Two Decades of Coastal Development across the Arabian Gulf: Insights from Remote Sensing and Machine Learning

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Abstract

This study analyzes land use and land cover (LULC) changes in the Arabian Gulf coastal zone between 2001 and 2021, revealing significant transformations driven by urbanization, coastal reclamation, inundation and urban vegetation expansion. Using Landsat imagery, classified with a high-accuracy Random Forest algorithm, the results show that urban areas expanded by 55.3% regionally, from 6,369.4 km² to 9,888.1 km², primarily due to large-scale infrastructure projects in key coastal urban centers. Developments like artificial islands and ports contributed to the conversion of barren land and coastal waters into urban environments. Water bodies experienced a modest net increase in area of 0.34% largely through growth in urban water features, with opposing trends: coastal reclamation reduced water coverage in some areas, while inundation driven by tidal expansion and possible sea-level rise increased it in low-lying regions. Vegetation cover increased by 41.8%, reflecting urban greening initiatives, though localized losses were observed in rapidly urbanizing areas. Barren land showed a slight net increase of 1.96%, influenced by land degradation, and land degradation. These findings emphasize the complex interactions between urbanization and environmental processes, underscoring the need for sustainable planning strategies. Future research will focus on detailed analyses of vegetation, urbanization trends, and long-term inundation patterns to better support climate adaptation and regional resilience planning in the Arabian Gulf.

1. Introduction

Since the start of the millennium, the Arabian Gulf has experienced rapid coastal urbanization, including expansion of waterfront cities, construction of artificial islands, growth of mega-developments, and development of supporting infrastructure (e.g. ports, breakwaters). The Gulf coast hosts important ecosystems like mangroves, mudflats, saltmarshes, sabkhas, and coral reefs, supporting biodiversity and offering ecological and commercial value (Burt, 2014). Urban transformations present significant environmental challenges, yet comprehensive, long-term, and Gulf-wide studies of coastal development remain limited (Dahy et al., 2024). This study aims to provide a regional analysis of land use and land cover (LULC) changes between 2001 and 2021, focusing on urbanization, coastal reclamation, and inundation processes. Using 42 moderate-resolution Landsat images, pan-sharpened to a 15-meter spatial resolution, and machine learning-based Random Forest classification, the research aims to (1) classify and map urban, vegetation, water, and barren land classes for both 2001 and 2021; (2) assess and quantify coastal urbanization, reclamation, and inundation across the Arabian Gulf region; and (3) perform a 'From-To-Change' analysis to track urbanization and land-water transitions over the study period. The study explores how large-scale projects, such as artificial islands, industrial zones, and urban greening, have reshaped natural and built environments, while identifying ecological vulnerabilities to inundation and potential sea-level rise. By leveraging remote sensing and machine learning innovations, this research provides, for the first time at a Gulf-wide scale, valuable insights to support sustainable urban planning, coastal management, and climate adaptation strategies for long-term regional resilience.

2. Study Area and Data Sources

The study area spans approximately 346,300 km^2, covering the Arabian Gulf along with a 30 km buffer zone extending inland (Figure 1). This buffer zone was designed to include major coastal and associated infrastructure, as these are critical factors influencing the coastal environment. The rationale for the 30 km buffer is based on empirical evidence that Dubai, one of the largest urban centers in the Gulf, has extensive coastal development extending to this distance. This buffer ensures that urbanization, industrial infrastructure, and land reclamation projects are adequately captured in the analysis. The study area includes urban centers and major cities located along the Arabian Gulf coast and within the designated buffer zone. These include Dubai, Ajman, Umm Al-Quwain, Ras Al Khaimah, and Abu Dhabi (UAE); Doha (Qatar); Manama (Bahrain); Al Dammam and Khobar (Saudi Arabia); Kuwait City (Kuwait); Basrah (Iraq); and Bandar Abbas and Bushehr (Iran). Several key developed islands, including Qeshm (Iran) and Boubyan (Kuwait), are also situated in the study area. Rapid economic growth in Gulf coastal zone, fuelled by oil revenues, has led to significant coastal transformation, including the construction of artificial islands, waterfront cities, and extensive industrial projects (Burt, 2014).

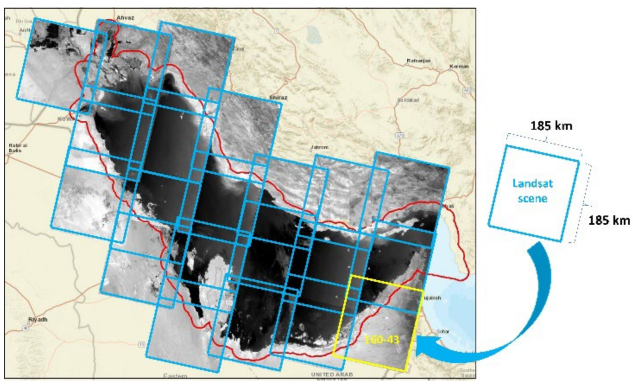

Figure 1. The Arabian Gulf study area, including waters and a 30 km inland buffer (red border), with 42 overlaid Landsat scenes (scene swath: 185 km).

This study utilized satellite imagery and geospatial vector data to analyze LULC changes (Table 1). The primary data source consisted of Landsat satellite images acquired from the United States Geological Survey (USGS)' platform (EarthExplorer). A total of 42 scenes were selected for two time points (2001 and 2021) during the summer months (May, June, and July), ensuring minimal cloud cover (<5%). Collection 2, Level 2 products were used for all bands, except for the panchromatic bands (PAN), which were Level 1. The Landsat data had an original spatial resolution of 30 meters, which was enhanced later to 15 meters using PAN bands (15 meters). Selected Landsat bands used in this study include three visible bands (blue, green, red) and three infrared bands (NIR, SWIR1, SWIR2). In addition to the raster data, shapefiles of the Arabian Gulf boundary and buffer zone were utilized for spatial analysis and visualization.

