Spatiotemporal Analysis of Land Use Changes of the Cape Town Table Bay Induced by Land Reclamation (14054)

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Key words: Land Reclamation (LR), Land Use Land Cover (LULC), Remote Sensing (RS), Google Earth Engine (GEE), Classification.

Abstract

Land Reclamation (LR) from the sea has been practised for decades by developing coastal cities in order to gain an economical forte through port expansion, increased investment opportunities, infrastructure development, and increased employment opportunities. Historically, LR represents one of the most significant anthropogenic modification of coastal lines, achieved through techniques such as Dredging and Poldering. While these processes are good for the economy, they are pervasive and induce environmental impacts such as loss of sand, altered hydrodynamics, reduced silt deposition, turbidity, wetland degradation, biodiversity shifts and increased flood risks in low- lying areas.

The entire world has espoused LR including South Africa's City of Cape Town, which is the administrative centre of the Western Cape Province and a major coastal metropolis in Southern Africa. The city's oldest building, the Castle of Good Hope (CoGH), built in the 17th century and once located adjacent to the shoreline, now lies about two (2) kilometres from the Table Bay Harbour, illustrating coastal changes induced by land reclamation.

A spatiotemporal analysis of the reclaimed land on the Cape Town foreshore was conducted using historical maps (1932, 1942), aerial photographs (1972 to 1992), and Landsat satellite imagery (1992-2022) processed through a hybrid classification approach, in order to determine the decadal land use land changes (LULC). Object-Based Image Analysis (OBIA) was applied to the historical maps in ArcGIS, Maximum Likelihood Classifier (MLC) for the aerial photographs in ArcGIS, and Random Forest (RF) classifier for Landsat satellite data processed via Google Earth Engine (GEE) cloud computing platform using JavaScript.

The classification results revealed sustained encroachment into coastal waters; an increase in Built_up areas (11,59% to 31,90%), a decrease in Bareground (14,81% to 4,10%), and Water (73, % to 56,07%), and a Vegetation enhancement (0,60% to 7,93%) of the total AOI extent respectively. The study quantifies the decadal LULC, and identifies spatial and temporal trends.

These findings provide critical insights for climate- resilient urban planning and sustainable coastal management.

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1. INTRODUCTION

1.1 Background

In human history, the need to improve infrastructure has been constant. The improvement of physical infrastructure requires land acquisition (W. Shi et al., 2017) and coastal areas tend to present appealing sceneries. Land Reclamation has been conducted for decades in developing coastal cities to gain an economic advantage (W. Wang et al., 2014). The key drivers of land reclamation is increasing population encouraged by economy dependency on the coastal zones. It was predicted that in the future, approximately 1700 million hectares of land across the world would be available for reclamation (Segeren, 1983).

Land Reclamation processes utilised by most coastal cities are unnatural and pervasive in nature as they go over the limit of the shorelines, alter the marine ecosystems, and modify the landscape elements (Zainal et al., 2012). This may cause loss of sand and subsequently affect hydrodynamics (Campmans et al., 2021).

The two commonly used land reclamation techniques in discussion are Dredging (Mario Martín-Antón et al., 2016) and Poldering (Segeren, 1983).

The entire world has adopted building into the sea around coastal areas (Mario Martín-Antón et al., 2016). West Asia, particularly Dubai is at the pinnacle of land reclamation using sand dredging techniques, which have resulted in multimillion-dollar residential islands attracting investors contributing to the city's economy (Insley, 2007). The once small port city of Doha is now the capital city of the Arab Emirate of Qatar and has increased its population and economy significantly by 60 times since the 1970s (Lecart et al., 2024; Rizzo, 2013). The Bangladesh coastal belt is protected by polders (Nowreen et al., 2014). The Kingdom of Bahrain is an archipelago that conducted 10 land reclamation projects over a decade, resulting in a cumulative major habitat loss of 153.58 square kilometres for the usable dry land (Zainal et al., 2012). Japan in East Asia has significantly reclaimed land due to urbanisation (TSUBAKI, 1996), the Persian Gulf in the West of Asia has mastered artificial islands residential areas (Gasemi et al., 2018), and China has completely altered its coastal topology, solidifying its economic dominance (Tang et al., 2022). The economic developments of Hong Kong, Singapore, and Macau are directly proportional to the rate of land reclamation (Glaser et al., 1991).

