Received: 25 Apr 2025 | Revised: 23 Aug 2025 | Accepted: 26 Jun 2026 | Published: 30 Jun 2026
Volume 4(1) Pages 1-25 DOI: https://doi.org/ 10.56279/jicts.v4i1.399

JICTS
Journal of ICT Systems

GIS and ICT Insights on Urbanization and Climate Change in Rapidly Growing Cities: A Case Study of Dar es Salaam, Tanzania

Joseph Mango

Department of Transportation and Geotechnical Engineering, University of Dar es Salaam, P. O. Box 35131, Dar es Salaam, Tanzania

Corresponding author
Email: *jsmmango@udsm.ac.tz*

Abstract

Rapid population growth and land-cover changes in Dar es Salaam have intensified climatic variability, yet their spatial and temporal dynamics remain insufficiently quantified and communicated for effective decision making. This study integrated Excel and R-Studio for statistical analyses, GIS for spatial modelling and visualization, and ICT insights to develop an interactive platform to address identified gaps. The results show that between 1990 and 2022, Dar es Salaam's population and built-up areas increased by 295.61% and 26.2%, respectively. Bushland grew by 5.1% while forest and grassland decreased by 4.2% and 25.9%, respectively. These changes were associated with a slight ($R^2 = 0.0219$) decrease in rainfall by 3.94 mm per year and an increase in temperature at 0.0469°C per year. A significant trend ($R^2 = 0.7514$) of rising temperatures occurred during long dry seasons and led to a severe drought between 2008 and 2016. A portion of these results is rendered dynamically in a web-based GIS dashboard, https://ilvjosem02.github.io/CoICT-Paper2/, designed to enhance visibility and practical applications of the study's findings. Testing queries demonstrate that the designed dashboard can be accessed to re-analyze and export its information based on users' demands.

Keywords
Climatic trends
Drought
GIS and ICT techniques
Population and land-cover dynamics
Web-based GIS dashboard

1. Introduction

Climate change is one of the key global challenges that has been caused by human and natural factors. A report by the Intergovernmental Panel on Climate Change (IPCC) shows that the world's mean temperature is expected to increase from 1.4°C to 5.8°C by 2100 due to industrial activities. Studies [1-4] indicate that agricultural activities significantly reduce natural vegetation, which is vital for reducing greenhouse gases and mitigating global warming. The loss of vegetation and rise in temperature also disrupt rainfall patterns and lead to drought [5-7]. In urban areas and cities

connected to coastal regions, the three key climatic variables—rainfall, drought and temperature—highlighted by the mentioned global studies are not critically studied alongside their underlying factors to help achieving Sustainable Development Goal No. 13 [8, 9].

Burian and Shepherd [10], for example, used rain gauges data to investigate the impact of urbanization on local diurnal rainfall in Houston. The results showed that urban areas exhibited different patterns, with significantly more rainfall than the upwind and downwind adjacent regions. Govender, Dube [11] and Huang, Zhang [12] used remote sensing and in-situ datasets and the indices of Standardized Precipitation Index (SPI), Palmer Drought Severity Index (PDSI), Normalized Difference Vegetation Index (NDVI) and Standardized Precipitation Evapotranspiration Index (SPEI) to explore the challenges of drought due to Land-Use and Land-cover (LULC) and rainfall variations. These studies sought to determine precipitation behaviors across regions.

Other studies, such as the one conducted by Nayak and Mandal [13], investigated the impacts of LULC changes on temperature trends using the 'observation minus reanalysis' method. The findings demonstrate that the Western India's temperature increases by 0.13°C per decade. Mukherjee and Singh [14] researched the impacts of vegetation changes on Land Surface Temperature (LST) in Surat and Bharuch. The study exhibits that the areas with decreased vegetation experienced an increase in LST. The increase in LST that primarily measures the influence of urbanization to climate change has also been reported in the cities of Osmaniye-Turkey, Delhi-India, and Hefei-China [15-18].

At the local scale, similar trends have been reported in rapidly growing cities, including Dar es Salaam, Tanzania. Land-use research by Mnyali and Materu [19] shows that approximately 33.7% of vegetation in Kinondoni municipal has been lost due to settlements, which increased by 30% from 1999 and 2019. This research also reports that there is an increase in temperature due to the expansion of built-up areas. Simon, Lyimo [20] also identified the rise in temperature from their work, demonstrating that, between 1995 and 2022, built-up areas and agricultural land in Dar es Salaam increased by 14.87% and 4.47%, respectively. Overall, these studies discuss the impacts of climate change as the consequence of urbanization studied with the remote sensing data.

A work by Kabanda [21] is among the very few research that employed in-situ datasets to examine trends in climatic parameters. In this work, Mann-Kendal and Sen's slope indices were used to assess rainfall, showing a declining trend from 1953 to 2011. Despite its significant contribution, this study lacks up-to-date rainfall information as it has more than 10 years old. Additionally, it lacks similar insights for the thermal and drought conditions, which are important for a comprehensive understanding of climate variability.

Besides this gap, the reviews of all studies show that there is a lack of an integrated analyses linking climate change with population growth and land-cover transformations. This void constrains a holistic understanding of the interactions between human activities and environmental dynamics in shaping adverse climatic outcomes. Another deficiency identified in the literature pertains to the manner in which findings are presented. All the reviewed studies used static platforms, such as journal articles and reports, to disseminate their findings [22-25]. Despite numerous advantages, such platforms limit opportunities for interactive exploration, real-time updates, and broader accessibility. As a result, the usability of the findings in decision-making, policy formulation, and public awareness remains constrained.

This study was designed to address the gaps identified using GIS and ICT techniques, and it aimed to realise this objective using remote sensing and in-situ datasets (1990–2022) from Dar es Salaam, Tanzania. The specific targets formulated in alignment with the main objective were as follows:

1. To determine spatiotemporal changes of population and land-cover.
2. To determine trends of rainfall and temperature at different temporal resolutions.
3. To assess drought conditions in relation to the rainfall trends.
4. To develop a web-based GIS dashboard to communicate the findings with spatial contexts.

The research questions formulated were as follows:

1. How did population and land-cover in Dar es Salaam changed from 1990 to 2022?
2. What are the temporal trends of rainfall and temperature in Dar es Salaam from 1990 to 2022?
3. Did Dar es Salaam experience drought between 1990 and 2022? When?
4. How can ICT be used with GIS to dynamically present the findings with spatial context to enhance their accessibility and usability in the society?

2. Method

2.1 Study area

Dar es Salaam, found along the eastern coast of Africa, is the largest city in Tanzania (Figure 1). It serves as a major economic hub of the country as it hosts the largest port, which is vital for international trade. The city area covers 1617 sq. Km and had a population of 5.5 million people by 2022 as per the National census. Its topography is mostly flat, though in other areas it has gentle hills and undulations reaching 270 m.

Climatologically, Dar es Salaam is classified under the tropical wet and dry climate type by the Köppen classification, and has two distinct seasons: wet and dry [26, 27]. The wet season occurs from October to December and from March to May, and receives short and long rains that reach up to 800 mm and 1,300 mm, respectively [25, 28]. The dry season occurs from June to September and from January to February, and experiences higher temperatures ranging from 28°C to 33°C. This climate, along with other factors such as the condition of its port serving multiple landlocked countries like Uganda, Rwanda, Burundi, Zambia, Congo, and Malawi, attracts many people to live and engage in various socio-economic activities.

2.2 Datasets

The study utilized in-situ and remote sensing datasets to achieve its objectives (Table 1). First, it used the 1988 and 2022 populations from the Tanzania National Bureau of Statistics (NBS). The 1988 population was used as the best estimate of the 1990 population because there were no census records in this year. Furthermore, the option of projecting the 1988 population to 1990 was considered insignificant due to the low population and growth rate by then [29, 30]. Second, the study used land-cover data from the Landsat 5 (TM) and 8 (OLI) sensors. These data with a 30-meter spatial resolution were downloaded using codes in Google Earth eEngine (GEE). The time set during data download was limited to the summer's months to get rid of clouds obstructing clear visibility of the mapped features.

In-situ climate data from the Tanzania Meteorological Agency (TMA) was also used to reveal precipitation, temperature and drought trends. The trends of this data were assessed in relation to population and land cover changes. Additionally, the study deployed Climate Hazards Group InfraRed Precipitation (CHIRPS) dataset and bands 6 and 10 of the Landsat imagery to investigate spatial temporal variations of precipitation and temperature, respectively. This dataset from the GEE was downloaded using codes as for the land-cover data. After being collected, all data were sorted and harmonized to the same spatial reference system and standardized format to ensure consistency and compatibility within the program/software used in the next stage.