Dataset	Scene (Path/Row)	Bands (μm)	Resolution (m)
2021 Landsat-8 OLI	160/42, 160/43, 161/43, 162/43, 163/42, 163/43, 164/41, 164/42, 165/40, 165/41, 165/39, 161/42, 162/41, 163/40, 163/41, 164/39, 164/40, 160/41, 161/41, 162/42, 166/39	B2-blue (0.45-0.51) B3-green (0.53-0.59) B4-red (0.64-0.67) B5-NIR (0.85-0.88) B6-SWIR1 (1.57-1.65) B7-SWIR1 (2.11-2.29) B8-PAN (0.50-0.68)	30 (expect B8-PAN with 15)
2001 Landsat-7 ETM+	160/42, 160/43, 161/43, 162/43, 163/42, 163/43, 164/41, 164/42, 165/40, 165/41, 165/39, 161/42, 162/41, 163/40, 163/41, 164/39, 164/40, 160/41, 161/41, 162/42, 166/39	B1-blue (0.45-0.52) B2-green (0.52-0.60) B3-red (0.63-0.69) B4-NIR (0.77-0.90) B5-SWIR1 (1.55-1.75) B7-SWIR2 (2.08-2.53) B8-PAN (0.52-0.90)	

Table 1. Landsat scenes and spectral band details used in this study.

3. Methodology

3.1 Data Preparation and LULC Classification

To enhance spatial resolution, 42 multispectral images were PAN-sharpened from 30 meters to 15 meters using the corresponding 42 panchromatic (PAN) images and the Hyperspectral Color Space (HCS) merge method. LULC classification was conducted using the Random Forest (RF) machine learning algorithm. Four primary LULC classes were identified: urban, vegetation, water, and barren land (Sultan et al., 2024; Dahy et al., 2022). Six spectral bands (blue, green, red, NIR, SWIR1, SWIR2) were stacked with three computed indices: the Normalized Difference Vegetation Index (NDVI), Normalized Difference Built-up Index (NDBI), and Modified Normalized Difference Water Index (MNDWI) (Eqs. 1–3).

$$\text{NDVI} = \frac{(\text{NIR} - \text{red})}{(\text{NIR} + \text{red})} \quad (1)$$

$$\text{NDBI} = \frac{(\text{SWIR1} - \text{NIR})}{(\text{SWIR1} + \text{NIR})} \quad (2)$$

$$\text{MNDWI} = \frac{(\text{green} - \text{SWIR1})}{(\text{green} + \text{SWIR1})} \quad (3)$$

Training datasets (from each of the 42 images) were created as polygons to represent the four classes (urban, vegetation, water, and barren land), with 80% of the data used to train RF classifier and 20% reserved for accuracy assessment. These polygons (train) were overlaid on the stacked nine raster layers (six spectral bands and three index layers) to extract the mean (spectral attribute) pixel digital number (DN) and the variance (spatial/textural attribute)—for input into the RF classification. Additionally, a compactness layer was generated and incorporated to capture shape characteristics (Eq. 4). The urban class, defined by man-made structures such as roads and buildings, generally exhibits higher compactness values (closer to 1), while non-urban classes show lower values due to irregularity and fragmentation.

$$\text{Compactness} = \frac{Pc}{Pf} \quad (4)$$

Where: Pc is the perimeter of a circle with the same area as the feature, and Pf is the perimeter of the feature.

3.2 LULC Analysis

The analytical framework focused on two primary components: urbanization trends and coastal vulnerability assessment. Each component aimed to address specific research objectives related to urban growth, coastal reclamation and inundation in the Gulf coastal zone (2001-2021).

3.2.1 Urbanization Trends Analysis: This component of the analysis focused on tracking spatial urban expansion across the study area over a 20-year period. Binary maps representing urban and non-urban areas were generated for both 2001 and 2021. A From-To-Change analysis was conducted to quantify transitions between these classes, enabling the calculation of total urbanized area in study area. Additionally, an analysis assessed urban sprawl in key urban centers, with results visualized through regional and zoom-in maps.

3.2.2 Coastal Vulnerability Assessment: The second component focused on assessing changes in water bodies, particularly those related to coastal reclamation and inundation. Binary maps of water and non-water areas were generated for both years. A trajectory analysis was conducted to identify two key types of transitions: inundation (water to urban) and reclamation (water to non-water). The total reclaimed and inundated area were calculated to provide a comprehensive understanding of patterns in the Gulf coastal zone. Maps were generated to identify and visualize areas of waterbody reduction or expansion near urban centers.

Accuracy assessments were performed on each of the LULC maps (42 in total) before mosaicking them and clipping the study area to ensure result reliability. Data processing, analysis, and visualization were carried out using ArcGIS Pro and ERDAS Imagine 2023 software packages.

4. Results and Discussion

4.1 Overview

The classification of Landsat images using the RF algorithm achieved high accuracy, with overall accuracy exceeding 85% for both time periods. Although all LULC classes demonstrated strong reliability, the urban class showed slightly lower accuracy due to spectral confusion with barren land surfaces, particularly in the mountainous and rocky regions of Iran, Oman, and northern UAE. Figure 2 presents the LULC map for the Gulf coastal zone in 2021, classifying the study area into four primary land cover types: urban, vegetation, water, and barren land. This map provides a comprehensive view of the spatial distribution of land cover across the study area, Key trends include:

- Significant urban expansion near major coastal cities and infrastructure projects.
- Shifts in water bodies, driven by both reclamation and inundation processes.

- Changes in vegetation coverage, particularly due to urban greening and reclamation efforts.

However, due to the large size of the study area, some land cover changes, particularly urban growth, coastal reclamation, and inundation expansion, may appear subtle or difficult to discern at this scale. Therefore, in subsequent sections, we present zoom-in maps of representative areas to highlight localized transformations, such as coastal urban development, reclamation, and inundation, in greater detail. These focused analyses will offer clearer insights into the spatial patterns and key areas of land cover change.

