

**Land Use and Land Cover Mapping of India, Bangladesh, Pakistan and Sri Lanka**

## Executive Summary

This study presents a comprehensive multi-temporal Land Use and Land Cover (LULC) analysis of coastal mangrove regions in India, Bangladesh, Pakistan, and Sri Lanka, spanning three decades from 1994 to 2024. Employing supervised classification techniques with the maximum likelihood algorithm in ERDAS IMAGINE 2014, Landsat satellite imagery was systematically analysed across four decadal intervals to map six dominant LULC classes: Mangrove, Other Vegetation, Bare Earth and Sand Deposit, Agricultural Land, Salt Pan and Aquafarm, and Waterbodies. The study area delineation was standardized using buffer zone approaches, including the Mangrove Influence Zone (MIZ) and Ecologically Critical Area (ECA), to capture anthropogenic impacts along mangrove fringes. The findings reveal divergent trajectories across countries—India demonstrating recent mangrove recovery (2014-2024) alongside agricultural expansion (24.30% by 2024), Bangladesh experiencing cyclical mangrove fluctuations with substantial aquaculture proliferation (13.98% by 2024) and significant mangrove decline (31.61% by 2024), Pakistan showing sustained mangrove contraction (20.48% by 2024) and bare earth conversion to agriculture (10.75% by 2024), and Sri Lanka exhibiting rapid agricultural intensification (37.60% by 2024) at the expense of mangrove cover (26.05% by 2024). Transformation matrices quantified precise land cover transitions, revealing that bare earth and sand deposits systematically converted to agricultural land and vegetation across all countries, waterbodies remained relatively stable, and mangrove dynamics varied significantly—India gained 1.08% mangrove loss between 2014-2024, Bangladesh lost 5.13%, Pakistan lost 5.52%, and Sri Lanka lost 3.55% during the same period. The spatio-temporal dynamics documented provide essential empirical foundations for modelling policy interventions, identifying gaps in coastal land management frameworks, spatially targeting conservation zones, and regulating land conversion activities with evidence-based zoning regulations. These geospatial datasets transform abstract policy objectives into spatially explicit, measurable actions, enabling adaptive management strategies that respond to ground realities, close implementation gaps between policy formulation and execution, and ensure sustainable coastal development trajectories aligned with both economic aspirations and ecological imperatives across the South Asian coastal belt. The study underscores the urgent need for transboundary collaboration, strengthened enforcement mechanisms, sustained monitoring through multi-temporal satellite imagery, and climate-responsive land-use planning to safeguard South Asia's coastal mangrove ecosystems for future generations while supporting sustainable development pathways for coastal communities.

## **1. Introduction:**

Coastal mangrove ecosystems in South Asia face unprecedented pressures from anthropogenic activities and climate change, necessitating robust geospatial monitoring to inform evidence-based conservation and development strategies. This study presents a comprehensive multi-temporal Land Use and Land Cover (LULC) analysis of coastal regions in India, Bangladesh, Pakistan, and Sri Lanka, spanning three decades from 1994 to 2024. Employing supervised classification techniques using the maximum likelihood algorithm in ERDAS IMAGINE 2014, Landsat satellite imagery was systematically analysed across four decadal intervals (1994, 2004, 2014, and 2024) to map six dominant LULC classes: Mangrove, Other Vegetation, Bare Earth and Sand Deposit, Agricultural Land, Salt Pan and Aquafarm, and Waterbodies. The study area delineation was standardized using buffer zone approaches, including the Mangrove Influence Zone (MIZ) and Ecologically Critical Area (ECA), to capture the spatial extent of agricultural intensification and anthropogenic impacts along mangrove fringes. Through change detection analysis and transformation matrices, this research quantifies spatio-temporal dynamics of land cover transitions, revealing patterns of mangrove decline and recovery, agricultural expansion, aquaculture proliferation, and sediment redistribution across the four countries. The findings provide critical baseline data for understanding the complex interplay between natural processes and human interventions shaping these ecologically and economically significant coastal landscapes.

## **2. Methodology:**

### **2.1.1 Delineation of the study area (India):**

The delineation of the study area for the Indian Sundarban was carried out using a standardized scheme based on visible distinctions between land under mangrove and non-mangrove areas. The mangrove forest boundary from the base year 1994 was taken as the reference line for this process. In this regard, two buffer zones were identified, firstly, a 20 km buffer referred to as the Mangrove Influence Zone (MIZ), which extends from the mangrove boundary into areas without mangroves, including land under agriculture, human settlements, and other land uses (IUCN, 2014). Secondly, a 10 km buffer known as the Ecologically Critical Area (ECA) was delineated from the mangrove boundary towards the forest side (IUCN, 2014). The zone between the MIZ and the ECA formed the Area of Interest (AOI) for evaluating the impact of agricultural intensification along the fringe mangrove areas in the Indian Sundarban.

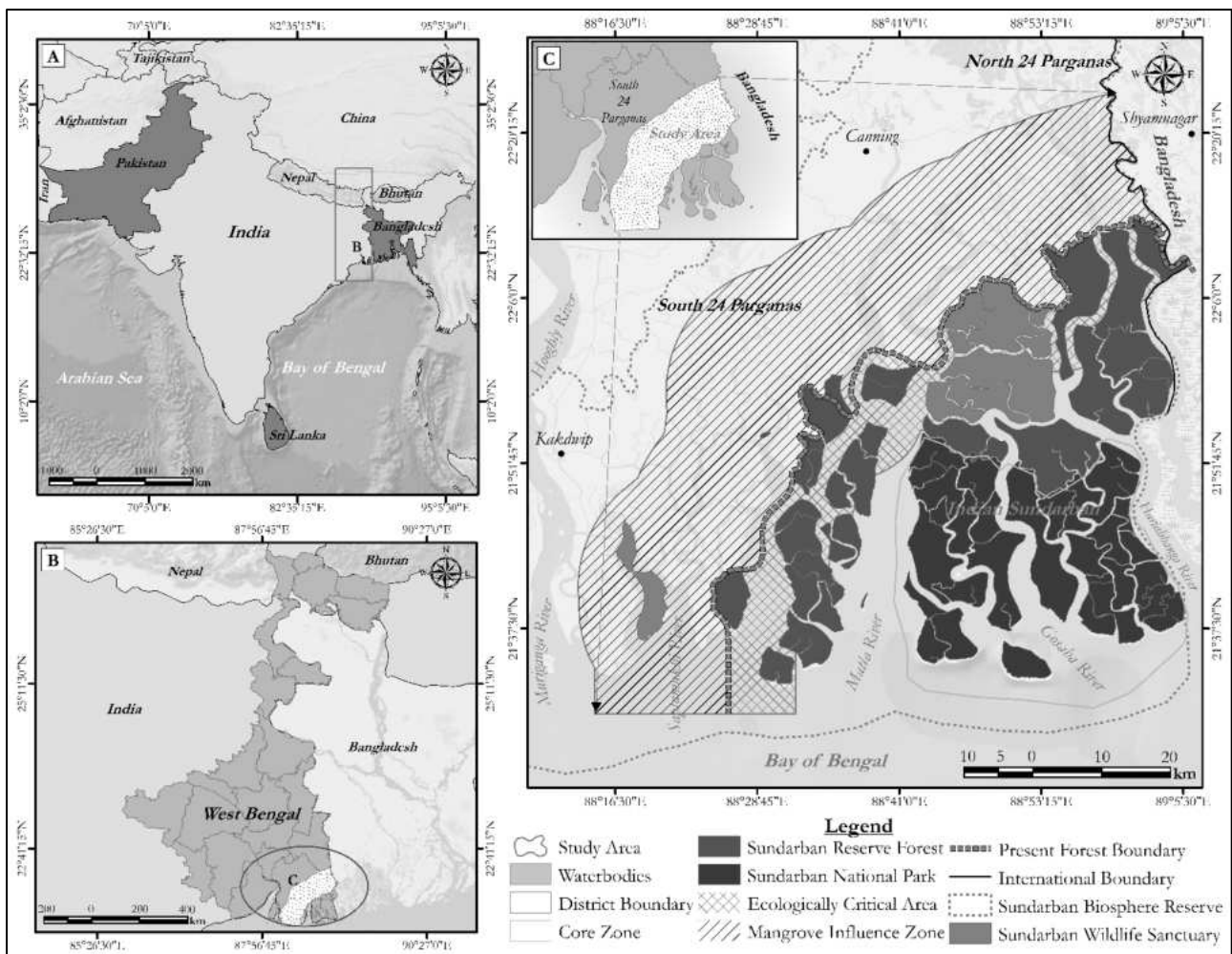
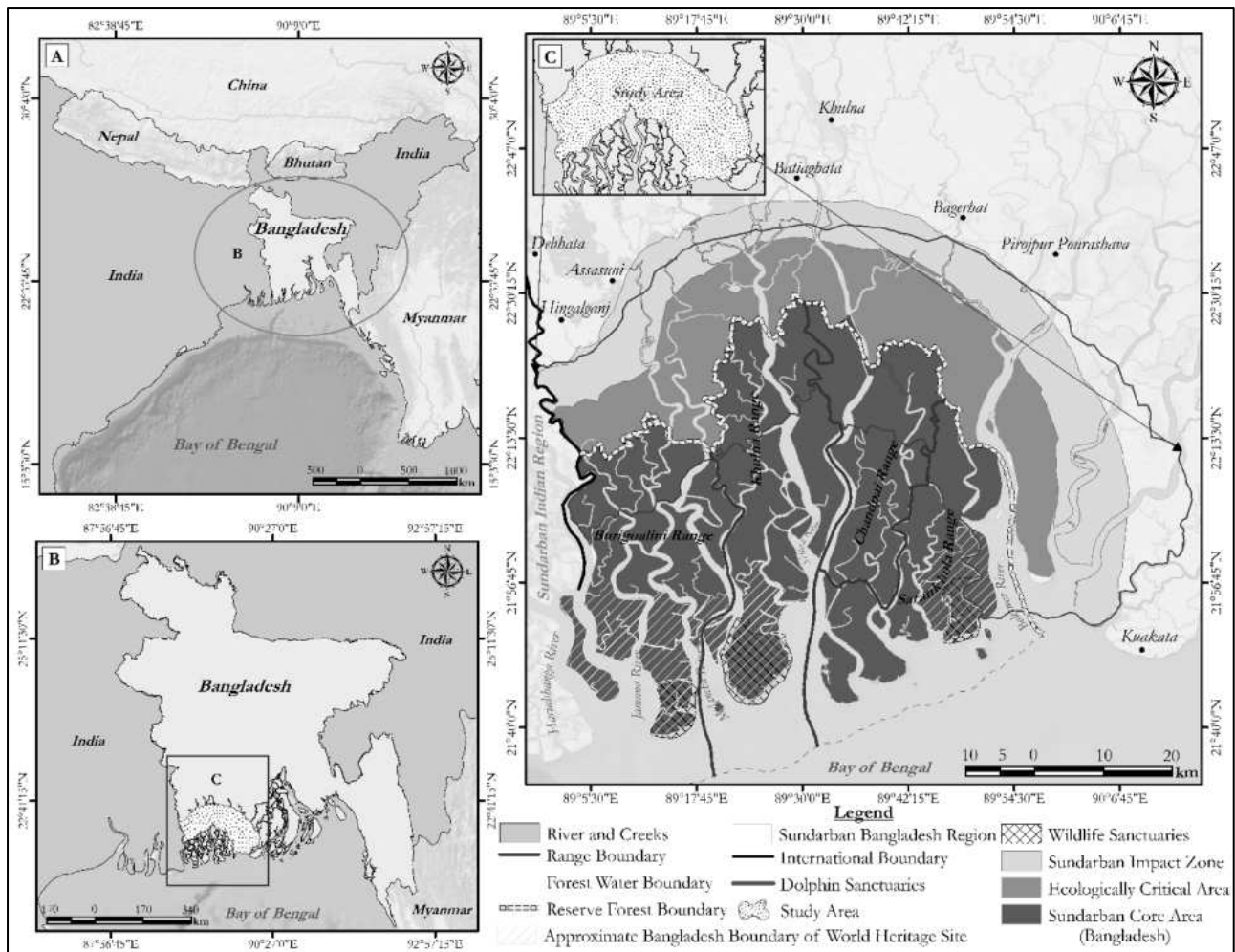


Figure 1: Location map of the study area.

### 2.1.2 Delineation of the study area (Bangladesh):

The study area within the Bangladesh Sundarban was delineated using a standardized geospatial framework based on distinct spectral and spatial contrasts between mangrove and non-mangrove land cover. The 1994 mangrove boundary was adopted as the reference baseline, from which two buffer zones were generated: a 20 km Mangrove Influence Zone (MIZ) extending outward into agricultural and settlement areas, and a 10 km Ecologically Critical Area (ECA) extending inward toward the forest core (IUCN, 2014). Encircling the Sundarbans Reserved Forest is the Ecologically Critical Area (ECA), a designated buffer zone established to safeguard the region's ecologically fragile and biodiversity-rich ecosystem. Beyond this boundary extends the Sundarbans Impact Zone (SIZ), where anthropogenic activities are strategically regulated to mitigate adverse environmental impacts and maintain ecological resilience. Collectively, the Greater Sundarbans Tourism Region integrates the ECA, SIZ, and adjacent landscapes into a unified management framework, promoting sustainable tourism development while ensuring the conservation of both the protected core and its surrounding socio-ecological interfaces

(Rahman et al., 2010). The intermediate zone between the MIZ and ECA defined the Area of Interest (AOI), representing the spatial extent for assessing agricultural intensification and anthropogenic impacts along the mangrove fringes of the Bangladesh Sundarban.



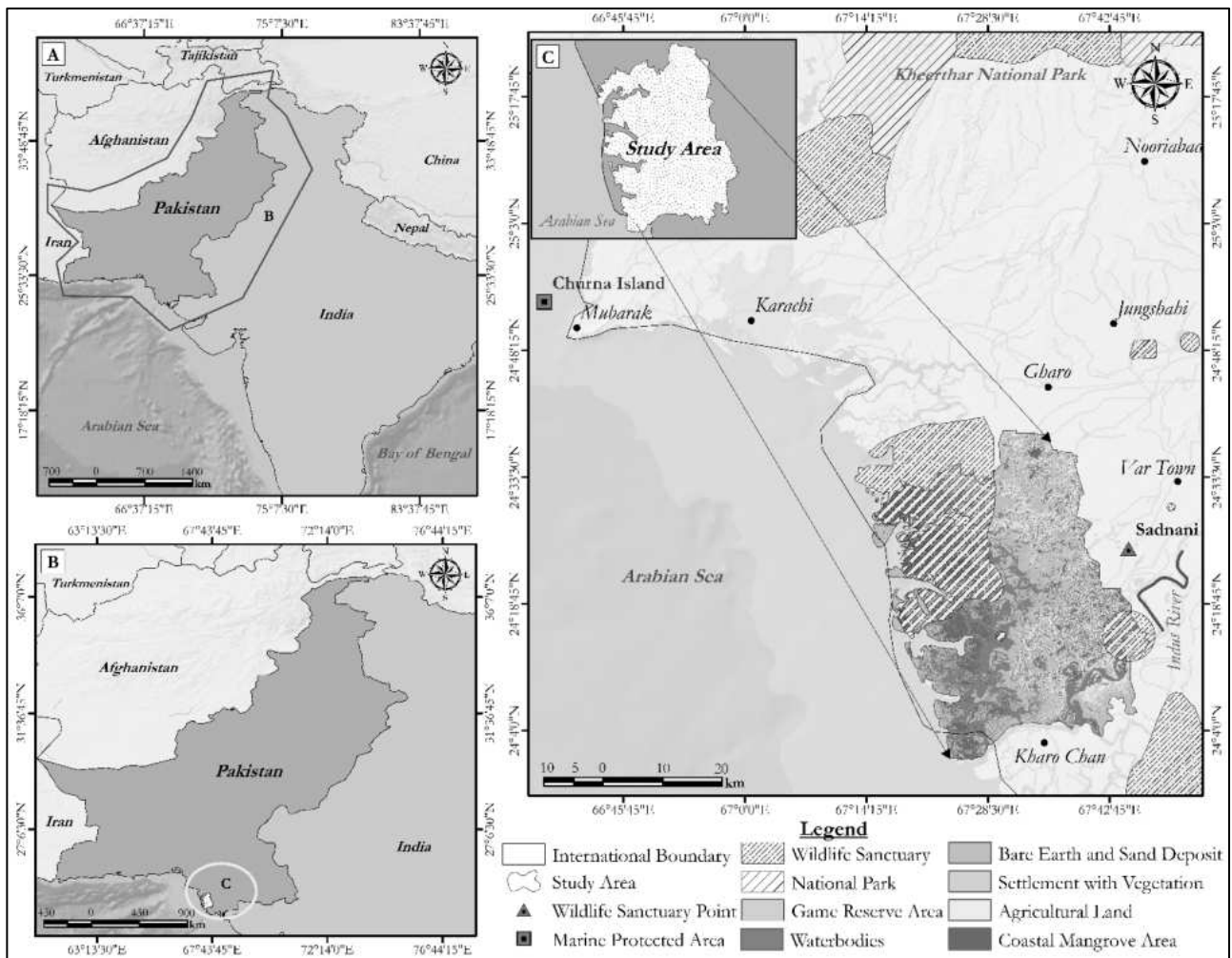
**Figure 2:** Location map of the study area.

### 2.1.3 Delineation of the study area (Pakistan):

The delineation of the Pakistan coastal mangrove study area was executed through an integrated geospatial framework to ensure precise spatial representation of the mangrove ecosystem and its surrounding coastal terrain. The analysis concentrated on the Indus Delta region along the Sindh coast—representing the largest and most ecologically critical mangrove complex in Pakistan—and the scattered mangrove patches distributed along the Baluchistan coast, collectively defining the major mangrove-bearing zones of the country. The core mangrove boundary was delineated using Landsat satellite imagery (base year 1994), supported by topographic maps and ancillary datasets obtained from national coastal and environmental authorities. The integration of multi-source datasets enabled accurate spectral and spatial discrimination between mangrove and non-mangrove classes within a GIS environment (Shalaby and Tateishi, 2007). To contextualize the broader ecological and anthropogenic influences, two buffer zones were generated outward from the delineated mangrove extent: first, a 10 km Immediate Influence Zone

(IIZ), encompassing tidal flats, aquaculture ponds, and saline mudflats; and second, a 20 km Mangrove Influence Zone (MIZ), incorporating adjacent agricultural, settlement, and industrial landscapes.

This geospatial delineation framework established a consistent baseline for multi-temporal land use and land cover (LULC) analysis, facilitating quantitative assessments of coastal ecosystem dynamics, spatial transformation patterns, and the interactions between natural and human-induced processes along the Pakistan coast. The approach aligns with IUCN guidelines for ecosystem mapping and management, supporting evidence-based conservation planning and sustainable coastal resource management.

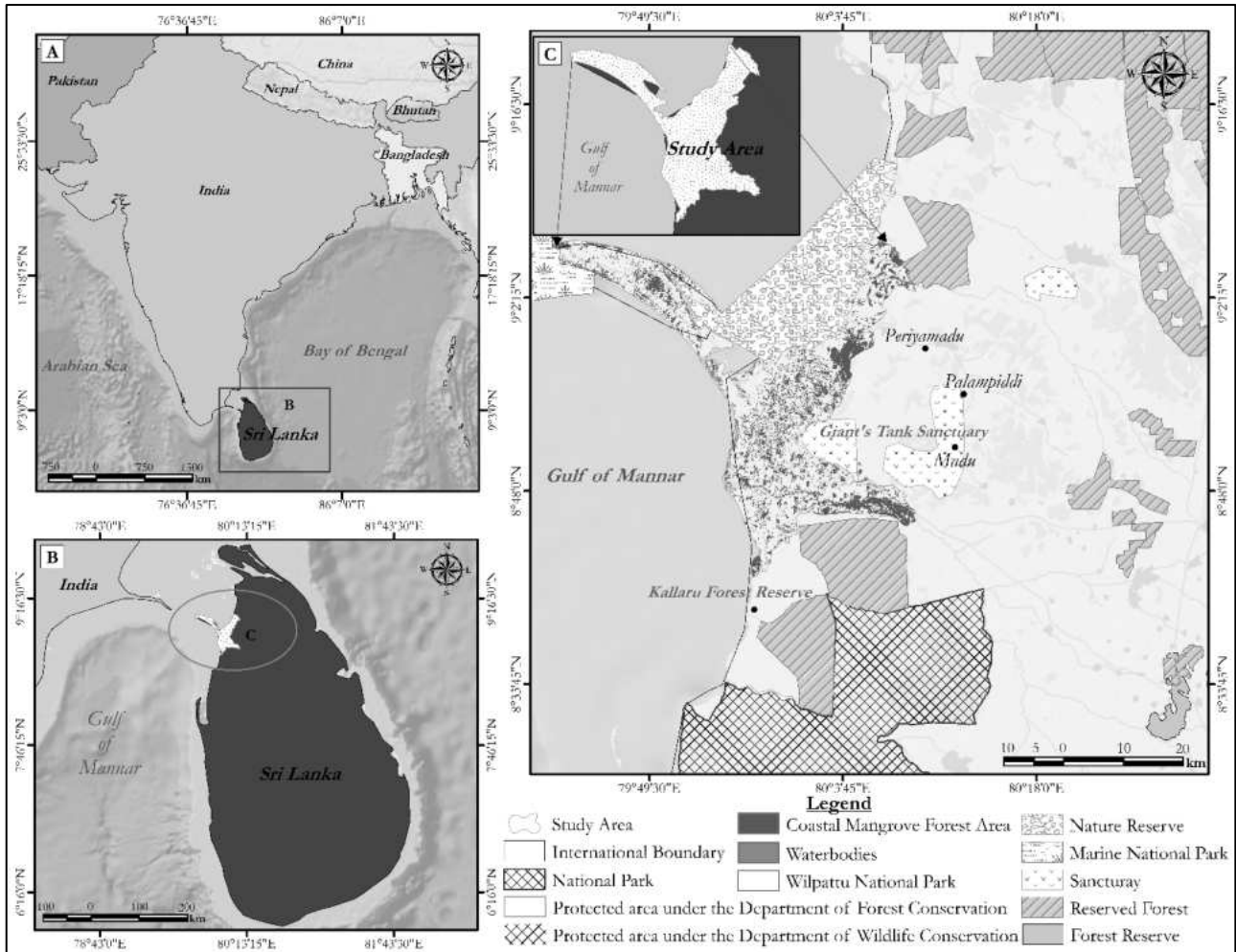


**Figure 3:** Location map of the study area.

### 2.1.4 Delineation of the study area (Sri Lanka):

The delineation of the Sri Lanka coastal mangrove study area along the northwest coastline, adjacent to the Gulf of Mannar, was undertaken through an integrated geospatial approach to ensure accurate spatial representation of the mangrove ecosystem and its surrounding coastal landscape. The study primarily focused on the mangrove clusters along the Mannar and Puttalam coastal belts, representing the major mangrove-bearing zones in this region. The core mangrove boundary was delineated using high-resolution satellite imagery (base year 2000) supported by topographic maps, historical land-use data, and ancillary spatial datasets from national coastal and environmental agencies. Prior to delineating the study area, the coastal zone was systematically interpreted using ancillary datasets, and a 10 km buffer was established along the national coastline to define the preliminary spatial extent.

This spatial delineation framework provides a consistent baseline for analysing temporal land use and land cover changes, evaluating coastal ecosystem dynamics, and understanding the spatial interplay between natural processes and human activities along the ecologically sensitive Gulf of Mannar coast.



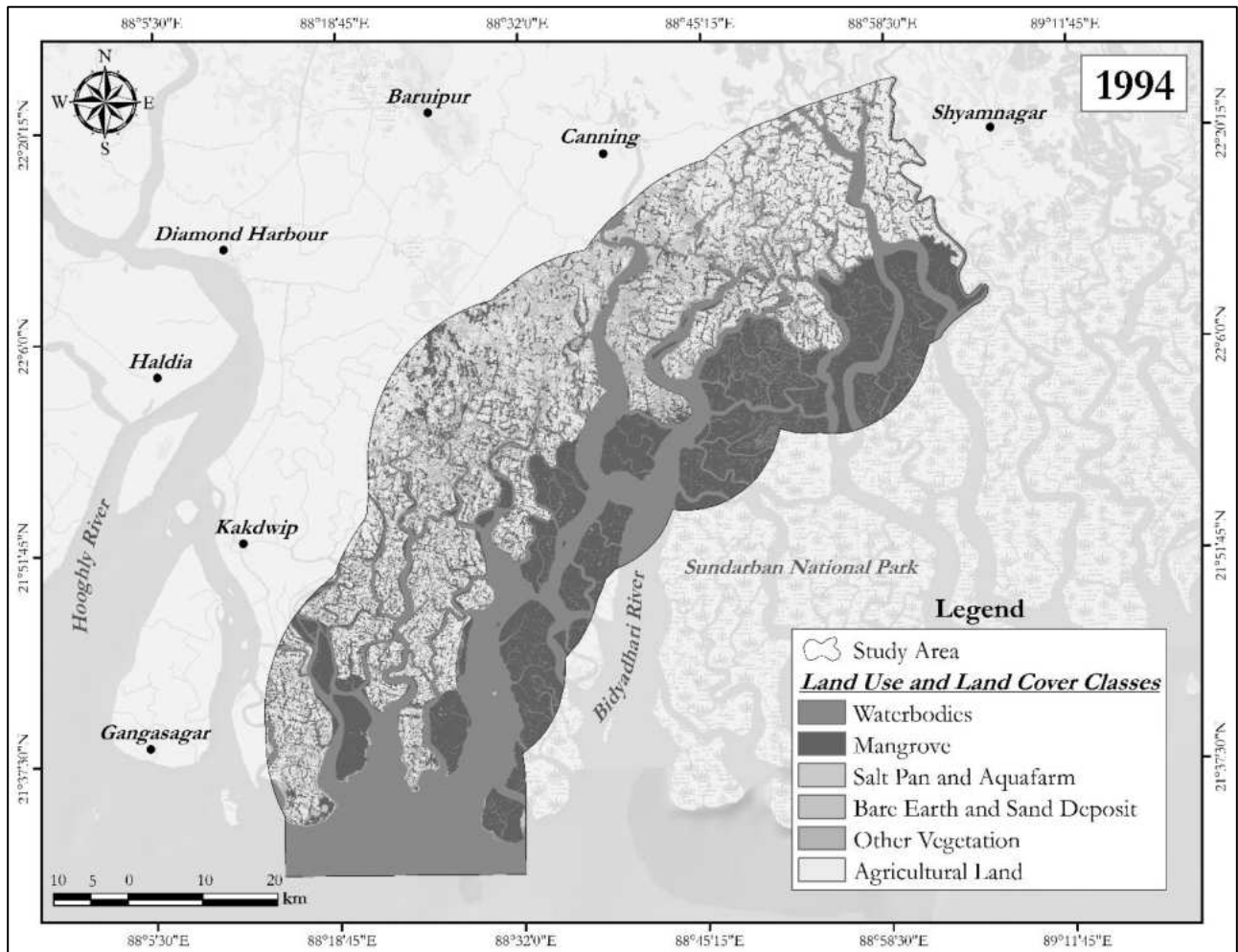
**Figure 4:** Location map of the study area.

### 2.2.1 Land use and land cover (LULC) mapping (India):

The methodology used to classify the multi-temporal satellite images of the Indian Sundarban involves several steps for image processing and classification. The image classification began in ERDAS IMAGINE 2014 (v14.01) software, where supervised classification approach was employed using the maximum likelihood algorithm, renowned for its classification accuracy (Roy and Datta, 2018). Six distinct LULC classes were identified based on pre-existing knowledge about the coastal features of this region. These classes include Mangrove, Other Vegetation, Bare Earth and Sand Deposit, Agricultural Land, Salt Pan and Aquafarm and Waterbodies. The other vegetation class encompassed both mixed vegetation and human settlement, while the bare earth and sand deposit category included mudflats, sandy beaches, and wasteland.