Europe follows Asia with land reclamation aggression. The Netherlands is densely populated and one-third of its low-lying reclaimed land is used for subsistence farming (Schultz, 1983). Using land reclamation, the country has recovered some land due to subsistence land lying below the water (Hoeksema, 2007). Spain has the Bay of Algeciras and the Portman's Bay which are land reclamation projects harbouring the economic hubs of Spain's traffic container port (Oyarzun et al., 2013).

America has also had its fair share as she utilises polders as plantations in the river delta areas of tropical South America (Meyer, 1983). Brazil used the dredge and diversion-reclamation technique for coastal habitat restoration (Caffey et al., 2014).

Land reclamation offers both positive and negative impacts on the environment. The positive being the general increase of land for development (J. Li et al., 2014), improvement of flood protection (Caffey et al., 2014) and the restoration of coastal habitats (Tu & Huang, 2023). While the negative spans from altering the natural coastal environments and processes associated with natural habitats leading to coastal erosion, loss of water quality and habitats (Subraelu et al., 2022a). Dredging disturbs marine ecologies by displacing habitats, raising turbidity and increasing sedimentation (Borland et al., 2022; Xie et al., 2020). Reclaimed areas are prone to instability and land subsidence caused by the removal of the seabed reducing natural sand reserves (Mario Martín-Antón et al., 2016; Wei et al., 2022). The very reclaimed areas may be threatened by rising sea levels, aggravating erosion and infrastructure vulnerability (Dube et al., 2021; Pfaff et al., 2019). The expansion of land for infrastructure development causes the shrinkage of the coastal wetlands which are critical for marine biodiversity and climate regulation (Y. Li et al., 2020).

The monitoring and assessment of reclaimed land has improved significantly with the use and advancements of Geographic Information Science (GIS) and Remote Sensing (RS), in real time analysis (Liu et al., 2018). Precise trend analysis facilitated by the use of satellite imagery, such as Landsat and Sentinel, over extended periods has allowed researchers to track land use and land use cover changes (Danladi et al., 2020). Other RS techniques, including Unmanned Aerial Vehicles (UAVs) and Light Detection and Ranging (LiDAR) enhance the accuracy of terrain analysis, making them essential for coastal management sustainability (Lee & Yun, 2024). Cloud computing platforms like Google Earth Engine (GEE), allows access to petabytes of satellite data, allowing for visualisation and monitoring of coastal changes (Jensen et al., 2022). The combination of GIS tools, historical maps and geospatial modelling provides the valuable insight into the impact of land reclamation on coastal ecosystems (Thilagam & Sivasamy, 2013), as well as the mitigating environmental risks associated with land reclamation through policy formulation (Tu & Huang, 2023). As coastal development expands, the deployment of these technologies will become increasingly important for assuring long-term land reclamation and coastal resilience.

1.2 Problem Statement

While numerous studies have applied remote sensing techniques to analyse Land Use and Land Cover (LULC) changes at global and regional scales, these studies primarily focus on broad land-cover transitions such as agriculture expansion, urban growth, and shoreline erosion or accretion. Explicit analysis of land reclamation dynamics including the processes, spatial patterns, and temporal evolution of reclaimed land, is largely absent in coastal environments.

In the South African context, coastal studies of the Western Cape, Eastern Cape and KwaZulu-Natal provinces mainly illustrate land use changes with limited emphasis on planned land reclamation activities. Furthermore, the application of multi-temporal remote sensing and GIS to monitor, quantify, and predict land reclamation dynamics over time remains underexplored.

The irreversible landscape modifications and environmental vulnerability associated with land reclamation, necessitates for a long-term analysis of reclaimed coastal lands. Addressing this gap through the integration of historical maps, satellite imagery, and geospatial modelling is essential for improving coastal management, risk assessment, and sustainable planning in South Africa.

1.3 Aims and Objective

The aim of the study is to depict the extent of land reclaimed from the sea by Land Reclamation in the Cape Town Table Bay.

The one objective focus is:

- To determine the spatial and temporal trends of the land accumulated between the Castle and the Table Bay Harbour from 1938 to 2021.

2. LITERATURE REVIEW

2.1 Overview of Land Reclamation Processes

Land reclamation is the process of creating new land from water bodies to support intensified and economically productive land use (Mario Martín-Antón et al., 2016). It has evolved from small-scale historical practices to large-scale, technology-driven projects widely adopted in land-scarce coastal countries (X. Wang et al., 2023; Zhang et al., 2021). In Cape Town, reclamation mainly involved dredging, where seabed sediments are relocated to form new land and support coastal development and restoration (Manap & Voulvoulis, 2015).