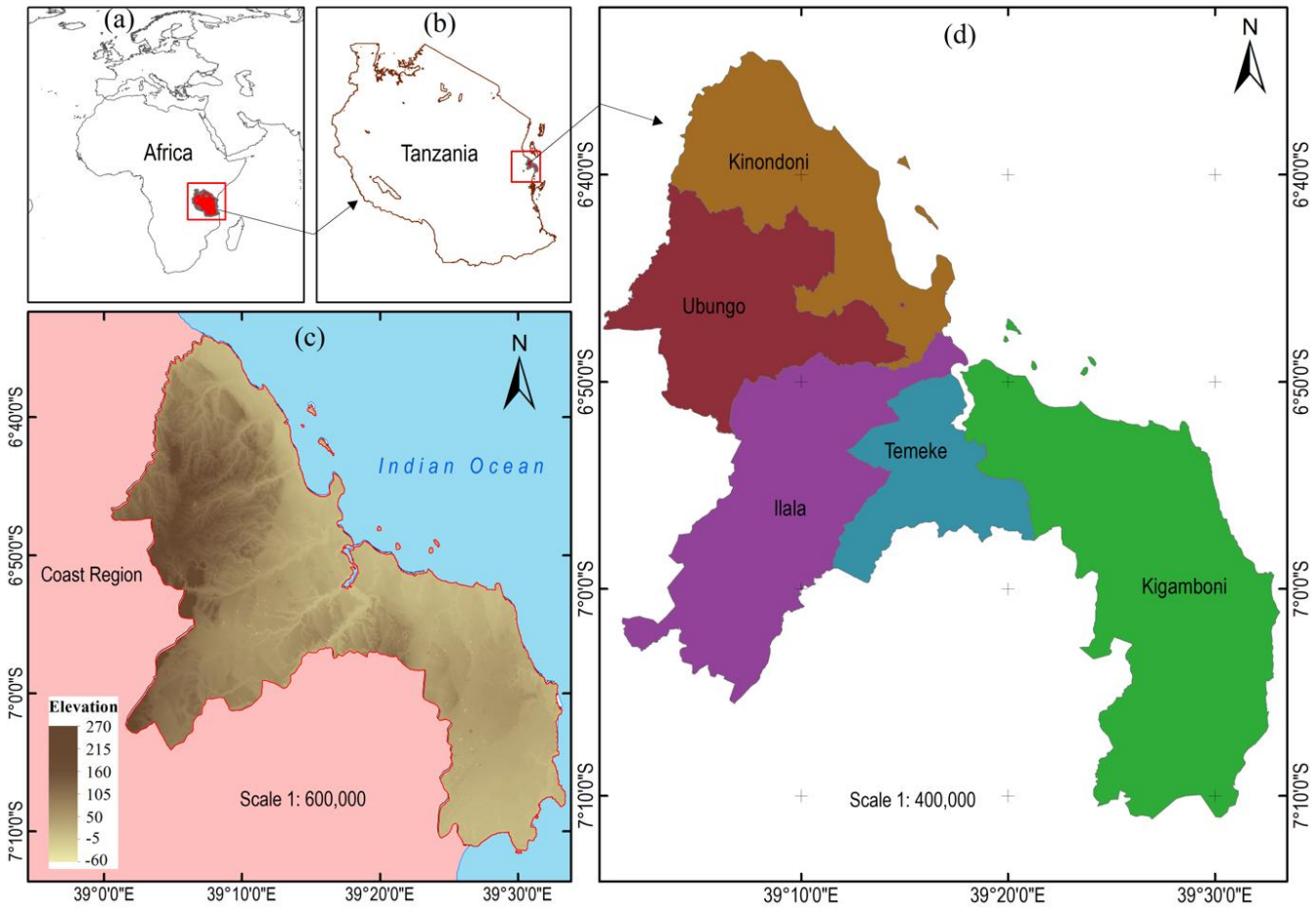


Figure 1. Location of Dar es Salaam in (a) Africa and (b) Tanzania maps (c) and (d) are elevation and districts of Dar es Salaam, respectively.

Table 1. Datasets deployed in the study.

SN	Data	Source	Time	Format
1	Population	NBS	1988 and 2022	Shapefile and CSV
2	Land cover	Landsat 5 imagery of the GEE	Summer, 8 August 1990	Raster
3	Land cover	Landsat 8 imagery of the GEE	Summer, 03 June 2022	Raster
4	In-situ Precipitation	TMA	Monthly from 1990 to 2022	CSV
5	In-situ Temperature	TMA	Monthly from 1990 to 2022	CSV
6	Remote Sensing Precipitation	CHIRPS of the GEE	1990 and 2022	Raster
7	Remote Sensing Land Surface Temperature	Band 6, Landsat 5 imagery of the GEE	1990	Raster
8	Remote Sensing Land Surface Temperature	Band 10, Landsat 8 imagery of the GEE	2022	Raster

2.3 Population and land-cover data processing

Population and land-cover data of the city was processed using Microsoft Excel and ArcGIS software. Residents' data from NBS was given in the *Excel and Shape* files. Using spatial join command within the ArcGIS, these two files were merged and checked by labelling street names and their corresponding codes. The analysis focused on determining spatial distribution and trends of people was performed on the merged files using the dot density function. This function processes qualitative information and has been widely applied in similar studies [31, 32]. The scale of a dot adopted was set to 5 for clarity and easy assessment of the patterns related to humans.

Land-cover of city was detected using a supervised classification method for seven classes (Table 2): agriculture, bare soil, built-up areas, bushland, forest, grassland, and water. The algorithm used to classify identified land-cover categories is of the Maximum likelihood. Accuracy analysis of the results was evaluated using Kappa coefficients indicated in equation (1). The assessment involved comparing classification results and Google Earth's data used as the ground data source. In the final stage, we computed transformation matrix to determine the probabilities of land-cover classes changing from one state to another within the system.

$$K = \frac{P_0 - P_e}{1 - P_e} \quad (1)$$

From (1), P_0 is the observed agreement (or observed accuracy) between the classification and the reference data, and P_e is the expected agreement (or chance agreement) between the classification and the reference data.

2.4 Rainfall and temperature data processing

Processing of the in-situ rainfall and temperature data from TMA was done using Excel. Step one removed the data whose scope was not defined in the study. Step two processed the remaining data to produce graphs and statistics, including maximum, minimum and mean values on a monthly, annual, and seasonal basis. The trends of both data were computed using regression equations, which have been used in many similar cases [33, 34]. The main focus put on the results with the mentioned equations aimed to determine whether rainfall and temperature were increasing, decreasing, or remaining stable across the study period. The next set of the temperature data with the

Table 2. Dar es Salaam' land-cover classes studied in this work.

Sn	Land cover	Definition	Colour used for recognition
1	Water	Streams, lakes, ponds, and reservoirs	Blue hue
2	Bareland	Uncovered soil and desolate lands	Brown hue
3	Grassland	Predominantly grassy areas	Brown/Light green shade
4	Forest	Areas with tree canopy, forestland, and dense growth	Dark green shade
5	Agriculture	Farmland and idle fields	Light green shade
6	Bushland	Areas mainly consisting of vegetation and sparse bush	Medium green shade
7	Built-up	Residential, industrial, transport, and mixed urban areas	Purple/silver shade

remote sensing source was processed to extract and calibrate monthly LST from bands 6 and 10 of the Landsat 5 and 8 imageries, respectively in GGE. Both bands contain same information, but their arrangement in sensors used in 1990 and 2022 are different. The monthly precipitation data which was also captured with the satellites was processed by smoothing coarse grids (4.8-km grid (1/20 deg)) into points which were later interpolated using the Inverse Distance Weighted (IDW) method [35-37]. The interpolation process aimed to harmonize spatial resolution of this data for consistency with other datasets used in the study.

2.5 Determination of Drought conditions

Drought conditions in Dar es Salaam were processed in R Studio. We used in-situ precipitation data to compute Standard Precipitation Index (SPI) values and analyze their distribution based on the categories outlined in Table 3. The SPI (Equation (2)) measures drought intensity by standardizing precipitation data over time, which can be analyzed at various intervals, such as monthly or yearly [38-41]. In this study, the time interval for SPI computations was set to every three-month period. Drought trends, on the other hand, were determined using a Sequential Mann-Kendall test at 95% confidence interval. This test, overall, identifies a point where a trend begins, how it develops over time and whether or not the trend is statistically significant [42]. The test-lines crossing interval-lines of the test reveal extreme drought. We carried out this test within the trend change package to generate the prograde (U(t)), retrograde (U'(t)), and confidence interval values exported to Excel to generate final graphs.

Table 3. Standard SPI information used in the study.

SPI range values	Category
-2.00 or more	Extreme drought
-1.50 to -1.99	Severe drought
-1.00 to -1.49	Moderate drought
-0.99 to 0.00	Mild drought

$$SPI = \frac{X_i - X_m}{SD} \quad (2)$$

From (2), the SPI stands for a Standardized Precipitation Index, the X_i refers the rainfall noted on monthly, seasonal and annual basis. The X_m and SD refer to the long-term mean and standard deviation of rainfall, respectively.

2.6 Web-Based GIS-Dashboard development

2.6.1 System architecture

The dashboard that we developed comprises three platforms for storing and sharing information (Figure 2). The first platform (GIS server) is responsible for collecting, storing, customizing, and displaying spatial data. It ensures that datasets are well-structured and maintained in a way that supports dynamic spatial queries and analyses. The second platform provides interface for users to access the disseminated information. It summarizes the key findings and integrates web maps hosted on the GIS server. The third platform is dedicated to live hosting and deployment of the web page and its associated resources. This platform ensures that the dashboard is publicly accessible.

2.6.2 Implementation design

Implementation design of the dashboard has various procedures at the back-end (developer side) and front-end (user side). At the front-end, the dashboard uses HTML (coded in Sublime Text Editor 2) to structure the web page with two sections: a header and a body. The header defines the page title and applies CSS and JavaScript for styling and interactivity, while the body displays the web maps using similar scripts [43, 44]. The back-end prepares thematic maps through the ArcGIS Server, which generates links for the web maps. These links are then embedded into the corresponding sections of the web page, which is hosted on GitHub for online access.

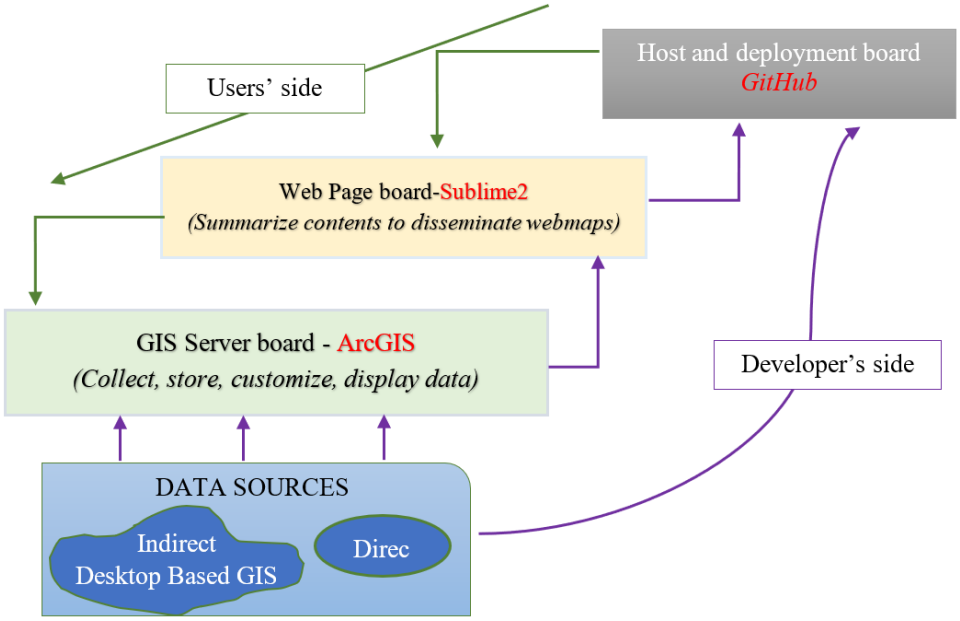


Figure 2. System for sharing information in the proposed dashboard.