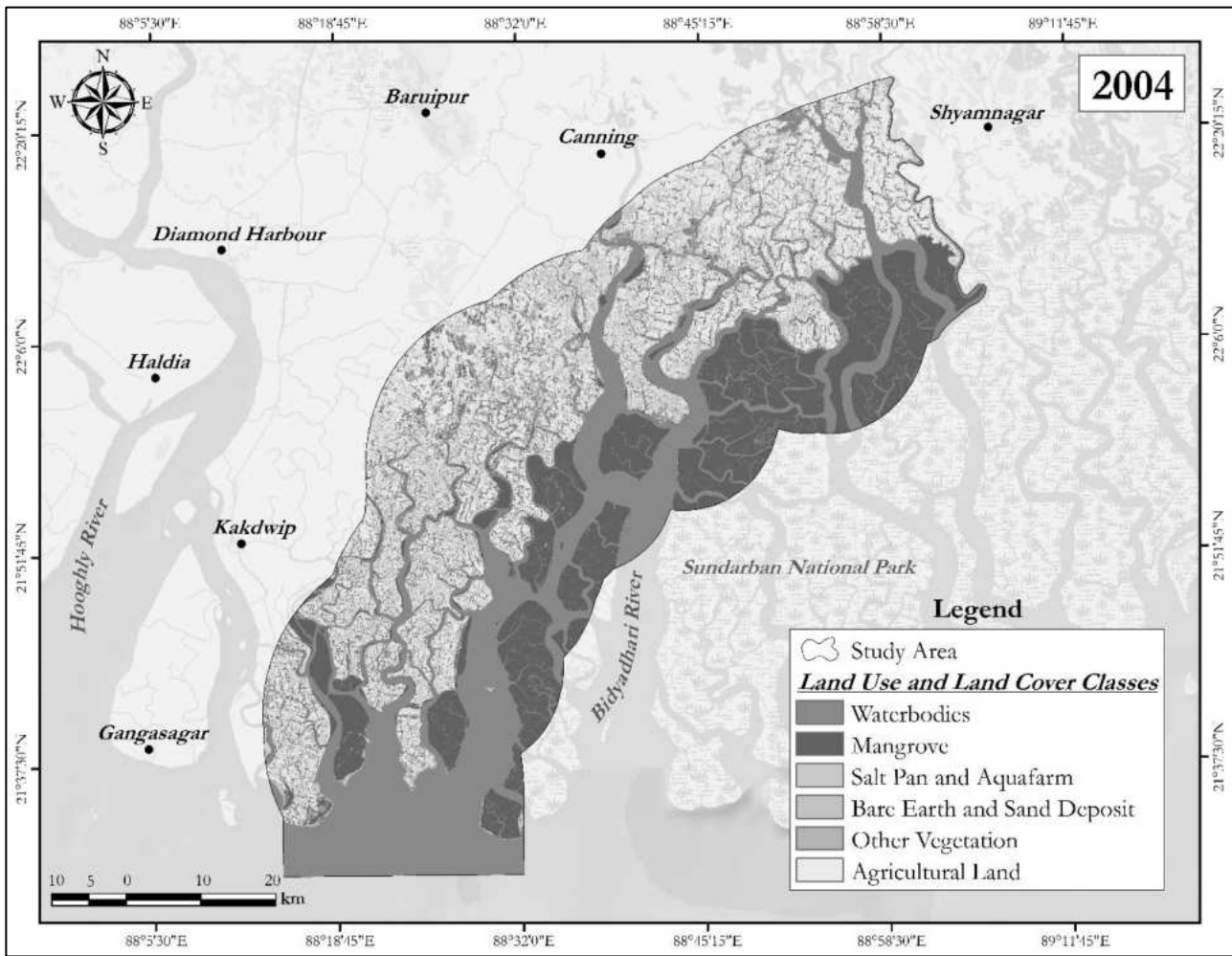
To assess the classification accuracy, error matrices were generated using 96 GCPs, which were stratified randomly across the site to cover its LULC diversity (Shalaby and Tateishi, 2007).

Post-classification, a multi-point time scale approach was adopted for change detection analysis, quantifying the areal changes in LULC classes between the time frames of successive image acquisitions (Disperati and Virdis, 2015). The area of each LULC class was calculated in hectares and then converted to percentage values. Net changes in the areal extent of each LULC class between successive periods were also computed (Roy and Datta, 2018). Furthermore, the transformation of individual pixels between LULC classes was captured functioning the transformation matrices for the period of 1994 – 2004, 2004 – 2014, and 2014 – 2024 (Islam et al., 2016).



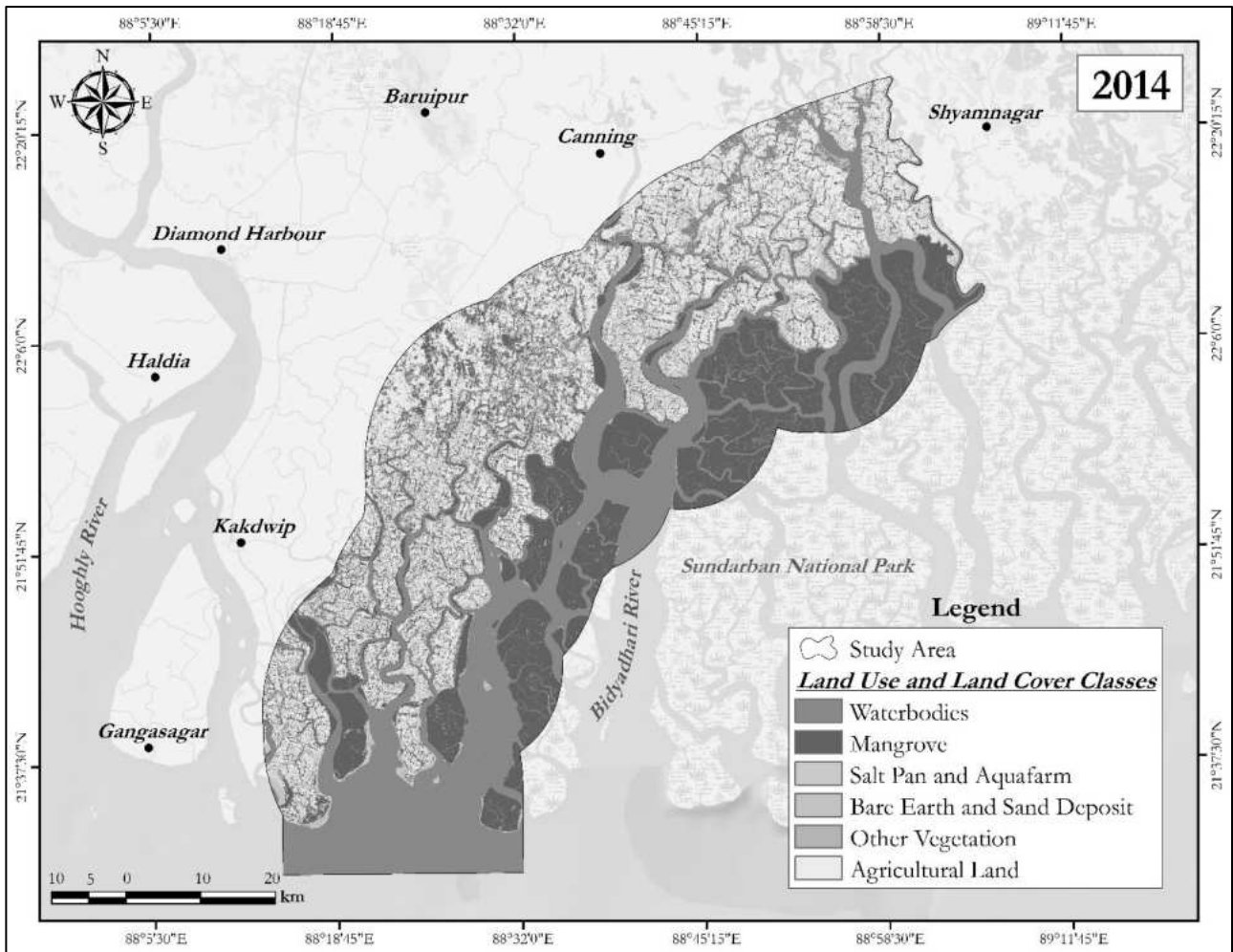
**Figure 5:** Distribution of dominant land use and land cover classes for the year of 1994.

During 1994, the waterbodies (30.72%) and mangrove (30.09%) are dominating the landscape, covering approximately 60% of the total study area, especially in the Central, East, South-East, North-East and Southern Regions. Whereas agricultural land (21.15%) and bare earth and sand deposit (12.41%) are sparse and mainly concentrated in the Northern and North-Western part of this region, with other vegetation (5.32%) that appears scattered but not widespread. Salt pan and aquafarm (0.31%) are visible but limited representing a more natural and predominately observed along riverside areas influenced by regular tidal activity.



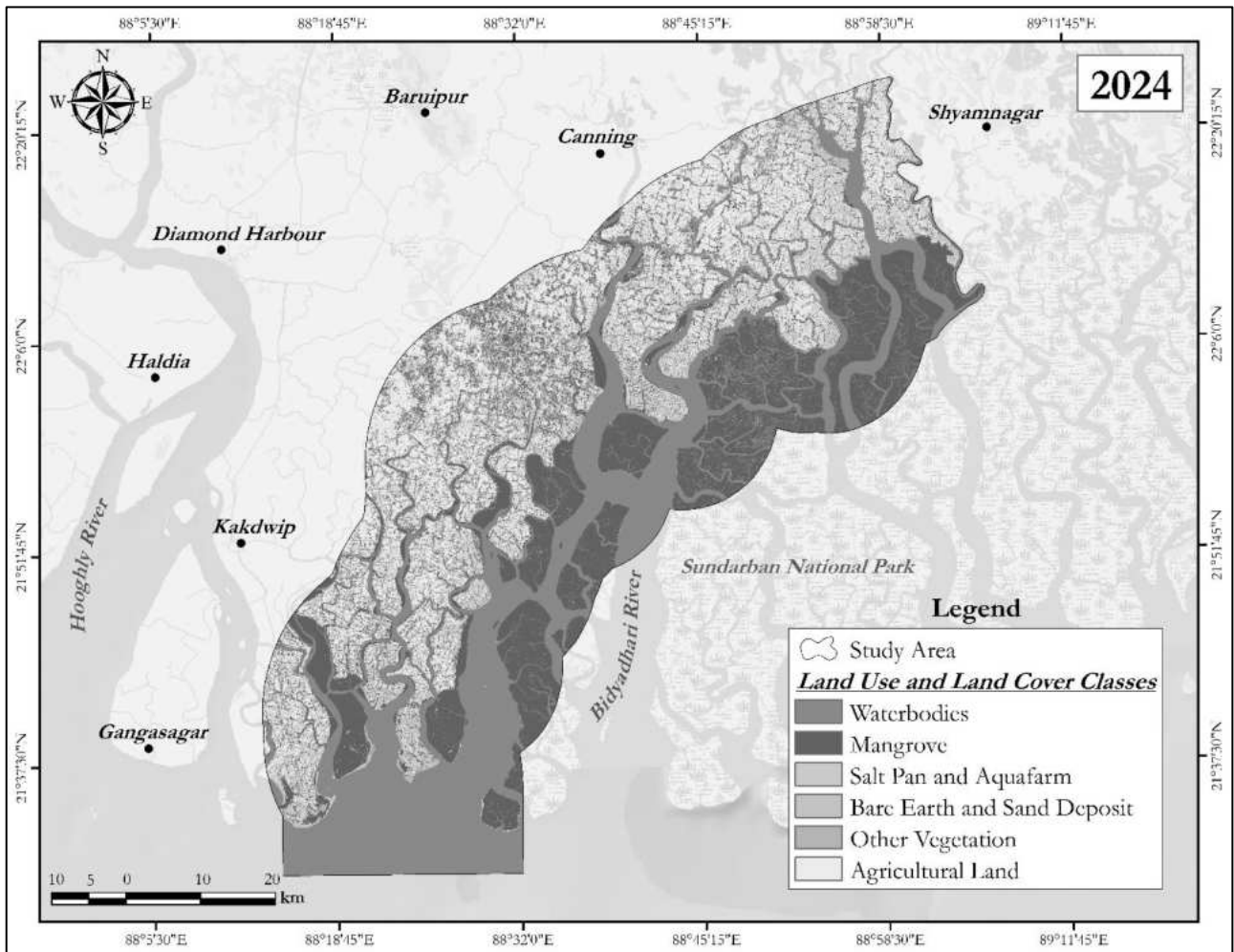
**Figure 6:** Distribution of dominant land use and land cover classes for the year of 2004.

Now for the year of 2004, there is a sharp expansion in the agricultural land (24.78%) and other vegetation (9.93%) whereas mangrove (26.46%) and waterbodies (29.80%) have declined compared to 1994 due to increase agricultural land and other vegetation, however bare earth and sand deposit (8.39%) decreased compared to previous decade year due to increase agricultural land. Around the riverside areas with salt pan and aquafarm (0.64%) remains relatively same but appears less prominent. Overall, it reflects agricultural land and other vegetation expansion over the decades.



**Figure 7:** Distribution of dominant land use and land cover classes for the year of 2014.

Now, if we move to the year 2014, we can observe that the extent of mangroves has slightly increased by 3% compared to the previous decade, now covering 29.80% of the area. The proportions of other vegetation, bare earth and sand deposit, and agricultural land have marginally decreased to 9.58%, 6.88%, and 22.68%, respectively. Conversely, the extent of saltpans and aquafarm (1.25%) has shown a slight increase, while the area under waterbodies (29.79%) has remained almost unchanged from the previous decade.



**Figure 8:** Distribution of dominant land use and land cover classes for the year of 2024.

For the year 2024, Other vegetation (11.10%) and agricultural land (24.30%) is the dominant trend so the settlement with vegetation areas have expanded in the Central, Western, North-Western and Northern part of this region significantly whereas mangrove (28.72%), bare earth and sand deposit (2.38%) has declining due to previous decade. Agricultural land (24.30%) and salt pan aquafarm (2.69%) has also shown up with due to the population growth last few years but the bare earth and sand deposit has been steadily declining being converted to settlement areas, with waterbodies (30.81%) remains minimal.

### 2.2.2 Land use and land cover (LULC) mapping (Bangladesh):

The methodology used to classify the multi-temporal satellite images of the Bangladesh Sundarban involves several steps for image processing and classification. The image classification began in ERDAS IMAGINE 2014 (v14.01) software, where supervised classification approach was employed using the maximum likelihood algorithm, renowned for its classification accuracy (Roy and Datta, 2018). Six distinct LULC classes were identified based on pre-existing knowledge about the coastal features of this region. These classes include Waterbodies, Mangrove, Salt Pan and Aquafarm, Bare Earth and Sand Deposit, Other Vegetation and Agricultural Land. The other vegetation class encompassed both mixed vegetation and human settlement, while the bare earth and sand deposit category included mudflats, sandy beaches, and wasteland (Rana et al., 2024). To assess the classification accuracy, error matrices were generated using 87 GCPs, which were stratified randomly across the site to cover its LULC diversity (Shalaby and Tateishi, 2007).

Post-classification, a multi-point time scale approach was adopted for change detection analysis, quantifying the areal changes in LULC classes between the time frames of successive image acquisitions (Disperati and Virdis, 2015). The area of each LULC class was calculated in hectares and then converted to percentage values. Net changes in the areal extent of each LULC class between successive periods were also computed (Roy and Datta, 2018). Furthermore, the transformation of individual pixels between LULC classes was captured functioning the transformation matrices for the period of 1994 – 2004, 2004 – 2014, and 2014 – 2024 (Islam et al., 2016).

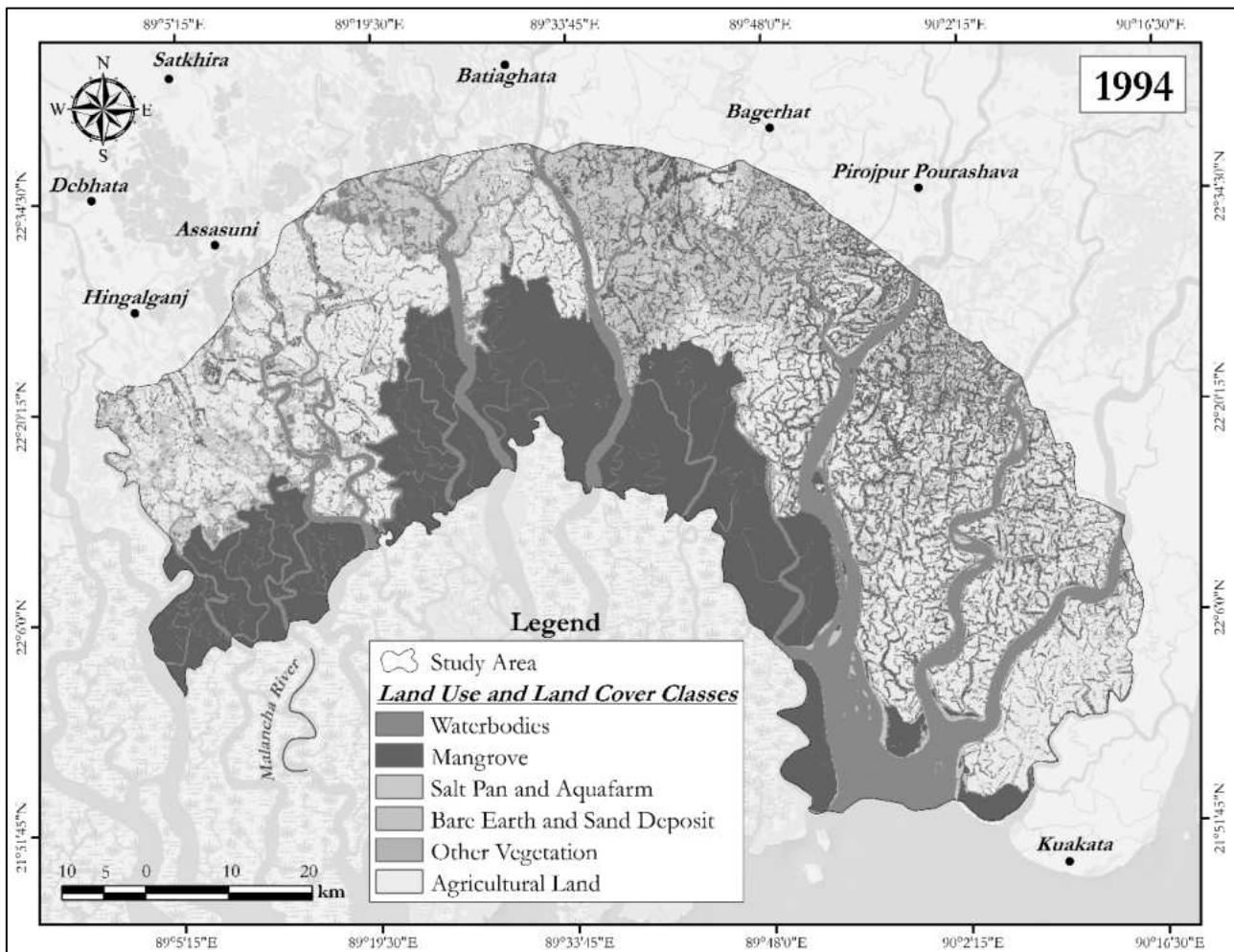
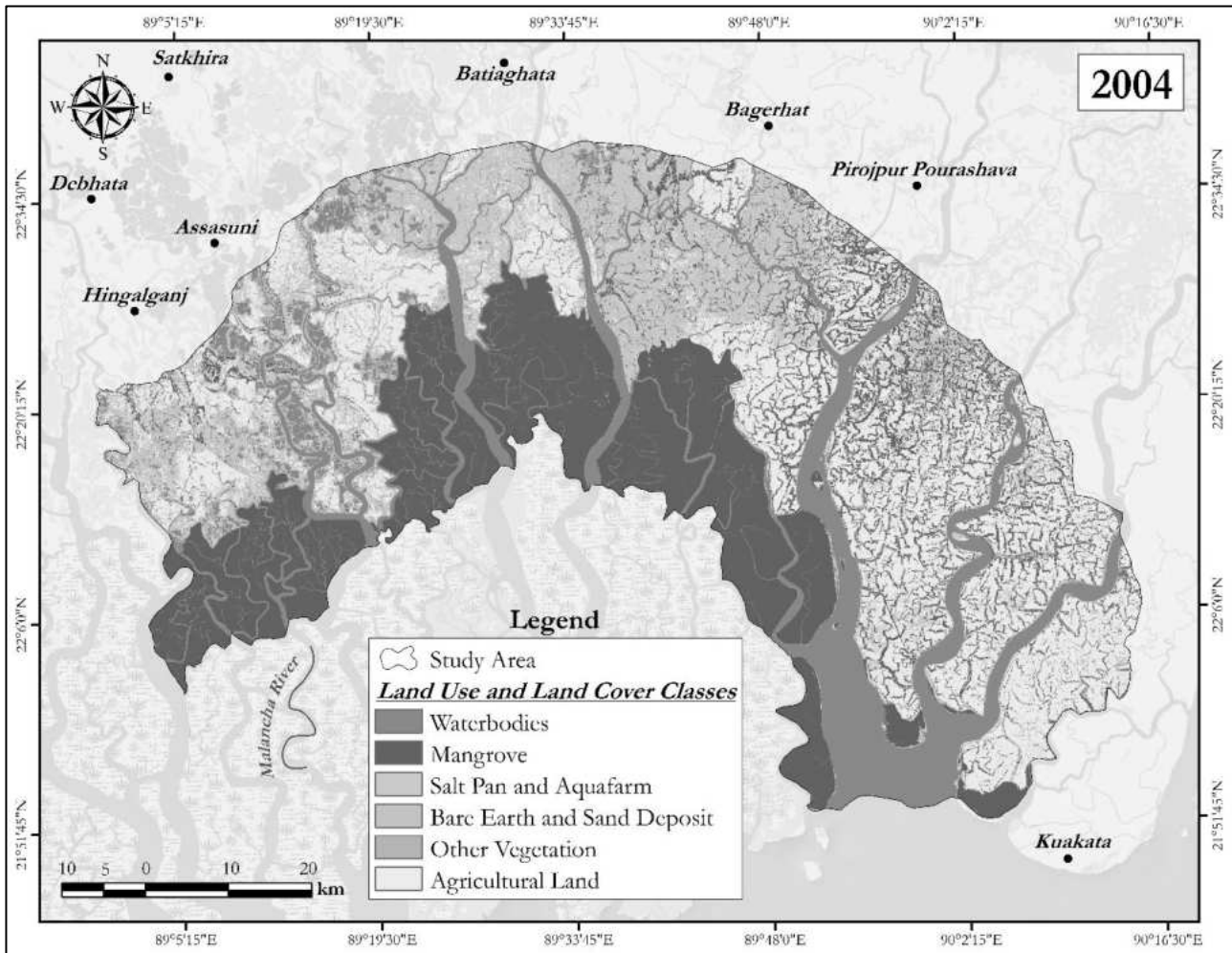


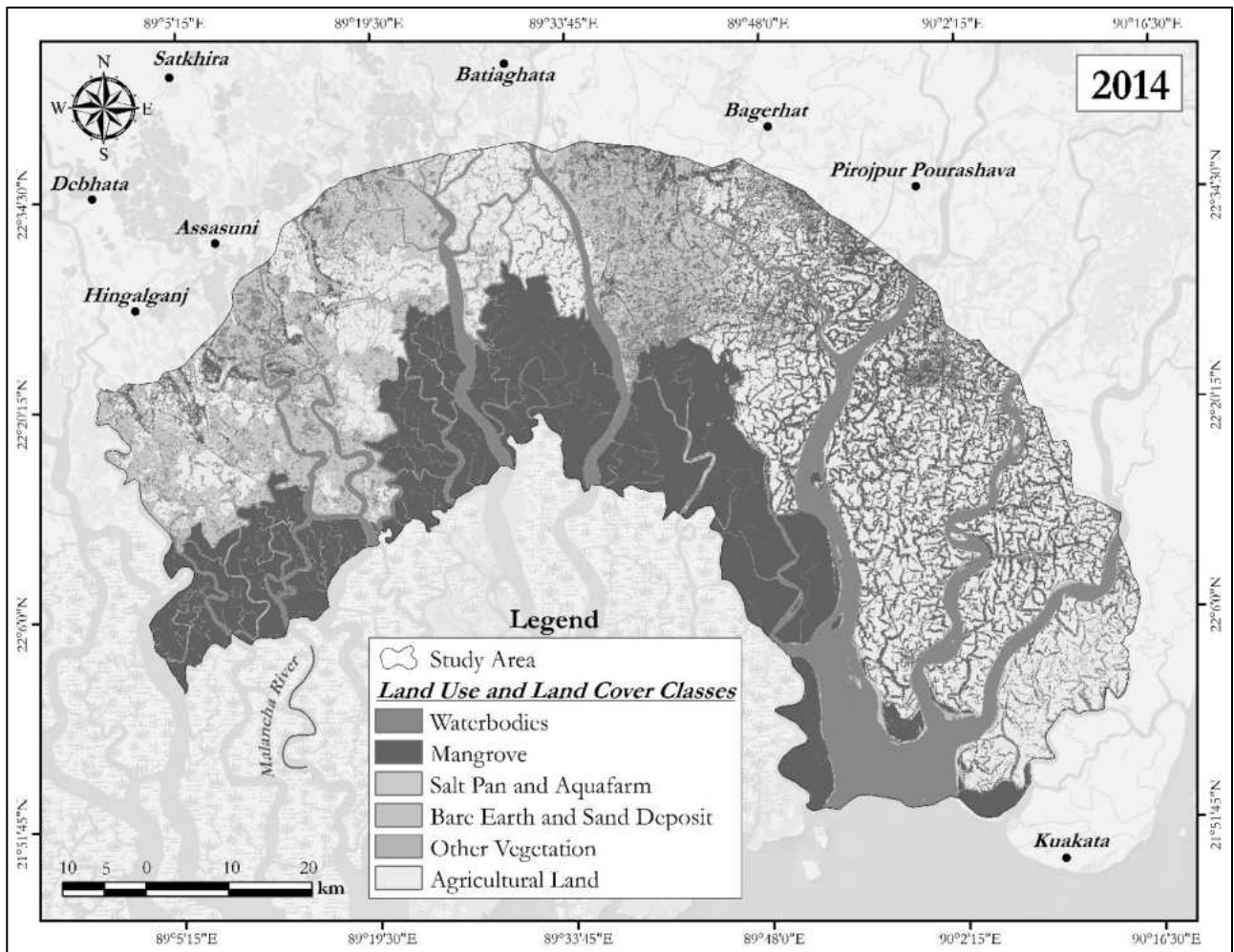
Figure 9: Distribution of dominant land use and land cover classes for the year of 1994.

During 1994, the mangrove (35.62%) and agricultural land (26.54%) are dominating the landscape, covering approximately 60% of the total study area, especially in the Central, East, South-East, North-East and part of Western regions. Whereas salt pan and aquafarm (14.37%) and waterbodies (14.26%) are sparse and mainly concentrated in the Northern and North-Western part of this region, with other vegetation (6.36%) that appears scattered but not widespread. Bare earth and sand deposit (2.85%) are visible but limited representing a more natural and predominately observed along riverside areas influenced by regular tidal activity.