2.2 Land reclamation in the Southern Africa Context

Cape Town has experienced the most pronounced coastal transformations in Southern Africa, particularly since the late nineteenth century, driven by extensive port excavation, seawall construction, and large-scale land reclamation (Anon, 2004; Pfaff et al., 2019). The Castle of Good Hope–Table Bay Harbour corridor represents a focal area, where the Castle was originally located on the shoreline and somehow was progressively isolated from the sea due to reclamation between the 1930s and 1950s (Bisset, 2012; LOKE et al., 2021). Major reclamation projects, including the Foreshore and Duncan Docks developments, reshaped over 200 hectares of coastline amid rapid urban population growth (Wilkinson, 2000). Subsequent redevelopment initiatives, notably the Victoria & Alfred Waterfront in the 1990s, further transformed reclaimed land into commercial and tourism hubs. These interventions collectively illustrate the long-term spatial and functional reconfiguration of Cape Town's coastline through reclamation (Anon, 2004; Pfaff et al., 2019).

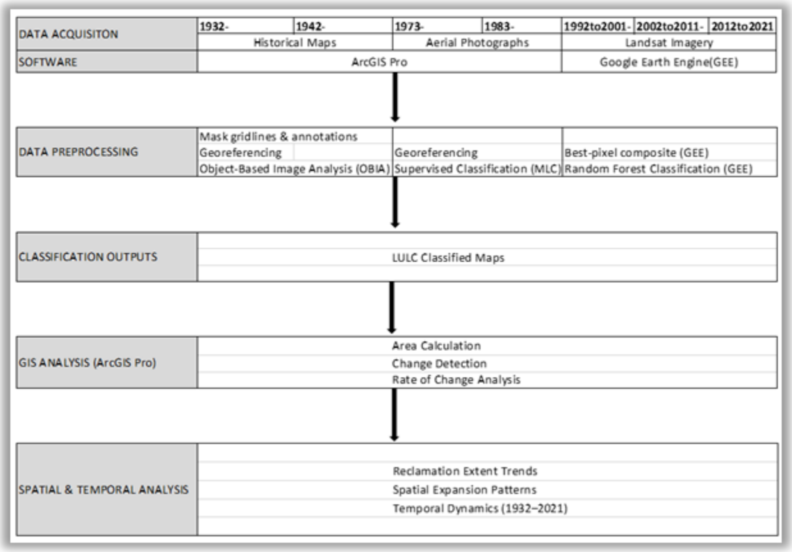
2.3 Effectiveness of GIS and Remote Sensing to analyse Land Reclamation

GIS and Remote Sensing (RS) provide powerful tools for monitoring and analyzing land reclamation, offering high-resolution, multi-temporal data to detect coastline changes and land-use dynamics (Danladi et al., 2020; Lu & and Weng, 2007). RS satellites, including Landsat and Sentinel series, coupled with platforms like Google Earth Engine, enable efficient mapping, classification, and trend analysis across large coastal areas (Jensen et al., 2022). Case studies from the UAE, China, Italy, and Nigeria demonstrate RS and GIS's capability to track historical and contemporary reclamation patterns, support urban planning, and inform sustainable coastal management (Adegboyega et al., 2019; Subraelu et al., 2022b). Overall, integrating GIS and RS reduces fieldwork, enhances accuracy, and facilitates long-term monitoring of coastal and reclaimed landscapes worldwide (Thilagam & Sivasamy, 2013; X. Wang et al., 2020).

3. METHODOLOGY

This study adopts an integrated, multi-source methodological framework to analyse the spatial and temporal dynamics of coastal land reclamation in Table Bay from 1932 to 2021. A hybrid classification approach was implemented to accommodate variations in data type, resolution, and historical context, combining historical maps (Object-Based Image Analysis), aerial photographs (Supervised Maximum Likelihood Classification), and multi-temporal Landsat imagery (Random Forest). The workflow integrates data preprocessing, classification, remote sensing and GIS-based spatial analysis to ensure consistent and comparable assessment of land reclamation patterns across the study period (Figure 1).