3. Results

3.1 Dar es Salaam 's population and land cover dynamics from 1990 to 2022

Population and land cover results show that Dar es Salaam experienced significant changes between 1990 and 2022. The 1988 census reveals that Dar es Salaam had 52 neighborhoods and 1,360,850 residents (Figure 3(a)). The 2022 census indicates that the city's neighborhoods increased to 102, and residents increased to 5,383,728 (Figure 2(b)). In percentage terms, the number of neighborhoods and residents increased by 96% and 295.61%, respectively. Spatial distribution maps show that population concentration is highest in the city centre, particularly in areas such as Kariakoo and Posta. Other densely populated areas are found in the northern parts of the city, particular in the Ilala, Ubungo, and Kinondoni districts. The southern areas, on the other hand, consistently exhibit the lowest population density. According to the Kigamboni Municipal Council's Socio-Economic Profile, the south areas, which include Kisarawe II, Kimbiji and Somangira wards are not well developed in terms of infrastructure, such as roads, electricity, water supply, health centers, and schools, and, therefore, their low populations could be attributed by the lack of such services. Additionally, the profile indicates that many areas of the mentioned wards are recently included in the urban master plan of the district, and hence, they are still in early stages of urbanization, with the ongoing land surveying and planning efforts [45-47].

On land-cover, the Kappa coefficient results show that all studied classes were accurately classified with the overall accuracy exceeding 80% (Tables 4 and 5). The classes with highest accuracies include water body (user-accuracy > 87%), agriculture (user-accuracy > 79%), built-up (user-accuracy > 79%) and forest (user-accuracy > 70%). According to Seto, Güneralp [48] and Baccini, Walker [49], the anthropogenic activities associated with these classes play significant roles in contributing to adverse climate change and, thus, their high accuracies achieved provide close approximations of the thoughts hypothesized in this study. Figure 4, which presents the results of classified imagery, shows that a large part of Dar es Salaam in 1990 was occupied by forest and agricultural areas. The 2022 land-cover results show that these areas have significantly decreased

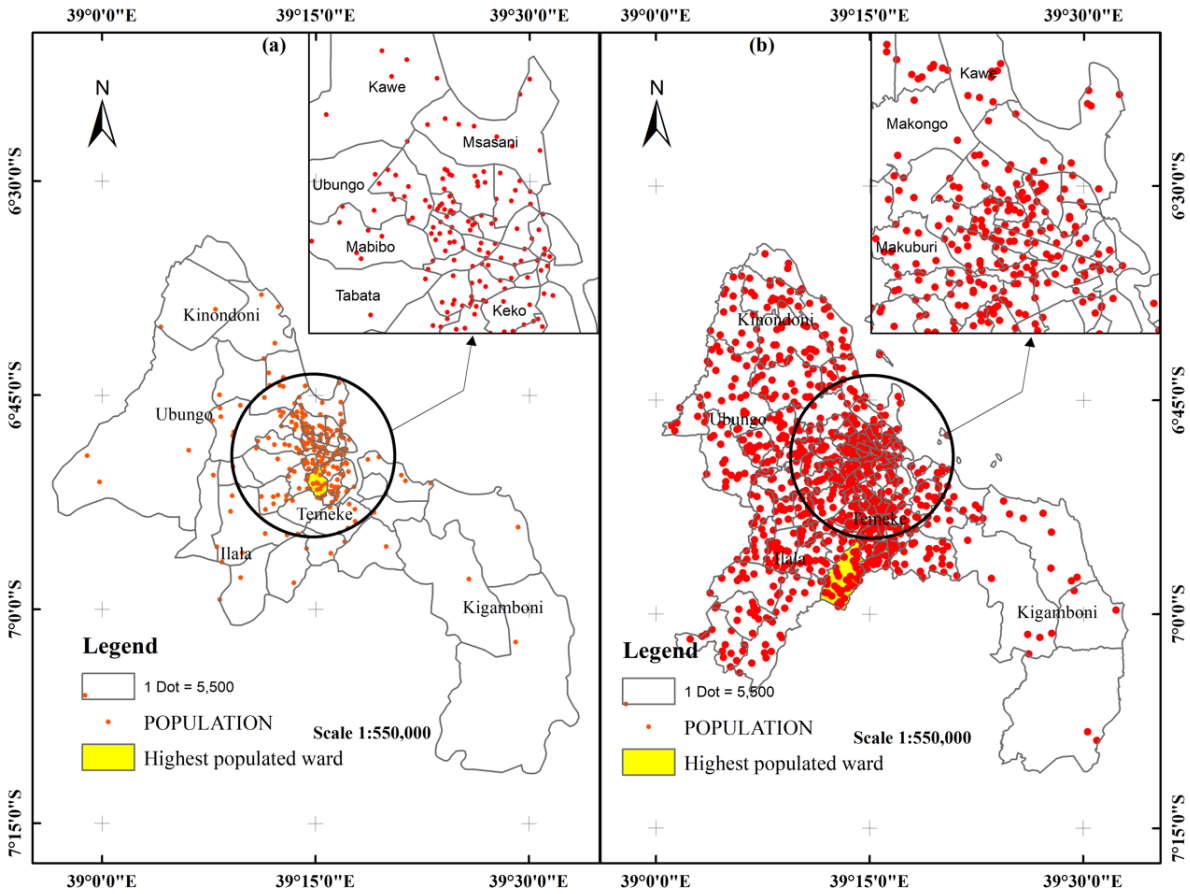


Figure 3. Dar es Salaam's population in 1988 (a) and 2022 (b).

with the expansion of the built-up area. The spatial patterns and trends of built-up areas from 1990 to 2022 align with population growth demonstrated in Figure 3.

Table 4. Classification accuracy results of the 1990 image shown in Figure 4(a).

Land cover	Agriculture	Bareland	Bushland	Forest	Grassland	Built_up	Water	Total	U-Accuracy
Agriculture	224	1	1	11	41	5	0	283	0.79
Bareland	1	1	0	0	0	0	0	2	0.5
Bushland	2	0	10	10	0	0	0	22	0.45
Forest	8	0	4	388	10	0	1	411	0.93
Grassland	40	0	3	21	131	11	1	210	0.62
Built-up	2	0	2	0	2	23	0	29	0.79
Water	0	0	0	1	0	0	22	23	0.87
Total	277	2	20	431	184	39	22	975	0
P-Accuracy	0.81	0.5	0.5	0.9	0.71	0.59	0.8		0.8

Table 5. Accuracy assessment results for the classified 2022 image shown in Figure 4(b).

Land cover	Agriculture	Bareland	Bushland	Forest	Grassland	Built up	Water	Total	U-Accuracy
Agriculture	10	0	0	0	0	0	0	10	1
Bareland	2	8	0	0	0	0	0	10	0.8
Bushland	1	0	7	0	0	2	0	10	0.7
Forest	0	0	1	7	0	1	1	10	0.7
Grassland	0	1	0	0	8	1	1	11	0.8
Built-up	1	0	0	0	1	8	0	10	0.8
Water	2	0	1	0	0	0	76	79	0.9
Total	16	9	9	7	9	12	78	140	0
P-Accuracy	0.63	0.88	0.78	0.89	0.89	0.66	0.8		0.89

