango delta in Southern Africa between 2014 – 2017 also yielded low salinity values which was attributed to the high floods that had caused dilution [4].

Mangroves are adapted to high salinity, however, low saline conditions are ideal for the initial establishment of mangrove seedlings, after about 4-5 months of initial establishment, seedlings need comparatively higher amounts of salt to gain optimum growth and to maintain optimum metabolic activities [27]. Similarly, according to FAO [28], salinity levels less than 4.48 ‰ has no effect on soil or cropping systems. Maize (Zea Mays) has the potential to give a full yield at concentrations lower than 7 ‰ (11 mS/cm) and a paddy rice variety (Oritza Sativa) to have a full yield potential at concentrations lower than 12.8‰ (20 mS/cm). Fruit crops generally have full yield potential below concentrations of

7 ppt. The salinity levels observed in this study are therefore suitable for growth Mangrove seedlings and crops like Maize along the tana river delta.

As shown in Figure 5, the average pH ranged from a mean of 6.85 to 7.43 indicative of neutral pH (6.6-7.3). The highest pH value was observed at Point E (7.49) and the lowest pH value observed at point G with the trend rising upward from the mouth of the river at Kipini to Ozi Village which is approximately 9.7 km upstream.

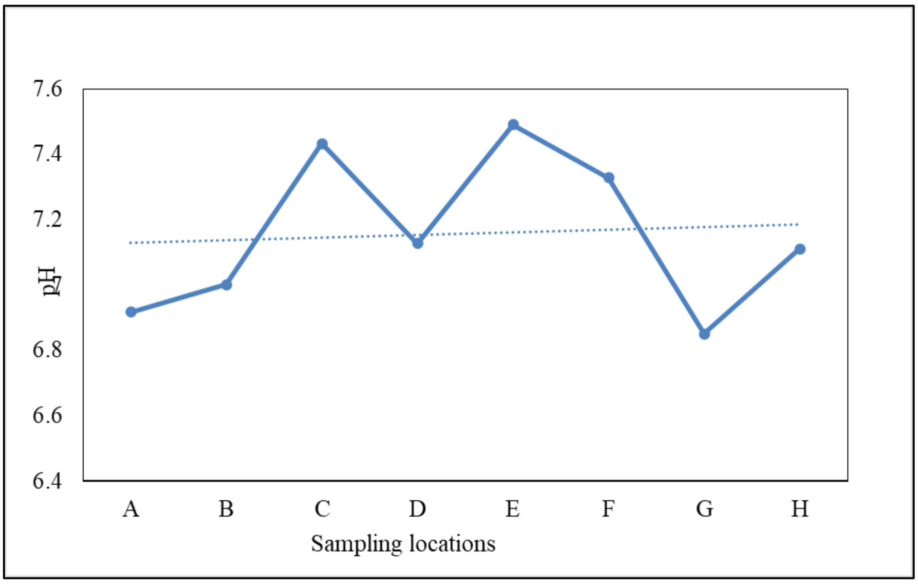


Figure 5 pH values of water samples across the sampling points

The amount of freshwater directly injected into Tana river by flood water from around the river as a result of heavy rains upstream displaced saltwater thereby leaving freshwater as shown by the results in Figure 6. For soil pH, the mean value of pH in mangrove soils was 7.028±0.127 with the maximum pH recorded at Point E, the furthest point from the mouth of the delta with a pH of 7.19 and the minimum pH recorded at Point A, 6.84. The average value of pH of cultivated areas' soil was 6.608±0.1333 with the maximum recorded at Point G1 (6.79) and the minimum at Point D1 (6.47) as shown in figure 6 below. Independent sample t-test undertaken between the two samples i.e. mangrove and cultivated area soils generated a P-value of 0.0018 against $\alpha = 0.05$, confirming that there is sufficient evidence statistically to show that mangrove soil's pH value is significantly different from that of farmland at α=0.05. and for this case, the mangrove soil's pH is higher than that of the farmland's.