Figure 1: Integrated methodological framework employing a hybrid classification approach for multi-temporal analysis of coastal land reclamation using historical maps, aerial photographs, and Landsat imagery (1932–2021)



3.1 Study Area (AOI)

Cape Town is the country's second-largest metropolis, situated on the south-western tip of South Africa's Western Cape province(Ndebele et al., 2022), and is highly esteemed as an international tourism destination (Martín-González et al., 2021; McCarroll et al., 2024). The city has a diverse and dynamic terrain which stretches from the Cape Peninsula in the southwest to the northern suburbs at the N1 motorway (Rebelo et al., 2011), including the inshore districts of Table Bay and False Bay (Ndebele et al., 2022). The city's coordinates are about 33.9249° S latitude and 18.4241° E longitude (Martín-González et al., 2021), bordered by Atlantic Ocean to the west and south, while the famed Table Mountain dominates the terrain to the north (Ndebele et al., 2022). Additionally, the Cape Town Foreshore, a major land reclamation project from the 1900s, altered the coastline, highlighting the role of reclamation on urban growth (Anon, 2004).

Figure 2: Study Area; Figure (a): National context showing the location of South Africa and provincial boundaries, Figure (b): Provincial context map of the Western Cape showing its position within South Africa, Figure (c): Area of interest (AOI) showing the location of the Castle of Good Hope within the Cape Town metropolitan area, Figure (d): Detailed map of the area of interest showing the Castle of Good Hope, AOI boundary, and base map features

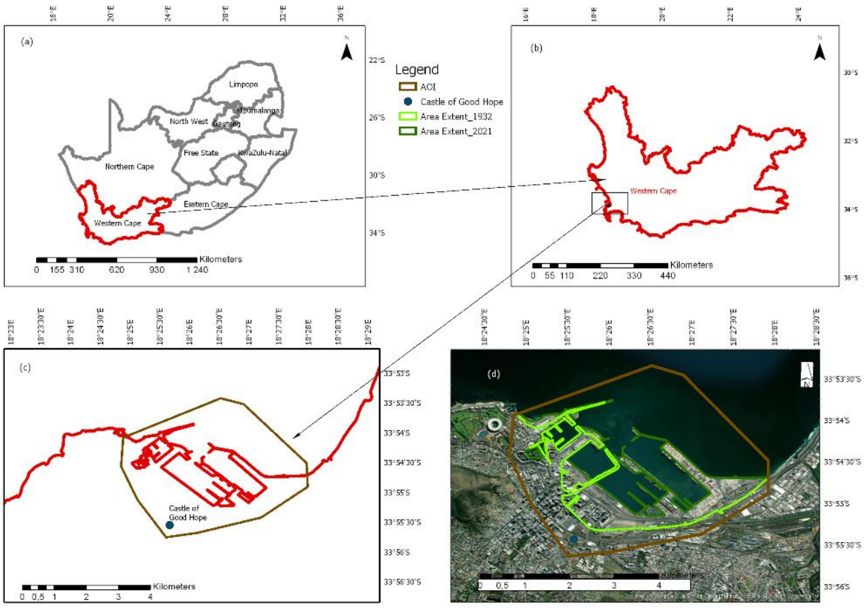


Figure 2(d) shows the Table Bay coastal zone, Cape Town, extending from the Castle of Good Hope to the harbour and foreshore. Established in 1652, the Castle marks the origin of urban development along a former shoreline (Abrahams, 1993; Bisset, 2012). Major land reclamation projects, particularly the Cape Town Foreshore, have significantly modified the coastline and enabled northward urban expansion since the early twentieth century (Anon, 2004).

3.2 Data Acquisition

Three sets of spatial data was used in the analysis of the land reclamation. These included the historical maps, aerial photographs and satellite data.

3.2.1 Historical Maps

Historical maps present significant documentation of topography changes over time (Pătru-Stupariu et al., 2011). The 1932 (1:25000) and 1942 (1:50000) historical topographic maps obtained from the National Geospatial Information Services (NGI) were the best available earliest high quality scanned maps illustrating sufficient spatial detail of the study area.

3.2.2 Aerial Photographs

Monochrome aerial photographs are suitable for providing evidence of historical landscape conditions (Chen & Tseng, 2016). The NGI portal furnished the 1973 and 1983 (1:20000 to 1:32000) photographs which were used due to their temporal coverage and comparable spatial extent of the study area.

