MODELLING AND VISUALIZING URBAN GROWTH TRAJECTORY IN ABU DHABI USING TIME SERIES SATELLITE IMAGERY

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ABSTRACT:

Anthropogenic activities are leading to massive changes in the natural environment. An assessment of these changes is crucial for sustainable development. The present study aims to characterize and geo-visualize the spatial and temporal changes in the capital city of Abu Dhabi (AD) in the United Arab Emirates (UAE) and to assess and identify the driving forces behind this process. The temporal assessment of urban growth in AD was carried out using eight Landsat images for the period between 1990 and 2022. Initially the images were classified into seven land use land cover (LULC) classes namely: Urban, Sparse vegetation, Dense vegetation, Shallow water, Deep Water, Sand, and Sabkha. The 7 classes were then collapsed and merged to create a binary mask showing urban/non-urban areas. The post-classification approach was implemented to track the dynamic changes and to quantify the urbanization process of the capital city during the study period. The study showed a rise of 21.4% in urban area at the expense of a significant fall in the sand and sabkha classes. It was also found that, unlike most world urban centers, AD city is not developing at the cost of green areas. To the contrary, vegetated areas (sparse and dense vegetation classes) of AD have doubled more than 60 times over the years 1972 to 2021. We concluded that urbanization in the UAE is supporting the sustainable environmental development in the region and is responding positively to the United Nations (UN)’ Sustainable Development Goals (SDGs).

1. INTRODUCTION

Urban areas play a vital role in social and economic development globally. Despite their socio-economic benefits, urban centers are also prone to multiple hazards and risks. Land use conversion for urban development is leading to higher carbon emissions and in turn causing environmental pollution. Urban expansion is a global trend and comes with its pros and cons. It has been reported that carbon footprint and resource consumption in cities is much higher than rural (Churkina, 2016). Therefore, urbanization is posing threat on natural resources. Consequently, accurate estimation and monitoring of urban growth is useful for planning services as well as water and land resources management (Das & Angadi, 2022, Aljaddani et al., 2022).

Urban development and growth patterns need to be monitored regularly to analyze the impact of development activities on natural environments. Hence assessment of LULC is prerequisite for sustainable urban development and planning. Traditional surveying and mapping methods are costly and time-consuming (Al Ahbabi, 2014). Consequently, studies are increasingly relying on remote sensing (RS) and GIS for monitoring urban growth (Ji et al., 2001, Maktav et al., 2005, Jat et al., 2008, Aljaddani et al., 2022, Shah et al., 2022). With the development of RS technology and the launch of new satellites in recent years, satellite or airborne spatial images and data have grown massively over the previous decades (Yu et al., 2014). High resolution data is not easily accessible. However, medium resolution satellites like Landsat series are freely available and provide archives of data (Wang et al., 2009; Sundarakumar et al., 2012; Vishwakarma et al., 2016). Furthermore, satellite images have been found highly effective in assessing the spatio-temporal changes over the earth’s surface (Das & Angadi, 2022, Aljaddani et al., 2022). Precise and updated information on variation in expansion trends and rate of LULC change are critical to ensure sustainable development. Over the years, advancements have been made in data acquisition, processing, and analysis (Issa et al., 2021). Change analysis has been successfully used in wide range of applications such as natural resource management, water quality monitoring, and urban planning (Asokan & Anitha, 2019).

Among several change detection techniques, the image difference algorithm (IDA) and the post- classification methods seem to be most advantageous in the case of monitoring and modelling urbanization (Issa, S. M., & Al Shuwaihi, A., 2011; Dahy et al., 2021). The IDA is one of the most effective change detection methods due to its simplicity and wide usage. However, since IDA measures binary change only, it can only compare two images at once, and therefore can be used to compare the earliest and the most recent images to illustrate dramatic growth. On the other hand, the post classification method can be implemented to compare multiple images at once and adjust for variations in atmospheric conditions (as it uses classified maps rather than raw images). The trade-off is that it great expertise, is dependent of the classified image, and is time consuming (Dahy et al., 2021; Dahy et al., 2022).