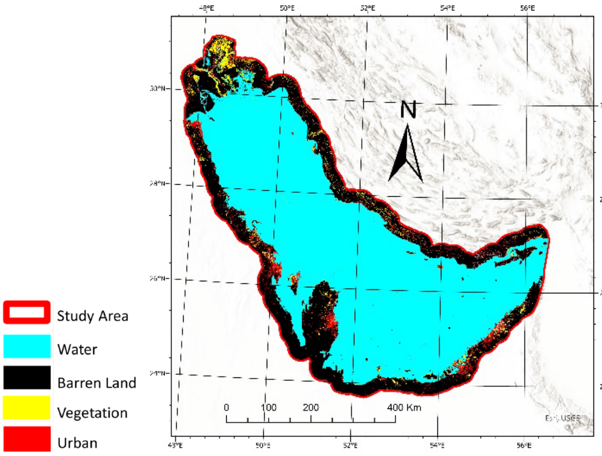

Figure 2: LULC Map of the Arabian Gulf coastal zone (2021).

4.2 LULC Changes (2001–2021)

Table 1 summarizes the absolute area changes, while additional calculations below provide net and percentage change insights.

LULC Class	Urban	Vegetation	Barren Land	Water
Area (km²) in 2001	6,369.4	6,091.4	285,037.4	267,840.2
Area (km²) in 2021	9,888.1	8,635.2	290,619.6	268,746.9
Net Change (km²)	+3,518.7	+2,543.8	+5,582.2	+906.7
Change (%)	+55.3%	+41.8%	+1.96%	+0.3%

Table 1: Summary of LULC changes in urban, vegetation, barren, and water areas in the Gulf coastal zone (2001–2021).

Urban areas increased from 6,369.4 km² in 2001 to 9,888.1 km² in 2021, representing a net gain of 3,518.7 km² and a 55.3% increase. This surge in urbanization reflects rapid development of cities and related infrastructure along the Gulf coastal zone, including residential, industrial, and commercial expansions, the construction of artificial islands, and the development of ports, industrial zones, and waterfront infrastructure. Urban development often occurred by converting previously barren land areas or water (coastal reclamation) into built-up environments, with concentrated growth near key coastal hubs. Figure 3 and 4 present comparative LULC maps for 2001 and 2021, highlighting areas of significant change.

Vegetation expanded from 6,091.4 km² in 2001 to 8,635.2 km² in 2021, a net gain of 2,543.8 km² (41.8% increase). This growth resulted from various factors, including urban greening initiatives such as the development of parks, green belts, and landscaped areas within cities, the conversion of barren lands to managed vegetation for environmental and aesthetic purposes, and afforestation projects or improved land management in certain regions. Figure 5 and 6 highlights areas with significant vegetation gains over the two decades.

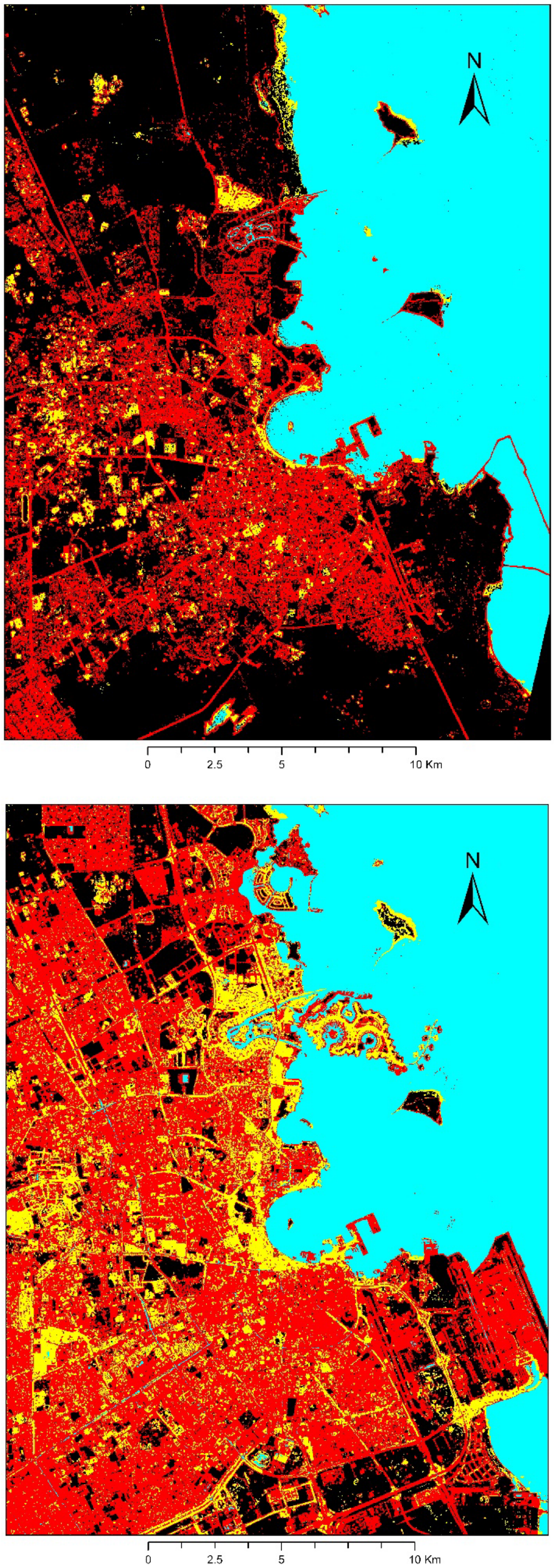

Figure 3. LULC changes from 2001 (top) to 2021 (bottom) in Doha, Qatar. Doha shows urban growth with The Pearl-Qatar and coastal developments.