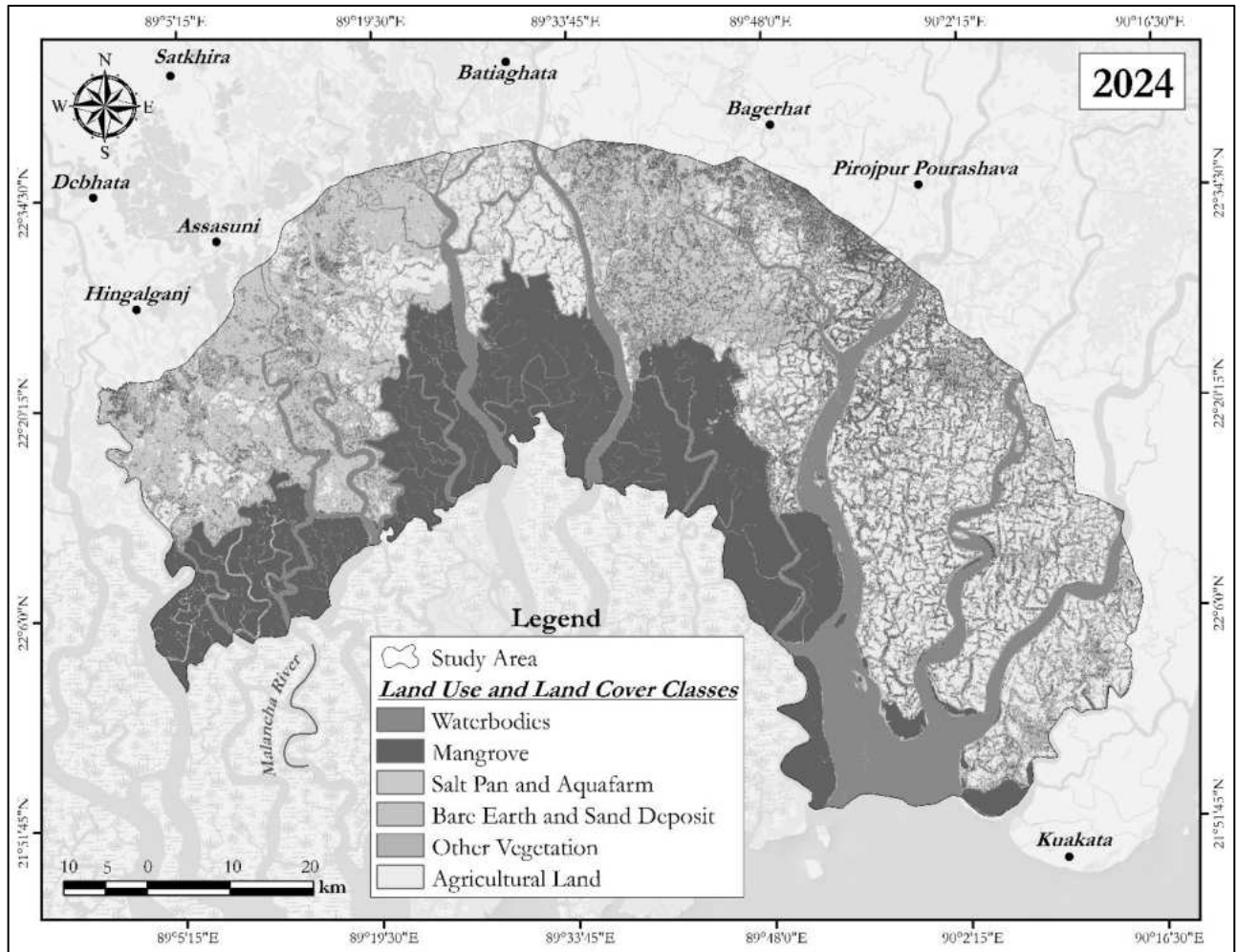
**Figure 10:** Distribution of dominant land use and land cover classes for the year of 2004.

Now for the year of 2004, there is a sharp expansion in the waterbodies (17.04%) and bare earth and sand deposit (9.63%) whereas mangrove (31.05%), salt pan and aquafarm (10.48%), other vegetation (6.03%) and agricultural land (25.77%) have declined compared to 1994 due to increase waterbodies and bare earth and sand deposit, however salt pan and aquafarm (10.48%) decreased compared to previous decade year due to increase waterbodies. Around the riverside areas with agricultural land (0.77%) and other vegetation (0.33%) remains relatively same but appears less prominent. Overall, it reflects waterbodies and bare earth and sand deposit expansion over the decades.



**Figure 11:** Distribution of dominant land use and land cover classes for the year of 2014.

Now, if we move to the year 2014, we can observe that the extent of mangroves has slightly increased by 5.69% compared to the previous decade, now covering 36.74% of the area. The proportions of waterbodies, salt pan and aquafarm, bare earth and sand deposit, and other vegetation have marginally decreased to 16.65%, 9.57%, 6.84% and 3.57%, respectively. Conversely, the extent of agricultural land (0.86%) has shown a slight increase, while the area under waterbodies (26.63%) has remained almost unchanged from the previous decade.



**Figure 12:** Distribution of dominant land use and land cover classes for the year of 2024.

For the year 2024, Salt pan and aquafarm (13.98%) and other vegetation (13.51%) is the dominant trend so the settlement with vegetation areas have expanded in the Central, Western, North-Western and Northern part of this region significantly whereas mangrove (31.61%), bare earth and sand deposit (6.70%) has declining due to previous decade. Agricultural land (17.70%) has also shown up with due to the population growth last few years but the bare earth and sand deposit has been steadily declining being converted to settlement areas, with waterbodies (16.50%) remains minimal.

### 2.2.3 Land use and land cover (LULC) mapping (Pakistan):

The methodology used to classify the multi-temporal satellite images of the Pakistan study area involves several steps for image processing and classification. The image classification began in ERDAS IMAGINE 2014 (v14.01) software, where supervised classification approach was employed using the maximum likelihood algorithm, renowned for its classification accuracy (Roy and Datta, 2018). Five distinct LULC classes were identified based on pre-existing knowledge about the coastal features of this region. These classes include Waterbodies, Bare Earth and Sand Deposit, Other Vegetation, Agricultural Land and Mangrove. The other vegetation class encompassed both mixed vegetation and human settlement, while the bare earth and sand deposit category included mudflats, sandy beaches, and wasteland. To assess the classification accuracy, error matrices were generated using 47 GCPs, which were stratified randomly across the site to cover its LULC diversity (Shalaby and Tateishi, 2007).

Post-classification, a multi-point time scale approach was adopted for change detection analysis, quantifying the areal changes in LULC classes between the time frames of successive image acquisitions (Shalaby and Tateishi (2007). The area of each LULC class was calculated in hectares and then converted to percentage values. Net changes in the areal extent of each LULC class between successive periods were also computed (Roy and Datta, 2018). Furthermore, the transformation of individual pixels between LULC classes was captured functioning the transformation matrices for the period of 1994 – 2004, 2004 – 2014, and 2014 – 2024 (Islam et al., 2016).

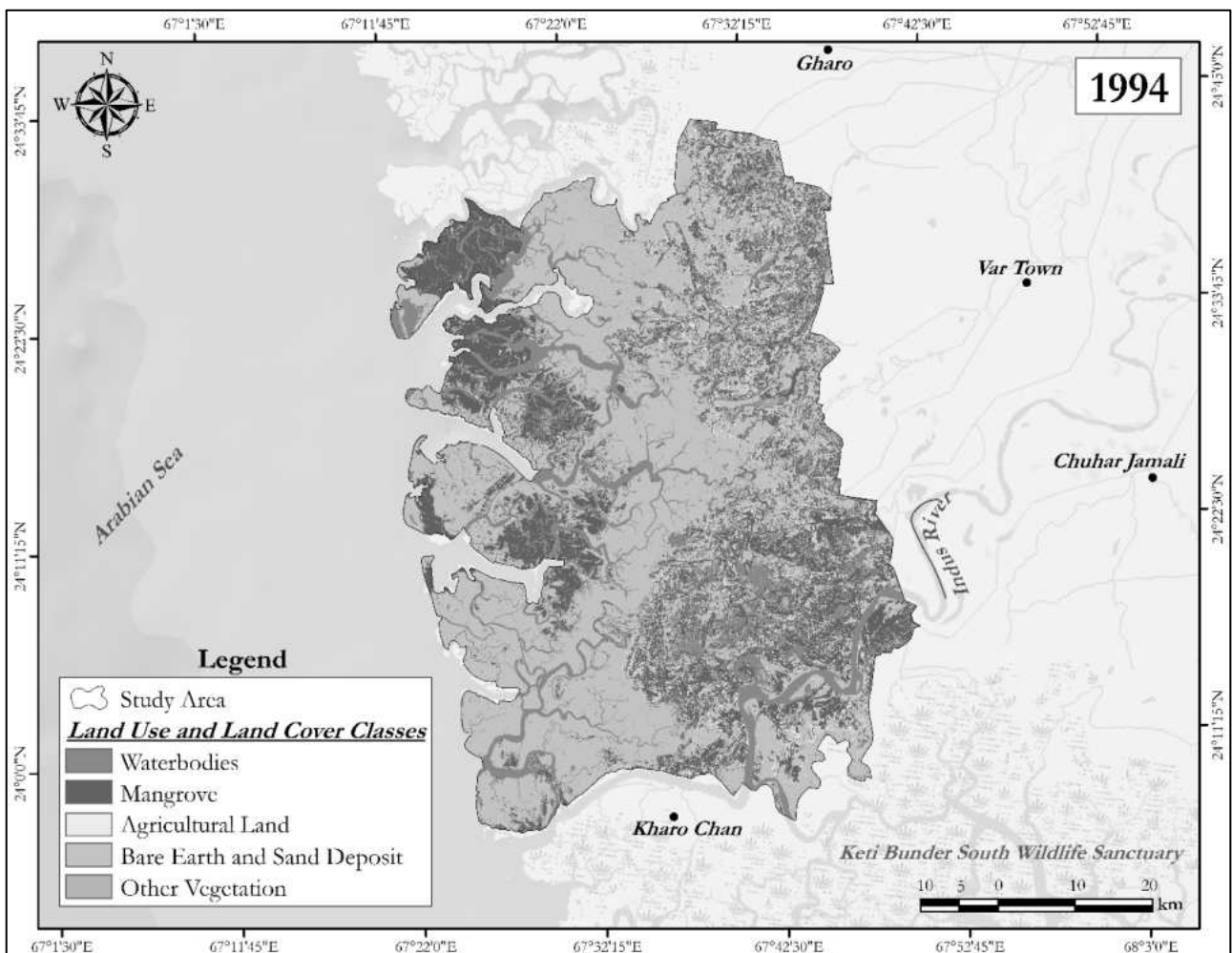
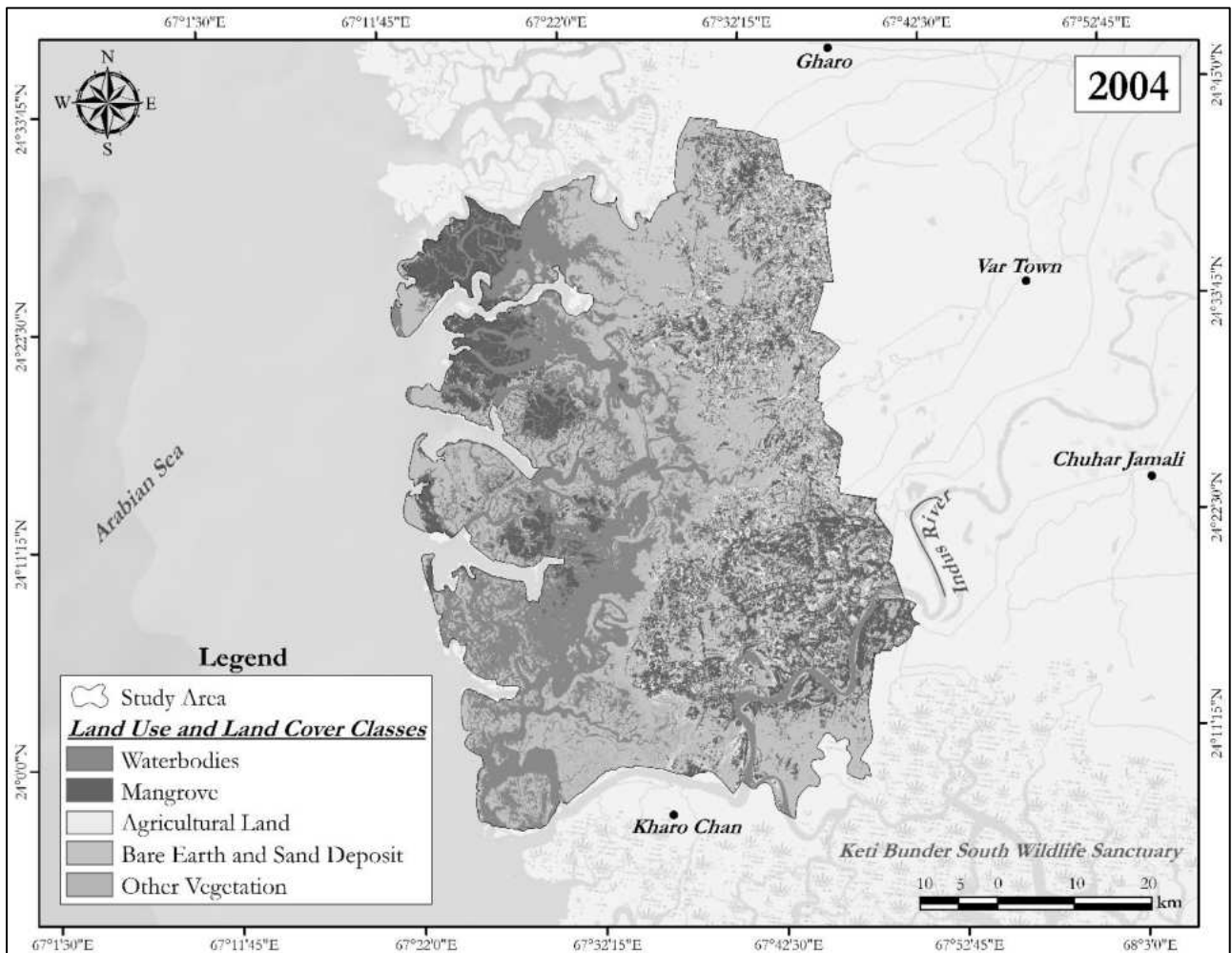


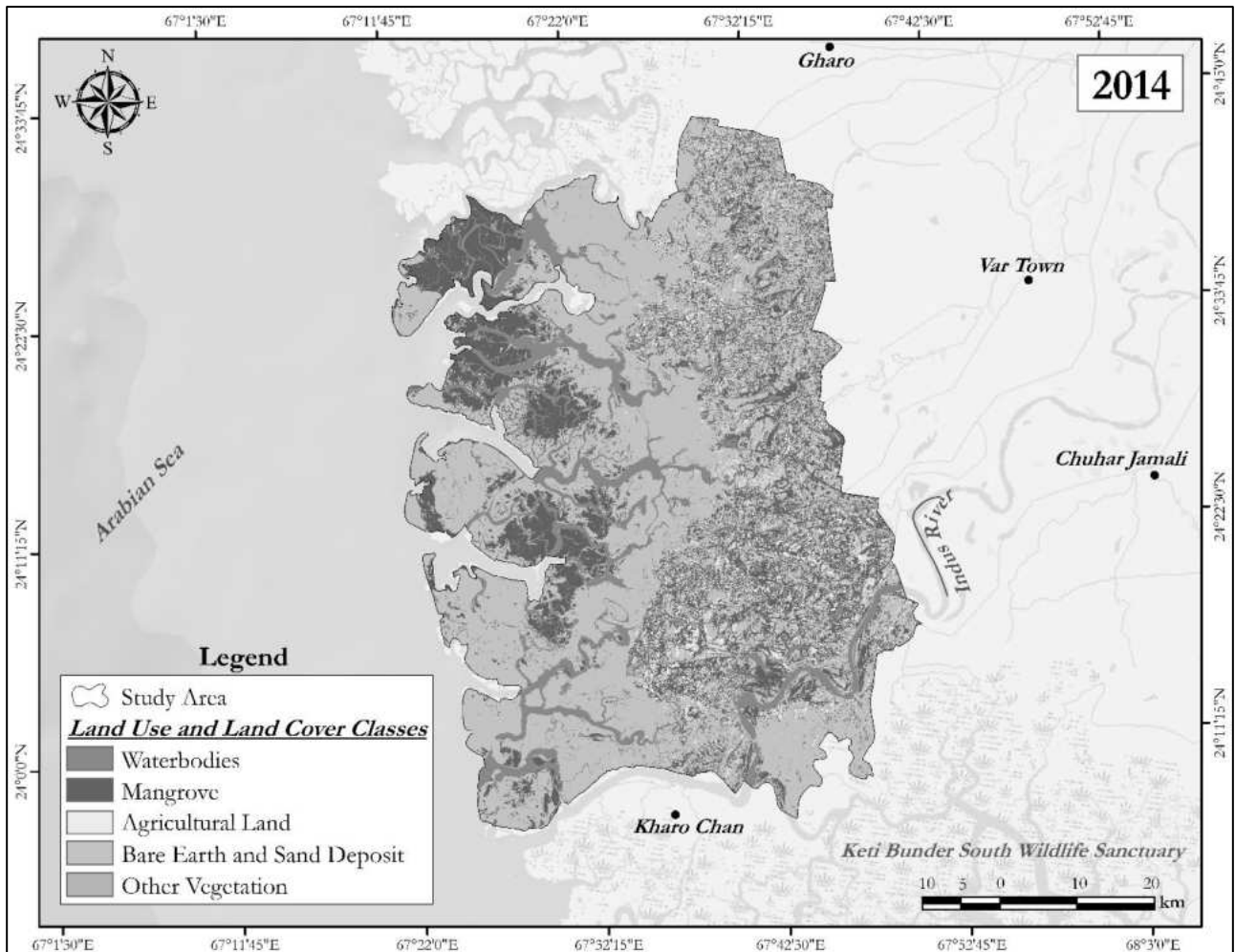
Figure 13: Distribution of dominant land use and land cover classes for the year of 1994.

During 1994, the Bare Earth and Sand Deposit (52.54%) and mangrove (27.56%) are dominating the landscape, covering approximately 79% of the total study area, especially in the West, North-Western and part of South-East Regions. Whereas Waterbodies (10.70%) are sparse and mainly concentrated in the Western, North-Western and South-Western part of this region, with other vegetation (5.55%) that appears scattered but not widespread. Agricultural land (3.65%) is visible in the Eastern, North-Eastern and South-Eastern part of this region, but limited representing a more natural and mainly found in the Indus River Basin, particularly in the provinces of Punjab and Sindh. These regions have fertile soil and extensive irrigation systems fed by the Indus River and its tributaries. Smaller agricultural areas are also found in Khyber Pakhtunkhwa and parts of Baluchistan, where irrigation is available.



**Figure 14:** Distribution of dominant land use and land cover classes for the year of 2004.

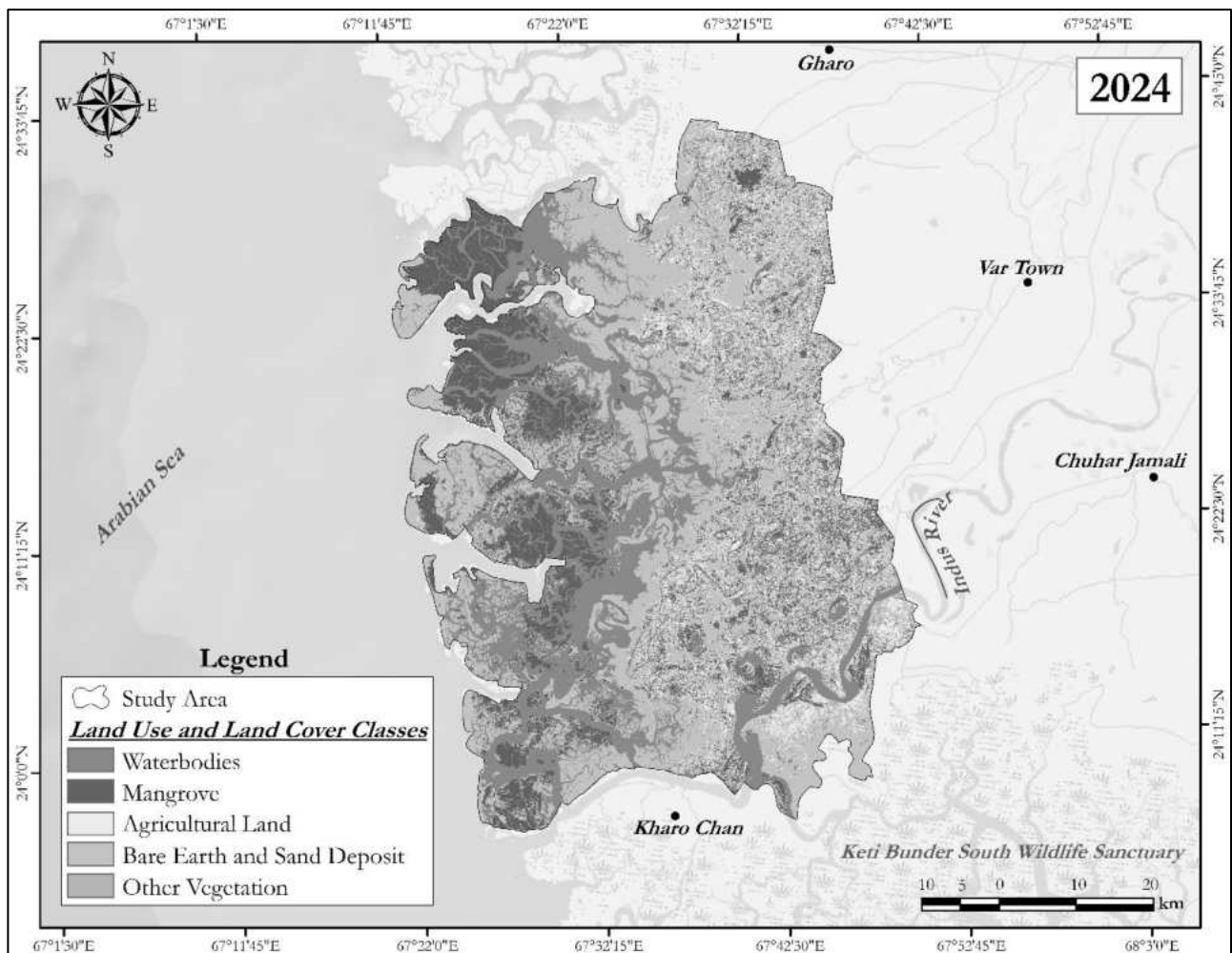
Now for the year of 2004, there is a sharp expansion in the waterbodies (24.41%), agricultural land (6.03%) and other vegetation (6.46%) whereas mangrove (21.94%) and bare earth and sand deposit (41.16%) have declined compared to 1994 due to increase waterbodies, 2004 experienced above-normal monsoon rainfall in parts of Pakistan, especially in Punjab, Sindh, and Khyber Pakhtunkhwa. This led to seasonal flooding, expansion of river channels, and formation of temporary floodplains, ponds, and wetlands. However bare earth and sand deposit (41.16%) decreased compared to previous decade year due to increase agricultural land and other vegetation. Around the central part of the study areas with other vegetation (6.46%) remains relatively same but appears less prominent. Overall it reflects agricultural land and waterbodies expansion over the decades.



**Figure 15:** Distribution of dominant land use and land cover classes for the year of 2014.

In 2014, the land cover composition of the study area exhibited notable yet moderate shifts compared to the previous decade. The extent of mangrove vegetation demonstrated a positive trend, increasing by approximately 5%, and now accounting for 26% of the total area. This gradual expansion likely reflects improved hydrological conditions and possible conservation or natural regeneration processes within the mangrove ecosystem. In contrast, both other vegetation (5.73%) and waterbodies (9.98%) recorded marginal declines, suggesting minor alterations in surface hydrology and vegetation dynamics. The agricultural land, however, exhibited a slight increase (6.42%), indicative of continued human intervention and land conversion for cultivation purposes. Meanwhile, the bare earth and sand deposit category remained dominant, occupying 51.87% of the landscape, though with substantial fluctuations in spatial distribution relative to the preceding decade. This persistence of exposed surfaces may be attributed to sedimentation processes, coastal erosion, and anthropogenic disturbances affecting the geomorphological stability of the region.

Overall, the 2014 landscape pattern reflects a complex interaction between natural regeneration, anthropogenic pressure, and geomorphic processes shaping the coastal environment.



**Figure 16:** Distribution of dominant land use and land cover classes for the year of 2024.

In the year 2024, the land use and land cover (LULC) analysis reveals a pronounced expansion of other vegetation (7.07%) and agricultural land (10.75%), indicating a dominant trend of vegetation-associated settlement development across the region. This expansion is particularly evident in the central, eastern, north-eastern, south-eastern, and northern sectors, where settlement areas with associated vegetation have increased markedly over the past decade. Conversely, a notable decline is observed in mangrove cover (20.48%) and bare earth and sand deposits (39.33%), reflecting substantial landscape transformation since the previous decade. The contraction of mangrove and barren zones can be attributed to anthropogenic pressures, land reclamation, and the progressive conversion of these areas into agricultural and settlement zones. The observed increase in agricultural land corresponds closely with the steady growth of population and associated livelihood expansion in recent years.

Meanwhile, waterbodies (22.38%) have exhibited minimal spatial fluctuation, suggesting relative hydrological stability despite surrounding land conversions. Overall, the 2024 LULC configuration underscores a continued shift from natural and semi-natural landscapes toward human-modified environments, particularly settlements integrated with vegetation and agricultural practices.

#### 2.2.4 Land use and land cover (LULC) mapping (Sri Lanka):

The methodology used to classify the multi-temporal satellite images of the Sri Lanka coastal study area involves several steps for image processing and classification. The image classification began in ERDAS IMAGINE 2014 (v14.01) software, where supervised classification approach was employed using the maximum likelihood algorithm, renowned for its classification accuracy (Roy and Datta, 2018). Five distinct LULC classes were identified based on pre-existing knowledge about the coastal features of this region. These classes include Waterbodies, Bare Earth and Sand Deposit, Agricultural Land, Other Vegetation, and Mangrove. The other vegetation class encompassed both mixed vegetation and human settlement, while the bare earth and sand deposit category included mudflats, sandy beaches, and wasteland. To assess the classification accuracy, error matrices were generated using 52 GCPs, which were stratified randomly across the site to cover its LULC diversity (Shalaby and Tateishi, 2007).

Post-classification, a multi-point time scale approach was adopted for change detection analysis, quantifying the areal changes in LULC classes between the time frames of successive image acquisitions (Shalaby and Tateishi (2007). The area of each LULC class was calculated in hectares and then converted to percentage values. Net changes in the areal extent of each LULC class between successive periods were also computed (Roy and Datta, 2018). Furthermore, the transformation of individual pixels between LULC classes was captured functioning the transformation matrices for the period of 1994 – 2004, 2004 – 2014, and 2014 – 2024 (Islam et al., 2016).