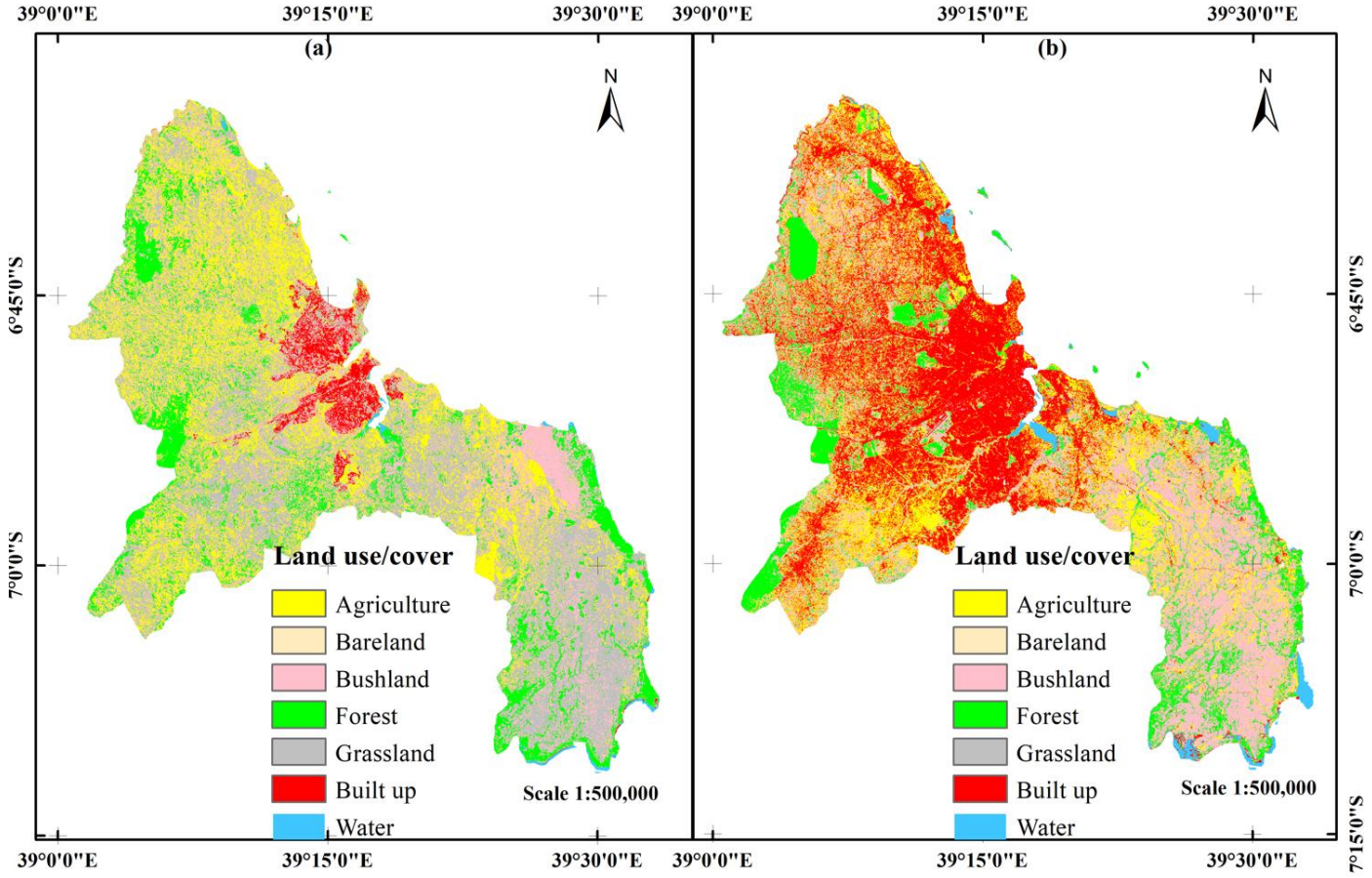


Figure 4. Dar es Salaam's land cover in 1990 (a) and 2022 (b).

When examined to understand land-cover transformations, the results revealed that, despite its dominance, bushland in some areas decreased significantly into built-up areas (12,389.56 ha, ≈28.31%) and agricultural areas (9,692.71 ha, ≈22.15%) (Tables 6 and 7). The significant conversion of bushland highlights the pressure of urban expansion and agricultural development on

natural landscapes. Other land covered with substantial transformations include agricultural, Bareland and forest areas. A large portion of agricultural areas from 1990 has been transformed into built-up areas (13,568.52 ha, ≈34.26%) and bushland areas (11,298.16 ha, ≈28.53%), indicating a shift in land use priorities driven by population growth and changing economic activities. Bare land areas have also undergone considerable transformations into bushland areas (138.36 ha, ≈28.94%), built-up areas (108.25 ha, ≈22.64%) and agricultural areas (84.98 ha, ≈17.77%). Furthermore, forest areas, which occupied 16.1% of the total land in Dar es Salaam in 1990, have been significantly reduced into bushland areas (6,638.99 ha, ≈30.27%), agricultural areas (4,819.50 ha, ≈18.93%), and built-up areas (4,674.29 ha, ≈18.35%). The extent of these transformations reveals significant gains in built-up areas at the expense of natural vegetation, including forests, bushland and grasslands. In 1990, natural vegetation covered 113,326.53 ha (70.30%) of the study area, but by 2022, this coverage decreased to 73,016.41 ha (45.29%). The dramatic reduction of natural vegetation underscores the profound impact of land-use changes on the region's natural ecosystems. This observation highlights the need for sustainable development strategies to balance the changes observed.

Table 6. Matrix of land-cover (in hectares) transformed from 1990 to 2022.

Land Class		Land cover 2022							Total
		Agriculture	Bare land	Built-up	Bush and	Forest	Grassland	Water	
Land cover 1990	Agriculture	10809.77	266.34	13568.52	11298.16	3317.62	232.87	105.65	39598.94
	Bare land	84.98	3.33	108.25	138.36	64.96	14.95	63.32	478.14
	Built up	380.03	15.97	5058.67	116.46	50.27	17.52	29.02	5667.93
	Bushland	9692.71	198.54	12389.56	15721.46	4919.37	427.16	417.72	43766.53
	Forest	4819.50	166.59	4674.29	7708.47	6638.99	214.04	1244.23	25466.11
	Grassland	10254.37	198.36	11392.68	17012.97	3282.10	368.72	99.23	42608.42
	Water	35.14	4.41	39.27	25.62	41.60	1.49	235.81	383.35
	Total	36076.52	853.53	47231.24	52021.50	18314.92	1276.75	2194.97	157969.43

Table 7. Matrix of land-cover (in percentage) transformed from 1990 to 2022.

Land cover		2022						
		Agriculture	Bare land	Built-up	Bush land	Forest	Grass land	Water
1990	Agriculture	27.30	0.67	34.26	28.53	8.38	0.59	0.27
	Bare land	17.77	0.70	22.64	28.94	13.59	3.13	13.24
	Built-up	6.70	0.28	89.25	2.05	0.89	0.31	0.51
	Bushland	22.15	0.45	28.31	35.92	11.24	0.98	0.95
	Forest	18.93	0.65	18.35	30.27	26.07	0.84	4.89
	Grassland	24.07	0.47	26.74	39.93	7.70	0.87	0.23
	Water	9.17	1.15	10.24	6.68	10.85	0.39	61.51

3.2 Trends of rainfall and temperature in Dar es Salaam from 1990 to 2022

The results show that the city's rainfall and temperature varied significantly. The linear regression equation indicates that annual rainfall slightly decreased by 3.94 mm per year (R^2 = 0.0219). The trend of decrease in rainfalls was more significant between 1990 and 1999 (Figure 5). During short dry seasons, rainfall also decreased but with the trend which was not statistically significant (R^2 = 0.0209). Specific results reveal that, before 2004 and between 2007 and 2015, high rainfalls occurred in February. Then, they shifted to January in the other years of the study (Figure 6). Rainfall during long dry seasons also decreased with the significant trend as during the short dry seasons (Figure 7). However, relatively, the coefficient of determination (R^2 = 0.0712) highlights a more decrease in rainfall. The sharp changes of decrease in rainfall during long dry seasons occurred in 2007.

Rainfall during short rainy seasons also decreased but with the insignificant trend, R^2 = 0.03 (Figure 8). During long rainy seasons, rainfall increased slightly due to interannual fluctuations as the graph does not display any consistent upward trend (Figure 9). Monthly results indicate that the average rainfall during short rainy seasons was 95 mm, whereas the long rainy seasons averaged 199 mm. They also demonstrate that a large part of

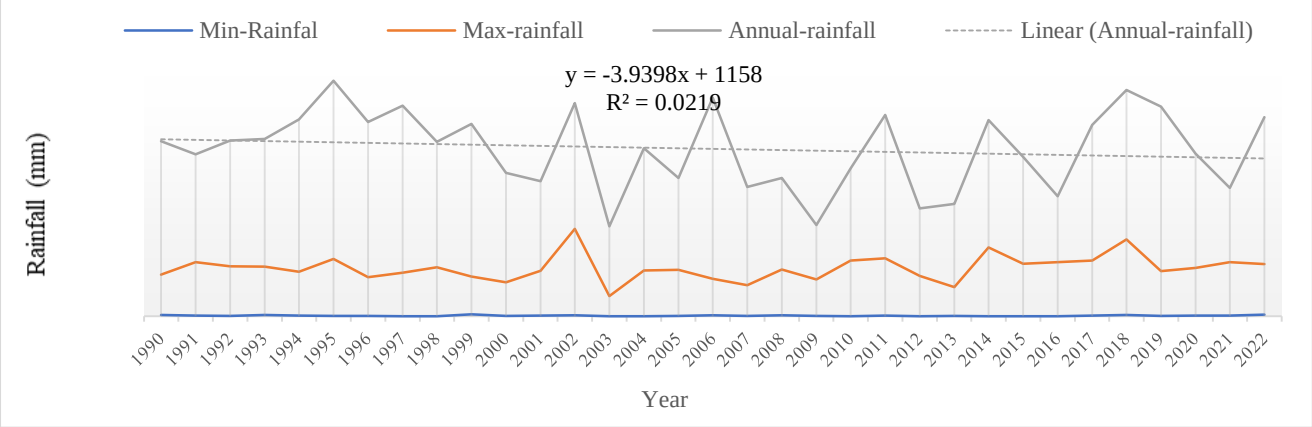


Figure 5. Yearly trend of rainfall in Dar es Salaam from 1990 to 2022.

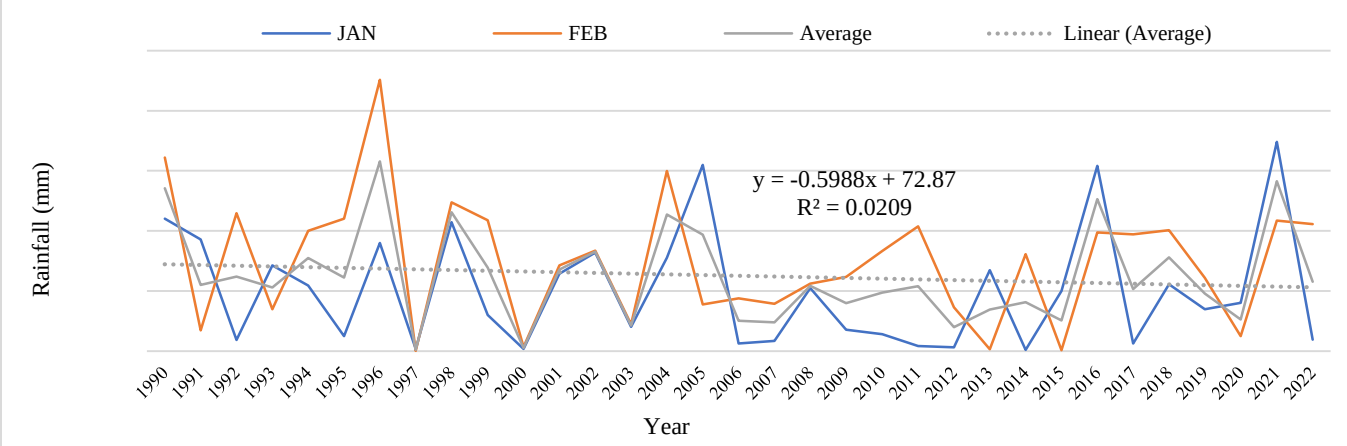


Figure 6. Trend of rainfall in Dar es Salaam during short dry seasons.