United Arab Emirates (UAE) is amongst the top tourist and immigrant destinations countries in the world. The large number of immigrants is in turn leading to urbanization (Elessawy & Zaidan, 2014). According to the 2020 Human Development Index Report published by the United Nations Development Program (UNDP), the UAE clinched the top spot in the Arab region, taking a leap of 4 positions from the previous year and ranking 31st globally out of a total of 189 countries (United Arab

Emirates Ministry of Foreign Affairs & International Cooperation, 2020). In the course of urbanization, LULC patterns are significantly altered. Changes in urban growth typically affect adversely water resources and vegetation, as well as land degradation (Aljaddani et al., 2022); however, studies indicate that this is not the case for the UAE (Dahy et al., 2022). Despite urban growth, the UAE has actually become greener over the past 50 years (Bardsley, 2022; Dahy et al., 2022).

Abu Dhabi (AD), the capital of UAE, has shown significant development in the late 20th century due to high rise in revenue from oil and gas exports. During the early 1970s, residents of AD city were depending on fishing and trade as a source of living. As the revenue from oil and gas exports has increased, AD turned into one of the fastest growing cities. Its population increased by approximately 1000% between 1975 and 2018 (Elessawy, 2021.). The immigrant workers form the major part of the population growth of the city, as they constitute around 90% of the population. Fueled by the population rise and economic growth, urbanization has increased drastically. Urban growth was so rapid that it is also termed as instant city development (Sharaf et al., 2018). For the residents of AD, a new era began with Sheikh Zayed bin Sultan Al Nahyan's succession. He initiated multiple projects to pave the path for AD's growth as a metropolis. Sheikh Khalifa continued the development trend, his vision included economic progress, urban development, and environmental stability.

The purpose of this study is to characterize and monitor the spatial and temporal changes in AD through focusing on the dynamics of the urban/non-urban classes in the study area between 1990 and 2022. Using animated maps, we illustrate and geo-visualize the changing aspects of urban growth and sprawl in AD city for the last 32 years. Specific objectives are: 1) To create a time-series of the seven LULC maps for the years: 1990, 1995, 2001, 2008, 2013, 2015, 2020 and 2022 with emphasis on urban/non-urban classes of the study area, 2) To create a From-To-Change map of the AD city over the study period and; 3) To create and publish an animated map showing dynamics of urban growth and urban sprawl of AD city for the past 32 years.

2. MATERIALS AND METHODS

2.1 Study Area

The study area lies between 54°16′ to 54°40′ E longitudes and 24°16′ to 24°41′ N latitudes. The Emirate of Abu Dhabi is located in the southern shore of the Arabian Gulf, within the UAE. The Emirate is bordered to the east by Oman, to the south by Saudi Arabia, and to the northeast by Dubai (Figure 1). With an area of 67,340 km2, the Emirate of Abu Dhabi covers over 75% of the UAE. Among the emirate's many oil fields are those both on land and in the Arabian Gulf. Salt marshes cover much of Abu Dhabi's coast, making it relatively arid. Around 200 islands fall under Abu Dhabi territory; some of the major ones include Al Hudairiyat, Saadiyat, and Yas Island. The Emirate of Abu Dhabi has a warm desert climate. Furthermore, summers are generally hot, humid, and temperature averages above 40°C from June to September. Additionally, frequent sandstorms can occur during this time, reducing visibility. From October to May, temperatures are relatively mild. The weather is coolest between January to February, during which time dense fog frequently forms.

The study area comprises the City of AD which is the capital of the Emirate of Abu Dhabi. Located in the Arabian Gulf, the city is situated on a long, narrow island. While most of the city is on the island of Abu Dhabi, residential projects (informally termed "cities" but typically considered part of the larger City of Abu Dhabi) have also been constructed on the mainland that connects the entire emirate, including Al Maqta City, Musaffah City, Mohamed Bin Zayed City, Khalifa City, Masdar City, Al Raha Beach, Shakhbout City and Bani Yas City (Elessawy, 2021). On nearby islands, such as Saadiyat and Al Reem Islands in the northeast, new projects are constantly being developed. The east comprises the Yas, Samaliyah, and Sas Al Nakheel islands. To the northwest of Abu Dhabi Island is Al Ras Al Akhdar, and to the west is Hudariyat island (Elessawy, 2021).