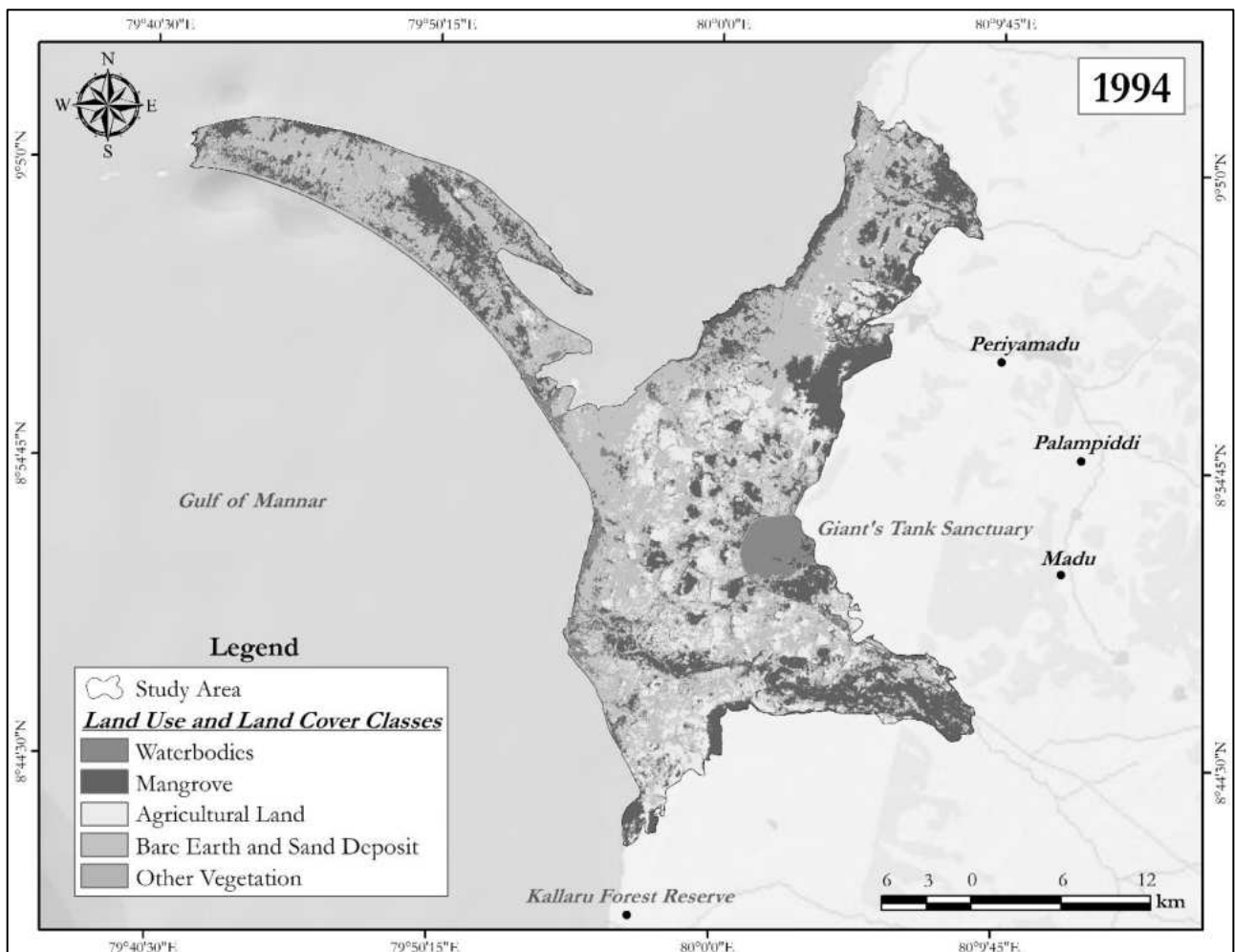
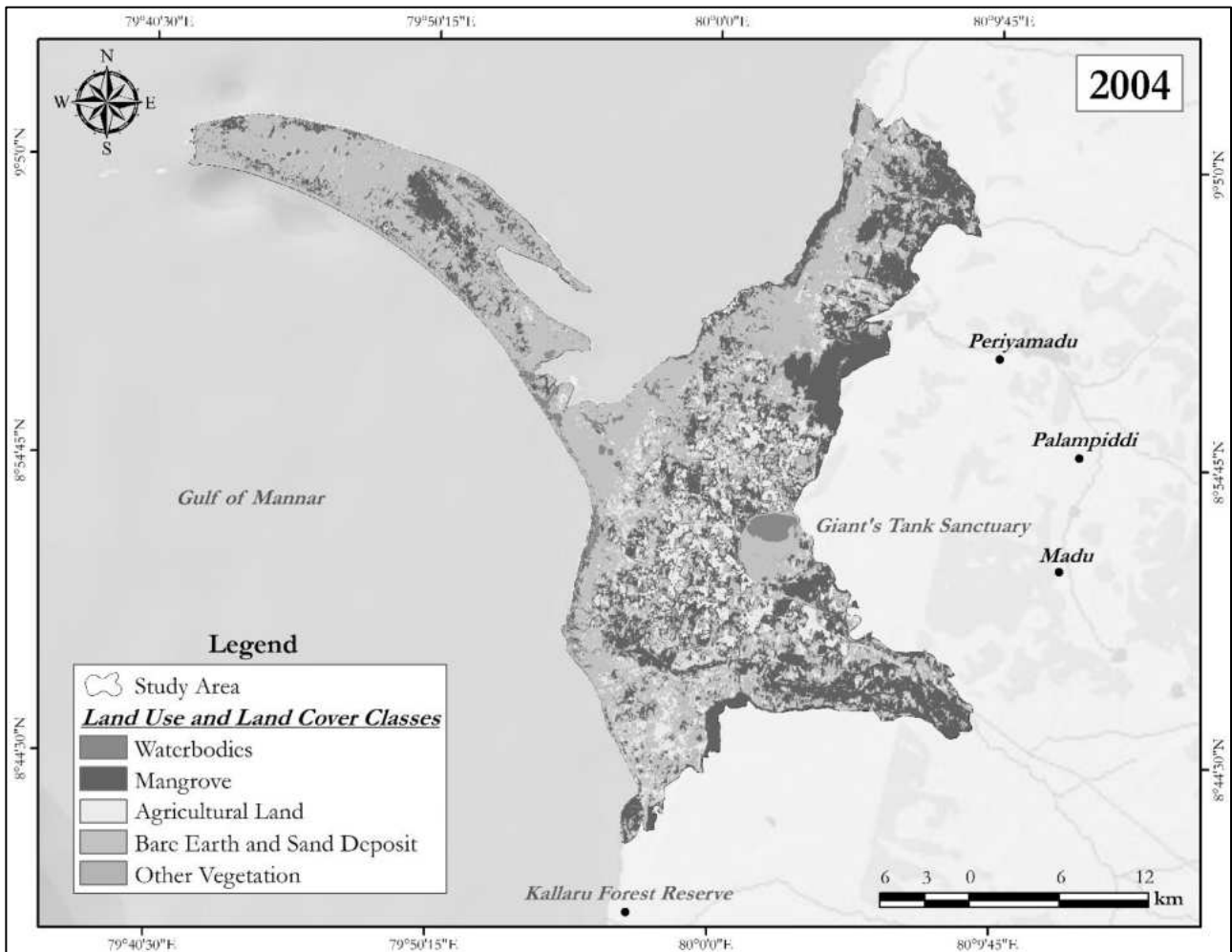


Figure 17: Distribution of dominant land use and land cover classes for the year of 1994.

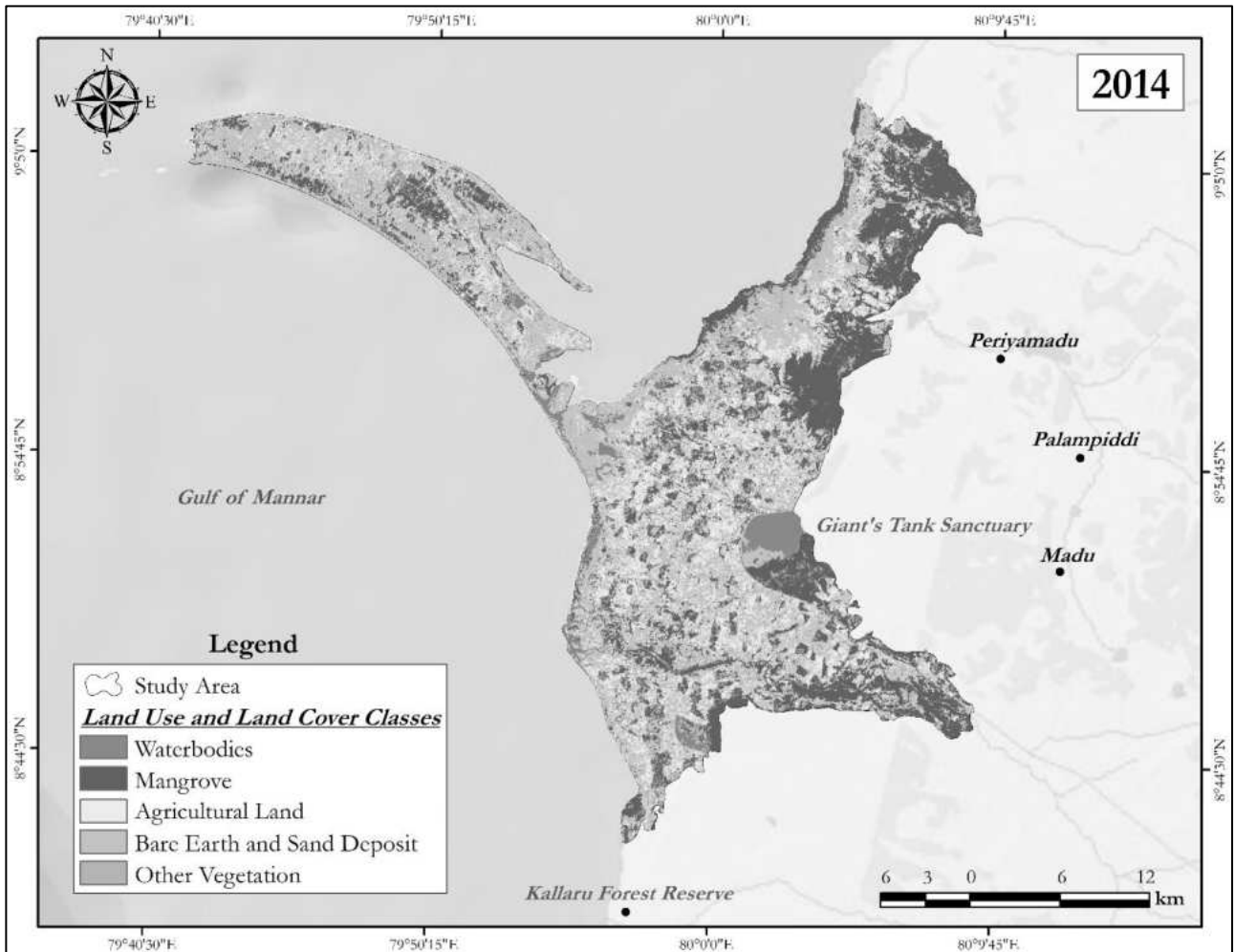
During 1994, the Bare Earth and Sand Deposit (50.94%) and mangrove (26.97%) are dominating the landscape, covering approximately 77% of the total study area, especially in the West, North, Central, South-Western, North-Western, North-Western and part of South-Eastern Regions. Whereas Waterbodies (3.50%) are sparse and mainly concentrated in the Eastern part of this region, with other vegetation (2.87%) that appears scattered but not widespread. Agricultural land (15.72%) are visible in the Central, Eastern, South, North-Eastern and South-Eastern part of this region, but limited representing a more natural and mainly found in the near Giant's Tank Sanctuary.

In this period, mangrove forests in Sri Lanka accounted for 26.97% of the total area, encompassing approximately 18483.62 hectares.



**Figure 18:** Distribution of dominant land use and land cover classes for the year of 2004.

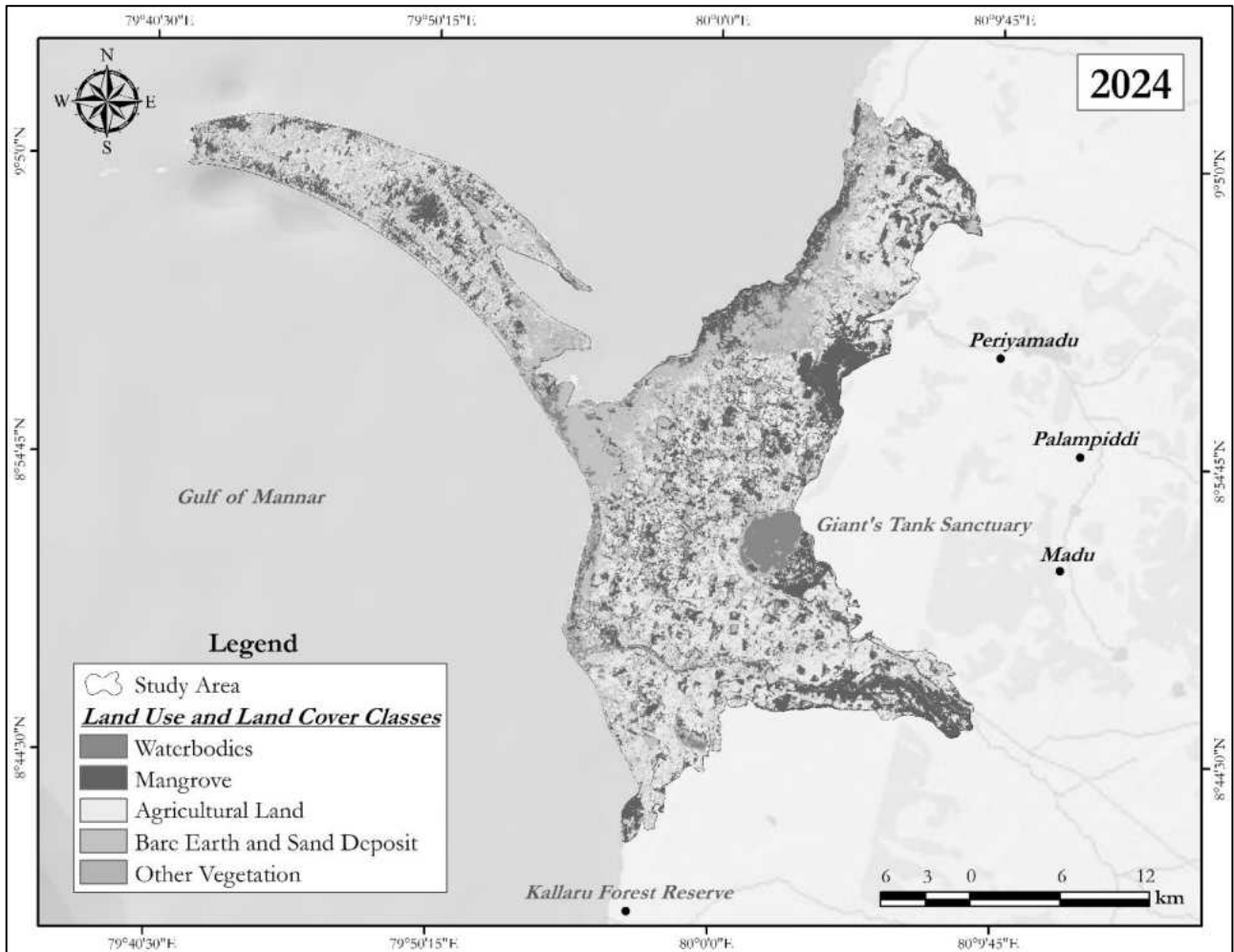
Now for the year of 2004, there is a sharp expansion in the mangrove (31.06%) and other vegetation (3.91%) whereas agricultural land (13.69%), waterbodies (1.87%) and bare earth and sand deposit (49.48%) have declined compared to 1994 due to increase mangrove. In 2004, Sri Lanka experienced notable Land Use and Land Cover (LULC) changes marked by a considerable expansion of agricultural land and settlements. Mangrove forests showed a moderate widening, primarily due to coastal development and aquaculture activities. Meanwhile, areas covered by water bodies and other vegetation exhibited minor fluctuations, reflecting a relatively stable natural landscape.



**Figure 19:** Distribution of dominant land use and land cover classes for the year of 2014.

In 2014, the land cover composition of the study area exhibited notable yet moderate shifts compared to the previous decade. The extent of agricultural land and other vegetation demonstrated a positive trend, increasing by approximately 8.72% and 2.82%. Now accounting for 22.41% and 6.73% of the total area. LULC dynamics for 2014 reveal a sustained positive trajectory in agricultural and vegetative land cover, indicative of continued anthropogenic influence on landscape transformation in Sri Lanka. In contrast, both bare earth and sand deposit (38.24%) and mangrove (29.60%) recorded marginal declines, the 2014 decline in mangrove cover likely resulted from coastal development, aquaculture expansion, and wetland conversion for agriculture and settlement, compounded by pollution, unregulated extraction, and coastal erosion. Concurrently, the reduction in bare earth and sand deposits reflects land stabilization, vegetative succession, and expanded agricultural use, further influenced by altered sediment dynamics due to river regulation and coastal protection interventions.

Overall, the 2014 landscape pattern reflects a complex interaction between natural regeneration, anthropogenic pressure, and geomorphic processes shaping the coastal environment.



**Figure 20:** Distribution of dominant land use and land cover classes for the year of 2024.

In the year 2024, the land use and land cover (LULC) analysis reveals a pronounced expansion of other vegetation (3.40%) and agricultural land (37.60%), indicating a dominant trend of vegetation-associated settlement development across the region. This expansion is particularly evident in the central, eastern, north-eastern, south-eastern, and southern sectors, where settlement areas with associated vegetation have increased markedly over the past decade. Conversely, a notable decline is observed in mangrove cover (26.05%) and bare earth and sand deposits (29.24%), reflecting substantial landscape transformation since the previous decade. The contraction of mangrove and barren zones can be attributed to anthropogenic pressures, land reclamation, and the progressive conversion of these areas into agricultural and settlement zones. The observed increase in agricultural land corresponds closely with the steady growth of population and associated livelihood expansion in recent years.

Meanwhile, waterbodies (3.72%) have exhibited minimal spatial fluctuation, suggesting relative hydrological stability despite surrounding land conversions. Overall, the 2024 LULC configuration underscores a continued shift from natural and semi-natural landscapes toward human-modified environments, particularly settlements integrated with vegetation and agricultural practices.

### 3. Result:

#### 3.1.1 Spatio-temporal dynamics of LULC mapping (India):

The LULC transformation in the Indian Sundarban between 1994 and 2024 reveals significant and complex changes in land use patterns, indicating a dynamic interplay between natural processes and anthropogenic interventions over the last three decades. Agricultural land, which initially dominated the landscape, covering 21.15% of the total area in 1994, experienced a dramatic flourish of 24.78% by 2004, gaining over 14482.66 hectares. This expansion might reflect increased pressure from expansive human habitation, and initiation of mono-specific brackish water aquafarming. However, from 2004 to 2014, agricultural land showed a partial decline, decreasing by over 8367.61 hectares (2.09%), which could be attributed to further encroachment by salt pans, aquaculture, or natural vegetation reclaiming former agricultural spaces. Nevertheless, from 2014 to 2024, agricultural land faced another drastic increase, expanding by 6470.70 hectares, a gentle enhancement of 1.62%, potentially due to efforts to reclaim agricultural areas or expand farming activities.

Bare earth and sand deposits, initially covering a small percentage of the area (12.41%) in 1994, decreased by 8.40% by 2004, likely due to changes in deposition patterns or land use conversions. However, this trend retains after 2004, with a gradual decrease in the area of bare earth and sand deposits, culminating in a gentle drop of 4.50% between 2014 and 2024, suggesting an intensification of sediment deposition, and subsequent expansion of mud banks and shoals.

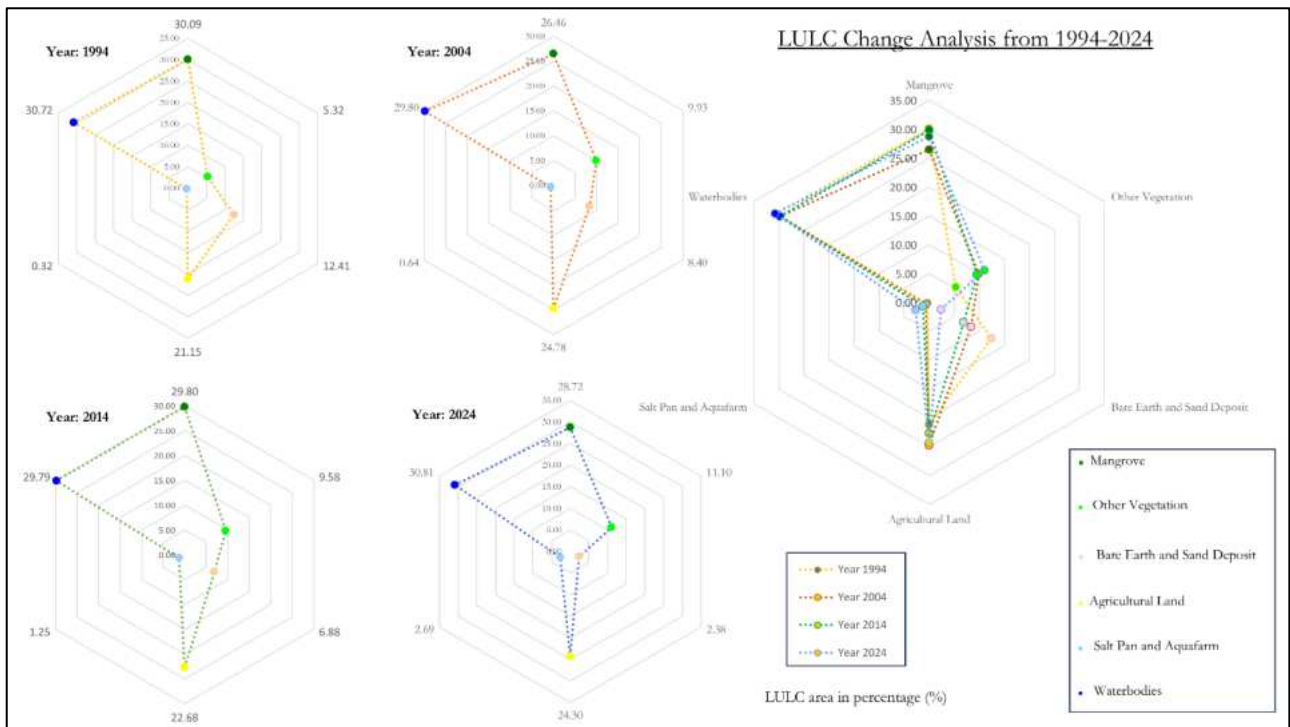
The mangrove cover, a critical component of the Sundarban ecosystem, showed a consistent decline from 1994 to 2014, losing over 3.63% of its area between 1994 and 2004 and a gaining additional 3.34% by 2014. This decline in mangrove cover, shrinking by more than 14492.90 hectares by 2004 and 13346.88 hectares by 2014, could be linked to deforestation along the fridge areas, land reclamation for agriculture and aquaculture, and the wide-spread effect of recurrent cyclonic events and changing inundation pattern. However, from 2014 to 2024, mangrove forests showed a substantial recovery, with a 1.08% shrink, regaining over 4294.35 hectares. This positive trend in recent years indicates the successful conservation programs, natural regeneration, and tangible policy interventions aimed at restoring and protecting the mangrove ecosystem in response to rising environmental concerns and the need for coastal protection against hazards such as sea-level rise and cyclones.

Other vegetation (habitation with vegetation) classes exhibited dramatic fluctuations during the study period. Between 1994 and 2004, the area under habitation with vegetation increased by an astounding 4.61%, with a gain of over 18432.81 hectares. This surge may be due to reforestation, the natural spread of vegetation in areas abandoned by agriculture, or shifts in land management practices. However, this trend reversed sharply between 2004 and 2014, with a decline of 0.35%, losing over 1383.19 hectares. The reduction might indicate deforestation, the expansion of agriculture, or other land uses encroaching on vegetated areas. Interestingly, from 2014 to 2024, habitation with vegetation showed another significant rebound, growing by 1.52% (6072.64 hectares), reflecting ongoing natural regrowth, land restoration efforts, and changes in land use management.

Salt pans and aquafarms, which occupy relatively small portions of the landscape, showed consistent and substantial growth throughout the study period. From 1994 to 2004, these areas expanded by 0.33%, increasing by over 1300.11 hectares, indicating preferred inclination towards brackish water aquaculture-based industries. Despite a small ascend of 0.61% between 2004 and 2014, salt pans and aquafarms rebounded strongly between 2014 and 2024, with a 1.43% increase, adding nearly 5725.64 hectares. This continued expansion of aquaculture and related activities reflects the rising demand for fish farming and

brackish water dependent agricultural practices in this region, which may be driven by economic pressures and the profitability of these ventures.

Overall, the LULC changes in the Indian Sundarban over the past three decades highlight the regional vulnerability to both human-induced alterations and natural processes. While there are positive signs of recovery, particularly in mangrove areas, the drastic reductions in bare earth and sand deposit and the expansion of aquaculture reflect ongoing challenges in land management, conservation, and sustainable development in and around the rich ecosystem of Sundarban mangrove. These trends underscore the need for continued monitoring, integrated land-use planning, and adaptive management strategies to ensure the long-term resilience of this ecologically and economically significant region.



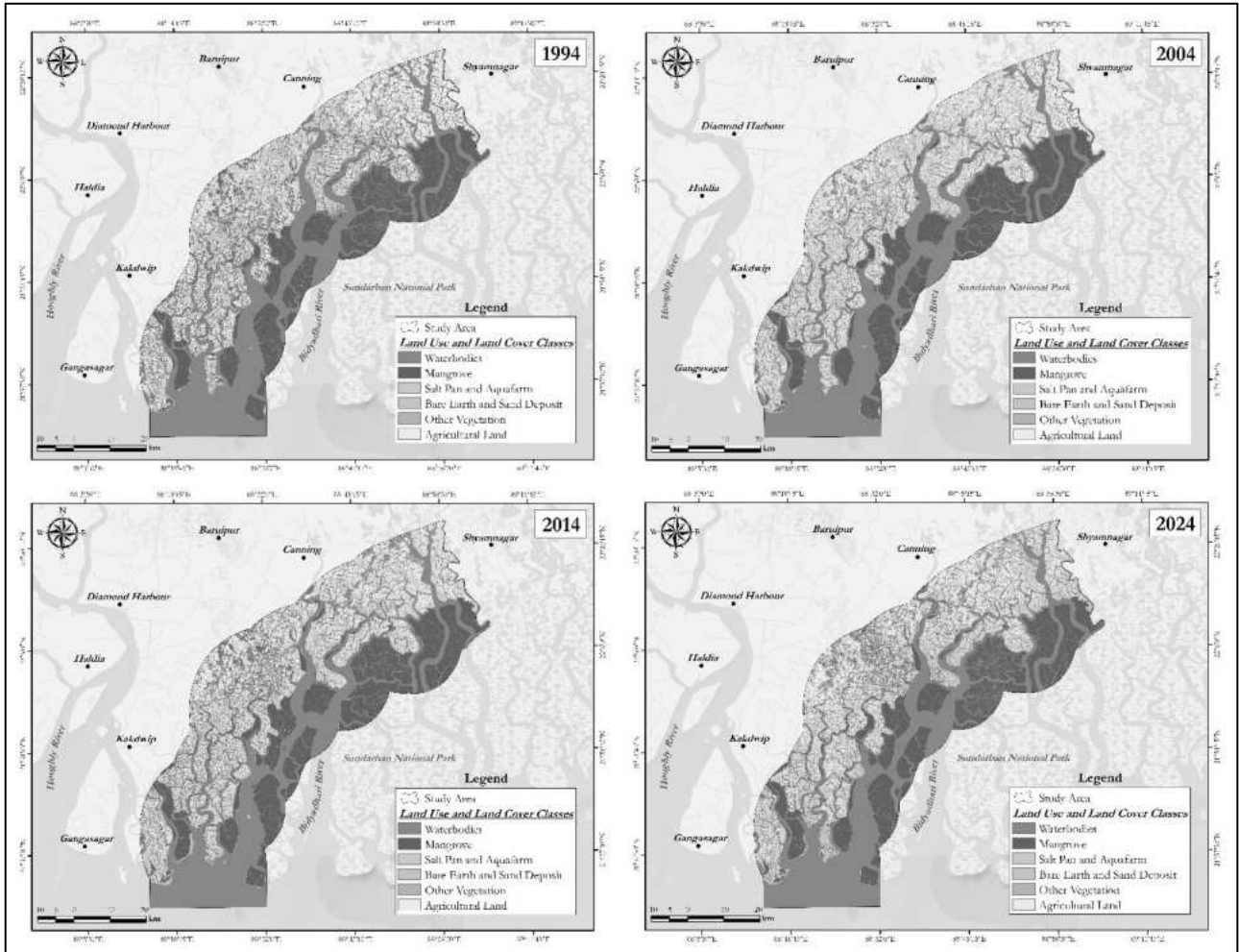
**Figure 21:** Temporal changes of the identified LULC classes within the Indian Sundarban.