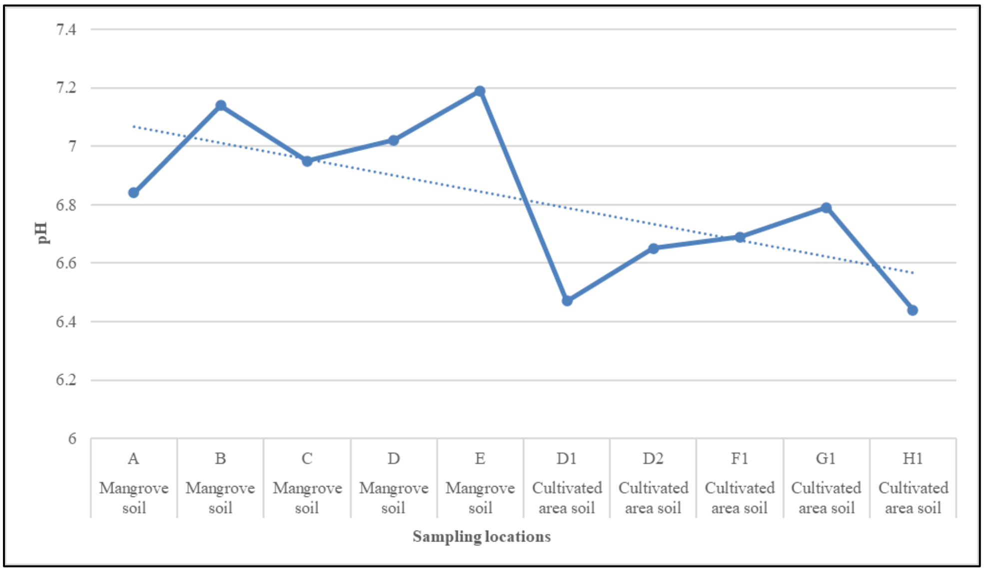


Figure 6 pH values for mangrove and cultivated area soil samples

The mangrove soils' pH observed in this study is favorable for growth of mangrove trees as soil pH values ranging from 6.7 to 7.3 is the most suitable for growth of mangrove trees [29]. Mangrove seedlings and trees can grow at their maximum rate even with a soil pH range from 5.16 to 7.72 because they can adapt to survive harsh environmental conditions and low nutrient availability. Alsumaiti [29] affirms that, mangroves, especially in germination stage, cannot tolerate extreme pH conditions (outside the range of 5.16 - 7.72) because they will cause nutrients to be inaccessible to the plants.

According to FAO [28] the desirable soil pH range for optimum plant growth varies among crops. Generally, a soil pH between 6.0-7.5 is acceptable for most plants, as most nutrients are available in this pH range. The ideal pH of rice soils is 5.5-6.5 [30]; for bananas its 5-7.0. Bananas can tolerate some soil acidity, however a pH below 5.0 means that elements such as aluminium and manganese become very soluble in the soil and their toxicity can reduce plant growth. According to Bally [31], the standard pH for Mangifera indica is between 5.5-7.5. The Soil pH values observed in this study were therefore suitable for growth of the crops, any further reduction in pH of the soil can have hazardous effects on the soil conditions that suits the crops grown within Tana delta.

Water temperature varied from an average of 26.67 °C to 30.33 °C. The maximum temperature was recorded as 30.33°C at Point A and a minimum temperature recorded as 26.67 °C at Points B and D as shown in Figure 7 below. The temperature variation is one of the factors in the coastal and estuarine system, which may influence the physicochemical characteristics and also influence the distribution and abundance of flora and fauna [32].