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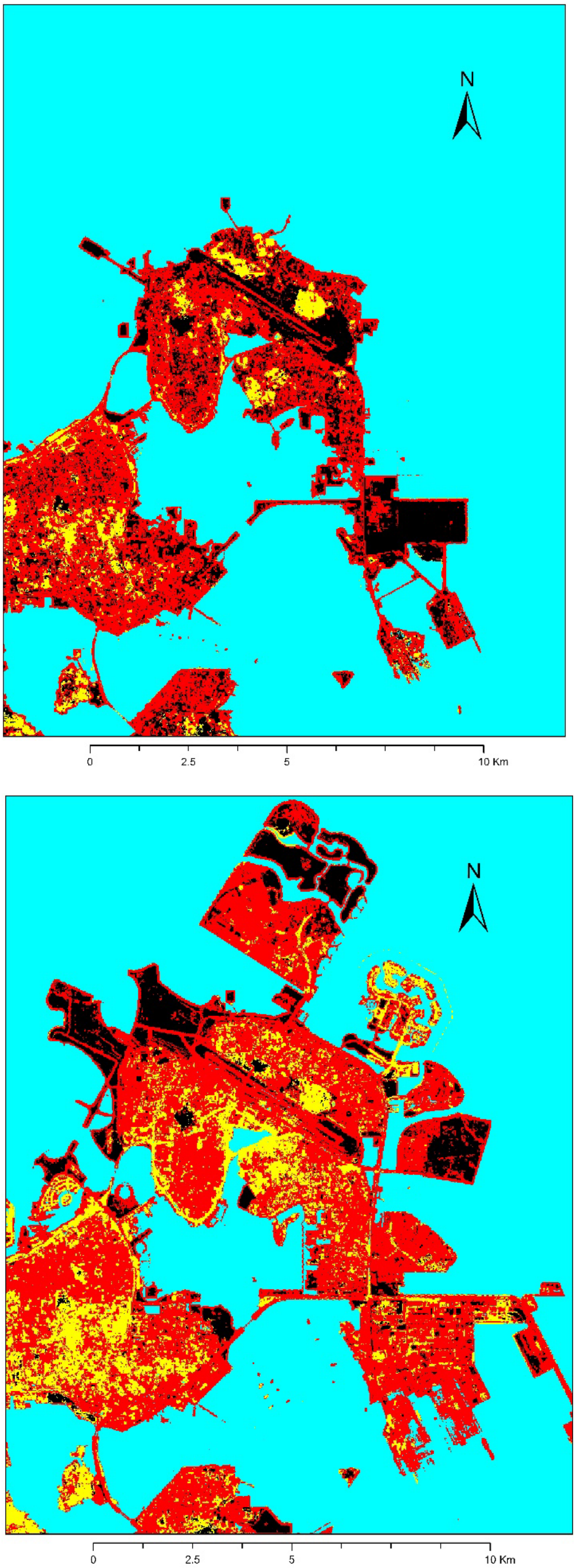

Figure 4. LULC changes from 2001 (top) to 2021 (bottom) in Manama, Bahrain. Manama demonstrates coastal reclamation transformation with Bahrain Bay and Financial Harbour projects.

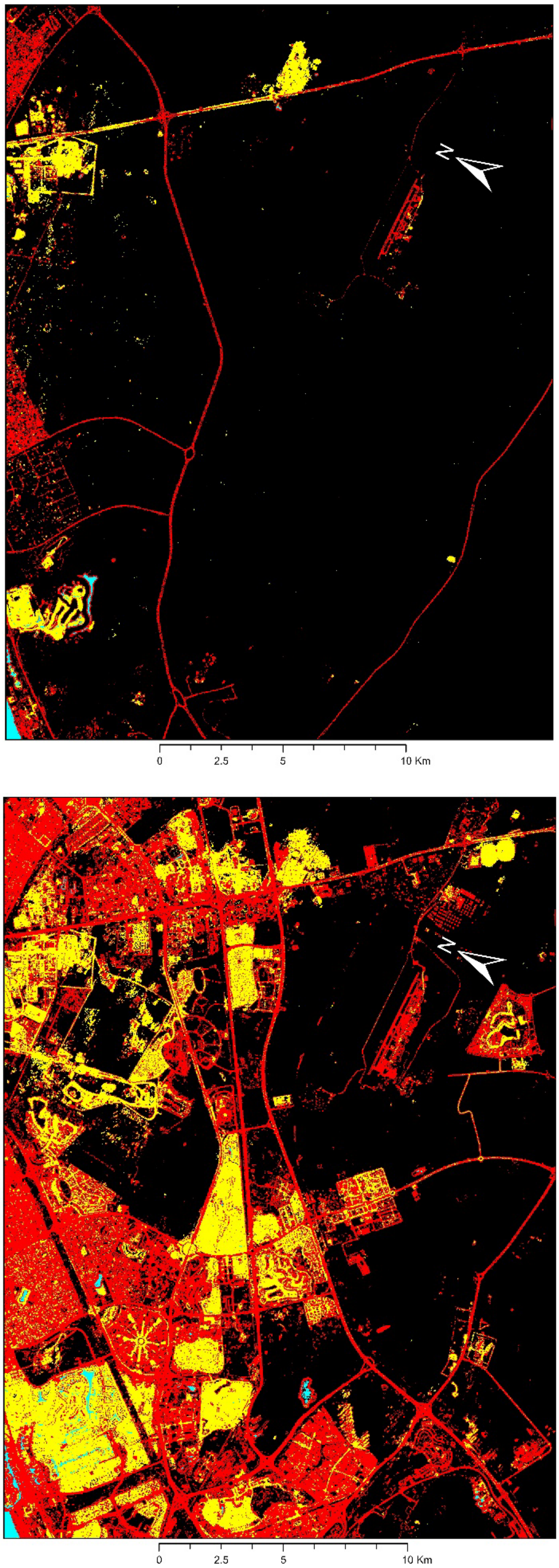

Figure 5. LULC changes from 2001 (top) to 2021 (bottom) in Dubai, UAE. Dubai demonstrates park development and tree planting (yellow) enhancing urbanized environmental conditions (red).