**Table 1:** Temporal statistics of the major LULC classes within the selected parts of Indian Sundarban

LULC class	Year								Change		Change		Change	
	1994		2004		2014		2024		(1994-2004)		(2004-2014)		(2014-2024)	
	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)	ha	%	ha	%	ha	%
Mangrove	120243.25	30.09	105743.91	26.46	119097.16	29.80	114792.08	28.72	-14492.90	-3.63	13346.88	3.34	-4294.35	-1.08
Other Vegetation	21260.03	5.32	39686.37	9.93	38309.56	9.58	44371.45	11.10	18432.81	4.61	-1383.19	-0.35	6072.64	1.52
Bare Earth and Sand Deposit	49596.45	12.41	33561.17	8.40	27515.90	6.88	9503.62	2.38	-16028.80	-4.01	-6051.65	-1.51	-18001.60	-4.50
Agricultural Land	84546.78	21.15	99022.98	24.78	90661.75	22.68	97121.71	24.30	14482.66	3.62	-8367.61	-2.09	6470.70	1.62
Salt Pan and Aquafarm	1266.83	0.32	2560.48	0.64	5011.98	1.25	10726.88	2.69	1300.11	0.33	2445.12	0.61	5725.64	1.43
Waterbodies	122759.65	30.72	119098.08	29.80	119076.63	29.79	123157.25	30.81	-3655.11	-0.92	-27.83	0.00	4091.36	1.02
Total	399672.98	100.00	399672.98	100.00	399672.98	100.00	399672.98	100.00	-	-	-	-	-	-

### 3.1.2 LULC Change Map of India (1994-2024):

The image contains three Land Use/Land Cover (LULC) transition matrices comparing classified satellite images from the years 1994, 2004, 2014, and 2024. Each matrix shows how different land cover classes (Mangrove, Other Vegetation, Bare Earth and Sand Deposit, Agricultural Land, Salt Pan and Aquafarm, and Waterbodies) changed or remained stable over time.



**Figure 22:** LULC change map of Indian Sundarban study area between 1994 to 2024.

### 3.1.3 Indian Sundarban Transition Map:

The Change Vector Map of Indian Sundarban, spanning from 1994 to 2024, reveals a dynamic transformation of land cover driven by rapid rural expansion and associated anthropogenic activities. The most prominent change observed is the extensive conversion of bare earth and sand deposit areas into other vegetation, salt pan and aquafarm, and agricultural land particularly concentrated around the study area core and radiating outward. This trend reflects the pressures of population growth, infrastructure development, and rural settlement.

Notably, bare lands have also been significantly transformed into agricultural land and other vegetation, indicating the areas entire growth into formerly undeveloped or marginal lands. The central and western regions exhibit strong signs of such expansion, suggesting a shift in rural development patterns.

Despite widespread change, certain areas, especially along the Hooghly River and in the western, northern, north-western and south-western extents, retain stable waterbodies. Changes in salt pan and aquaculture, though relatively limited, include instances of bare earth and sand deposit to agricultural land or other vegetation, or salt pan and aquafarm, or mangrove conversions, which may reflect rural development, population growth, and people's socio-economic activities. Conversely, isolated transitions from bare earth and sand deposit to mangrove or water may indicate reforestation initiatives, biodiversity and ecosystem developments, or restoration projects, although these are less common.

Overall, the map illustrates a clear trajectory of rural dominance over natural land cover, while simultaneously highlighting the need for sustainable land use planning. If the present pattern of land use continues, no major issues may arise in the region; however, any disturbance to the ecological balance could adversely affect the biodiversity of the Indian Sundarbans. Therefore, it is essential to emphasise the integration of green infrastructure and conservation strategies, along with enhancing public awareness to safeguard biodiversity and the ecosystem.

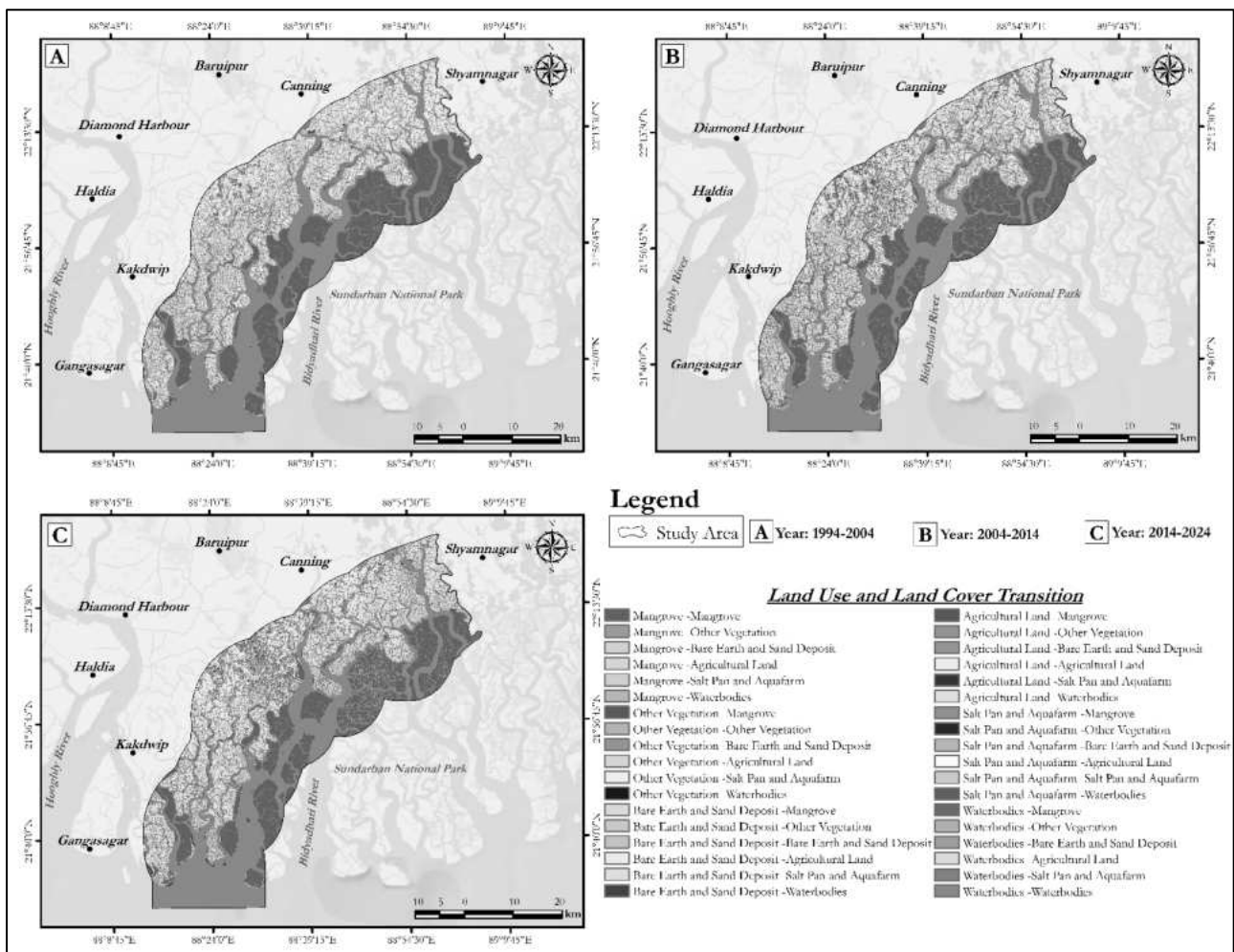


Figure 23: Transition map of LULC changes from 1994 to 2024

### 3.1.4 Transformation pattern of dominant LULCs:

The transformation matrix of identified LULC classes between 1994 and 2024 in the Indian Sundarban provides an insightful understanding of how different categories of LULCs, such as mangrove, other vegetation, bare earth and sand deposit, agricultural land, salt pan and aquafarm, and waterbodies, have shifted from one class to another class over time. The data for each period (1994-2004, 2004-2014, and 2014-2024) illustrate dynamic transitions across these categories, highlighting substantial ecological and anthropogenic changes in the landscape.

#### 3.1.4.1 Transition Matrix of 1994 and 2004:

In the 1994 to 2004 period, a significant portion of mangrove remained stable, retaining its classification (93285.70 hectares). Waterbodies area increased significantly, especially from 113818.20 hectares remained waterbodies 2198.68 hectares from bare earth and sand deposit, and 1908.75 hectares from mangrove converted to waterbodies. Mangrove reduced slightly, as much of it converted to other vegetation, bare earth and sand deposit, and agricultural land. Waterbodies high stability (113818.21 hectares remained waterbodies) but also contributed to other classes. Salt pan and aquafarm are relatively stable, though some transitions to other vegetation are seen. However, a notable transition of 3866.24 hectares of mangrove converted to agricultural land, indicating either natural regeneration or reforestation efforts. A smaller but ecologically meaningful transformation was the conversion of approximately 1450.38 hectares of agricultural land into mangroves, suggesting possible ecological restoration or natural mangrove regeneration processes. The matrix also reveals minor shifts from mangrove to salt pan and aquafarm areas (1103.18 hectares), which could reflect increasing aquaculture activities in the region. Similarly, bare earth and sand deposits transitioned into mangroves (2000.81 hectares) and waterbodies (2198.68 hectares), indicating dynamic geomorphological processes, likely related to sediment deposition and tidal action.

**Insight:** Rapid increase agricultural land and waterbodies expansion with significant conversion from bare earth and sand deposit, and mangrove into agricultural land areas.

#### 3.1.4.2 Transition Matrix of 2004 and 2014:

From 2004 to 2014, 14875.03 hectares of agricultural land transformed into habitation with other vegetation, which is consistent with the trend of land being reclaimed by natural systems. Interestingly, the mangrove cover expanded during this period, as 4179.79 hectares of agricultural land converted to mangroves, continuing the restoration or natural recolonization trend observed in the previous decade. Other vegetation area recently to grow, 110017.53 hectares of waterbodies remained. Significant increase from mangrove (4315.59 hectares), saltpan and aquafarm (633.28 hectares) and agricultural land (1040.63 hectares). Bare earth and sand deposit shows slight gain but also notable conversion to agricultural land. Bare earth and sand deposit continues transitioning to salt pan and aquafarm and other vegetation. Salt pan and aquafarm show minimal but noticeable transition to waterbodies. A substantial increase in mangrove area was also seen from the bare earth and sand deposit class, where 2216.12 hectares shifted to mangroves, suggesting enhanced mangrove restoration in degraded zones. The total mangrove area showed an increase of over 93364.46 hectares in 2014, further indicating successful natural recovery or conservation interventions.

**Insight:** Agricultural land, salt pan and aquafarm, and other vegetation trend intensely, reducing bare earth and sand deposit and waterbodies further.

#### 3.1.4.3 Transition Matrix of 2014 and 2024:

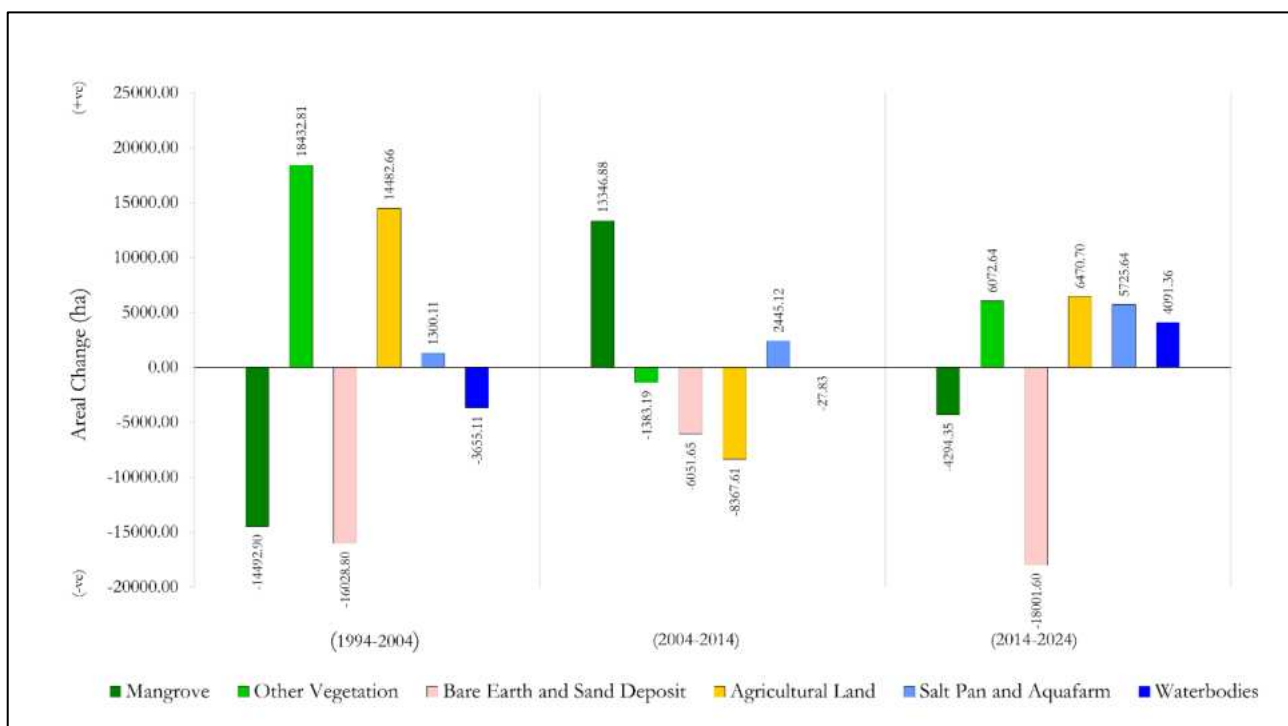
In the final period from 2014 to 2024, the rate of change became even more pronounced. Bare earth and sand deposit experienced a drastic reduction, with only 3389.36 hectares remaining by 2024. A significant portion of agricultural land, amounting to 15297.79 hectares, converted into other vegetation, while another

1184.73 hectares shifted to salt pan and aquafarm, reflecting a growing influence of aquaculture and possibly the effects of land abandonment or unsuitability for agriculture due to salinity intrusion. Waterbodies area expansion accelerates; 111652.92 hectares remain as waterbodies. Large conversion from mangrove (7419.54 hectares) and salt pan and aquafarm (709.45 hectares). Other vegetation (562.07 hectares) and agricultural land (569.54 hectares) show decline. Bare Land has notable conversions into agricultural land and other vegetation. Waterbodies mostly stable, slight ascend (from 119056.92 to 123089.34 hectares total). Mangroves continued to expand significantly, as approximately 3561.82 hectares of agricultural land were converted to mangrove areas, underscoring the adaptive capacity of mangroves in this coastal region. The overall mangrove covers in 2024 reached 95591.43 hectares, a notable increase, reflecting ongoing conservation efforts and possibly positive effects of climate resilience strategies.

**Insight:** Massive mangrove area growth continues, replacing both other vegetation, bare earth and sand deposit; waterbodies remain relatively unchanged.

### 3.1.4.4 Overall Interpretation of Transition Matrix (1994 to 2024):

- Mangrove areas show a consistent and sharp increase, highlighting showed a substantial recovery.
- Other Vegetation and agricultural land are the major land types being converted.
- Water bodies show slight expand but are mostly stable.
- The area of bare earth and sand deposit has decreased due to landscape transformation is driven primarily by human development, likely due to population growth and infrastructure expansion.
- This data is valuable for development planning, sustainability analysis, and environmental impact assessments.



**Figure 24:** LULC change bar of Indian Sundarban study area between 1994 to 2024.

**Table 2:** India LULC transformation statistics from 1994 to 2004.

LULC Class	Mangrove	Other Vegetation	Bare Earth and Sand Deposit	Agricultural Land	Salt Pan and Aquafarm	Waterbodies	Grand Total (1994)
Mangrove	<b>93285.70231</b>	18324.43026	1735.658751	3866.239103	1103.175185	1908.745655	120223.9513
Other Vegetation	1990.141535	<b>8597.635082</b>	1451.703203	8750.682504	206.617448	251.167837	21247.94761
Bare Earth and Sand Deposit	2000.808452	4688.51473	<b>15785.69199</b>	24329.73105	572.72418	2198.681185	49576.15159
Agricultural Land	1450.378443	7633.774113	12920.05692	<b>61584.60376</b>	226.070074	704.851972	84519.73528
Salt Pan and Aquafarm	235.307574	237.48216	175.17919	351.660564	<b>90.131171</b>	172.562461	1262.32312
Waterbodies	6753.54767	196.450096	1485.700527	123.389201	363.18412	<b>113818.2078</b>	122740.4794
Grand Total (2004)	105715.886	39678.28645	33553.99058	99006.30619	2561.902178	119054.2169	<b>399570.5882</b>

**Table 3:** India LULC transformation statistics from 2004 to 2014.

LULC Class	Mangrove	Other Vegetation	Bare Earth and Sand Deposit	Agricultural Land	Salt Pan and Aquafarm	Waterbodies	Grand Total (2004)
Mangrove	<b>93364.46283</b>	4939.22422	549.799993	1686.925851	861.195929	4315.585367	105717.1942
Other Vegetation	13306.89321	<b>15959.08737</b>	904.729172	8000.355566	716.457299	790.792974	39678.31559
Bare Earth and Sand Deposit	2216.121102	1877.57579	<b>10404.11985</b>	15312.14099	1484.647585	2259.090855	33553.69618
Agricultural Land	4179.788057	14875.03303	13163.19488	<b>64894.50313</b>	852.066194	1040.630887	99005.21618
Salt Pan and Aquafarm	927.51248	368.777771	105.680248	245.077573	<b>281.487176</b>	633.282616	2561.817864
Waterbodies	5082.078952	272.563141	2375.911561	494.856505	809.875103	<b>110017.5328</b>	119052.818
Grand Total (2014)	119076.8566	38292.26133	27503.43571	90633.85962	5005.729286	119056.9155	<b>399569.058</b>

**Table 4:** India LULC transformation statistics from 2014 to 2024.

LULC Class	Mangrove	Other Vegetation	Bare Earth and Sand Deposit	Agricultural Land	Salt Pan and Aquafarm	Waterbodies	Grand Total (2014)
Mangrove	<b>95591.4257</b>	9701.257049	297.952005	4559.228672	1496.243233	7419.544525	119065.6512
Other Vegetation	10097.64547	<b>15055.87107</b>	410.366802	11193.85301	978.051359	562.066567	38297.85428
Bare Earth and Sand Deposit	909.154478	3624.187576	<b>3389.358117</b>	15740.44776	1666.47662	2175.821102	27505.44566
Agricultural Land	3561.822216	15297.78562	4801.340478	<b>27060.59973</b>	2972.552365	569.541505	54263.64191
Salt Pan and Aquafarm	1184.872479	333.863466	82.826488	1184.734278	<b>1511.159353</b>	709.445582	5006.901646
Waterbodies	3417.353374	353.318709	527.509369	986.621106	2105.707007	<b>111652.9235</b>	119043.433
Grand Total (2024)	114762.2737	44366.28349	9509.353259	60725.48456	10730.18994	123089.3428	<b>363182.9277</b>

### 3.2.1 Spatio-temporal dynamics of LULC mapping (Bangladesh):

The LULC transformation in the Bangladesh Sundarban between 1994 and 2024 reveals significant and complex changes in land use patterns, indicating a dynamic interplay between natural processes and anthropogenic interventions over the last three decades. The mangrove cover, a critical component of the Sundarban ecosystem, showed a consistent decline from 1994 to 2014, losing over 4.57% of its area between 1994 and 2004 and an additional 5.69% increasing by 2014. This decline in mangrove cover, shrinking by more than 27225.74 hectares by 2004 and 33889.50 hectares by 2014, could be linked to afforestation along the fringe areas, land reclamation for agriculture and aquaculture, and the wide-spread effect of recurrent cyclonic events and changing inundation pattern. However, from 2014 to 2024, mangrove forests showed a significant deterioration, with a 5.13% decrease, losing over 30574.93 hectares. This negative trend in recent years indicates the successful coastal erosion and sea-level rise, cyclones and storm surges, increased salinity, human encroachment and deforestation, unplanned development project, expansion of shrimp farming, decreased freshwater flow, overexploitation of forest resources, pollution and sedimentation. The mangrove ecosystem in response to rising environmental concerns and the need for coastal protection against hazards such as sea-level rise and cyclones.

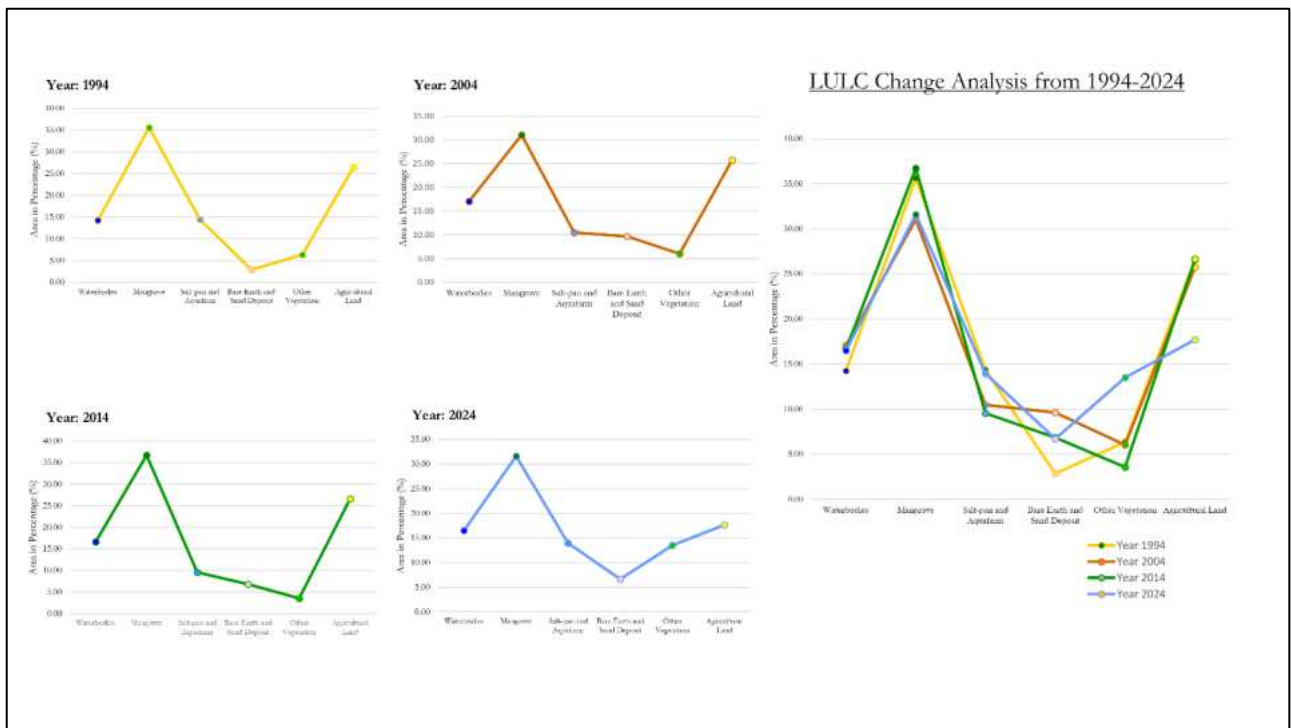
Salt pans and aquafarms, which occupy relatively small portions of the landscape, showed consistent and substantial growth throughout the study period. From 1994 to 2004, these areas expanded by 3.90%, increasing by over 23219.45 hectares, indicating preferred inclination towards brackish water aquaculture-based industries. Despite a small decline of 0.90% between 2004 and 2014, salt pans and aquafarms rebounded strongly between 2014 and 2024, with a 4.41% increase, adding nearly 26288.94 hectares. This continued expansion of aquaculture and related activities reflects the rising demand for fish farming and brackish water dependent agricultural practices in this region, which may be driven by economic pressures and the profitability of these ventures.

Bare earth and sand deposits, initially covering a small percentage of the area (2.85%) in 1994, increased by 9.63% by 2004, likely due to changes in deposition patterns or land use conversions. However, this trend retains after 2004, with a gradual decrease in the area of bare earth and sand deposits, culminating in a gentle drop of 0.14% between 2014 and 2024, suggesting an intensification of sediment deposition, and subsequent expansion of mud banks and shoals.

Other vegetation (habitation with vegetation) classes exhibited dramatic fluctuations during the study period. Between 1994 and 2004, the area under habitation with vegetation slight decreased by an astounding 0.33%, with a loss of over 1957.24 hectares. This surge may be due to deforestation, the natural spread of vegetation in areas abandoned by agriculture, or shifts in land management practices. However, this trend forward sharply between 2004 and 2014, with a decline of 2.46%, losing over 14688.59 hectares. The reduction might indicate deforestation, the expansion of agriculture, or other land uses encroaching on vegetated areas. Interestingly, from 2014 to 2024, habitation with vegetation showed another significant rebound, growing by 9.94% (59252.62 hectares), reflecting ongoing natural regrowth, land restoration efforts, and changes in land use management.

Agricultural land, which initially dominated the landscape, covering 26.54% of the total area in 1994, experienced a dramatic decline of 25.77% by 2004, losing over 4593.59 hectares. This reduction might reflect increased pressure from expansive human habitation, and initiation of mono-specific brackish water aquafarming. However, from 2004 to 2014, agricultural land showed a partial recovery, increasing by over 5121.19 hectares (0.86%), potentially due to efforts to reclaim agricultural areas or expand farming activities. Nevertheless, from 2014 to 2024, agricultural land faced another drastic decline, shrinking by 53182.99 hectares, a steep reduction of 8.92%, which could be attributed to further encroachment by salt pans, aquaculture, or natural vegetation reclaiming former agricultural spaces.

Over the last three decades, the land use and land cover (LULC) dynamics in the Sundarban of Bangladesh have revealed the region’s pronounced susceptibility to both human-induced activities and natural processes. While certain positive and negative indications of recovery-particularly within mangrove zones-have emerged, the extensive expansion of agricultural land, the marked growth of habitation mixed with other vegetation, and the proliferation of aquaculture underscore persistent challenges in land management, conservation, and sustainable development. These patterns highlight the critical need for continuous monitoring, integrated land-use planning, and adaptive management approaches to safeguard the long-term resilience of this ecologically rich mangrove ecosystem.



**Figure 25:** Temporal changes of the identified LULC classes within the Bangladesh Sundarban.

**Table 5:** Temporal statistics of the major LULC classes within the selected parts of Bangladesh Sundarban

LULC class	Year								Change		Change		Change	
	1994		2004		2014		2024		(1994-2004)		(2004-2014)		(2014-2024)	
	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)	ha	%	ha	%	ha	%
Waterbodies	85003.58	14.26	101575.99	17.04	99255.01	16.65	98322.02	16.50	16572.41	2.78	-2320.97	-0.39	-932.99	-0.16
Mangrove	212289.27	35.62	185063.53	31.05	218953.02	36.74	188378.09	31.61	-27225.74	-4.57	33889.50	5.69	-30574.93	-5.13
Salt Pan and Aquafarm	85653.39	14.37	62433.94	10.48	57047.36	9.57	83336.30	13.98	-23219.45	-3.90	-5386.58	-0.90	26288.94	4.41
Bare Earth and Sand Deposit	16981.14	2.85	57404.73	9.63	40790.21	6.84	39939.56	6.70	40423.61	6.78	-16614.53	-2.79	-850.65	-0.14
Other Vegetation	37895.94	6.36	35938.70	6.03	21250.10	3.57	80502.73	13.51	-1957.24	-0.33	-14688.59	-2.46	59252.62	9.94
Agricultural Land	158176.85	26.54	153583.26	25.77	158704.45	26.63	105521.46	17.70	-4593.59	-0.77	5121.19	0.86	-53182.99	-8.92
Total	596000.16	100.00	596000.16	100.00	596000.16	100.00	596000.16	100.00	-	-	-	-	-	-

### 3.2.2 LULC Change Map of Bangladesh (1994-2024):

The image contains three Land Use and Land Cover (LULC) transition matrices comparing classified satellite images from the years 1994, 2004, 2014, and 2024. Each matrix shows how different land cover classes (Waterbodies, Mangrove, Salt Pan and Aquafarm, Bare Earth and Sand Deposit, Other Vegetation, and Agricultural Land) changed or remained stable over time.