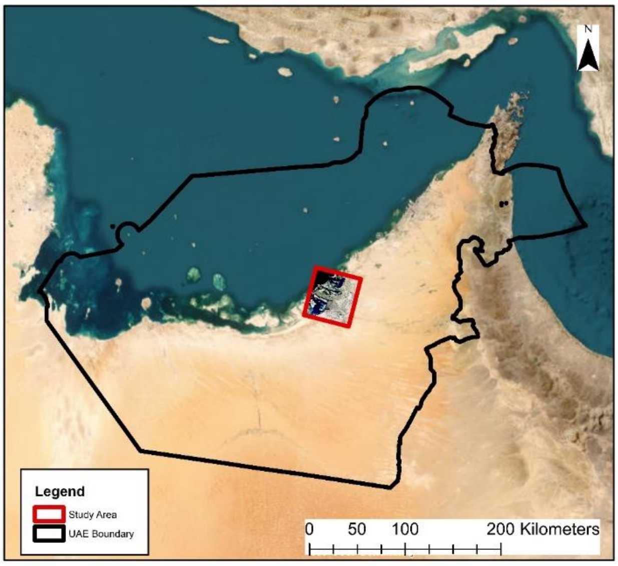

Figure 1. Location map of the study area.

2.2 Data Acquisition

Based on the data availability, image quality, land clouds cover (less than 10%), eight different dates of Landsat scene no 160/43 (path/row) were selected to study and analyze the urban change dynamics of AD city during last 32 years. The Collection 2 and Level 2 (C2, L2) product of OLI, ETM+, and TM images were downloaded from USGS Website. Additionally, panchromatic bands (Level 1) of the same scenes of Landsat-8 OLI and Landsat-7 ETM+ were downloaded and later used in the pan-sharpening process. Table 1 summarizes the data and sources used in this study.

Landsat Sensors	Date	Bands Used
TM	16/05/1990 30/05/1995	B1 (Blue) B2 (Green) B3 (Red) B4 (NIR) B7 (SWIR-2)
ETM+	22/05/2001 17/05/2008	B1 (Blue) B2 (Green) B3 (Red) B4 (NIR) B7 (SWIR-2) B8 (PAN)
OLI	16/06/2013 21/05/2015 18/05/2020 24/05/2022	B2 (Blue) B3 (Green) B4 (Red) B5 (NIR) B7 (SWIR-2) B8 (PAN)

Table 1. Summary of data used in the study.

Land cover classification and mapping are important tools for assessment of the landscape characteristics. Figure 2 displays a flowchart covering steps that were carried out in this study. Main steps include (i) image processing (ii) classification (iii) urban/non-urban mask production (iv) change detection analysis (v) geovisualization and map animation.

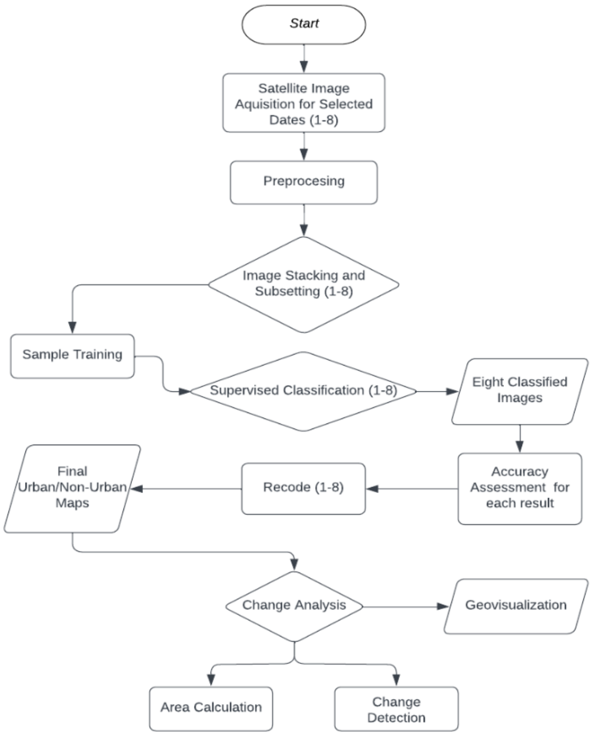

Figure 2. Flowchart showing the methodology of research of the study area.