3.2.3 Landsat Satellite Imagery

Multi-temporal Landsat 5 TM (L5) and Landsat 7 ETM+ (L7) Surface Reflectance (SR) images (30m resolution) is valuable for studying land use land cover change analysis over time since it provides a long-term record of Earth observations, and have been used for land reclamation on coastal surfaces. The data was accessed through Google Earth Engine (GEE) for the 1992-2001 (L5) , and 2002-2021 (L7) (Adegboyega et al., 2019; Lu & and Weng, 2007; Y. Shi et al., 2022; Yu et al., 2021).

3.3 Data Pre-processing

All datasets were referenced to the WGS84 coordinate system and clipped to the AOI to ensure spatial consistency. Hybrid classification approach was used for four (4) generic land cover classes; Bareground(0), Built_up(1), Vegetation(2) and Water(3), were used for training the classifiers.

3.3.1 Historical Maps (1932, 1942)

ArcGIS was used to georeferenced the maps using identifiable ground control points (GCPs) (Alberico et al., 2012), primarily the Castle of Good Hope bastions and harbour boundaries. Gridlines and annotations were masked to prevent misclassification of non-land features prior to object-based image analysis (OBIA) (Schlegel, 2023).

3.3.2 Aerial Photographs (1973, 1983)

ESRI ArcMap 10.8.2 was used for georeferencing the photos (Szostak et al., 2015) Accuracy was assessed using the root mean square error (RMSE) (Persia et al., 2020), and achieved RMSE ranging from 0,0000338397 to 0,000049. Since the photographs are single-band monochrome imagery, Supervised Maximum Likelihood Classification (MLC) was performed for the LULC

3.3.3 Landsat Satellite Imagery (1992-2021)

Best-pixel composites were generated for decadal epochs (1992–2001, 2002–2011 and 2012–2021) on GEE by removing atmospheric noise using pixel quality masks. All bands were converted to Float32 to optimise computational efficiency. And a supervised Random Forest (RF) algorithm was used for land cover classification due to robustness to noise and high accuracy in multi-spectral data.

3.4 Data Analysis

ArcGIS was used for post- classification analysis to compute area calculation, change detection and the rate-of-change (Sengupta et al., 2019).

Spatial and temporal analysis of land reclamation in Table Bay (1932–2021) was conducted using multi-temporal classified LULC datasets. ArcGIS was used to calculate area, detect changes, and compute rates of change for Bareground (0), Built_up(1), Vegetation(2), and Water(3) classes. Spatial analysis highlighted the geographic distribution and expansion of reclaimed land along nearshore and harbour zones. Temporal analysis quantified class-wise area changes across seven epochs, revealing long-term trends and inter-epoch variability. Results show significant reduction in water extent and expansion of built-up and bare ground, illustrating targeted coastal development and landscape transformation.