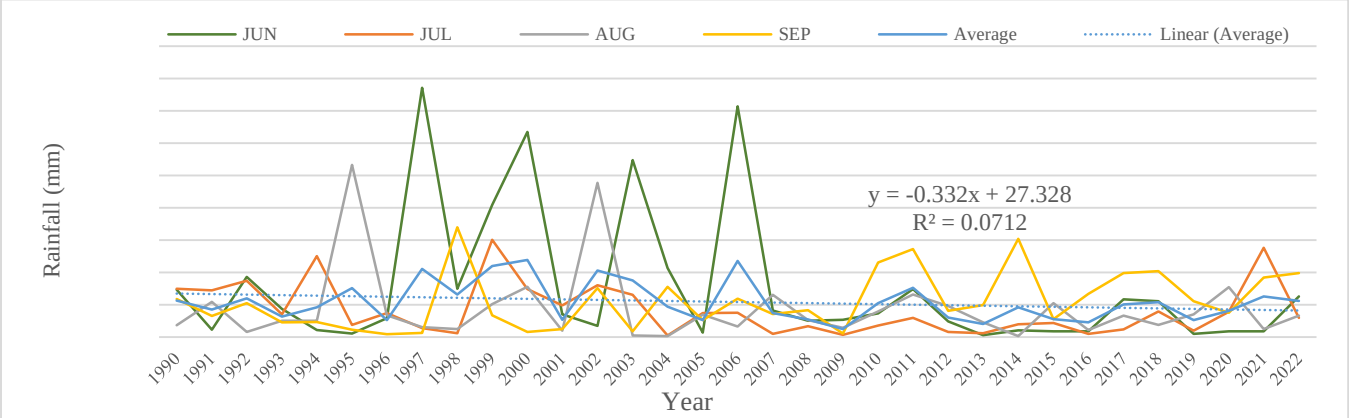


Figure 7. Trend of rainfall in Dar es Salaam during long dry seasons.

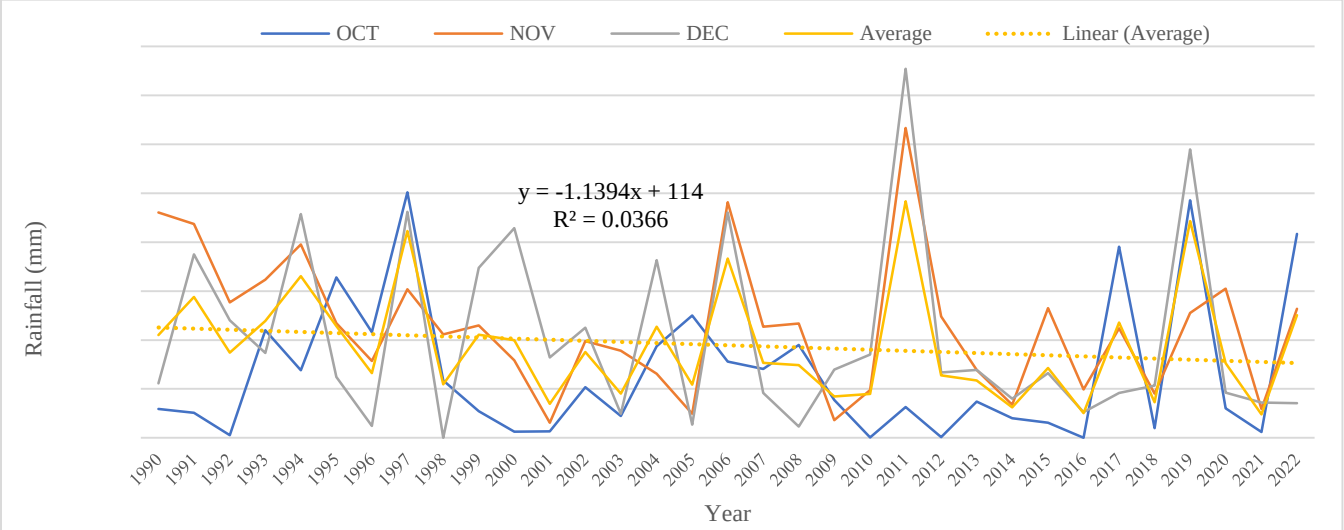


Figure 8. Trend of rainfall in Dar es Salaam during short rainy seasons.

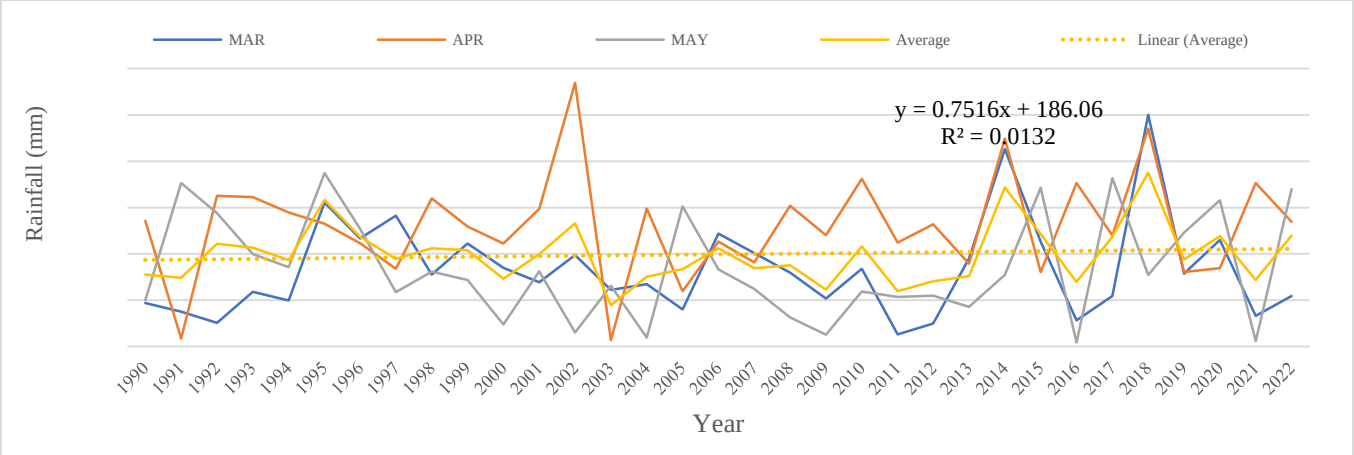


Figure 9. Trend of rainfall in Dar es Salaam during long rainy seasons.

rainfall during short rainy seasons was large part of rainfall during short rainy seasons ranged between 10 mm and 250 mm, and the peak of 377.2 mm was recorded in October 2011. For the long rainy seasons, the average rainfall typically ranged between 100 mm and 300 mm, and the peak of 569.4 mm was observed in April 2002.

A study on spatial distribution demonstrates that between 1990 and 2022, rainfall decreased more in the northern and coastal areas, which include Somangila ward, and increased more in the central and southwest areas, which include Ukonga, Segerea, and Kipawa wards (Figure 10). These results, overall, highlight the complex interplay between natural and human factors in shaping local climate patterns. For instance, Somangila Ward, which experienced a decrease in rainfall, is not extensively developed and has a relatively lower population compared with other areas that recorded higher rainfall.

Temperature, on the other hand, consistently increased at a rate of 0.0469°C per year. The increased rate is statistically significant with an R^2 value of 0.6226 (Figure 11).

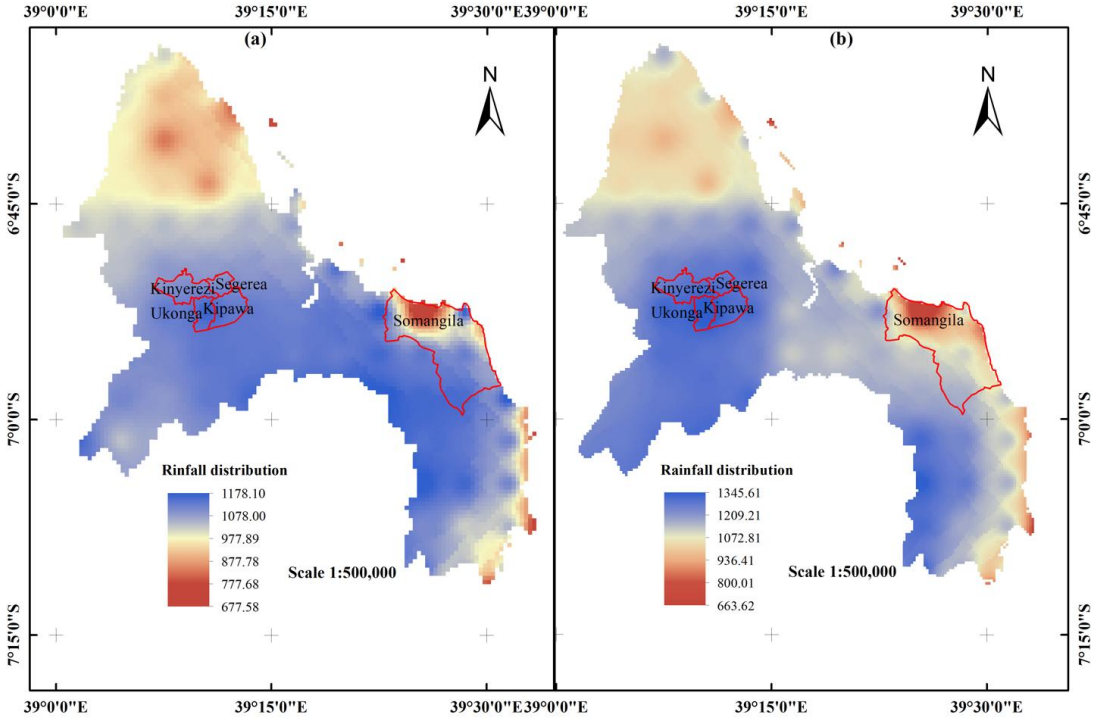


Figure 10. Spatial distribution of rainfall in Dar es Salaam in 1990 (a) and 2022 (b).