2.3 Methods

2.3.1 Image Processing: Landsat images covering the study area were acquired from the USGS website. The first step was stacking the bands together to create a multiband image for each study year. The blue, green, red, near-infrared (NIR), and shortwave infrared 2 (SWIR2) bands, in addition to the panchromatic band (for ETM+ and OLI sensors), were used. This task was achieved using ERDAS Imagine 2020 software package. Then the images were pansharpened using the Hyperspherical Colour Sharpening (HCS) resolution method (Padwick et al., 2010) to benefit from the enhanced pixel size of 15 m. The pansharpening task was conducted only for ETM+ and OLI sensors scene (the year 2001 onward), as TM sensor scene has no panchromatic band. For the older dates, the pixel size was resampled to 15 m resolution for compatibility with the other images.

2.3.2 Classification: This paper uses the integrated classification approach, combining both supervised and unsupervised classification while the change detection was carried using the union matrix tool of ERDAS Imagine 2020. The first step was to attempt an unsupervised classification. Twenty clusters (classes) were explored initially. After investigation, seven final classes were produced namely: 1. urban, 2. sparse vegetation, 3. dense vegetation, 4. shallow water, 5. deep water, 6. sand, and 7. sabkha. To produce the final land cover maps of the study area for each of the eight dates (1990, 1995, 2001, 2008, 2013, 2015, 2020, and 2022), a supervised classification was conducted through selecting a number of training sets and by collecting and creating the set of spectral signatures for each class, using the previously produced 8 clusters.

2.3.3 Urban/Non-Urban Mask Production: The seven-class LULC data was simplified using a binary mask to clearly distinguish between urban and non-urban areas. The binary mask generated eight maps that only represented two classes: Urban and Non-Urban. The urban class comprises roads infrastructure in addition to built-up areas. The non-urban class includes all other classes including, sparse vegetation, dense vegetation, shallow water, deep, Water, sand, and sabkha desert.

2.3.4 Change Detection Analysis: Post-classification change detection was applied using the before and after thematic images through union matrix tool in ERDAS Imagine 2020. Union matrix tool is a powerful geospatial analysis tool in comparative studies. The tool helps in comparing and analyzing datasets and it compares pixel values in each layer and produces a map and attribute table which helps is assessing change detection. Through this tool we calculated the change in area of each land use type relative to the other land use classes and produced a map showing change between non-urban and urban class.

2.3.5 Geovisualizing and Map Animation: Geovisualization is the visual representation of geographic data. Geovisualization acts as a strong tool in studies that involve the analysis and understanding of spatial and temporals trends. It has been effectively used in various fields such as geography, statistics, visual analytics, scientific visualization, computer science, art, and cognitive science (Çöltekin et al., 2018). This study has also attempted to display the LULCC in the form a video containing maps of study area. The video shows conversion on landcover classes and urban growth during the period of 32 years i.e., 1990-2022.

3. RESULTS AND DISCUSSION

3.1 Multi-temporal Classification and Mapping of AD LULC Classes with Emphasis on the Urban Change

LULC changes are common worldwide due to natural and human causes, with urbanization playing a major role. The UN predicts global urban population will reach 60% by 2030, and the UAE's urban population is expected to increase from 79% in 1990 to 89% in 2030 (UN & DESA, 2019). Understanding the trends of urban growth over time is crucial for sustainable urban development. Urbanization has both positive and negative impacts, such as improving the economy and degrading groundwater (Sohl, 1999). Hence, mapping and assessment of urban dynamics is crucial for sustainable city development (Elessawy, 2020).

Multiple techniques have been employed for detecting changes in LULC. In areas where comprehensive cartographic information is scarce, geospatial technologies can play a vital role in supplying a foundation for land utilization planning, management, and preservation efforts (Issa et al., 2021). Landsat program including Multispectral Scanner System (MSS), Thematic Mapper (TM), Enhanced Thematic Mapper (ETM+), and Operational Land Imager (OLI) provided moderate-resolution multispectral images with long history repetitive coverage on a regional scale. The data provided a unique baseline for analyzing land-cover changes over the past 50 years. LULC change have become a high priority area for research. Furthermore, analyzing LULC change has become one of the most critical research topics. LULC maps and datasets are essential for understanding and modeling complex interactions and impacts between human and natural systems (Yagoub & Kolan, 2006).