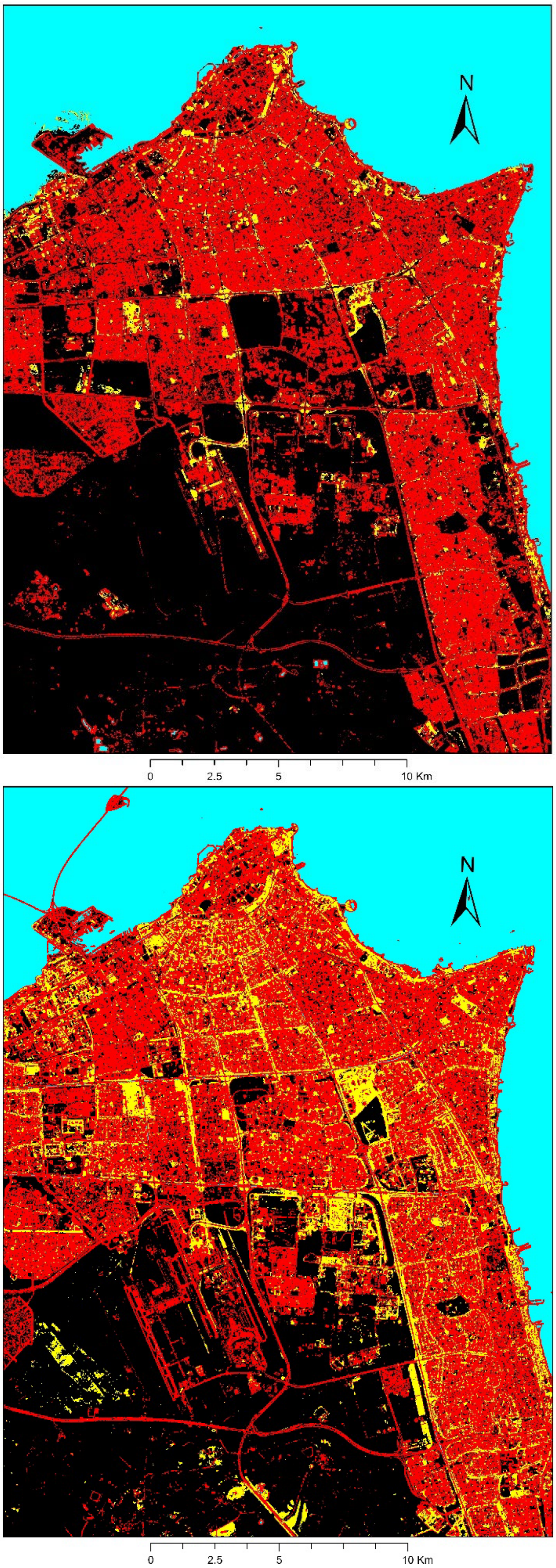

Figure 6. LULC changes from 2001 (top) to 2021 (bottom) in Kuwait City. Kuwait City shows urban greening (yellow) with parks converting urban areas (red) to green spaces.

Barren land remained the dominant land cover class, increasing slightly from 285,037.4 km² to 290,619.6 km², with a net increase of 5,582.2 km² (2.0%). Although barren land experienced localized reductions due to urban and vegetation expansion, vegetation clearance, which preceded development, resulted in barren zones (Figures 8 and 9). This change suggests a complex interplay between land degradation and land use conversion, requiring further localized studies for a more detailed understanding.

Water area increased from 267,840.2 km² in 2001 to 268,746.8 km² in 2021, a net rise of 906.7 km² (0.34%). This modest change conceals contrasting processes of coastal reclamation and inundation. Reclamation activities for ports, artificial islands, and industrial developments reduced water areas near some coastal regions, while inundation from dredging, artificial reservoirs, and potential sea-level rise expanded water coverage in low-lying areas.

During the same period, the Gulf coastal zone experienced significant land use changes driven by urbanization, land reclamation, and inundation (Figure 7). Urbanized areas expanded by 6,824.7 km², particularly around major coastal centers, reflecting construction of large-scale infrastructure projects such as residential developments, industrial zones, and artificial islands. Reclaimed areas increased by 1,010.5 km² due to extensive coastal modification, including port expansions and waterfront projects. Inundated areas grew by 1,810.2 km², influenced by dredging activities, artificial reservoirs, and sea-level rise. These changes demonstrate the ongoing transformation of land use and land cover in response to both human development and environmental factors across the Gulf coastal zone. Further insights into these processes are provided in Sections 4.3 and 4.4.

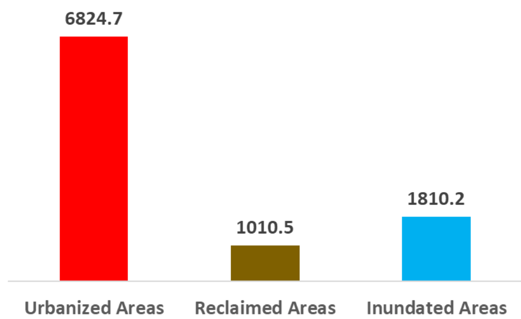

Figure 7. Urbanization, land reclamation, and inundation changes in the Gulf coastal zone (2001–2021) in km².