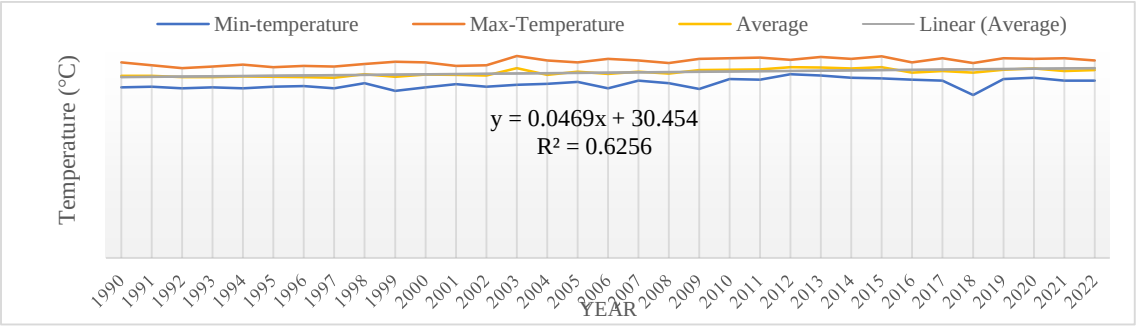


Figure 11. Yearly trend of temperature in Dar es Salaam from 1990 to 2022.

The average temperatures in 1990 and 2022 were 30.75 °C and 31.68 °C, respectively. Monthly analysis shows that April 2018 was the coolest month, with an average temperature of 27.5 °C and March 2003 was the warmest month with an average temperature of 34.1 °C.

The seasonal analysis also reveals that temperature increased consistently during all seasons. During short dry seasons, temperature increased insignificantly ($R^2 = 0.3604$) from 31.7°C to 33.3°C (Figure 12). Long dry seasons demonstrate a statistically significant ($R^2 = 0.7514$) increase in temperature from 29.1°C to 31.1°C (Figure 13).

Temperature during short rainy seasons increased moderately ($R^2 = 0.4203$) at a rate of 0.0495°C (Figure 14). This rate is almost similar with the yearly trend observed from 1990 to 2022. The long rainy seasons show an increase in temperature, which is not statistically significant ($R^2 = 0.2243$). The highest temperatures occurred in May (Figure 15).

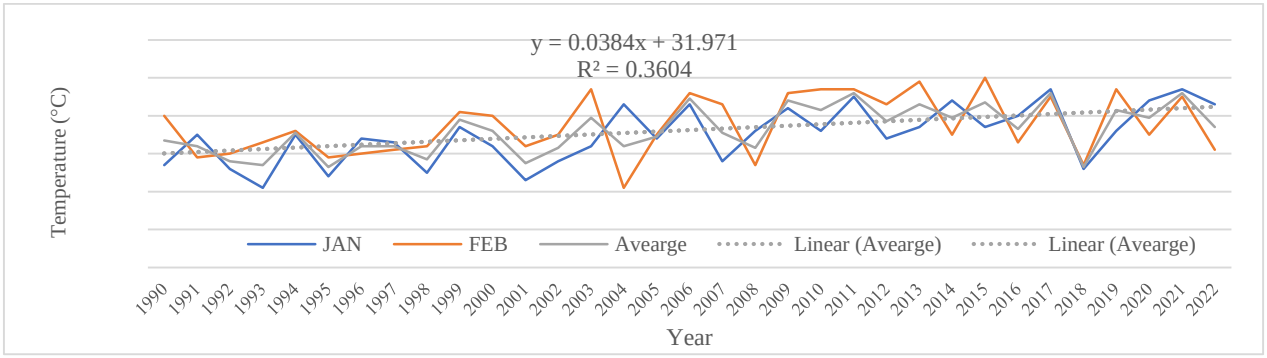


Figure 12. Trend of temperature in Dar es Salaam during short dry seasons.

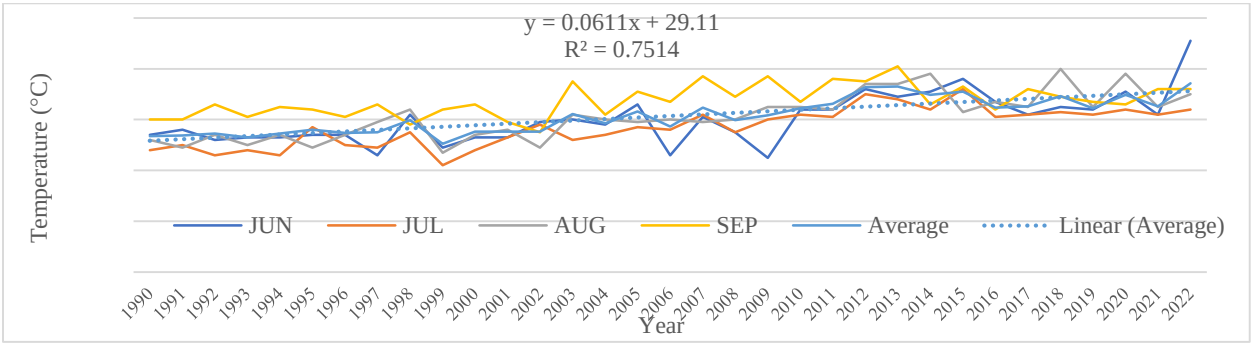


Figure 13. Trend of temperature in Dar es Salaam during long dry seasons.

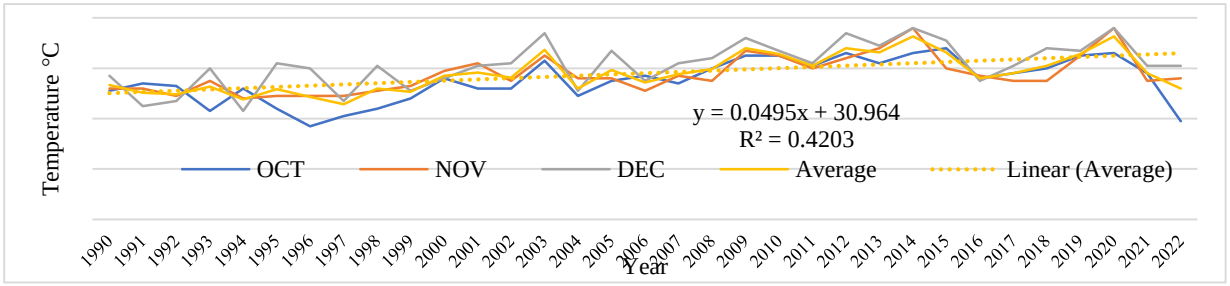


Figure 14. Trend of temperature in Dar es Salaam during short rainy seasons.

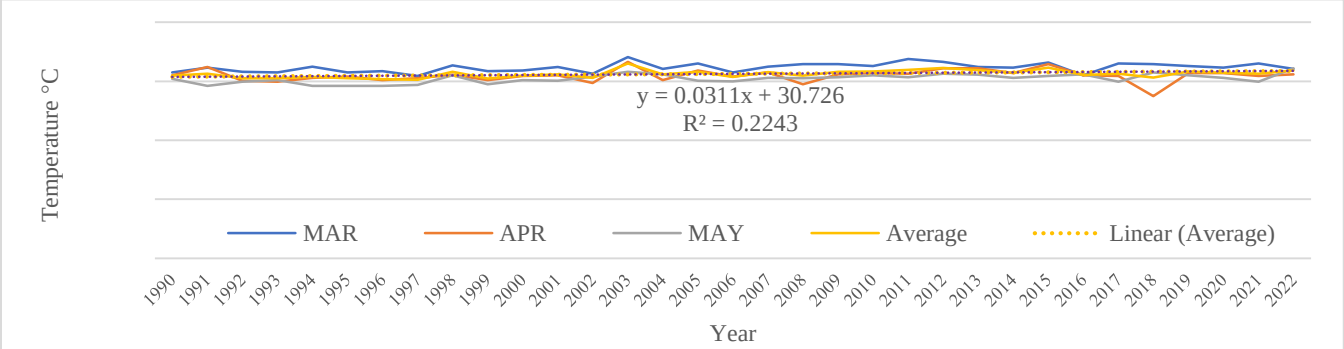


Figure 15. Trend of temperature in Dar es Salaam during long rainy seasons.