The study used Landsat data to create 8 maps of LULC from 1990 to 2022. 20 clusters (classes) were first made through unsupervised classification. Later, these clusters where improved with supervised classification to improve the quality of results. In this step, seven classes were created that provide an accurate illustration of LULC in the the study area. Figure 3 displays LULC maps of study area for the 8 selected years. The maps show 7 major LULC classes: urban, sparse vegetation, dense vegetation, shallow water, deep water, sand, and sabkha. The urban area increased from 3831.48 ha in 1990 to 56968.9 ha in 2022.

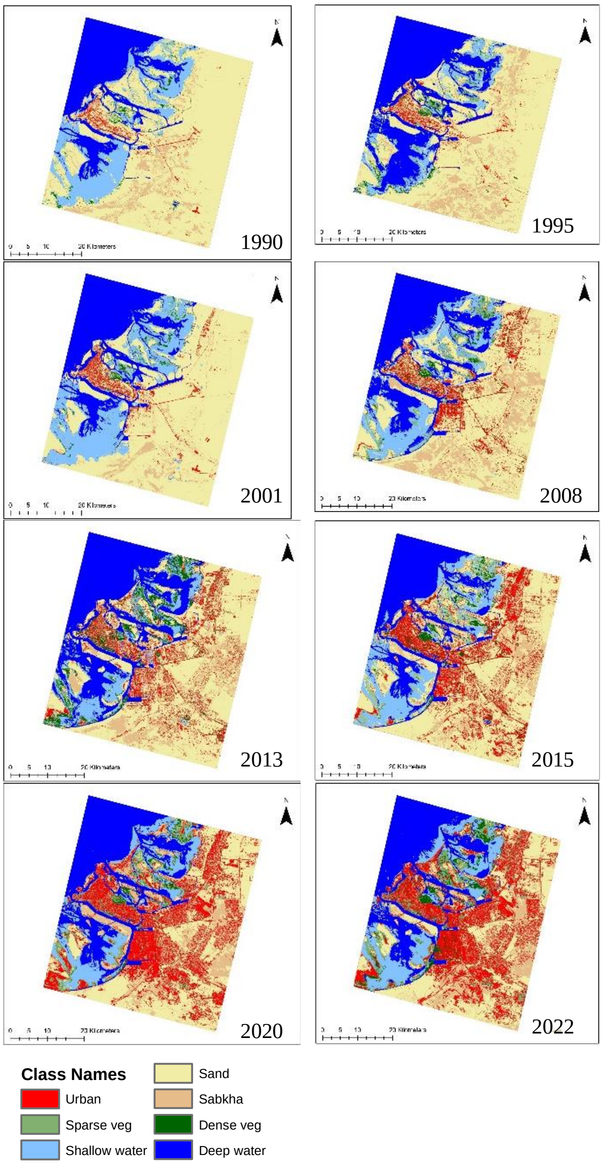

Figure 3. LULC maps of the study area for the years 1990, 1995, 2001, 2008, 2013, 2015, 2020, and 2022.

Urban land in the study area is increasing while sand and sabkha are decreasing. Numerous factors contribute to the urban sprawl of AD city. The prominent factors include population growth, economic development, and government policies (Taileb et al., 2008). Multitemporal analyses of LULC provide insight into long-term trends and help identify future determinants of change. The UAE is a rich oil-producing country that has experienced rapid urbanization and modernization in recent decades. The capital city of Abu Dhabi has grown significantly and become a global economic and financial center (Elessawy, 2021). A variety of developments were approved to be built in the 1990s including schools, hotels, restaurants, and offices. Hence the urban area, which was covering only 1.55% in 1990, became 1.6% in 1995 and since then the pace of urban growth is rising. By 1995, the emirate of Abu Dhabi had 33 public parks (Abu Dhabi Municipality, 1996). The emirate also has a rising green cover, with vegetation increasing from 2.1% in 1990 to 3.5% in 1995, due to policies that consider both urban development and green diversity. Throughout the island's urbanization process, old buildings were converted to newer, more modern structures. By 2001, reclamation and dredging had increased the landmass of the island to 96 km2, with the urban area growing from 3831.48 ha in 1990 to 8217 ha in 2001.