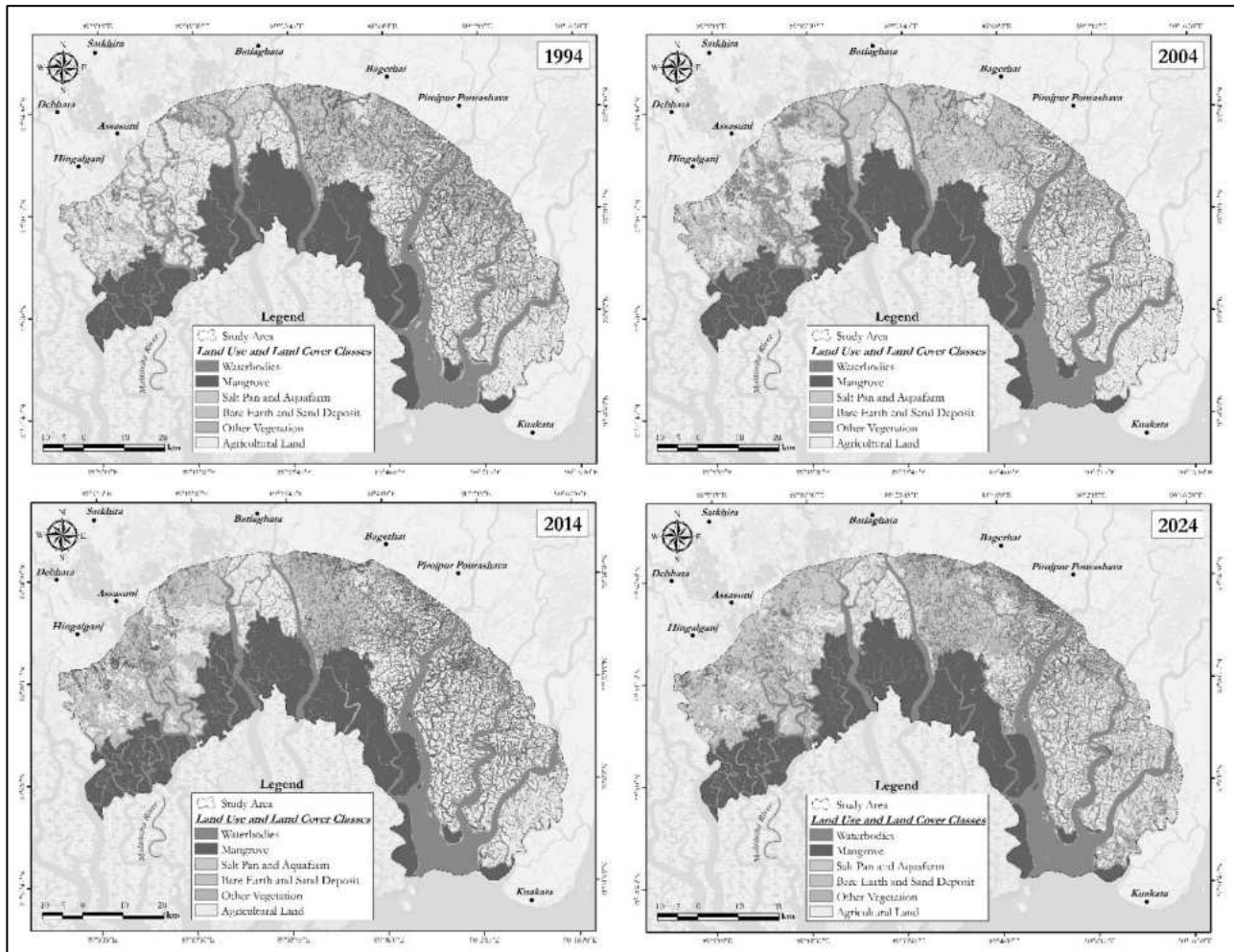


Figure 26: LULC change map of Bangladesh Sundarban study area between 1994 to 2024.

### 3.2.3 Bangladesh Sundarban Transition Map:

The Change Vector Map of the Bangladesh Sundarbans, covering the period from 1994 to 2024, reveals a dynamic and complex transformation in land cover driven predominantly by rapid rural expansion and associated anthropogenic influences. The most prominent alteration is the extensive conversion of bare earth and sand deposit areas into other vegetation, salt pans and aquafarms, and agricultural land, particularly concentrated within the core of the study area and radiating outward. This spatial pattern underscores the pressures exerted by population growth, infrastructural development, and rural settlement expansion.

A substantial portion of bare land has been transformed into agricultural land and vegetated areas, reflecting the utilisation of previously undeveloped or marginal lands. Such transformations are particularly evident in the central and eastern zones, signifying a distinct shift in rural development dynamics and land-use priorities.

Despite these widespread changes, certain regions-especially along the Arpangasia River and within the western, southern, north-western, and south-western sectors-have maintained relatively stable waterbodies. Variations in salt pan and aquaculture areas, although comparatively limited, involve the conversion of bare earth and sand deposits into agricultural land, other vegetation, mangrove cover, or aquafarms. These transitions are likely indicative of rural development pressures, population increase, and evolving socio-economic practices. Conversely, isolated shifts from bare earth and sand deposits to mangrove or waterbody categories may signify reforestation efforts, ecological restoration initiatives, or natural regeneration processes, though such instances remain relatively infrequent.

Overall, the observed spatio-temporal dynamics illustrate a distinct trajectory of rural dominance over natural land cover types, emphasising the urgent necessity for sustainable land-use planning and management. If the prevailing patterns of land utilisation persist, significant disruptions may not be immediate; however, any disturbance to the existing ecological equilibrium could adversely impact the biodiversity and ecological integrity of the Bangladesh Sundarbans. Therefore, it is imperative to promote the integration of green infrastructure, conservation-oriented land management, and community awareness initiatives to ensure the long-term preservation of the region’s biodiversity and ecosystem stability.

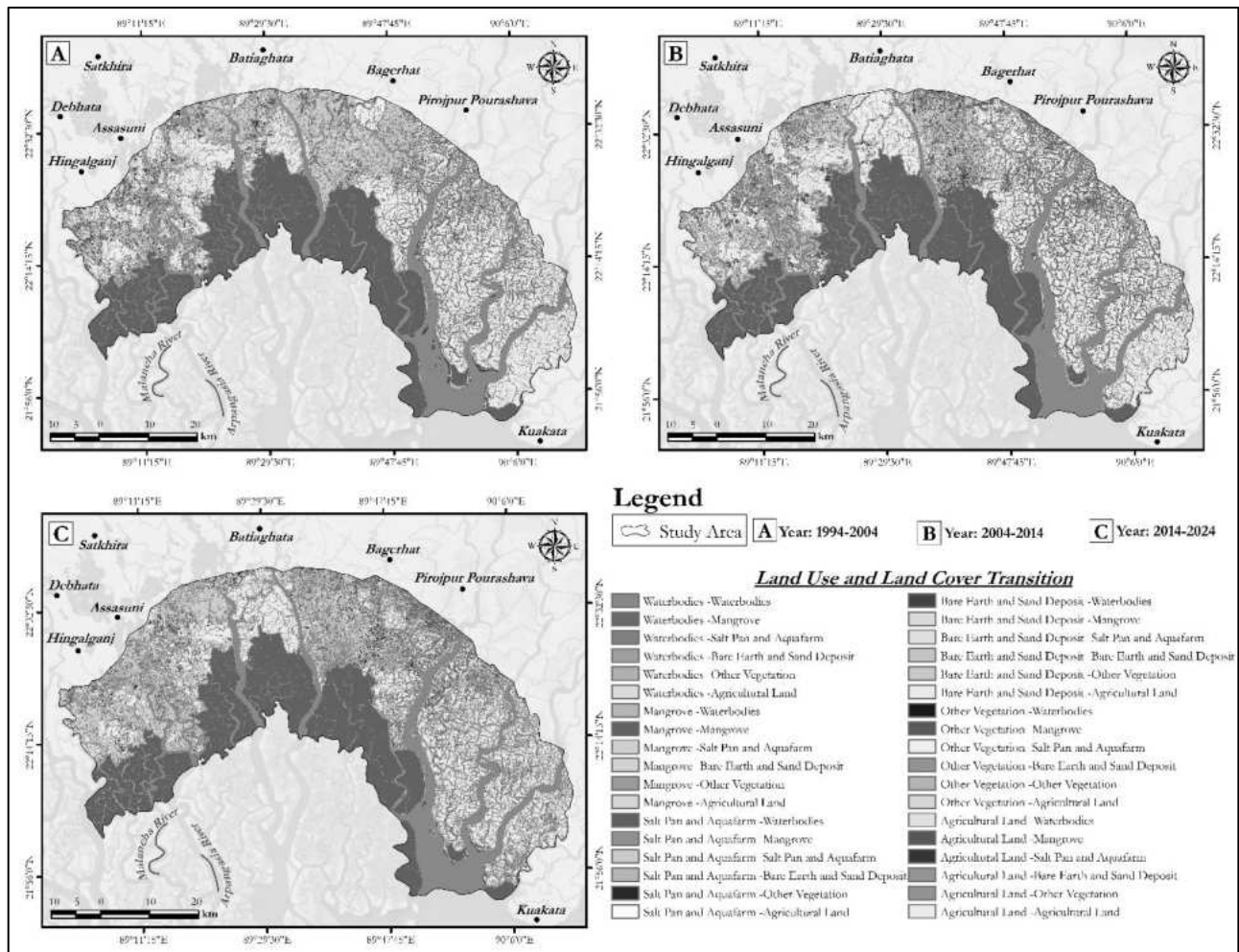


Figure 27: Transition map of LULC changes from 1994 to 2024.

### 3.2.4 Transformation pattern of dominant LULCs:

The transformation matrix of identified LULC classes between 1994 and 2024 in the Bangladesh Sundarban provides an insightful understanding of how different categories of LULCs, such as waterbodies, mangrove, salt pan and aquafarm, bare earth and sand deposit, other vegetation, and, agricultural land, have shifted from one class to another class over time. The data for each period (1994-2004, 2004-2014, and 2014-2024) illustrate dynamic transitions across these categories, highlighting substantial ecological and anthropogenic changes in the landscape.

#### 3.2.4.1 Transition Matrix of 1994 and 2004:

In the 1994 to 2004 period, a significant portion of mangrove remained stable, retaining its classification (179339.47 hectares). Waterbodies area increased significantly, especially from 79953.82 hectares remained waterbodies 2554.91 hectares from bare earth and sand deposit, and 3952.76 hectares from mangrove converted to waterbodies. Mangrove reduced slightly, as much of it converted to other vegetation, bare earth and sand deposit, and agricultural land. Waterbodies high stability (79953.82 hectares remained waterbodies) but also contributed to other classes. Salt pan and aquafarm are relatively stable, though some transitions to other vegetation are seen. However, a notable transition of 2962.40 hectares of mangrove converted to agricultural land, indicating either natural regeneration or reforestation efforts. A smaller but ecologically meaningful transformation was the conversion of approximately 449.36 hectares of agricultural land into mangroves, suggesting possible ecological restoration or natural mangrove regeneration processes. The matrix also reveals minor shifts from mangrove to salt pan and aquafarm areas (3689.93 hectares), which could reflect increasing aquaculture activities in the region. Similarly, bare earth and sand deposits transitioned into mangroves (635.44 hectares) and waterbodies (5923.99 hectares), indicating dynamic geomorphological processes, likely related to sediment deposition and tidal action.

**Insight:** The extent of water bodies and bare earth and sand deposit has exhibited a slight increase. Conversely, the areas under mangrove vegetation and agricultural land have experienced a noticeable decline.

#### 3.2.4.2 Transition Matrix of 2004 and 2014:

From 2004 to 2014, 7591.87 hectares of agricultural land transformed into habitation with other vegetation, which is consistent with the trend of land being reclaimed by natural systems. Interestingly, the mangrove cover expanded during this period, as 10362.57 hectares of agricultural land converted to mangroves, continuing the restoration or natural recolonization trend observed in the previous decade. Other vegetation area recently to grow, 219.24 hectares of waterbodies remained. Significant increase from mangrove (1810.15 hectares), saltpan and aquafarm (1786.55 hectares) and agricultural land (7591.87 hectares). Bare earth and sand deposit shows slight loss but also notable conversion to agricultural land. Bare earth and sand deposit continues transitioning to salt pan and aquafarm and other vegetation. Salt pan and aquafarm show minimal but noticeable transition to waterbodies (7097.28 hectares). A substantial increase in mangrove area was also seen from the bare earth and sand deposit class, where 2796.27 hectares shifted to mangroves, suggesting enhanced mangrove restoration in degraded zones. The total mangrove area showed an increase of over 177513.68 hectares in 2014, further indicating successful natural recovery or conservation interventions.

**Insight:** The area covered by mangrove and agricultural land has expanded relative to the previous decade, while bare earth and sand deposits have shown a noticeable decline. This trend reflects the escalating impact of population growth and the increasing human-induced pressure on land resources.

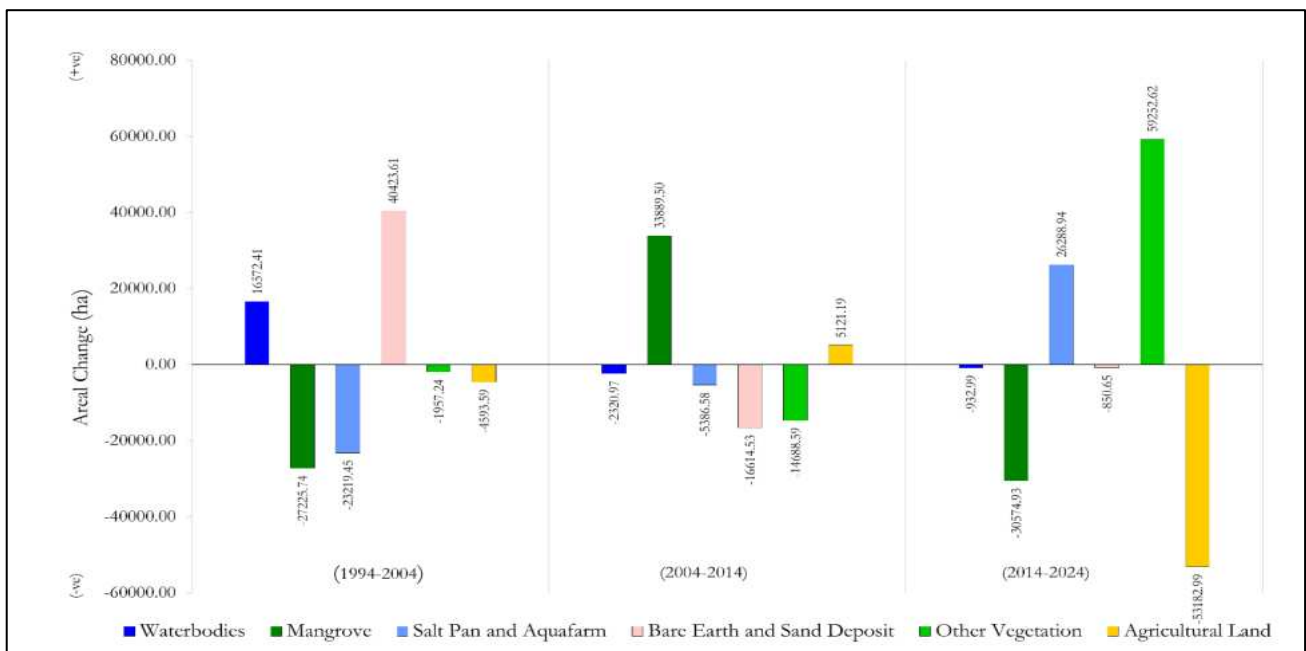
### 3.2.4.3 Transition Matrix of 2014 and 2024:

In the final period from 2014 to 2024, the rate of change became even more pronounced. Bare earth and sand deposit experienced a drastic reduction, with only 39939.56 hectares remaining by 2024. A significant portion of agricultural land, amounting to 12302.79 hectares, converted into other vegetation, while another 3222.87 hectares shifted to salt pan and aquafarm, reflecting a growing influence of aquaculture and possibly the effects of land abandonment or unsuitability for agriculture due to salinity intrusion. Waterbodies area expansion restrain; 82023.27 hectares remain as waterbodies. Large conversion from mangrove (1107.13 hectares) and salt pan and aquafarm (8678.53 hectares). Other vegetation (59252.62 hectares) has exhibited a positive growth trend compared to previous period and agricultural land (53182.99 hectares) shows decline. Bare Land has notable conversions into agricultural land and other vegetation. Waterbodies mostly stable, slight deteriorate (from 99255.01 to 98322.02 hectares total). Mangroves continued to shrink considerably, as approximately 1441.03 hectares of mangrove were converted to salt pan and aquafarm areas, underscoring the pattern of salt pan and aquafarm related activities within this coastal area. The overall mangrove covers in 2024 reached 30574.93 hectares, a notable decrease, reflecting require conservation scheme and possibly negative effects of climate resilience strategies.

**Insight:** Massive salt pan and aquafarm area growth continues, replacing bare earth and sand deposit; waterbodies remain relatively unchanged.

### 3.2.4.4 Overall Interpretation of Transition Matrix (1994 to 2024):

- Waterbodies have exhibited a marginal increase in extent, while overall remaining largely stable.
- Mangrove areas show a consistent and sharp decrease, highlighting showed a substantial recovery practice.
- The area of bare earth and sand deposit has decreased due to landscape transformation like salt pan and aquafarm is driven primarily by human development, likely due to population growth and infrastructure expansion.
- Other Vegetation and agricultural land constitute the primary land types undergoing conversion.
- This data is valuable for development planning, sustainability analysis, and environmental impact assessments.



**Figure 28:** LULC change map of Bangladesh Sundarban study area between 1994 to 2024.

**Table 6:** Bangladesh LULC transformation statistics from 1994 to 2004.

LULC Class	Mangrove	Other Vegetation	Bare Earth and Sand Deposit	Agricultural Land	Salt Pan and Aquafarm	Waterbodies	Grand Total (1994)
Waterbodies	<b>79953.81795</b>	259.316732	1655.998065	2554.906496	171.890821	397.038021	84992.96809
Mangrove	3952.759062	<b>179339.4731</b>	3689.932861	5914.268358	16403.24859	2962.401097	212262.0831
Salt-pan and Aquafarm	5932.482369	783.234842	<b>37628.61969</b>	21974.58104	4307.300735	15011.28657	85637.50525
Bare Earth and Sand Deposit	5923.985684	635.439326	3840.652894	<b>5295.389193</b>	797.579438	482.661493	16975.70803
Other Vegetation	200.090299	3581.997089	2363.438023	4785.297027	<b>10236.09333</b>	16724.77039	37891.68616
Agricultural Land	5592.541079	449.359939	13246.20105	16869.11215	4015.867139	<b>117994.6385</b>	158167.7199
Grand Total (2004)	101555.6764	185048.821	62424.84259	57393.55427	35931.98006	153572.7961	<b>595927.6705</b>

**Table 7:** Bangladesh LULC transformation statistics from 2004 to 2014.

LULC Class	Mangrove	Other Vegetation	Bare Earth and Sand Deposit	Agricultural Land	Salt Pan and Aquafarm	Waterbodies	Grand Total (2004)
Waterbodies	<b>80178.34897</b>	2500.67481	12335.03397	5715.06532	219.239668	606.304148	101554.6669
Mangrove	1851.986484	<b>177513.6789</b>	488.547223	2796.271908	1810.147437	583.488953	185044.1209
Salt-pan and Aquafarm	7097.27664	4390.079098	<b>19659.54738</b>	10818.39202	1786.544765	18673.24881	62425.08871
Bare Earth and Sand Deposit	6270.981648	7107.699802	14906.31997	<b>9977.037994</b>	2592.244898	16540.81462	57395.09893
Other Vegetation	1073.141635	17057.12452	1722.411935	4790.386247	<b>7246.666187</b>	4042.256249	35931.98677
Agricultural Land	2768.60152	10362.57277	7922.606121	6680.944721	7591.868818	<b>118247.0601</b>	153573.654
Grand Total (2014)	99240.3369	218931.8299	57034.4666	40778.09821	21246.71177	158693.1728	<b>595924.6162</b>

**Table 8:** Bangladesh LULC transformation statistics from 2014 to 2024.

LULC Class	Mangrove	Other Vegetation	Bare Earth and Sand Deposit	Agricultural Land	Salt Pan and Aquafarm	Waterbodies	Grand Total (2014)
Waterbodies	<b>82023.2684</b>	2052.337162	12226.07771	1970.757127	351.161415	620.649959	99244.25176
Mangrove	1107.127818	<b>168533.3436</b>	2757.713809	11809.46792	33098.64223	1620.579855	218926.8753
Salt-pan and Aquafarm	8618.530098	1441.030911	<b>38302.99085</b>	4091.446642	1359.360099	3222.872586	57036.23118
Bare Earth and Sand Deposit	3833.933344	5970.505052	16668.20201	<b>7811.155804</b>	4433.89131	2063.706013	40781.39353
Other Vegetation	218.38995	2502.384812	739.139031	4242.591013	<b>12302.78484</b>	1241.607013	21246.89666
Agricultural Land	2508.336859	7858.660378	12624.80628	10006.01155	28946.93093	<b>96747.21218</b>	158691.9582
Grand Total (2024)	98309.58646	188358.262	83318.92968	39931.43006	80492.77082	105516.6276	<b>595927.6066</b>

### 3.3.1 Spatio-temporal dynamics of LULC mapping (Pakistan):

The LULC transformation in the Pakistan coastal area between 1994 and 2024 reveals significant and complex changes in land use patterns, indicating a dynamic interplay between natural processes and anthropogenic interventions over the last three decades. Agricultural land, which initially marginal the landscape, covering 3.65% of the total area in 1994, experienced a dramatic flourish of 6.03% by 2004, gaining over 5433.03 hectares. This expansion might reflect increased pressure from expansive human habitation, and associate activities. However, from 2004 to 2014, agricultural land showed a partial expansion, increasing by over 878.72 hectares (0.39%), which could be attributed to further encroachment by bare earth and sand deposit reclaiming former agricultural land. Nevertheless, from 2014 to 2024, agricultural land faced another drastic increase, expanding by 9863.95 hectares, a gentle enhancement of 4.33%, potentially due to efforts to reclaim agricultural areas or expand farming activities.

The bare earth and sand deposit class, initially covering 52.54% of the study area in 1994, declined sharply by 41.16% by 2004, reflecting substantial alterations in sediment dynamics and land use conversion, likely due to anthropogenic activities (agriculture, other vegetation) and natural geomorphic processes such as erosion, tidal redistribution, and fluvial sediment transport. Post-2004, the decline slowed, with a 12.54% reduction between 2014 and 2024, indicative of stabilized depositional patterns and progressive sediment accumulation, including mud bank and shoal formation. These trends highlight the transition from a highly dynamic, erosion-prone system to a more stabilized geomorphic state, with implications for coastal landform development, habitat dynamics, and sustainable land management.

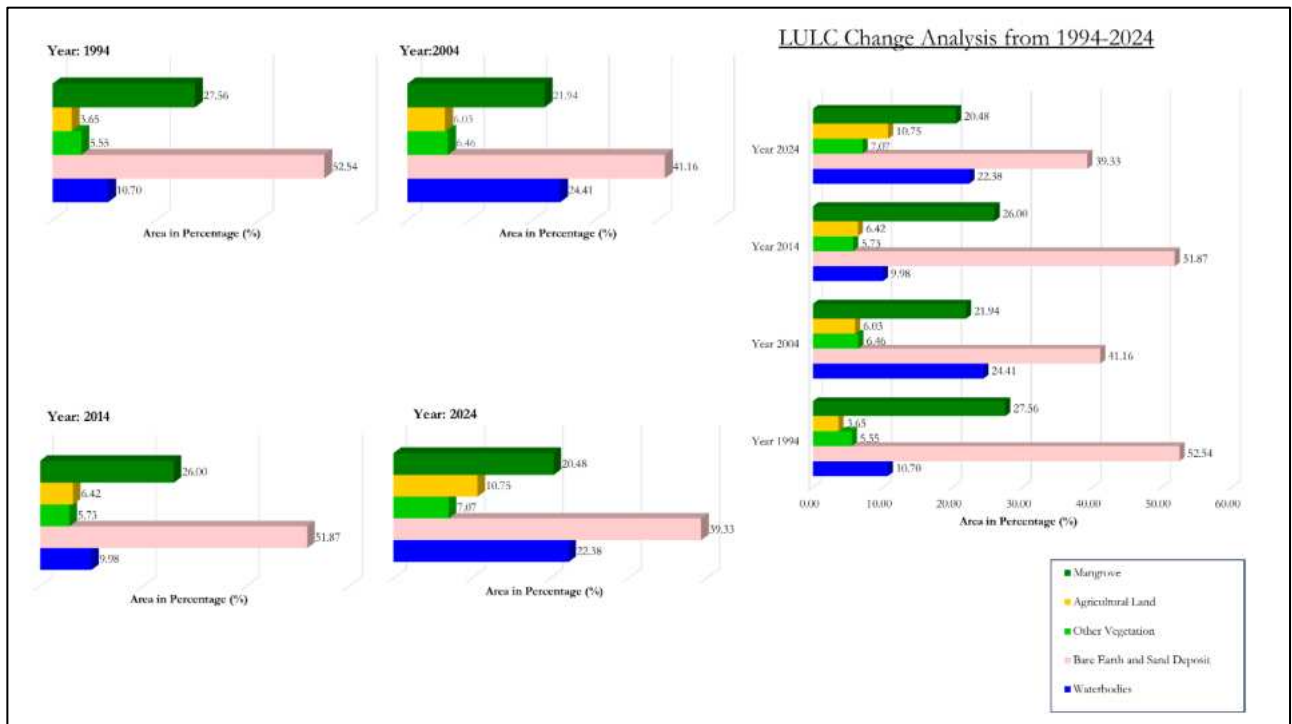
The mangroves cover in Pakistan are mainly along the Indus Delta (Sindh), showed a consistent decline from 1994 to 2014, losing over 5.62% of its area between 1994 and 2004 and a gaining additional 4.06% by 2014. This decline in mangrove cover, shrinking by more than 49974.43 hectares by 2004 and 59221.26 hectares by 2014, could be linked to deforestation along the fridge areas, land reclamation for agriculture and other vegetation, and the wide-spread effect of recurrent pollution, and shrimp farming. However, from 2014 to 2024, mangrove forests showed a significant deterioration, with a 5.52% shrink, losing over 12575.21 hectares. Pakistan's mangrove forests show declining health due to sea-level rise and coastal erosion, industrial and urban pollution, and localized degradation from freshwater scarcity and drought, underscoring the need for urgent conservation and restoration interventions.

The other vegetation class exhibited notable temporal variability over three decades. 1994 to 2004 saw a 0.91% increase (2081.62 hectares), likely driven by reforestation, natural succession, or altered land management. This trend reversed during 2004 to 2014, declining 0.74% (1676.75 hectares), reflecting deforestation, agricultural expansion, or encroachment. 2014 to 2024 marked a pronounced rebound of 1.34% (3051.58 hectares), indicative of natural regrowth, restoration initiatives, and improved land-use practices. These fluctuations underscore the dynamic interplay of anthropogenic and ecological drivers in shaping vegetated landscapes.

Waterbodies, which occupy relatively minimal part of the landscape, Showed consistent and substantial growth throughout the study period. From 1994 to 2004, these areas expanded by 13.71%, increasing by over 31223.80 hectares, indicating irrigation expansion and seasonal floods, though some arid regions experienced minor shrinkage. Despite a large ascend of 14.42% between 2004 and 2014, Overall, a slight decline was observed due to intensified water withdrawal, dam regulation, and encroachment on wetlands. Between 2014 and 2024, with a 12.39% increase, adding nearly 28232.97 hectares. This partial recovery occurred in certain riverine and reservoir areas, reflecting improved water management and occasional flood events, while some regions continued to experience reduction from prolonged droughts and climate stress.