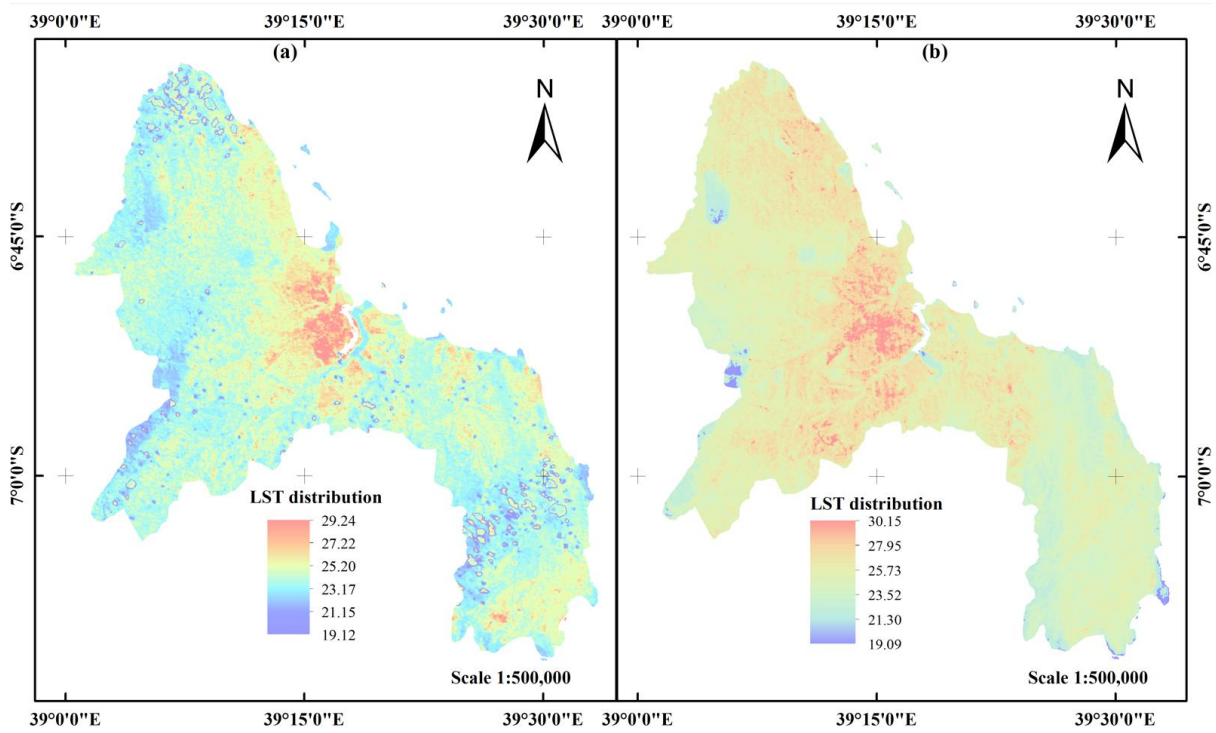


Figure 16. Distribution of temperature in Dar es Salaam in 1990 (a) and 2022 (b).

Furthermore, the study examined the spatial distribution of temperature derived from satellite data, revealing a linear relationship between land surface temperature (LST), population growth, and urban development, which have substantially altered the city's land cover (Figure 16). In 1990, LST ranged from 19.12°C to 29.24°C, while in 2022 it ranged from 19.09°C to 30.15°C. High-temperature areas, shown in red in Figure 16, expanded notably from the city center toward the outskirts. Cooler areas, mainly in the southern and peripheral regions, remained relatively stable, with minimal changes in minimum temperature. Overall, the findings indicate that the maximum LST increased by approximately 0.91°C, while the lowest temperatures remained nearly constant throughout the study period.

3.3 Drought conditions in Dar es Salaam from 1990 to 2022

A study with the in-situ rainfall data shows that Dar es Salaam experienced extreme drought (SPI <-2.5 in 1991, 1997, 2009, 2012, 2017 and 2021) (Figure 17). The Sequential Mann-Kendall test at 95% confidence interval reveals that the drought trend started between 1994 and 1996 and reached at the statistically significant part (P<0.05) between 2008 and 2016 (Figure 18). Before 1996 and after 2016, the prograde line (U(t)), representing the standard test statistic and its sequential counterpart (U'(t)) indicate the positive/upward trend within the 95% confidence interval.

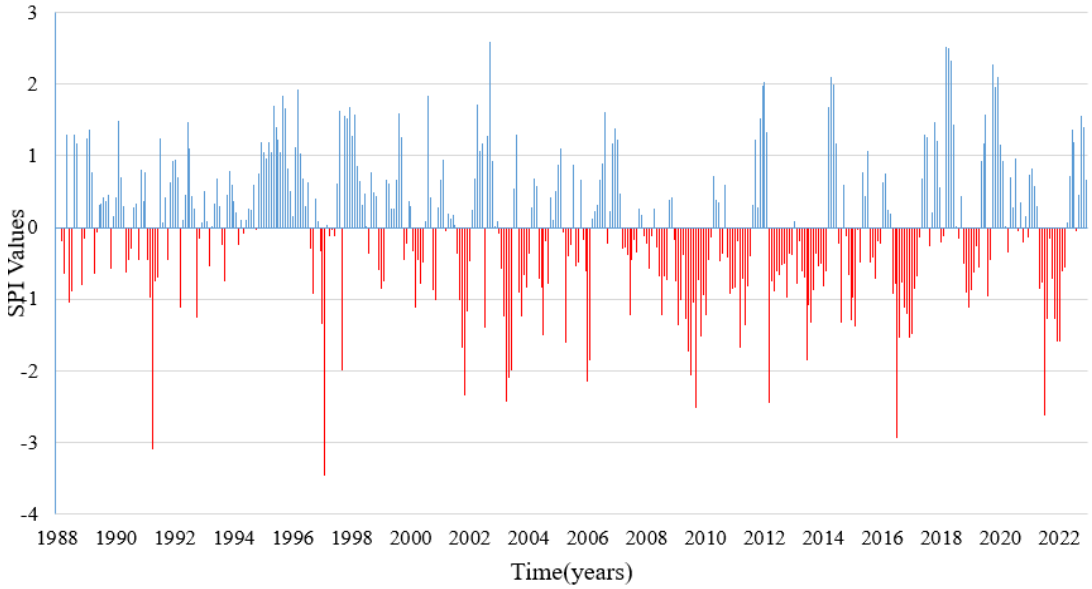


Figure 17. Incidence of drought in Dar es Salaam by the SPI.

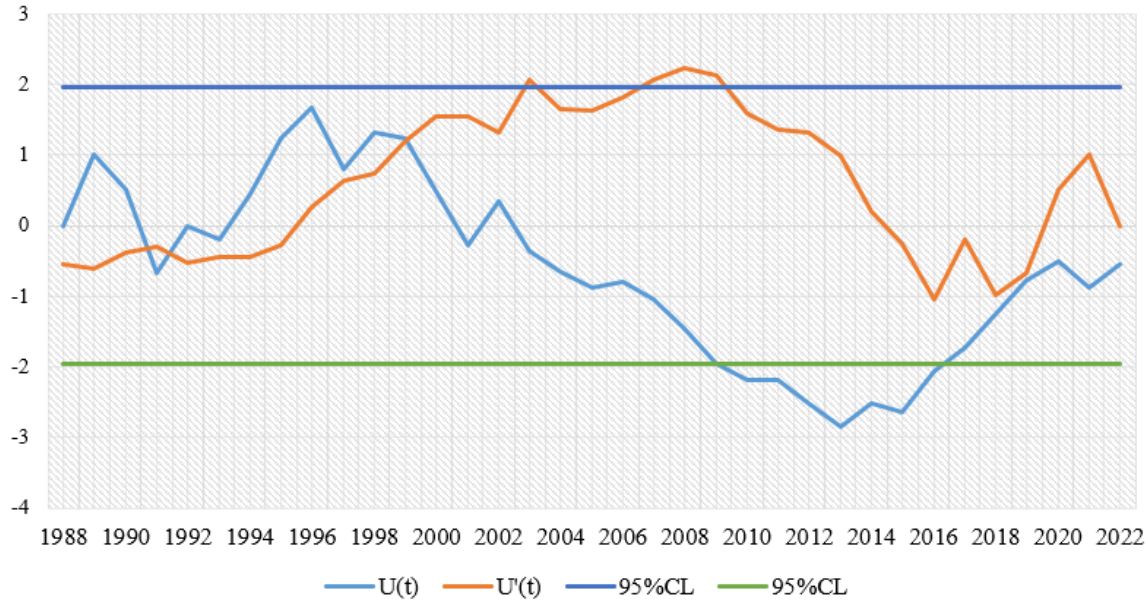


Figure 18. Trend of drought in Dar es Salaam by the Sequential Mann-Kendall test.

3.4 Web-Based GIS Dashboard

A Web-based GIS dashboard is available at https://ilvjosem02.github.io/CoICT-Paper2/ and its design includes an interface and webmaps to display and analyze population, land-cover, and climatic trends in Dar es Salaam from 1990 to 2022 (Figure 19). Additionally, it features three comment boxes that allow users to request or update information related to this work. To validate the dashboard's functionality, we accessed it to display population and LST webmaps (Figures 20 and 21).

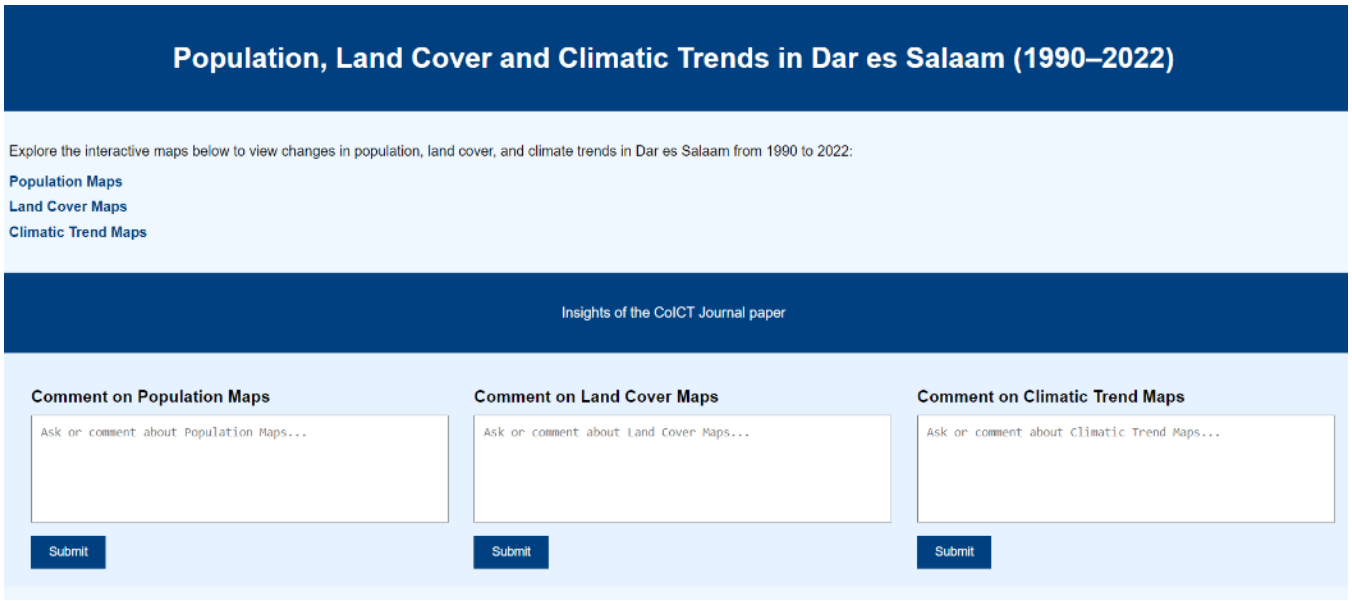


Figure 19. Dashboard containing spatial information of population, land cover and climatic trends in Dar es Salaam from 1990 to 2022.