After the passing away of HH Sheikh Zayed and his succession by HH Sheikh Khalifa in 2004, some changes to boost urban development were introduced. Urban development remained the focus of this era too, however, attention was also given to sustainable development. Sustainable development considered peripheral development along with the development of urban centre which is focus of attention for investors (Kyriazis et al., 2017). In particular, new laws allowing Emirati nationals to sell land granted by the government and introducing and legalizing foreign ownership. Moreover, the road network was expanded, and new landmarks such as the Emirates Palace Hotel and Sheikh Zayed Grand Mosque were built in 2005. Despite the global economic crisis of 2008, Abu Dhabi managed to remain stable by building Masdar City, the first "carbon-free" city in the world. Urban cover of AD became 7% in 2005 and reached 10.5% in 2013. Built area kept increasing and was found to be 15.6% in 2015, 21.7% in 2020 and reached near 23% in the year 2022.

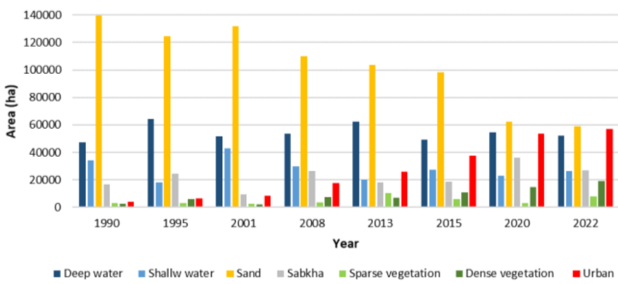

Figure 4: LULC maps in Abu Dhabi from 1990 to 2022.

Figure 4 demonstrates the gradual change in land cover from 1990 to 2022, with a decrease in sand coverage and an increase in urban coverage. The scope of this paper is to find the urban growth in the study area, hence, to enhance the clarity of change between urban and non-urban class binary mask was applied. The use of a binary urban/non-urban mask provided a simple, yet useful, representation of the urban-rural dichotomy. Figure 5 presents the binary maps with urban and non-urban class between 1990 and 2022.

The population of Abu Dhabi is rising due to economic growth, job opportunities, and high rates of immigration. The demand for housing and infrastructure also increases with the rise in population. The statistical data shows a rising trend in population, and urbanization follows the same trend as displayed in Figure 6. Urban sprawl and population growth of AD are showing significant rise between the years 1990 and 2022.

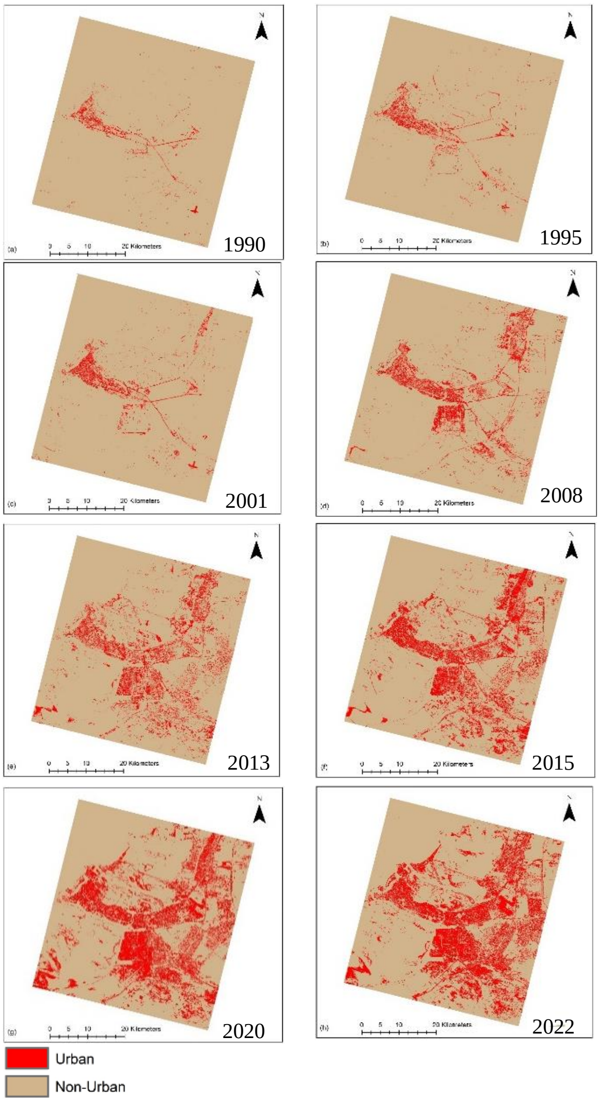

Figure 5: Urban/Non-Urban maps in Abu Dhabi from 1990 to 2022.