4.3 Spatial Distribution of Urban Expansion

Urban expansion in the Gulf coastal zone between 2001 and 2021 occurred primarily along the coastline, with significant growth concentrated near major urban hubs such as Dubai (UAE), Doha (Qatar), and Kuwait City (Kuwait). Areas previously classified as vegetation or barren land were converted to urban through large-scale infrastructure and residential developments. Figure 10 presents the spatial distribution of urban change across the Gulf coastal zone as a heat map, with high urban growth shown in dark red. The map highlights urban expansion near major coastal centers, such as Dubai, Jebel Ali Port, and the Abu Dhabi coastal zone (UAE), Doha and Al Wakrah (Qatar), and the Dammam-Khobar complex (Saudi Arabia), including artificial islands, ports, and industrial zones. Zoomed-in maps of selected regions illustrate the spatial distribution and magnitude of these changes (Figures 11, 12, and 13).

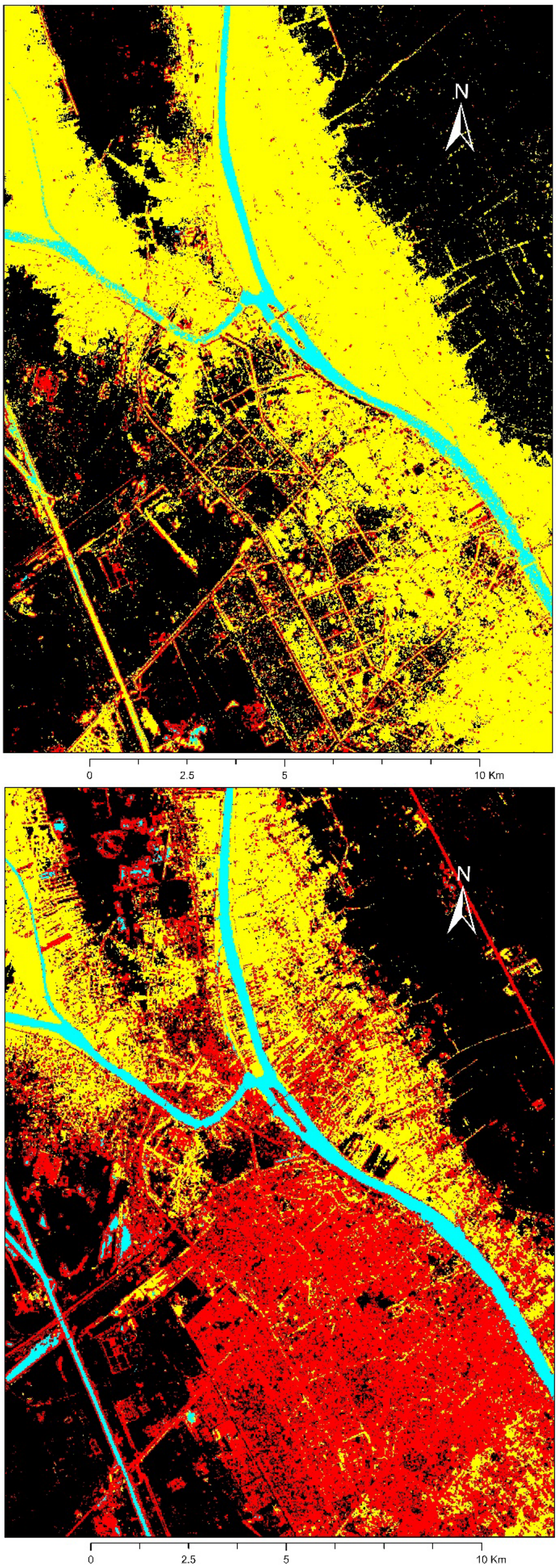

Figure 8. LULC changes from 2001 (top) to 2021 (bottom) in Basra, Iraq. Basra shows reduced barren land (black) due to urban growth (red), with vegetation loss (yellow).