Overall, the Pakistan regions experienced significant land use and land cover (LULC) changes driven by both natural processes and human interventions. Agricultural land expanded, largely due to increased

settlements and land reclamation, while bare earth and sand deposits declined, reflecting stabilised sedimentary processes and the formation of new mud banks and shoals. Mangrove cover consistently decreased, owing to deforestation, land conversion, pollution, aquaculture, and coastal hazards, emphasising the urgent need for conservation. Other vegetation showed temporal fluctuations, initially increasing, then declining, and later recovering, indicative of ecological succession and restoration efforts. Waterbodies, though limited in extent, generally expanded due to irrigation, seasonal floods, and improved water management, despite localized reductions from drought and human pressures. Collectively, these trends highlight the dynamic interplay of natural processes and human activities in shaping Pakistan’s coastal and estuarine landscapes.



**Figure 29:** Temporal changes of the identified LULC classes within the Pakistan Coastal Region.

**Table 9:** Temporal statistics of the major LULC classes within the selected parts of Pakistan

LULC class	Year								Change		Change		Change	
	1994		2004		2014		2024		(1994-2004)		(2004-2014)		(2014-2024)	
	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)	ha	%	ha	%	ha	%
Waterbodies	24367.36	10.70	55591.16	24.41	22734.19	9.98	50966.40	22.38	31223.80	13.71	-32856.97	-14.42	28232.21	12.39
Bare Earth and Sand Deposit	119678.37	52.54	93747.42	41.16	118155.58	51.87	89583.06	39.33	-25930.95	-11.38	24408.16	10.72	-28572.52	-12.54
Other Vegetation	12644.42	5.55	14726.05	6.46	13049.30	5.73	16100.88	7.07	2081.62	0.91	-1676.75	-0.74	3051.58	1.34
Agricultural Land	8305.47	3.65	13738.50	6.03	14617.22	6.42	24481.17	10.75	5433.04	2.39	878.72	0.39	9863.94	4.33
Mangrove	62781.94	27.56	49974.43	21.94	59221.26	26.00	46646.05	20.48	-12807.51	-5.62	9246.83	4.06	-12575.21	-5.52
Total	227777.56	100	227777.56	100	227777.56	100	227777.56	100	-	-	-	-	-	-

### 3.3.2 LULC Change Map of Pakistan (1994-2024):

The image contains three Land Use and Land Cover (LULC) transition matrices comparing classified satellite images from the years 1994, 2004, 2014, and 2024. Each matrix shows how different land cover classes (Waterbodies, Bare Earth and Sand Deposit, Other Vegetation, Agricultural Land, and Mangrove) changed or remained stable over time.

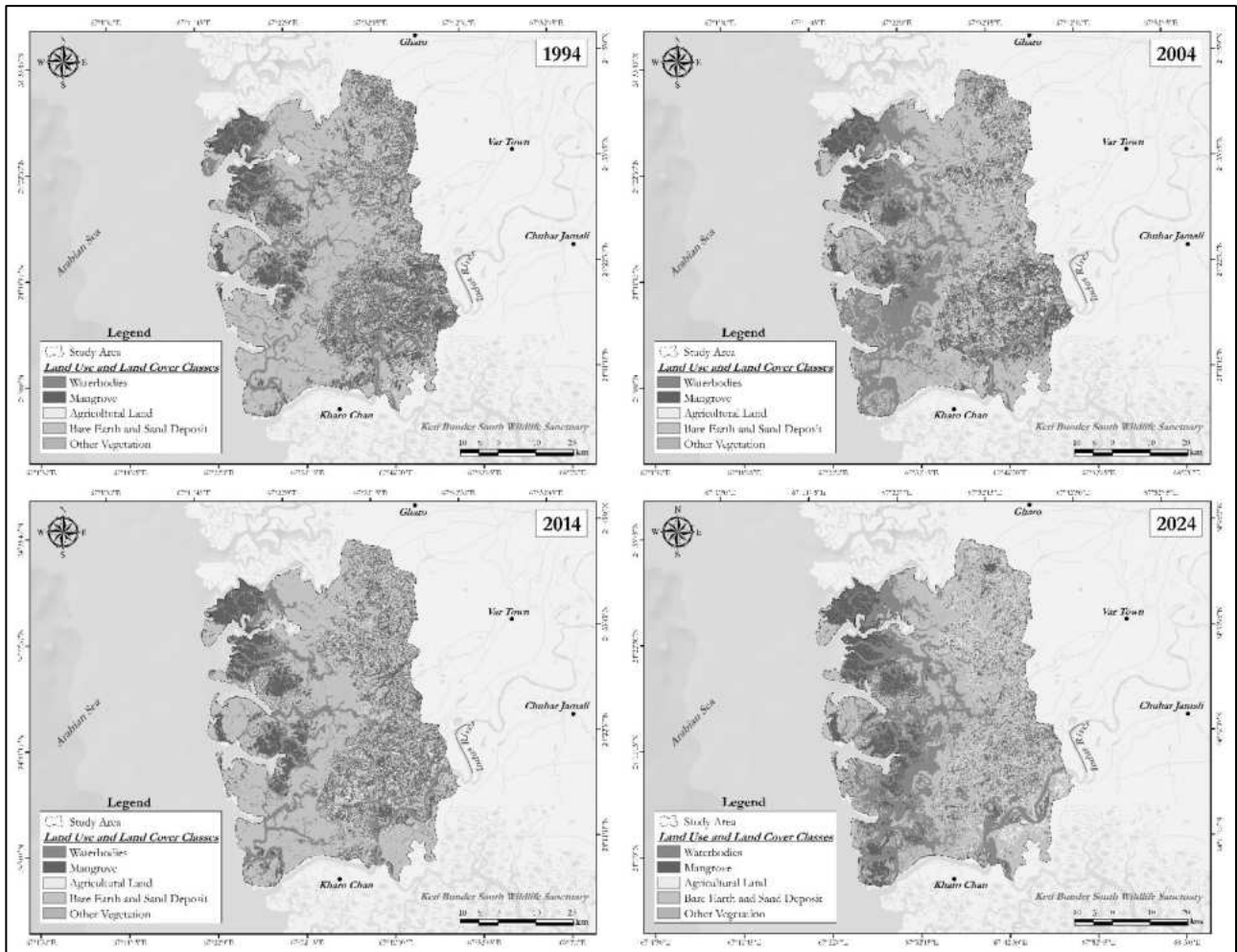


Figure 30: LULC change map of Pakistan study area between 1994 to 2024.

### 3.3.3 Pakistan Transition Map:

The Change Vector Map of Pakistan, spanning from 1994 to 2024, reveals a dynamic transformation of land cover driven by rapid rural expansion and associated anthropogenic activities. The most prominent change observed is the extensive conversion of bare earth and sand deposit areas into other vegetation, and agricultural land particularly concentrated around the study area core and radiating outward. This trend reflects the pressures of population growth, infrastructure development, and rural settlement.

Notably, bare lands have also been significantly transformed into agricultural land and other vegetation, indicating the areas entire growth into formerly undeveloped or marginal lands. The eastern, north-eastern and south-eastern regions exhibit strong signs of such expansion, suggesting a shift in rural development patterns.

Despite widespread change, certain areas, especially along the Indus River and in the eastern, north, western, north-western, north-eastern and south-eastern extents, retain stable waterbodies. Changes in other vegetation, though relatively limited, include instances of bare earth and sand deposit to agricultural land or other vegetation, which may reflect rural development, population growth, and people’s socio-economic activities. Conversely, isolated transitions from bare earth and sand deposit to mangrove or water may indicate reforestation initiatives, biodiversity and ecosystem developments, or restoration projects, although these are less common.

Overall, the map illustrates a clear trajectory of rural dominance over natural land cover, while simultaneously highlighting the need for sustainable land use planning. If the present pattern of land use continues, no major issues may arise in the region; however, any disturbance to the ecological balance could adversely affect the biodiversity of the Pakistan coastal area. Therefore, it is essential to emphasise the integration of green infrastructure and conservation strategies, along with enhancing public awareness to safeguard biodiversity and the ecosystem.

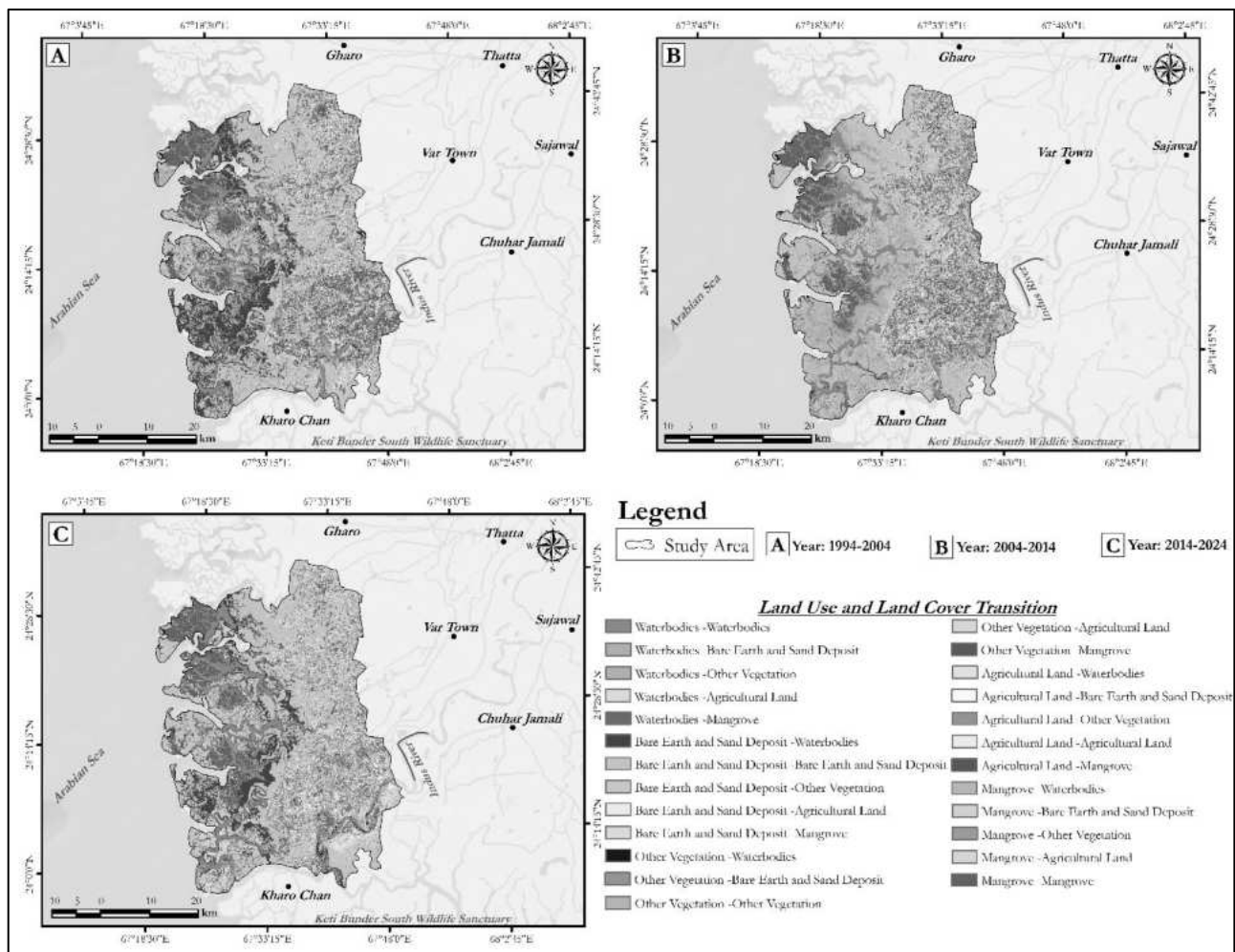


Figure 31: Transition map of LULC changes from 1994 to 2024

### 3.3.4 Transformation pattern of dominant LULCs:

The transformation matrix of identified LULC classes between 1994 and 2024 in the Pakistan Coastal region provides an insightful understanding of how different categories of LULCs, such as Waterbodies, Bare Earth and Sand Deposit, Other Vegetation, Agricultural Land, and Mangrove, have shifted from one class to another class over time. The data for each period (1994-2004, 2004-2014, and 2014-2024) illustrate dynamic transitions across these categories, highlighting substantial ecological and anthropogenic changes in the landscape.

#### 3.3.4.1 Transition Matrix of 1994 and 2004:

In the 1994 to 2004 period, a significant portion of mangrove remained stable, retaining its classification (33631.45 hectares). Waterbodies area increased significantly, especially from 18605.17 hectares remained waterbodies 30827.91 hectares from bare earth and sand deposit, and 5815.92 hectares from mangrove converted to waterbodies. Mangrove reduced slightly, as much of it converted to other vegetation, bare earth and sand deposit, and agricultural land. Waterbodies high stability (18605.17 hectares remained waterbodies) but also contributed to other classes. Other vegetation is relatively stable, though some transitions to other vegetation are seen. However, a notable transition of 6445.49 hectares of mangrove converted to agricultural land, indicating either natural regeneration or reforestation efforts. A smaller but ecologically meaningful transformation was the conversion of approximately 2586.88 hectares of agricultural land into mangroves, suggesting possible ecological restoration or natural mangrove regeneration processes. The matrix also reveals minor shifts from waterbodies to agricultural land areas (591.64 hectares), which could reflect increasing agricultural activities in the region. Similarly, bare earth and sand deposits transitioned into mangroves (7388.55 hectares) and waterbodies (30827.91 hectares), indicating dynamic geomorphological processes, likely related to sediment deposition and tidal action.

**Insight:** The extent of waterbodies has increased rapidly, while the areas of other vegetation and agricultural land have increased but only slightly. As a result, the extent of bare earth and sand deposits has decreased.

#### 3.3.4.2 Transition Matrix of 2004 and 2014:

From 2004 to 2014, 2159.25 hectares of agricultural land transformed into habitation with other vegetation, which is consistent with the trend of land being reclaimed by natural systems. Interestingly, the mangrove cover expanded during this period, as 6255.32 hectares of agricultural land converted to mangroves, continuing the restoration or natural recolonization trend observed in the previous decade. Other vegetation area recently to grow, 19913.34 hectares of waterbodies remained. Significant increase from mangrove (30567.96 hectares), other vegetation (121.42 hectares) and agricultural land (180.29 hectares). Bare earth and sand deposit shows slight gain but also notable conversion to agricultural land (4660.28 hectares). Bare earth and sand deposit continues transitioning to mangrove and other vegetation. Other vegetation shows minimal but noticeable transition to waterbodies (41.58 hectares). A substantial increase in mangrove area was also seen from the bare earth and sand deposit class, where 10379.44 hectares shifted to mangroves, suggesting enhanced mangrove restoration in degraded zones. The total mangrove area showed an increase of over 9246.83 hectares in 2014, further indicating successful natural recovery or conservation interventions.

**Insight:** The spatial extent of waterbodies exhibited a noticeable decline relative to the preceding decade, whereas both agricultural land and mangrove cover demonstrated a substantial and progressive expansion, reflecting significant anthropogenic and ecological transformations within the landscape.

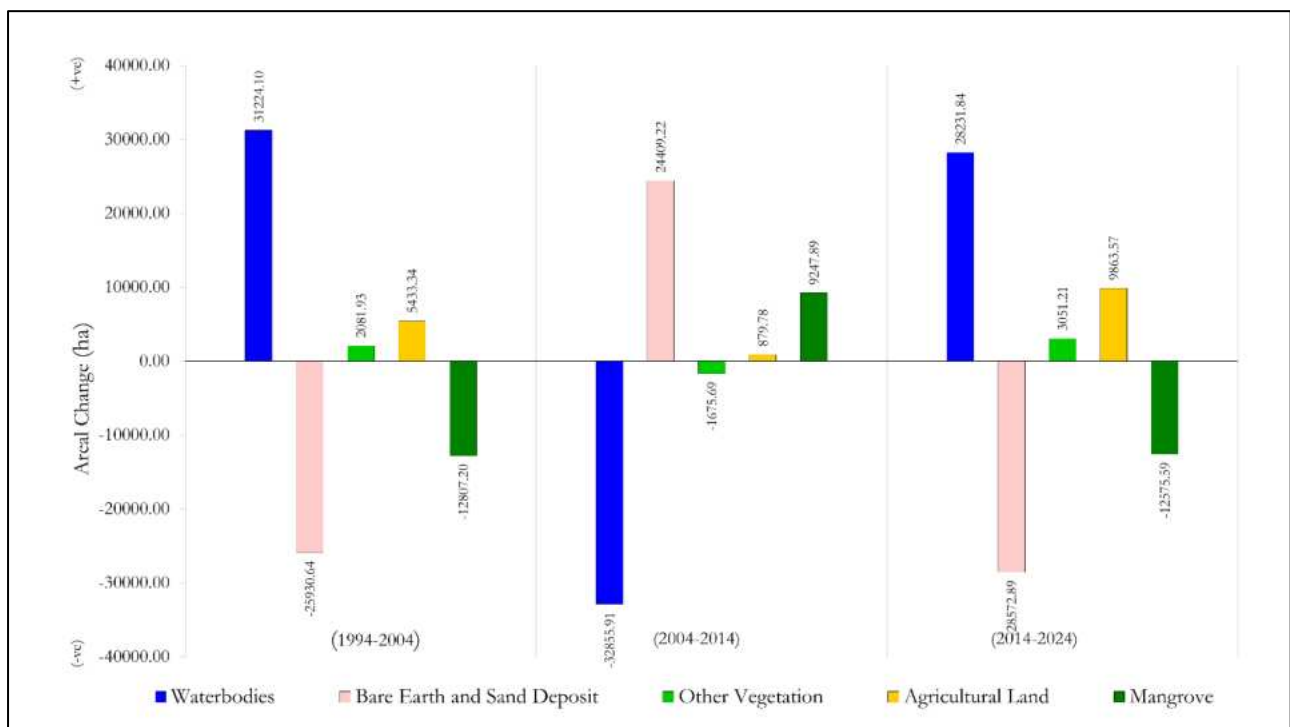
### 3.3.4.3 Transition Matrix of 2014 and 2024:

In the final period from 2014 to 2024, the rate of change became even more pronounced. Bare earth and sand deposit experienced a drastic reduction, with only 70061.28 hectares remaining by 2024. A significant portion of mangrove, amounting to 6968.16 hectares, converted into other vegetation, while another 8231.50 hectares shifted to agricultural land, it reflects the growing impact of population growth and possibly indicates the tendency of increasing human pressure on land. Waterbodies area expansion accelerates; 21086.54 hectares remain as waterbodies. Large conversion from mangrove (474.99 hectares) and bare earth and sand deposit (39.80 hectares). Other vegetation (3051.58 hectares) and agricultural land (9863.94 hectares) show increase in nature. Bare Land has notable conversions into agricultural land and other vegetation. Waterbodies mostly stable, slight ascend (from 22734.19 to 50966.40 hectares total). Mangroves persisted in declining substantially, as approximately 2444.64 hectares of agricultural land were converted to mangrove areas, underscoring the adaptive capacity of mangroves in this coastal region. The overall mangrove covers in 2024 reached 28515.46 hectares, a substantial reduction, showing limited conservation efforts and possible harmful effects on climate resilience strategies.

**Insight:** Massive growth of waterbodies, agricultural land and other vegetation continues, replacing bare earth and sand deposit; while mangrove have remained relatively unchanged.

### 3.3.4.4 Overall Interpretation of Transition Matrix (1994 to 2024):

- The spatial extent of waterbodies has exhibited a marginal yet measurable increase over the observed period.
- Coverage of bare earth and sand deposits has shown a quantifiable reduction.
- Agricultural and other vegetated areas have exhibited notable expansion.
- Mangrove extent has contracted.
- These datasets provide critical insights for strategic development planning, rigorous sustainability assessments, and comprehensive evaluation of environmental impacts.



**Figure 32:** LULC change bar of Pakistan study area between 1994 to 2024.

**Table 10:** Pakistan LULC transformation statistics from 1994 to 2004.

LULC Class	Waterbodies	Bare Earth and Sand Deposit	Other Vegetation	Agricultural Land	Mangrove	Grand Total (1994)
Waterbodies	<b>18605.16492</b>	3097.183209	331.504846	591.64403	1735.372704	24360.86971
Bare Earth and Sand Deposit	30827.91394	<b>70962.83436</b>	6555.802745	3894.880715	7388.550699	119629.9825
Other Vegetation	255.525433	4451.620038	<b>1467.894079</b>	1847.46079	4617.415859	12639.9162
Agricultural Land	60.163785	3590.107467	1110.036775	<b>955.964764</b>	2586.875056	8303.147847
Mangrove	5815.917051	11607.31593	5258.072169	6445.488761	<b>33631.23076</b>	62758.02468
Grand Total (2004)	55564.68513	93709.061	14723.31061	13735.43906	49959.44508	<b>227691.9409</b>

**Table 11:** Pakistan LULC transformation statistics from 2004 to 2014.

LULC Class	Waterbodies	Bare Earth and Sand Deposit	Other Vegetation	Agricultural Land	Mangrove	Grand Total (2004)
Waterbodies	<b>19913.34383</b>	27503.03685	41.580913	59.831481	8045.210926	55563.004
Bare Earth and Sand Deposit	1517.692612	<b>73347.229</b>	3814.053538	4660.279795	10379.44076	93718.6957
Other Vegetation	121.423002	6645.903356	<b>2057.25865</b>	1945.704752	3952.641305	14722.93107
Agricultural Land	180.290463	3250.233763	2159.247269	<b>1890.524634</b>	6255.322262	13735.61839
Mangrove	996.770564	7361.154488	4975.197378	6059.652928	<b>30567.34099</b>	49960.11635
Grand Total (2014)	22729.52047	118107.5575	13047.33775	14615.99359	59199.95624	<b>227700.3655</b>

**Table 12:** Pakistan LULC transformation statistics from 2014 to 2024.

LULC Class	Waterbodies	Bare Earth and Sand Deposit	Other Vegetation	Agricultural Land	Mangrove	Grand Total (2014)
Waterbodies	<b>21086.54148</b>	1002.074378	39.797865	126.099749	474.994676	22729.50815
Bare Earth and Sand Deposit	24056.31465	<b>70061.27861</b>	3003.877811	8296.799803	12688.3091	118106.58
Other Vegetation	372.450868	3944.678473	<b>2730.321158</b>	3489.05018	2511.219508	13047.72019
Agricultural Land	312.333209	4169.908466	3356.509661	<b>4332.556316</b>	2444.636764	14615.94442
Mangrove	5109.523796	10376.1713	6968.164131	8231.501401	<b>28515.45682</b>	59200.81745
Grand Total (2024)	50937.164	89554.11122	16098.67063	24476.00745	46634.61686	<b>227700.5702</b>

### 3.4.1 Spatio-temporal dynamics of LULC mapping (Sri Lanka):

The LULC transformation in the Sri Lanka coastal area between 1994 and 2024 reveals significant and complex changes in land use patterns, indicating a dynamic interplay between natural processes and anthropogenic interventions over the last three decades. Agricultural land, which initially marginal the landscape, covering 15.72% of the total area in 1994, experienced a subtle decrease of 2.03% by 2004, losing over 1394.36 hectares. However, from 2004 to 2014, agricultural land showed a partial expansion, increasing by over 5975.96 hectares (8.72%), which could be attributed to further encroachment by bare earth and sand deposit reclaiming former agricultural land. Nevertheless, from 2014 to 2024, agricultural land faced another drastic increase, expanding by 10412.81 hectares, a gentle enhancement of 15.19%, potentially due to efforts to reclaim agricultural areas or expand farming activities. This expansion might reflect increased pressure from expansive human habitation, and associate activities.

The bare earth and sand deposit class, initially covering 50.94% of the study area in 1994, declined sharply by 49.48% by 2004, reflecting substantial alterations in sediment dynamics and land use conversion, likely due to anthropogenic activities (agriculture, other vegetation) and natural geomorphic processes such as erosion, tidal redistribution, and fluvial sediment transport. Post-2004, the decline slowed, with a 9.00% reduction between 2014 and 2024, indicative of stabilized depositional patterns and progressive sediment accumulation, including mud bank and shoal formation. These trends highlight the transition from a highly dynamic, erosion-prone system to a more stabilized geomorphic state, with implications for coastal landform development, habitat dynamics, and sustainable land management.

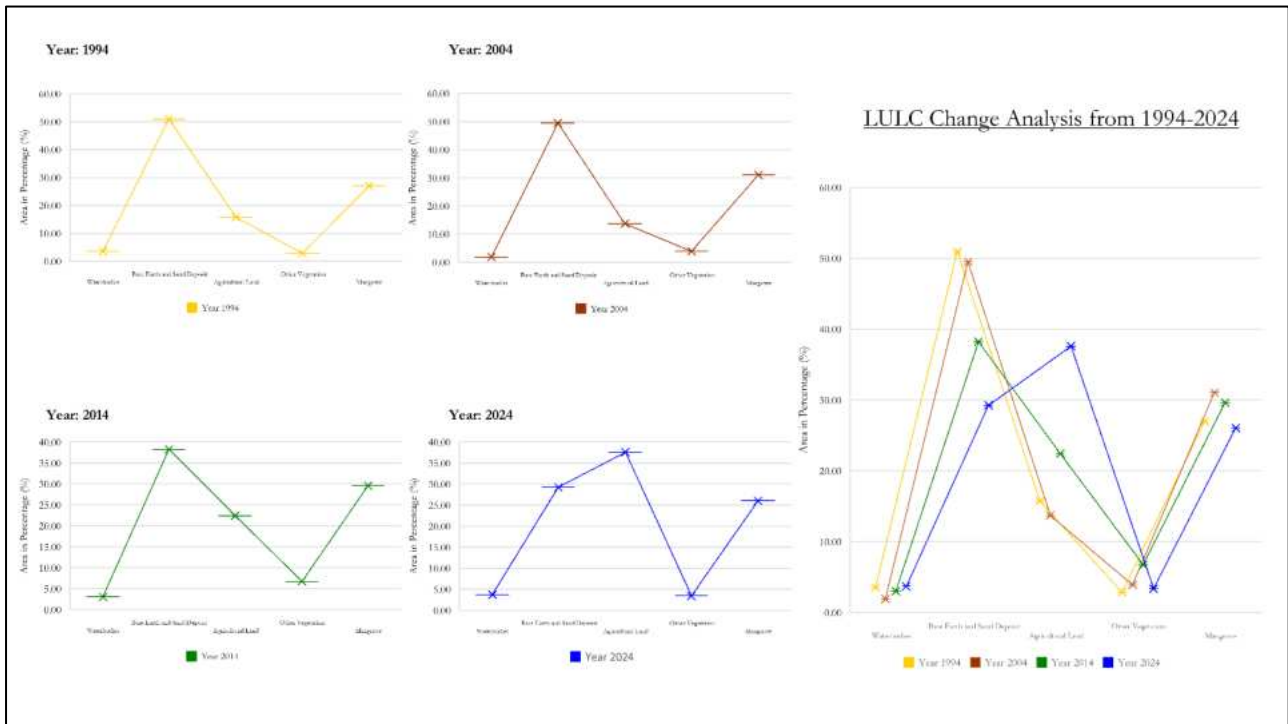
The mangroves cover in Sri Lanka are mainly along the coast side areas, showed a consistent decline from 2004 to 2024, gaining over 4.09% of its area between 1994 and 2004 and a losing additional 1.46% by 2014. This decline in mangrove cover, expand by more than 2802.05 hectares by 2004 and losing by more than 995.81 hectares by 2014. However, from 2014 to 2024, mangrove forests showed a significant deterioration, with a 3.56% shrink, losing over 2437.33 hectares. Sri Lanka was primarily driven by coastal development, aquaculture expansion, and agricultural conversion, compounded by pollution, unregulated harvesting, coastal erosion, reflecting the growing anthropogenic pressure on fragile coastal ecosystems.

The other vegetation class exhibited notable temporal variability over three decades. 1994 to 2004 saw a 1.04% increase (712.57 hectares), likely driven by reforestation, natural succession, or altered land management. This trend reversed during 2004 to 2014, declining 2.82% (1933.25 hectares), reflecting deforestation, agricultural expansion, or encroachment. From 2014 to 2024, the extent of other vegetation decreased by 3.33%, amounting to 2284.45 hectares, due to agricultural expansion, urbanization, deforestation, and climate-related stresses.