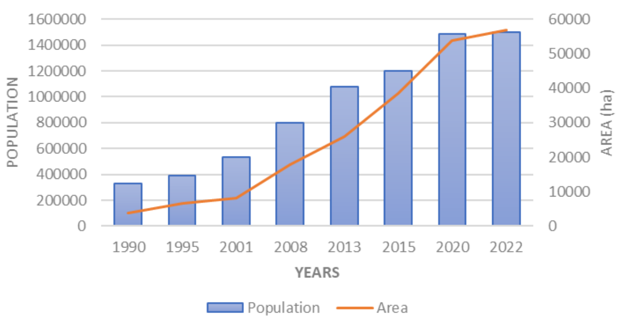

Figure 6: The relationship between population growth and urban sprawl in Abu Dhabi from 1990 to 2022

3.2 Change Detection Analysis

There are various techniques for change detection analysis. The method that was used in this study was post-classification change detection with respect to area as it is the most relevant to the objectives of the study. The method was applied to detect the changes across 7 different classes over the study period.

Change in class	Area (ha)
Deep water to Urban	511.987
Shallow water to Urban	1066.07
Sand to Urban	50216.7
Sabkha to Urban	6428.09
Sparse veg to Urban	66.3075
Dense veg to Urban	85.3425

Table 2. Change in Non-Urban areas to Urban areas in hectares (ha) between 1990 and 2022 in the study area.

The results in (Table 2) and (Figure 7.) indicate that the class that was most affected by urbanization in AD was the sand class; with an overall change of 6564 ha. A total of approximately 19 hectares of the vegetation classes were urbanized between 1990 and 2022, indicating that the vegetation cover was the least affected by the urbanization sprawl.

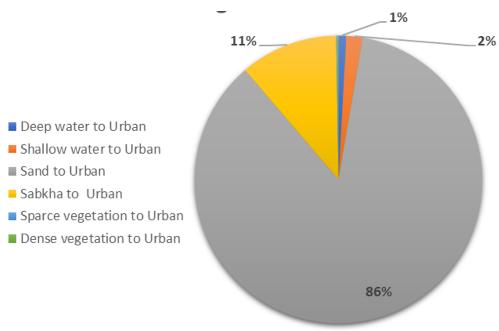

Figure 7: Growth of Urban class in study area from 1990 to 2022 with respect to other classes

3.3 Urban Cover Change

3.3.1 Quantification: To accurately measure and represent the change in the urban class in AD City, a quantification method was applied in which the urban and non-urban areas were measured in hectares and percentages. Table 3. and Figure 8. confirm that the urban cover in the study area has increased significantly between 1990 and 2022. An overall 21.4% of the total area has changed into the urban cover between 1990 and 2022; subsequently decreasing the non-urban area by 21.4%.

Year	Urban		Non-Urban	
	Area (ha)	%	Area (ha)	%
1990	3831.48	1.55	243491	98.45
1995	6579.34	2.66	240870	97.34
2001	8216.91	3.31	240339	96.69
2008	17864.7	7.17	231171	92.83
2013	26093.3	10.52	221865	89.48
2015	38571.6	15.60	208723	84.40
2020	53746.9	21.70	194013	78.30
2022	56968.9	22.95	191338	77.05

Table 3. Urban and Non-Urban areas (ha) and their percentages in the study area from 1990 to 2022.

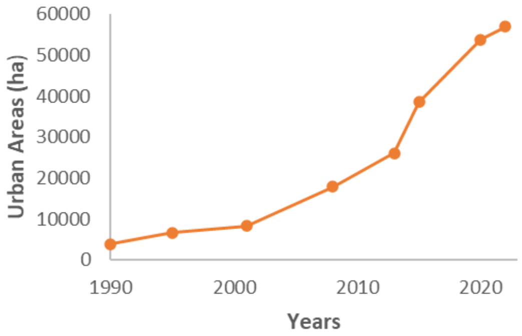

Figure 8: Growth of Urban in Abu Dhabi from 1990 to 2022.