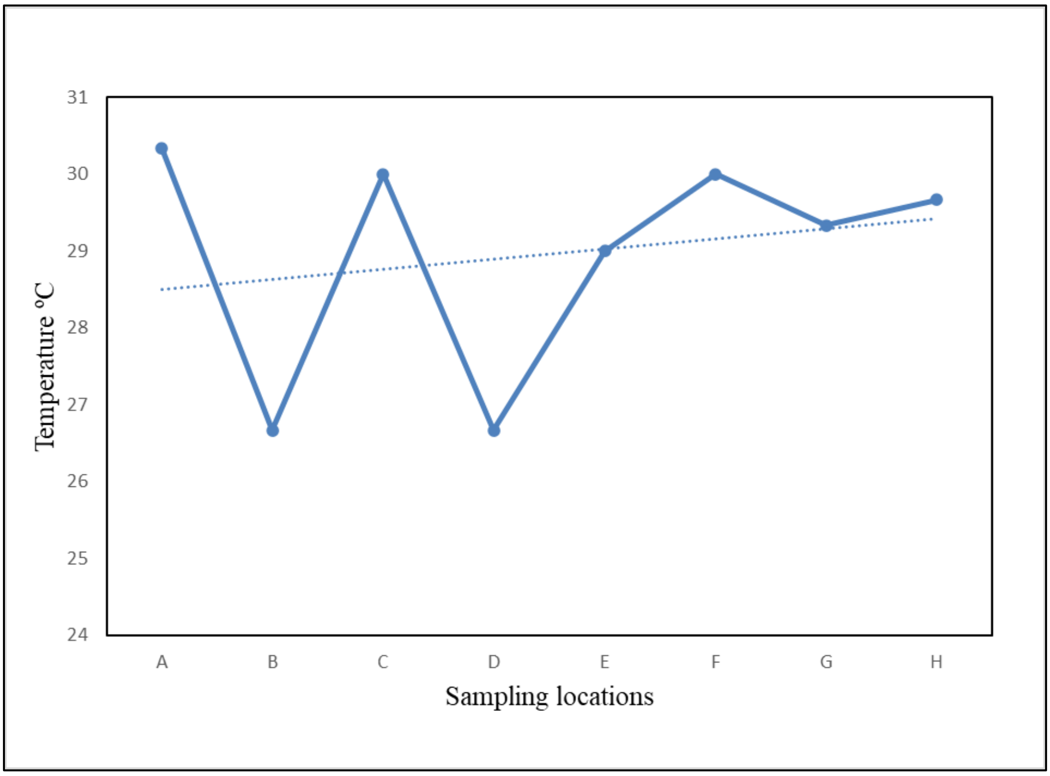


Figure 7 Temperature variations of water samples

3.3. Community perspectives on salt water effects on local livelihoods

During interviews, participants highlighted the key challenges they faced in the Tana River Delta, with a focus on farming and fishing. Among the farmers interviewed, 67% identified saline intrusion as a major concern. Similarly, fishermen cited seawater intrusion as their most significant problem. Farmers reported that saline intrusion led to salt buildup and the encroachment of saline water into their fields, resulting in reduced crop yields, lower incomes, and adverse effects on their livelihoods. Fishermen expressed concern over the disruption of freshwater habitats and breeding grounds, which led to the decline or disappearance of certain freshwater fish species. This decline negatively impacted the local fish market, reducing income opportunities. Some of the fishermen mentioned traveling upstream in search of freshwater fish, while others shifted to fishing in the sea for saltwater species to sustain their livelihoods.

A related study conducted from 2005 to 2006 in the Blackwater River drainage (Cambridge, Maryland, USA) examined fish assemblages to assess how salinity intrusion affected freshwater wetlands. The findings indicated that differences in species diversity and composition of freshwater fish, such as brown bullhead and black crappie, between the Blackwater River and Little Blackwater River were linked to higher salinity and increased upstream connectivity. The study concluded that habitat shifts caused by seawater intrusion and varying salt concentrations influenced fish populations, affecting growth and metabolism essential for aquaculture species. Similarly, in Florida's Everglades, alterations in hydrology due to natural events and human development have reduced suitable conditions for fish production, negatively impacting native fish communities [33].

A clear consequence of seawater intrusion is its detrimental effect on crop yields, which directly impacts farmers' incomes. Many farmers reported experiencing income losses due to reduced yields and declining fruit production. Three farmers stated that their current harvests are less than half of what they produced 5 to 10 years ago.

The drop in income has led to various hardships. Two farmers expressed difficulty in affording their children's school fees and accessing adequate healthcare. For subsistence farmers, lower yields have significantly reduced their food consumption, a reality reflected in their visibly thin physiques. Fluctuations in income—whether increases or decreases—affect the entire household and livelihood. Notably, income reductions were more prevalent among the farmers and fishermen interviewed.

A similar situation was observed in the Mekong Delta, where saltwater intrusion severely damaged agricultural production, including rice, horticulture, and fruit orchards. The 2015-2016 intrusion affected over 160,000 hectares of agricultural land, primarily rice fields, as well as fruit and vegetable crops, resulting in estimated economic losses of approximately 3,000 billion Vietnamese dong [34].

Regarding the temporal dynamics of saltwater intrusion, the vast majority of farmers and fishermen (over 94%) reported that saline water has long been a characteristic of the area. 67% noted that salinity levels were particularly severe about two years ago and had been progressively increasing over the past five years.

When asked about the future of saltwater intrusion, most farmers (77%) and fishermen (75%) believed that salinity levels would continue to rise. However, following the recent El Niño rains, which diluted the saline water, some farmers expressed uncertainty about future trends, while the fishermen anticipated that salinity levels would remain stable.

Farmers and fishermen were asked about current and future adaptations to mitigate saltwater intrusion. A majority of farmers (92%) and fishermen (90%) believed little could be done, attributing seawater intrusion to natural climate change processes. However, all six farmers (100%) agreed that adaptation was essential, with some already implementing measures. For example, FMR5 shifted to cultivating mangoes (Mangifera indica) on land previously used for other crops, while FMR3 adopted mixed cropping to minimize losses (See Figure 13).

In other coastal regions facing similar challenges, such as the Mekong Delta in Vietnam, farmers have introduced alternative farming methods to protect livelihoods. These measures include planting salt-tolerant rice varieties, adjusting crop calendars to avoid peak saltwater intrusion, and transitioning to salt-tolerant crops like coconut [35]. Additionally, some farmers have embraced aquaculture, adopting models such as prawn-rice rotational cropping (PRRC). This system alternates between rice cultivation during the wet season and shrimp farming in the dry season, utilizing shrimp strains that tolerate salinity levels up to 45 g/l [36].