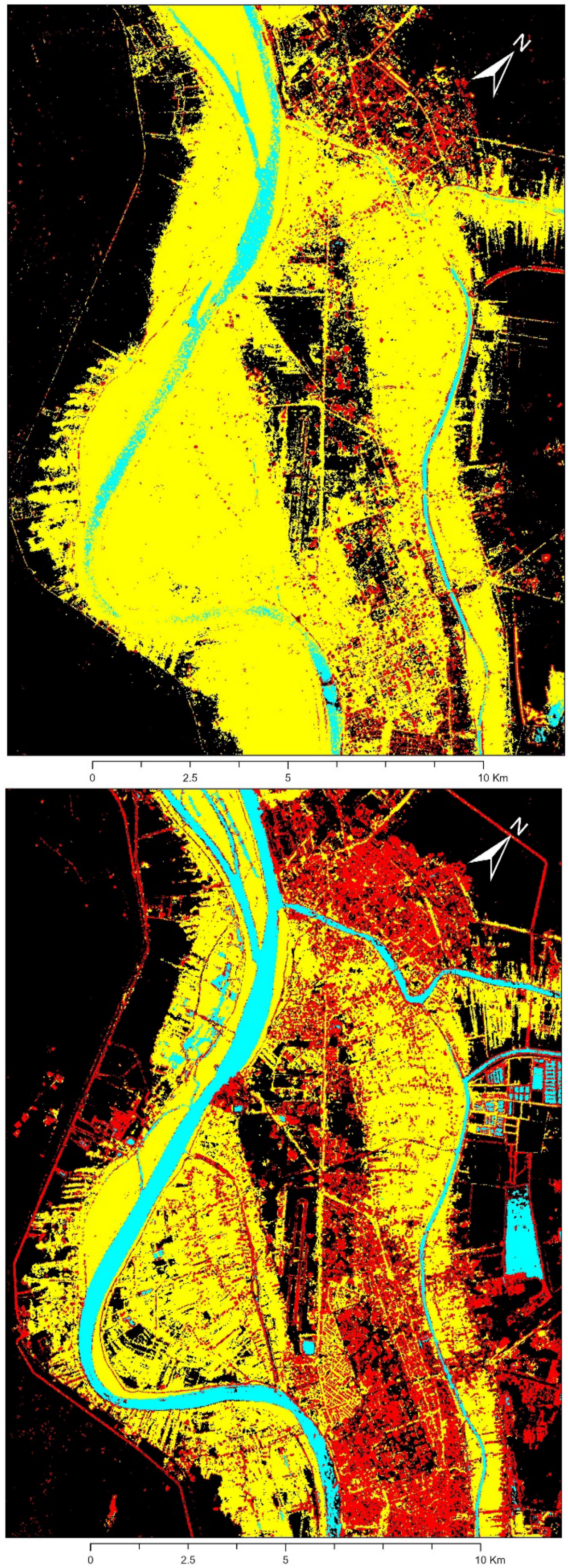

Figure 9. LULC changes from 2001 (top) to 2021 (bottom) in Abadan, Iran. Abadan demonstrates industrial development (red) reducing local barren areas but increasing vegetation degradation elsewhere (yellow).

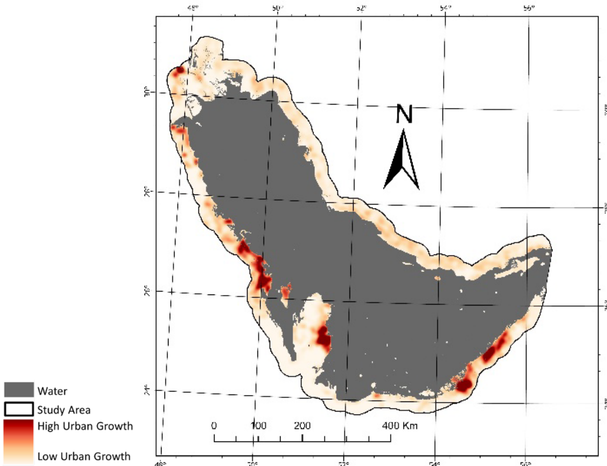

Figure 10. Urban land cover changes (2001–2021) in the Gulf coastal zone. Red areas indicate urbanization after 2001.

Figure 11. Urban land cover changes before 2001 (yellow) and from 2001 to 2021 (pink) in the Abu Dhabi coastal zone (UAE). Extensive urban growth, including residential and commercial developments on reclaimed land, transformed previously barren areas into built-up infrastructure.

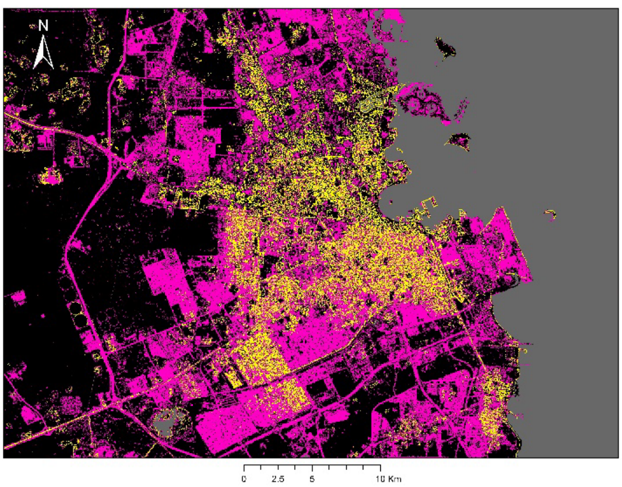

Figure 12. Urban land cover changes before 2001 (yellow) and from 2001 to 2021 (pink) in the Doha and Al Wakrah region (Qatar). Urban expansion extended southward, driven by major infrastructure projects, including transportation networks and sports-related developments.

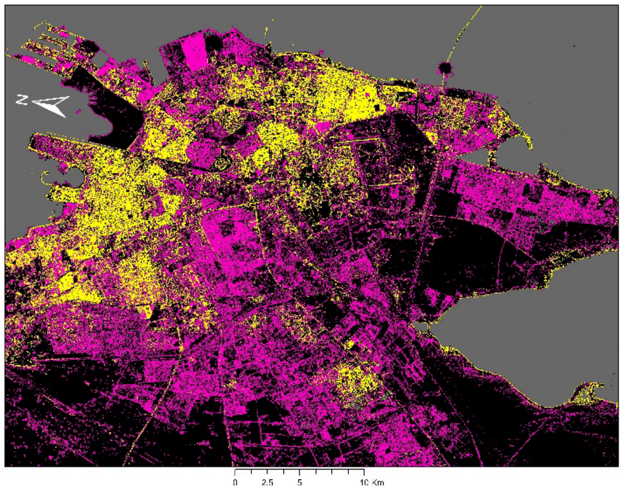

Figure 13. Urban land cover changes before 2001 (yellow) and from 2001 to 2021 (pink) in the Dammam-Khobar complex (Saudi Arabia). Urbanization was driven by commercial, industrial, and residential growth, with infrastructure projects expanding the built-up area further inland from the coast.

4.4 Coastal Vulnerability: Reclamation and Inundation

Coastal zones in the Gulf coastal zone experienced substantial changes between 2001 and 2021 due to reclamation and inundation, both of which have reshaped the natural coastline and heightened vulnerability to environmental pressures.

4.4.1 Reclamation: Approximately 1,010 km² of coastal water was reclaimed between 2001 and 2021. Large-scale reclamation projects have transformed significant portions of the coastline, particularly in Dubai (UAE) and Bahrain. In Dubai, the construction of artificial islands such as Palm Jumeirah and The World Islands contributed to a dramatic expansion of built-up areas over reclaimed land (Figure 14). Similarly, Bahrain's extensive land reclamation efforts supported the development of projects like Bahrain Bay and Financial Harbour at the north and Durrat Al Bahrain Island in the south, reshaping the coastal urban seascape (Figure 14).