All The study area has experienced significant conversion from non-urban to urban class during the 32 years between 1990 and 2022. The change detection map created using the union matrix tool in ERDAS Imagine displays the conversions between non-urban and urban classes figure 9.

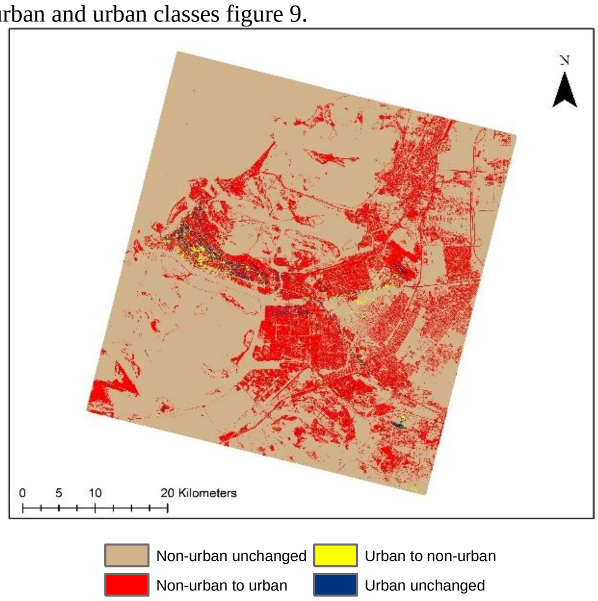

Figure 9: Change map between Non-Urban and Urban classes in the study area (1990-2022).

The conversion from non-urban to urban is very high, while urban to non-urban is very small and the areas of change are on the roadsides which signal the creation of green belts along the roads.

The urbanization of AD has been rising, and major driving factors are population growth, economic growth, and government policies. Urbanization has its positive and negative impacts on the sustainable development. It is therefore crucial to continuously monitor urban growth in order to ensure that growth is in accordance with sustainable development goals. In this regard, current study provides view of LULC changes and urban sprawl trends in AD over a period of 32 years. The study helps tracking trends in urban development, such as conversion of one landcover type to another. The prominent land cover class declining in the study area is sand while urban area is increasing. On one side this is sustainable and environmentally safe approach but on the other hand increased urbanization might lead to groundwater pollution. Therefore, continued monitoring of LULC change and assessment of its impacts is crucial to achieve sustainable development.

4. CONCLUSION AND RECOMMENDATIONS

In terms of urban planning and maintaining sustainable development, it is very critical for decision-makers and planners to be able to analyze the urban cover of the area. The spectral variability in desert environments like AD, caused by the presence of highly reflective surfaces like sand dunes and low reflectance areas like shadows or areas with sparse vegetation, can pose difficulties in accurately mapping and identifying different land covers through remote sensing techniques. Therefore, approaches like integrated classification can be effective. As shown by the results obtained from the study area (AD city) using RS technologies, as well as the results acquired from the study area, it is evident that the urban area's extent has been growing at a constant rate for almost three decades, increasing by approximately 1486.86% from only 3,831.48 ha in 1990 to 56,968.9 ha by 2022 as illustrated by trajectory maps produced earlier. The class most affected by this drastic change was the sand class, which makes this development trend closer to the sustainable development goals. Urban growth in AD is mainly resulting from economic and population growth. Urbanized development is not being carried out at the cost of sustainable development. Along with urban areas, vegetation cover is also increasing, while sabkha and sand are gradually decreasing. These trends are encouraging as desert is being converted into urban land, yet continued monitoring is encouraged. It has been observed that urbanization in arid areas leads to groundwater scarcity and degradation. Future studies may focus on this aspect of urban growth. Temporal change detection and mapping is beneficial for planners and policymakers to continue planned development.

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APPENDIX

1. VIDEO SHOWING THE LULC CHANGE OF STUDY AREA BETWEEN 1990 AND 2022

2. VIDEO SHOWING URBAN/NON-URBAN CHANGE OF STUDY AREA BETWEEN 1990 AND 2022