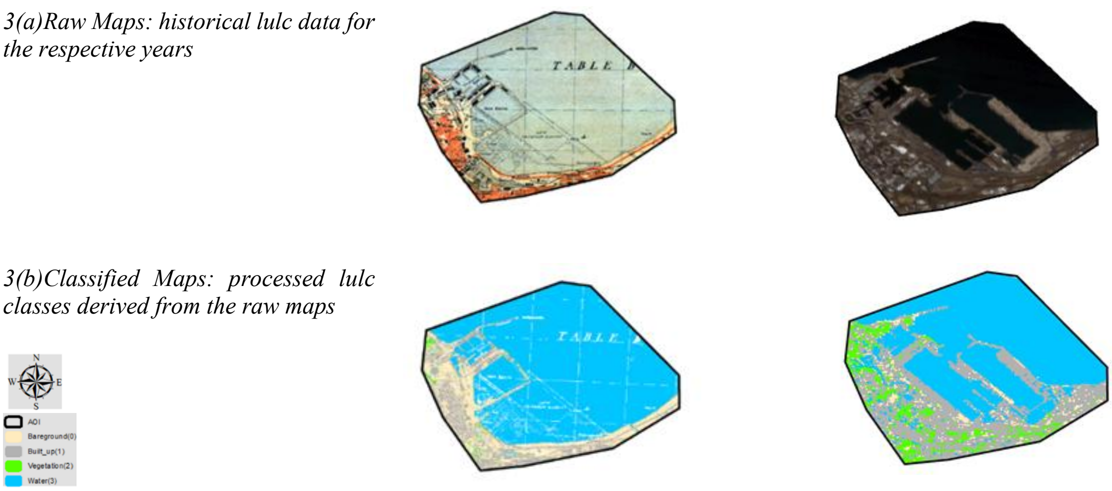
4. RESULTS AND DISCUSSION

4.1 Results

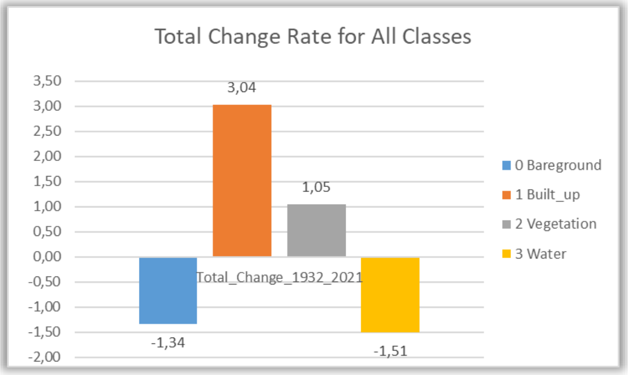
The classification results in Figure 3 revealed increase of the built-up area into coastal waters; an increase in Built_up areas (11,59% to 31,90%), a decrease in Bareground (14,81% to 4,10%), and Water (73, % to 56,07%), and a Vegetation enhancement (0,60% to 7,93%) of the total study area extent respectively.

Figure 3.(a)&(b) Raw and Classified Temporal variation in land cover classes, (c) Net Change rates of the land cover classes and (d)Decadal classification derived from multi-temporal LULC classification of Table Bay from 1932 to 2021. Water loss and built-up expansion indicate sustained land reclamation activity over the study period.

1932 **2012-2021**



3(c)Net Change rates of the land cover classes



The chart and table show a significant increase in of +3.04 in built-up areas, indicating urban expansion over the study period. Vegetation experienced a moderate increase of +1.05, while bareground experienced loss of -1.34 sqkm and water (-1.51 km²) areas declined, reflecting both coastal transformation and land reclamation activities. The figure highlights the dominant trend of anthropogenic development at the expense of natural land cover.

Figure 4(i): Temporal changes in land cover classes (1932–2021)

Gridcode	Class	1932		1942		1973		1983		1992to2001		2002to2011		2012to2021	
		Area(km2)	Area(%)	Area(km2)	Area(%)	Area(km2)	Area(%)	Area(km2)	Area(%)	Area(km2)	Area(%)	Area(km2)	Area(%)	Area(km2)	Area(%)
0	Bareground	1,93	14,81	3,50	26,89	1,84	12,92	2,87	20,17	0,34	2,37	0,36	2,53	0,58	4,10
1	Built_up	1,51	11,59	1,52	11,67	4,77	33,48	1,01	7,08	4,47	31,43	4,81	33,74	4,54	31,90
2	Vegetation	0,08	0,60	0,07	0,51	2,86	20,09	6,53	45,87	1,13	7,97	0,90	6,29	1,13	7,93
3	Water	9,49	73,00	7,94	60,95	4,77	33,48	3,83	26,88	8,29	58,27	8,18	57,43	7,98	56,07
		13,00	100,00	13,04	100,01	14,24	99,98	14,24	100,00	14,24	100,05	14,24	100,00	14,24	100,00

The area extents for 1932 and 1942 differ from the study area by 1,24sqkm (Figure 4(i)) from other periods. The difference is ascribed to the masked gridlines and annotations.

Figure 4(ii): Land Reclamation area trends in Table Bay (1932–2021)

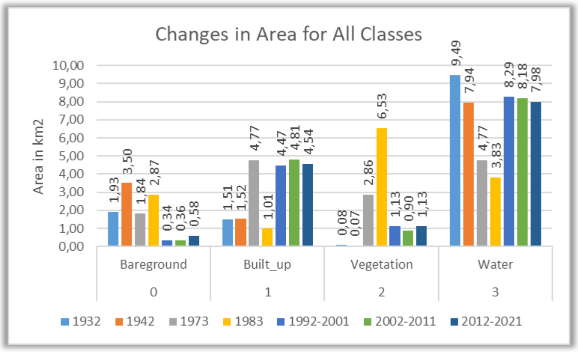
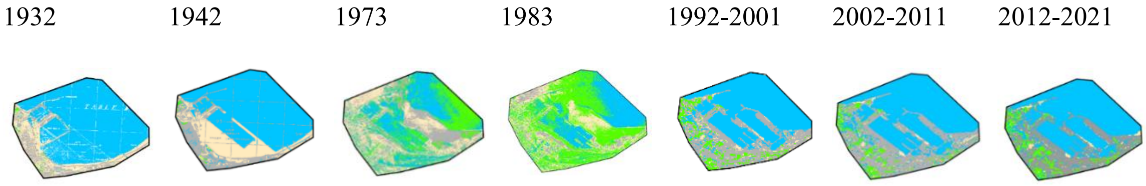