Participants were also asked about the influence of El Niño rains on saltwater intrusion (SWI). Over 70% viewed the rains as a mixed blessing. While El Niño caused widespread damage through flooding and displacement, the influx of freshwater helped push back seawater. According to the Kenya Meteorological Department, heavy rains from October 2023 led to flash floods, displacement, and damage to infrastructure, livestock, and property across Kenya. In Tana River County, floods submerged farms, displaced households, and destroyed crops and homes as the river overflowed its banks.

Despite the devastation, five fishermen reported the return of fish species such as catfish, tilapia, and freshwater prawns, which had previously disappeared due to SWI. However, three farmers (50%) and two fishermen (29%) felt El Niño brought no benefits, emphasizing the extensive damage.

Local administrators and experts acknowledged that SWI negatively impacts farming, the primary livelihood in the area. However, the head of the Community Forest Association (CFA) viewed SWI as an opportunity, highlighting increased mangrove growth in saline conditions. Mangrove expansion indicates the inland progression of salinity, which may lead to the conversion of freshwater marshes to open water or mangrove-dominated areas [37].

The area chief raised concerns about the risks of salt contaminating drinking water, rendering it unsuitable for consumption or irrigation [38]. He warned that climate change is expected to push the saline front further upstream, reducing arable land and affecting irrigation potential [39]. The chief also noted that salt pollution could harm livestock, citing its negative impact on poultry weight. He predicted that rising salt levels would remain a critical challenge for the community in the coming years.

Regarding the temporal dynamics of SWI, most participants indicated that saltwater intrusion had long been present. However, the area chief specifically traced the onset of severe intrusion to the 1997 El Niño, suggesting SWI has been an issue for 27 years. Sub-chiefs reported increased salinity in recent years, attributing the rise to prolonged droughts in 2022 and 2023, which affected much of northern and eastern Kenya, including Tana River County. A Kenya Marine and Fisheries Research Institute (KMFRI) official concurred, emphasizing that the dry season was unusually intense and prolonged, contributing to severe drought conditions – the worst in 40 years.

When asked about El Niño's potential to reverse SWI, the head of the Lower Tana Delta anticipated significant freshwater influx to counteract saline intrusion. She compared the 2023 El Niño to the 1997 event. The Kenya Meteorological Department confirmed this assessment, reporting that the 2023 El Niño, driven by an Oceanic Niño Index (ONI) of approximately 2.0, was nearly as severe as the 1997 El Niño (ONI 2.4), the most destructive event to date.

4. Conclusions and recommendations

The study highlights significant land use and cover changes in the Tana Delta between 1999 and 2021, driven by natural processes and human activities. Notable findings include an overall increase in mangrove cover, with scattered mangroves expanding by 72%, while dense mangroves declined by 19.6%. This shift suggests sediment deposition and saltwater intrusion from reduced upstream freshwater flow, consistent with other studies. Water quality analysis showed decreasing salinity levels moving upstream from the delta's mouth, attributed to heavy rains diluting saline water. Soil salinity trends also reflected this, remaining within acceptable ranges for crop growth. These results indicate that, while mangrove expansion may provide ecological benefits, saltwater intrusion poses a threat to agriculture and freshwater systems, necessitating continued monitoring and adaptive land management strategies.

Community perspectives reveal that saltwater intrusion adversely impacts local livelihoods, particularly in farming and fishing, with many respondents reporting declining crop yields, reduced income, and disruption of freshwater fish populations. El Niño rains in 2023 temporarily alleviated saline conditions but caused widespread flooding and displacement. Farmers have begun adopting adaptive measures, such as cultivating salt-tolerant crops, but many believe the long-term trend of increasing salinity will persist due to climate change and human activities upstream. The study underscores the urgent need for sustainable water management and climate adaptation strategies to mitigate the impacts of saltwater intrusion and ensure the resilience of the Tana Delta's communities and ecosystems.

Future research should focus on analyzing the long-term hydrological patterns of the Tana River, including the impacts of upstream damming, irrigation projects, and land use changes. This could provide insights into how human activities and climate variability influence freshwater flow, sediment transport, and saltwater intrusion, guiding sustainable water resource management and infrastructure planning.

Research should explore the effectiveness of community-driven adaptation strategies, such as salt-tolerant crops, mangrove restoration, and alternative livelihoods, in mitigating the impacts of saltwater intrusion. By assessing how local knowledge and adaptive practices contribute to ecosystem resilience, future studies can inform policy frameworks that integrate scientific and indigenous approaches to enhance food security and ecosystem health in the Tana Delta.

Compliance with ethical standards

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No conflict of interest to be disclosed.

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