Waterbodies, which occupy relatively minimal part of the landscape, Showed consistent and substantial growth throughout the study period. From 1994 to 2004, these areas contract by 1.63%, decreasing by over 1115.15 hectares, indicating agricultural expansion, hydrological modifications, and climate variability, resulting in both reduction and creation of waterbodies areas. Despite a large ascend of 1.16% between 2004 and 2014, Overall, a slight enhancement was observed due to irrigation practices, and hydrological interventions. Between 2014 and 2024, with a 0.69% increase, adding nearly 474.44 hectares. This partial recovery occurred in certain riverine and reservoir areas, reflecting improved water management and occasional flood events, while some regions continued to experience reduction from prolonged droughts and climate stress.

Between 1994 and 2024, Sri Lanka's coastal areas underwent significant and complex LULC changes driven by both natural processes and human interventions. Agricultural land initially declined slightly (1994–2004) but expanded considerably in subsequent decades, reflecting reclamation and increasing anthropogenic pressure. Bare earth and sand deposits decreased sharply until 2004, then stabilized,

indicating a shift from highly dynamic, erosion-prone conditions to more stable sedimentary patterns. Mangroves consistently declined, particularly after 2014, due to coastal development, aquaculture, agricultural conversion, and environmental stressors. Other vegetation showed temporal fluctuations, increasing modestly in the 1990s but declining thereafter due to deforestation, urbanization, and agricultural expansion. Waterbodies experienced minor overall growth, influenced by hydrological interventions, irrigation, and climate variability. Collectively, these trends highlight the interplay of human activity and natural processes shaping coastal ecosystems, with implications for sustainable land and resource management.



**Figure 33:** Temporal changes of the identified LULC classes within the Sri Lanka Coastal Region.

**Table 13:** Temporal statistics of the major LULC classes within the selected parts of Sri Lanka

LULC class	Year								Change		Change		Change	
	1994		2004		2014		2024		(1994-2004)		(2004-2014)		(2014-2024)	
	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)	ha	%	ha	%	ha	%
Waterbodies	2395.77	3.50	1280.62	1.87	2073.16	3.02	2547.60	3.72	-1115.15	-1.63	792.54	1.16	474.44	0.69
Bare Earth and Sand Deposit	34915.88	50.94	33910.77	49.48	26204.83	38.24	20039.36	29.24	-1005.11	-1.47	-7705.94	-11.24	-6165.47	-9.00
Agricultural Land	10774.83	15.72	9380.47	13.69	15356.43	22.41	25769.24	37.60	-1394.36	-2.03	5975.96	8.72	10412.81	15.19
Other Vegetation	1965.74	2.87	2678.30	3.91	4611.56	6.73	2327.10	3.40	712.57	1.04	1933.25	2.82	-2284.45	-3.33
Mangrove	18483.62	26.97	21285.68	31.06	20289.86	29.60	17852.54	26.05	2802.05	4.09	-995.81	-1.45	-2437.33	-3.56
Total	68535.84	100.00	68535.84	100.00	68535.84	100.00	68535.84	100.00	-	-	-	-	-	-

### 3.4.2 LULC Change Map of Sri Lanka (1994-2024):

The image contains three Land Use and Land Cover (LULC) transition matrices comparing classified satellite images from the years 1994, 2004, 2014, and 2024. Each matrix shows how different land cover classes (Waterbodies, Bare Earth and Sand Deposit, Agricultural Land, Other Vegetation, and Mangrove) changed or remained stable over time.

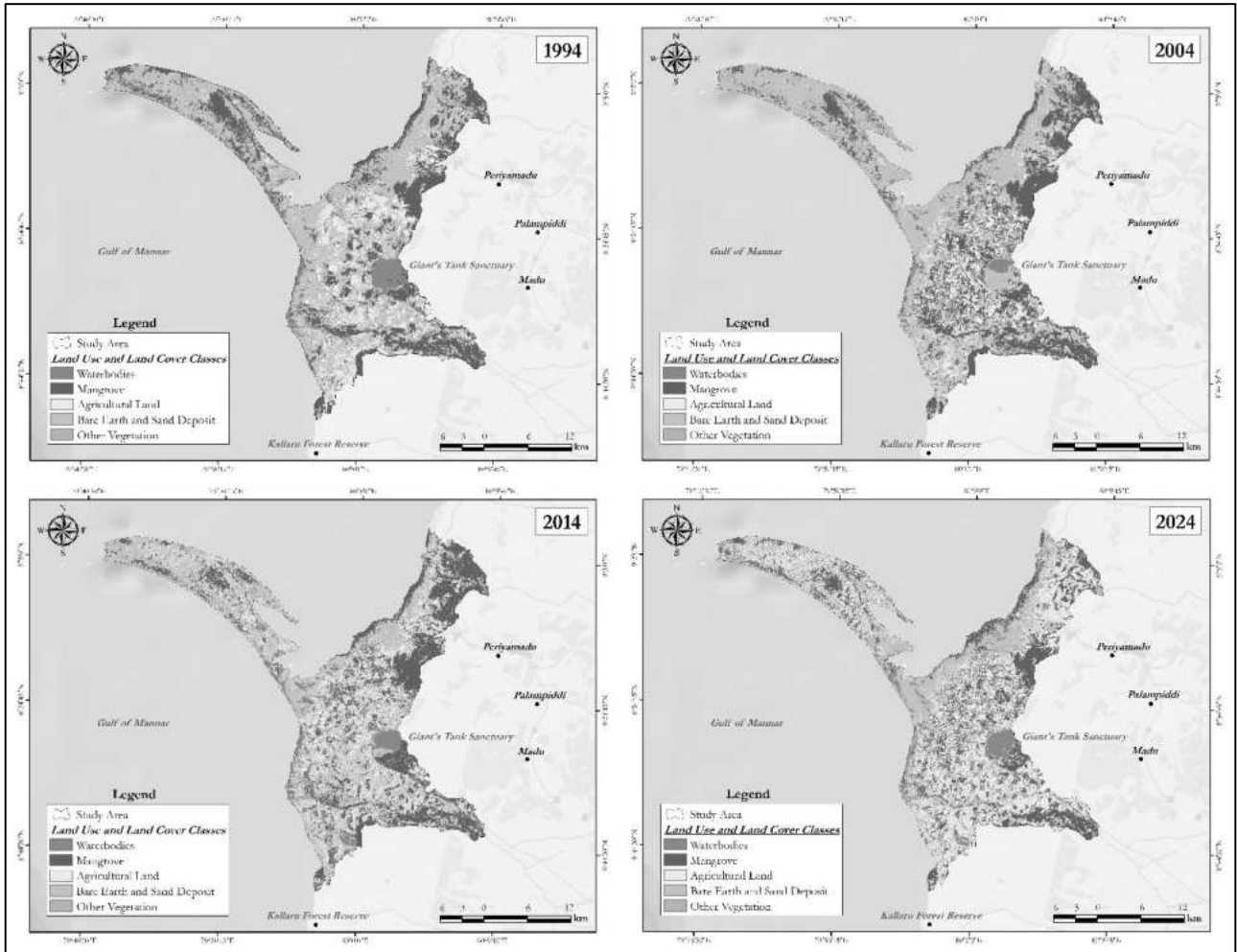


Figure 34: LULC change map of Sri Lanka study area between 1994 to 2024.

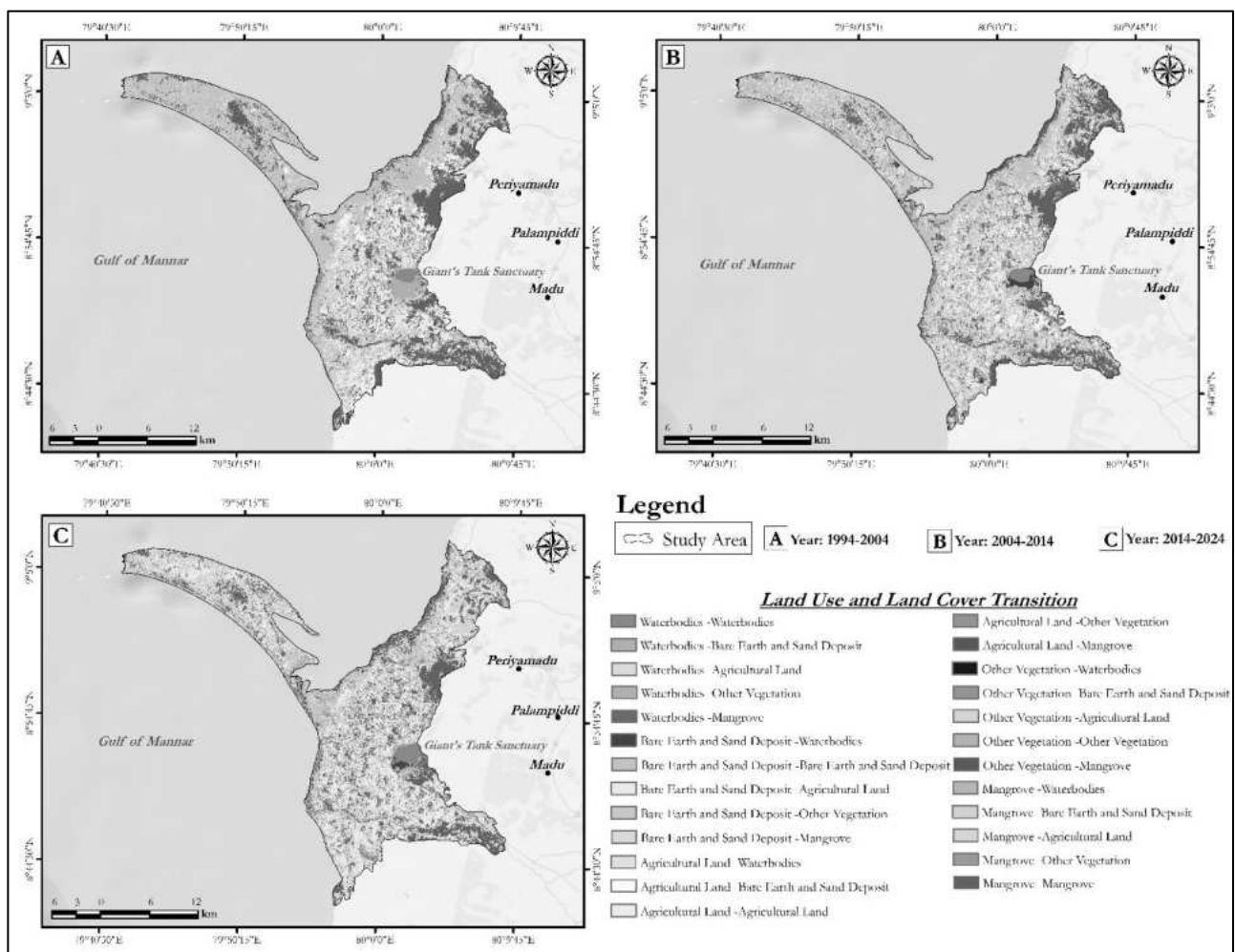
### 3.4.3 Sri Lanka Transition Map:

The Change Vector Map of Sri Lanka, spanning from 1994 to 2024, reveals a dynamic transformation of land cover driven by rapid rural expansion and associated anthropogenic activities. The most prominent change observed is the extensive conversion of bare earth and sand deposit areas into other vegetation, and agricultural land particularly concentrated around the study area core and radiating outward. This trend reflects the pressures of population growth, infrastructure development, and rural settlement.

Notably, bare lands have also been significantly transformed into agricultural land and other vegetation, indicating the areas entire growth into formerly undeveloped or marginal lands. The eastern, western, north-eastern and south-eastern regions exhibit strong signs of such expansion, suggesting a shift in settlement development patterns.

Despite widespread change, certain areas, especially along the central and in the eastern, north, western, south-western, north-eastern and south-eastern extents, retain stable waterbodies. Changes in other vegetation, though relatively limited, include instances of bare earth and sand deposit to agricultural land or other vegetation, which may reflect rural development, population growth, and people’s socio-economic activities. Conversely, isolated transitions from bare earth and sand deposit to mangrove or water may indicate reforestation initiatives, biodiversity and ecosystem developments, or restoration projects, although these are less common.

Overall, the map illustrates anthropogenic land use pressures have driven widespread replacement of bare and sandy terrains by agriculture and vegetation, reflecting rural expansion and population dynamics, whereas waterbodies remain relatively stable, with sporadic ecological interventions.



**Figure 35:** Transition map of LULC changes from 1994 to 2024.

### 3.4.4 Transformation pattern of dominant LULCs:

The transformation matrix of identified LULC classes between 1994 and 2024 in the Sri Lanka Coastal region provides an insightful understanding of how different categories of LULCs, such as Waterbodies, Bare Earth and Sand Deposit, Agricultural Land, Other Vegetation, and Mangrove, have shifted from one class to another class over time. The data for each period (1994-2004, 2004-2014, and 2014-2024) illustrate dynamic transitions across these categories, highlighting substantial ecological and anthropogenic changes in the landscape.

#### **3.4.4.1 Transition Matrix of 1994 and 2004:**

In the 1994 to 2004 period, a significant portion of mangrove remained stable, retaining its classification (12872.78 hectares). Waterbodies area decreased significantly, especially from 998.97 hectares remained waterbodies 245.69 hectares from bare earth and sand deposit, and 29.36 hectares from mangrove converted to waterbodies. Mangrove reduced slightly, as much of it converted to other vegetation, bare earth and sand deposit, and agricultural land. Mangrove high stability (12872.78 hectares remained mangrove) but also contributed to other classes. Other vegetation is relatively stable, though some transitions to other vegetation are seen. However, a notable transition of 911.08 hectares of mangrove converted to agricultural land, indicating either natural regeneration or reforestation efforts. A smaller but ecologically meaningful transformation was the conversion of approximately 2135.13 hectares of agricultural land into mangroves, suggesting possible ecological restoration or natural mangrove regeneration processes. The matrix also reveals minor shifts from waterbodies to agricultural land areas (1.75 hectares), which could reflect increasing agricultural activities in the region. Similarly, bare earth and sand deposits transitioned into mangroves (5149.32 hectares) and waterbodies (148.38 hectares), indicating dynamic geomorphological processes, likely related to sediment deposition and tidal action.

**Insight:** Mangrove cover has expanded rapidly, whereas other vegetation and agricultural land have experienced only marginal increases. Consequently, the extent of bare earth, sand deposits, and waterbodies has declined.

#### **3.4.4.2 Transition Matrix of 2004 and 2014:**

From 2004 to 2014, 799.84 hectares of agricultural land transformed into habitation with other vegetation, which is consistent with the trend of land being reclaimed by natural systems. Interestingly, the mangrove cover expanded during this period, as 1245.91 hectares of agricultural land converted to mangroves, continuing the restoration or natural recolonization trend observed in the previous decade. Other vegetation area recently to grow, 1045.19 hectares of waterbodies remained. Significant increase from mangrove (3218.77 hectares), other vegetation (229.01 hectares) and agricultural land (878.93 hectares). Bare earth and sand deposit shows slight gain but also notable conversion to agricultural land (7700.24 hectares). Bare earth and sand deposit continues transitioning to mangrove and other vegetation. Other vegetation shows minimal but noticeable transition to waterbodies (24.13 hectares). A substantial increase in mangrove area was also seen from the bare earth and sand deposit class, where 6045.79 hectares shifted to mangroves, suggesting enhanced mangrove restoration in degraded zones. The total mangrove area showed an increase of over 20289.86 hectares in 2014, further indicating successful natural recovery or conservation interventions.

**Insight:** The spatial extent of mangrove exhibited a noticeable decline relative to the preceding decade, whereas both agricultural land and other vegetation cover demonstrated a substantial and progressive expansion, reflecting significant anthropogenic and ecological transformations within the landscape.

#### **3.4.4.3 Transition Matrix of 2014 and 2024:**

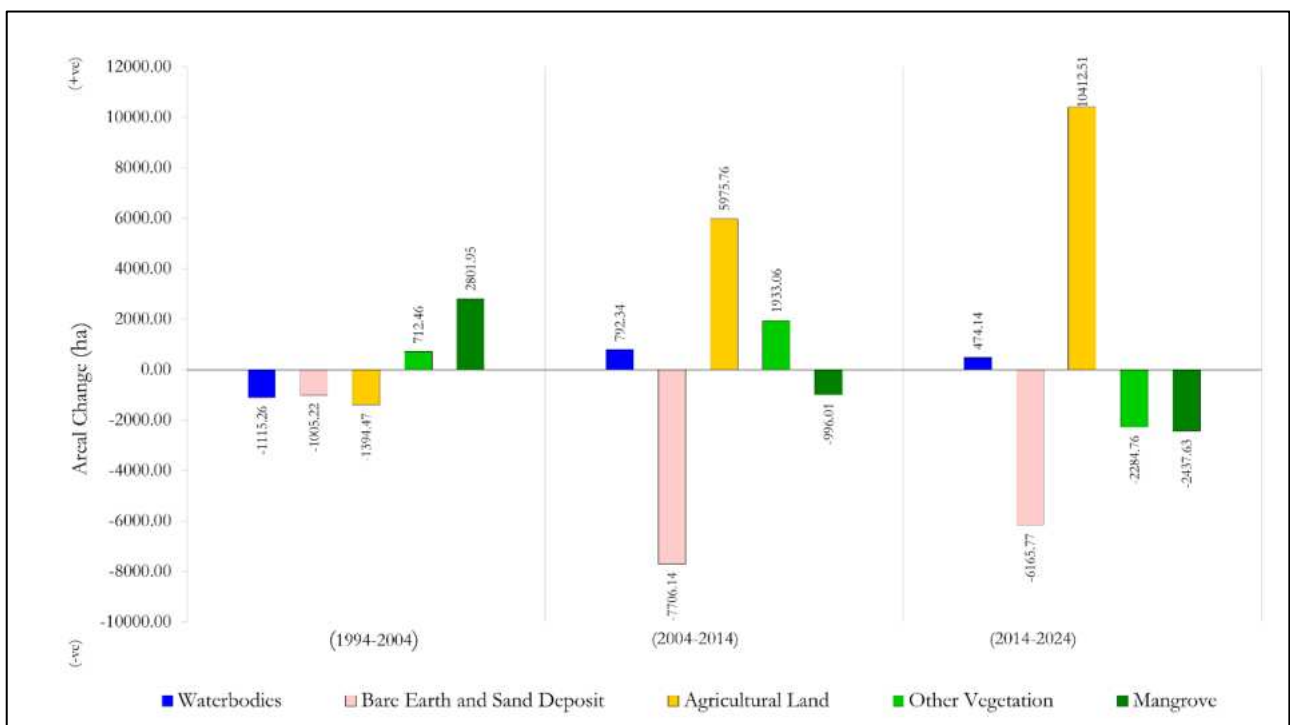
In the final period from 2014 to 2024, the rate of change became even more pronounced. Bare earth and sand deposit experienced a drastic reduction, with only 20039.36 hectares remaining by 2024. A significant portion of mangrove, amounting to 314.56 hectares, converted into other vegetation, while another 5896.10 hectares shifted to agricultural land, it reflects the growing impact of population growth and possibly indicates the tendency of increasing human pressure on land. Waterbodies area expansion accelerates; 1210.70 hectares remain as waterbodies. Large conversion from mangrove (240.74 hectares) and bare earth and sand deposit (1007.07 hectares). Agricultural land (10412.81 hectares) shows increase in nature. Bare

Land has notable conversions into agricultural land and other vegetation. Waterbodies mostly stable, slight ascend (from 2073.16 to 2547.60 hectares total). Mangroves persisted in declining substantially, as approximately 5896.10 hectares of mangrove were converted to agricultural land areas, highlighting the expansion of agricultural land in the coastal region. The overall mangrove covers in 2024 reached 17852.54 hectares, a substantial reduction, showing limited conservation efforts and possible harmful effects on climate resilience strategies.

**Insight:** Massive growth of agricultural land continues, replacing mangrove, and bare earth and sand deposit; while waterbodies have remained relatively unchanged.

### 3.4.4.4 Overall Interpretation of Transition Matrix (1994 to 2024):

- The spatial extent of waterbodies exhibited a marginal yet distinct increase over the study period, indicating subtle hydrological recovery or landscape reconfiguration.
- Bare earth and sand-covered surfaces experienced a measurable reduction, reflecting progressive land stabilization and reduced erosional exposure.
- Agricultural and other vegetated areas expanded appreciably, consistent with intensified land utilisation and successional vegetation growth.
- Conversely, mangrove coverage declined noticeably, suggesting possible anthropogenic pressures or coastal geomorphic alterations.
- These spatio-temporal transitions provide critical insights for evidence-based land use planning, sustainability monitoring, and holistic evaluation of environmental transformations driven by both natural and anthropogenic processes.



**Figure 36:** LULC change bar of Sri Lanka study area between 1994 to 2024.

**Table 14:** Sri Lanka LULC transformation statistics from 1994 to 2004.

LULC Class	Waterbodies	Bare Earth and Sand Deposit	Agricultural Land	Other Vegetation	Mangrove	Grand Total (1994)
Waterbodies	<b>998.972671</b>	1169.806045	30.298559	35.157827	148.377719	2382.612821
Bare Earth and Sand Deposit	245.696895	<b>22266.19343</b>	5234.472423	2004.366474	5149.319746	34900.04897
Agricultural Land	1.747474	5276.83642	<b>3054.8745</b>	304.458193	2135.128178	10773.04476
Other Vegetation	0.104084	815.621764	148.790533	<b>34.001029</b>	965.973955	1964.491365
Mangrove	29.36226	4358.785154	911.083658	299.731638	<b>12872.78149</b>	18471.7442
Grand Total (2004)	1275.883384	33887.24281	9379.519673	2677.715161	21271.58109	<b>68491.94212</b>

**Table 15:** Sri Lanka LULC transformation statistics from 2004 to 2014.

LULC Class	Waterbodies	Bare Earth and Sand Deposit	Agricultural Land	Other Vegetation	Mangrove	Grand Total (2004)
Waterbodies	<b>1045.194181</b>	151.639647	2.986908	7.893183	67.278356	1274.992275
Bare Earth and Sand Deposit	909.480567	<b>16855.94448</b>	7700.242126	2373.634914	6045.786951	33885.08904
Agricultural Land	64.154941	3719.147019	<b>3550.496171</b>	799.842297	1245.909375	9379.549803
Other Vegetation	24.130445	1164.4561	878.924567	<b>229.006183</b>	381.501637	2678.018932
Mangrove	25.305744	4291.012817	3218.769105	1199.01128	<b>12534.26976</b>	21268.3687
Grand Total (2014)	2068.265878	26182.20006	15351.41888	4609.387857	20274.74608	<b>68486.01875</b>

**Table 16:** Sri Lanka LULC transformation statistics from 2014 to 2024.

LULC Class	Waterbodies	Bare Earth and Sand Deposit	Agricultural Land	Other Vegetation	Mangrove	Grand Total (2014)
Waterbodies	<b>1210.70307</b>	808.486552	13.72606	6.600797	28.678143	2068.194622
Bare Earth and Sand Deposit	1007.066167	<b>10526.03016</b>	10045.59247	931.036459	3669.736943	26179.46219
Agricultural Land	52.910445	4219.185396	<b>7907.278247</b>	984.832444	2188.156512	15352.36304
Other Vegetation	32.878524	1431.304445	1899.761357	<b>88.304273</b>	1157.505124	4609.753723
Mangrove	240.737178	3026.815103	5896.102926	314.556435	<b>10794.15811</b>	20272.36975
Grand Total (2024)	2544.295384	20011.82165	25762.46106	2325.330408	17838.23483	<b>68482.14333</b>

#### **4. Discussion:**

The spatio-temporal LULC dynamics documented in this study provide essential empirical foundations for modelling policy interventions and identifying gaps in coastal land management frameworks across South Asia. By quantifying precise trajectories of mangrove loss and recovery, agricultural encroachment, and aquaculture expansion, these maps will enable policymakers to spatially target conservation zones, designate priority areas for mangrove restoration, and regulate land conversion activities with evidence-based zoning regulations. The transformation matrices revealing conversions between LULC classes over successive decades will offer critical insights into the effectiveness of existing policies—for instance, periods of mangrove recovery (India 2014-2024, Bangladesh 2004-2014) can be correlated with specific conservation initiatives, while sustained declines (Bangladesh 2014-2024, Pakistan throughout the study period) signal urgent policy gaps requiring immediate intervention through strengthened enforcement, community-based management, and alternative livelihood programs to reduce pressure on coastal ecosystems. Furthermore, the identification of hotspots where bare earth transitions to agricultural land or salt pans enables proactive planning to balance livelihood needs with ecological integrity, informing policy frameworks such as Coastal Zone Management Plans, Climate Adaptation Strategies, and Integrated Mangrove Management Programs. The granular spatial data on agricultural intensification patterns and waterbody stability also facilitates targeted deployment of climate-resilient agricultural practices, salinity management interventions, and infrastructure development that minimizes ecological disruption. Ultimately, this geospatial intelligence transforms abstract policy objectives into spatially explicit, measurable actions, enabling adaptive management strategies that respond to ground realities, close implementation gaps between policy formulation and execution, and ensure sustainable coastal development trajectories aligned with both economic aspirations and ecological imperatives across the South Asian coastal belt.

#### **5. Conclusion:**

This comprehensive three-decade LULC analysis of coastal regions in India, Bangladesh, Pakistan, and Sri Lanka reveals profound and complex transformations driven by the dynamic interplay of natural processes and anthropogenic pressures, underscoring the vulnerability of South Asian coastal ecosystems to ongoing environmental and socio-economic changes. The study documents divergent trajectories across countries—India demonstrating recent mangrove recovery alongside persistent agricultural expansion, Bangladesh experiencing cyclical mangrove gains and losses coupled with substantial aquaculture proliferation, Pakistan showing sustained mangrove decline and bare earth conversion to agriculture, and Sri Lanka exhibiting rapid agricultural intensification at the expense of mangrove and natural vegetation cover. These quantified spatio-temporal patterns highlight critical challenges in balancing livelihood needs with ecosystem conservation, particularly as population growth, climate variability, and economic pressures continue to reshape coastal landscapes. The transformation matrices and change detection maps generated through this study provide indispensable baseline data for integrated coastal zone management, enabling evidence-based policy interventions, targeted conservation investments, and adaptive management strategies tailored to country-specific contexts. Moving forward, sustained monitoring through multi-temporal satellite imagery, combined with robust policy frameworks that integrate green infrastructure, community participation, and alternative livelihood development, will be essential to ensuring the long-term resilience and ecological integrity of these economically vital and biodiversity-rich coastal regions. The findings underscore the urgent need for transboundary collaboration, strengthened enforcement mechanisms, and climate-responsive land-use planning to safeguard South Asia's coastal mangrove ecosystems for future generations while supporting sustainable development pathways for coastal communities.

## 6. Reference:

- Ghosh, A., Schmidt, S., Fickert, T., & Nüsser, M. (2015). The Indian Sundarban mangrove forests: history, utilization, conservation strategies and local perception. *Diversity*, 7(2), 149-169.
- Osipova, E., Emslie-Smith, M., Osti, M., Murai, M., Åberg, U., & Shadie, P. (2020). IUCN World Heritage Outlook 3: A conservation assessment of all natural World Heritage sites, November 2020. Gland, Switzerland: IUCN. x+ 90pp.
- Rana, M. S., Anik, A. R., Islam, M. R., & Jahan, M. (2024). Sustainable wheat production strategies in blast-affected areas of Bangladesh. *Outlook on Agriculture*, 53(1), 60-71.
- Rahman, M. M., Rahman, M. M., & Islam, K. S. (2010). The causes of deterioration of Sundarban mangrove forest ecosystem of Bangladesh: conservation and sustainable management issues. *Aquaculture, Aquarium, Conservation & Legislation*, 3(2), 77-90.
- ROY, A. K., GHOSH, P. K., & DATTA, D. (2020). Typological inventorization and rapid ecological health assessment of the wetlands of Medinipur coastal plain, India. *Folia Geographica*, 62(2), 22.
- Shalaby, A., & Tateishi, R. (2007). Remote sensing and GIS for mapping and monitoring land cover and land-use changes in the Northwestern coastal zone of Egypt. *Applied geography*, 27(1), 28-41.