Figure 4(ii) illustrates the quantitative results derived from area statistics

Figure 4(iii): Rate of Change across study period (1932-2021)

Gridcode	Class	1932	1942	1973	1983	1992-2001	2002-2011	2012-2021	Total Change 1932-2021
0	Bareground	1,58	-0,63	1,03	-2,53	0,02	0,22	-1,34	-1,34
1	Built_up	0,01	-0,51	-3,76	3,47	0,33	-0,26	3,04	3,04
2	Vegetation	-0,01	6,46	3,67	-5,40	-0,24	0,23	1,05	1,05
3	Water	-1,55	-4,12	-0,94	4,47	-0,11	-0,19	-1,51	-1,51

Figure 4(iv): LULC classification analysis (1932–2021) to highlight the dynamics of the classes over nearly nine decades providing a thorough visual representation of coastal transformation



4.2 Discussion

4.2.1 Bareground (0)

Bareground reached its highest proportional coverage in 1942, accounting for 26.89% of the total study area. The most pronounced decline occurred during the 1992–2001 period, when bareground decreased to 2.37%, reflecting extensive land transformation. A slight recovery is observed in the 2012–2021 period, however, the coverage remains substantially lower than mid-twentieth-century levels. The overall decline in bareground area from 1932 to 2001 likely corresponds with progressive urban expansion and land reclamation.

4.2.2 Built_up (1)

The Built-up class consistently exceeded 30% of the total land cover between 1973 and 2021 illustrating sustained increase post 1973. This trend corresponds with major phases of harbour and port expansion during the latter half of the twentieth century. The observed increase of approximately 3.04 sqkm in built-up land suggests heightened economic and industrial activity associated with port operations and urban growth. A decline to 7.08% in 1983 is attributed to classification inconsistencies, where portions of built-up areas were misclassified as vegetation or water.

4.2.3 Vegetation (2)

The Vegetation cover shows temporal inconsistency across the study period. The 1983 dataset records a high vegetation fraction of 45.87%, largely due to spectral confusion in the aerial imagery, murky water surfaces were classified as vegetation. Furthermore, a steady long-term increase is evident, rising from 0.60% (1932) to 7.93% (2021). This increase may reflect landscaped areas, rehabilitated zones, or enhanced vegetated surfaces associated with urban development.

4.2.4 Water (3)

Water was the dominant land-cover class in five out of seven periods, occupying ~73% (9.49 km²) of the study area in 1932. A decline in water coverage is observed in subsequent periods, reaching a minimum of 26.88% by 1973. This apparent reduction is partly exaggerated by the spectral limitations of monochrome imagery used for the 1973 classification, largely due to spectral confusion in the aerial imagery, turbid water surfaces were classified as vegetation. By the 2012–2021 period, water coverage stabilised at ~7.98 km² (56.07%), reflecting the long-term effects of land reclamation while still maintaining its dominance in the study area.

5. CONCLUSION

The study reveals a significant long-term land use and land cover changes associated with the gradual land reclamation from the sea in the Table Bay Harbour between 1932 and 2021. The use of remotely sensed data and GIS-based analysis, demonstrated a considerable increase of reclaimed land at the expense of open waters, indicating changes of the coastal landscape. The reduction of the Water class from 9,49 to 7,98 sqkm reflects the cumulative harbour development and land reclamation activities, supported by empirical findings across multiple temporal datasets.

The precision of the change detection is resultant of the temporal gaps in the data and resolution of the historical data. Incomplete records limits the full reconstruction of land cover dynamics, whilst lower spatial resolution may introduce georeferencing errors. The study relies mainly on remotely sensed data; this approach is appropriate for long-term historical analysis where field validation is not always feasible. However, the classification accuracy could be enhanced with field observations to give confidence to the empirical findings. The use of simplified classification of the four generic classes may generalize more complex land cover types potentially masking mixed-use areas.

This study highlights the importance of long-term geospatial monitoring for sustainable coastal landscape planning and management.

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