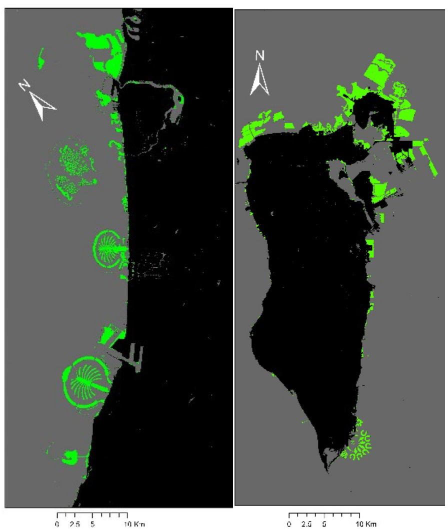

Figure 14. Urban coastal reclamation in the Gulf coastal zone (2001–2021) (green), including major projects such as Palm Jumeirah and The World Islands in Dubai (left), and Bahrain Bay, Financial Harbour, and Durrat Al Bahrain Island in Bahrain (right).

4.4.2 Inundation: Inundation processes affected approximately 1,810 km² of non-water areas between 2001 and 2021, driven by tidal zone expansion and dynamic sea-level rise. The northern Gulf, including Iran's coast near Bandar Mahshaher and Imam Khomeini ports and Iraq's Shatt al-Arab, experienced significant tidal encroachment, likely influenced by both natural and anthropogenic factors (Figure 13). Similarly, the southern Gulf, particularly Abu Dhabi (UAE), saw inundation in low-lying areas, threatening infrastructure and ecosystems (Figure 15). In Kuwait, the Al Khiran Pearl City project exemplifies this trend, where an extensive system of artificial tidal channels was created to expand water frontage and manage tidal flows, impacting coastal vulnerability. These patterns demonstrate the Gulf's growing susceptibility to inundation and highlight the interplay between human-driven reclamation and natural processes, with significant implications for coastal resilience and adaptation planning.

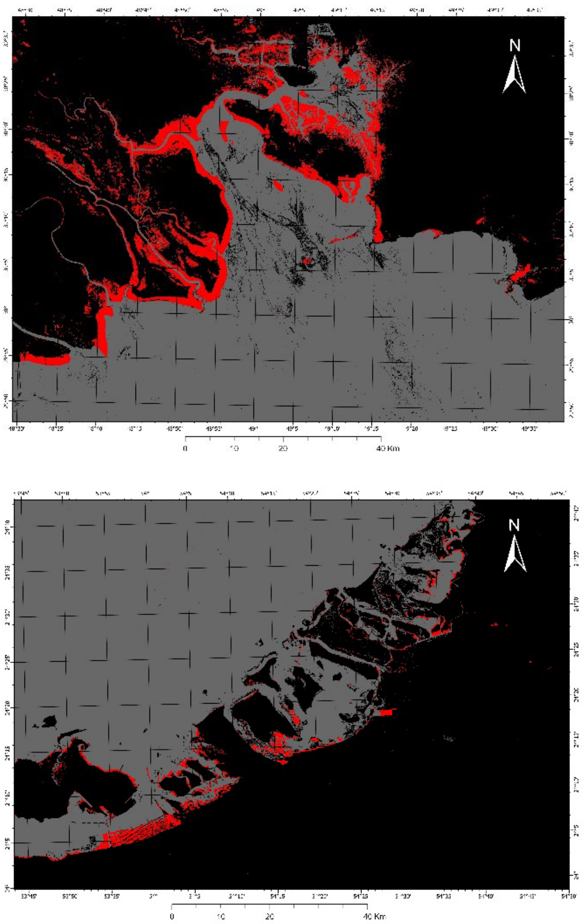

Figure 15. Inundation impacts in the Gulf coastal zone (2001–2021) (red), showing tidal zone expansion and increased flood vulnerability in the northern Gulf (Top: Iran's Bandar Mahshaher, Imam Khomeini ports, and Iraq's Shatt al-Arab) and the southern Gulf (Bottom: Abu Dhabi coastal zone, UAE).

5. Conclusion

This study has assessed land use and land cover (LULC) changes across the Gulf coastal zone between 2001 and 2021, revealing substantial transformations due to urbanization, vegetation expansion, coastal reclamation, and inundation. Landsat image analysis using a high-accuracy Random Forest classifier demonstrated that urban areas grew by 55.3%, from 6,369.4 km² to 9,888.1 km², driven by large-scale infrastructure projects in major coastal cities like Dubai, Doha, and Kuwait City. Urban expansion rates vary due to differing government policies, economic investments, and development priorities. Population growth has further fueled land cover changes, with rising demand for housing, infrastructure, and services. These developments, including artificial islands and ports, transformed barren land and water areas into urban environments.

Vegetation cover increased by 41.8% due to urban greening, reforestation efforts, and improved land management. However, local vegetation losses occurred in regions of intense urban growth. Barren land saw a marginal net increase (2.0%), with reductions near expanding urban and vegetated areas, offset by degradation and land clearance elsewhere. Water bodies exhibited a modest net rise of 0.34%, concealing contrasting trends: reclamation activities reduced coastal water areas, while inundation driven by tidal expansion, subsidence, and possible sea-level rise increased water coverage in low-lying areas like Abu Dhabi and Shatt al-Arab.

These findings highlight the dynamic interplay between human activities and environmental change, underscoring the need for sustainable development strategies that address both growth and coastal vulnerability. Future research will focus on a detailed analysis of vegetation cover changes. In addition, deeper studies of urbanization trends will target major development regions, including comparative analyses of infrastructure growth and reclamation. Lastly, inundation patterns will be examined to better understand tidal encroachment, sea-level rise, and their impacts on regional ecosystems and infrastructure resilience. These efforts will provide vital insights to guide sustainable planning and climate adaptation in the Gulf coastal zone. Researchers may also benefit from SAR-based analysis to investigate subsidence, uplift, or overall land deformation in coastal areas, providing a more comprehensive understanding of landscape dynamics.

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