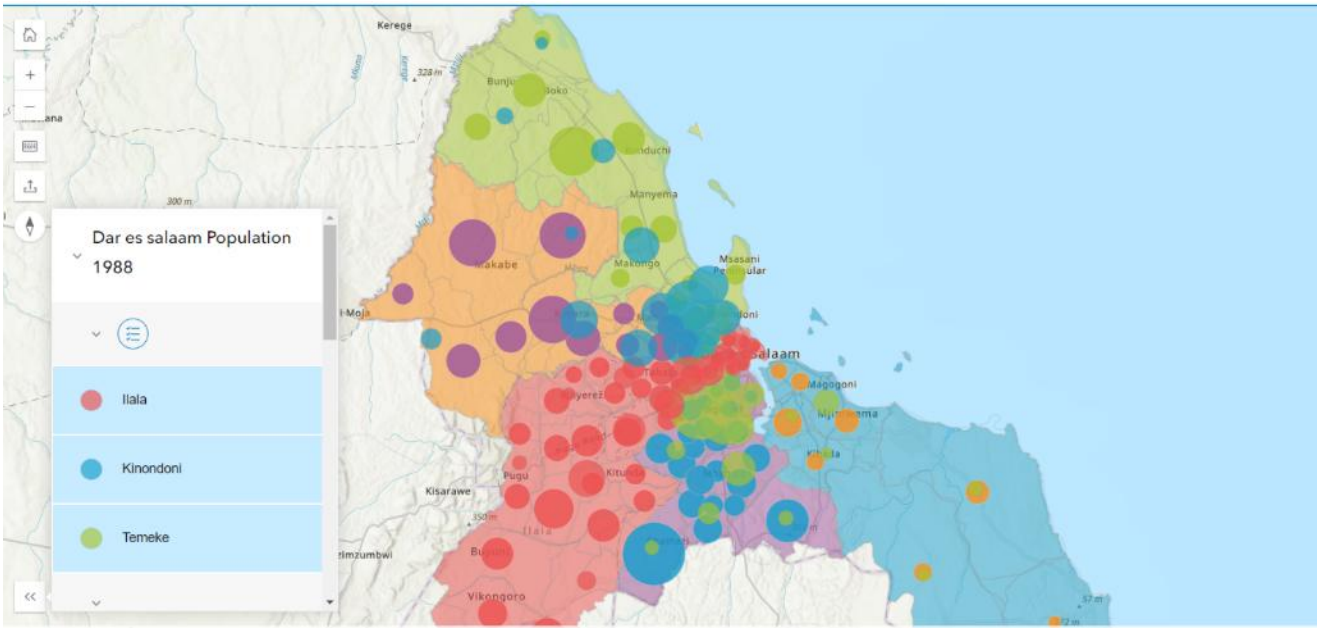


Figure 20. Webmap page created to display and access population information in Dar es Salaam.

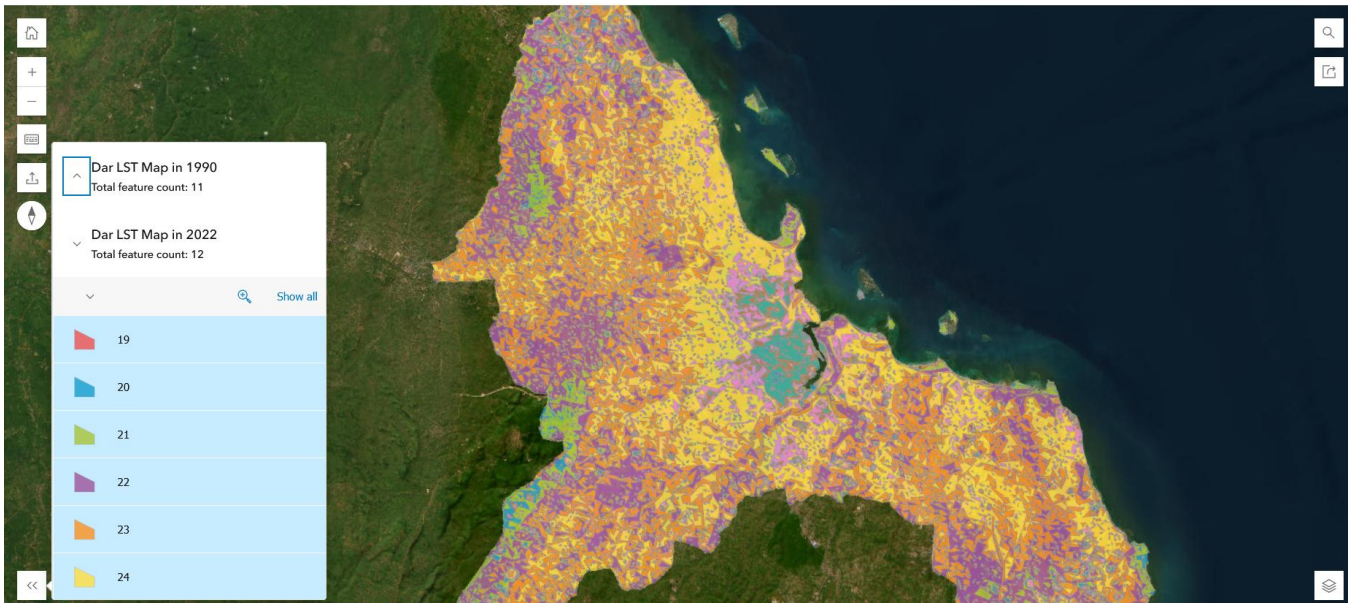


Figure 21. Webmap page created to display and access LST in Dar es Salaam.

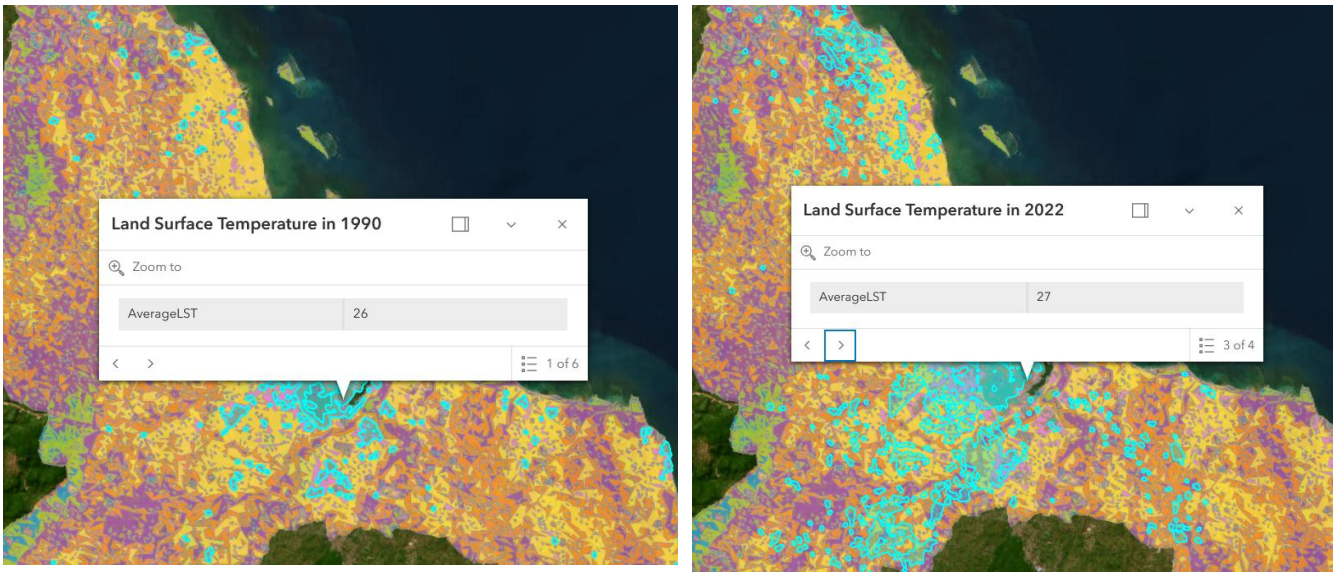


Figure 22. Results of LST queried with a pointer at Miburani in Temeke district.

To validate its functionality, we queried to retrieve LST information of the Miburan ward used as an example in this case. The results with the pointer tool indicate that, in 1990, this ward and much of the city had an average temperature of 26°C (Figure 19a). At the same location, the 2022 map showed an average temperature of 27°C (Figure 19b). Areas registering 27°C are relatively larger than those with 26°C, indicating that the temperature change was not uniform across the city. This result provides additional insights that were not presented in the findings rendered statistically in the previous sections.

Overall, the dashboard's results complement earlier findings by providing a quantified, spatially detailed, and temporally extensive assessment of urban climatic and environmental transformations, offering new insights that go beyond previous fragmented studies in Tanzania and across Sub-Saharan Africa. Between 1990 and 2022, the study revealed a 35.57% loss of natural vegetation, reducing green cover from 70.3% to 45.29% of the city's land area. This quantification establishes the first comprehensive measure of long-term vegetation depletion associated with urban expansion in Dar es Salaam. The results also demonstrated that forest, bushland, and grassland were systematically converted into built-up and agricultural areas, emphasizing the accelerating urbanization and its ecological costs.

Temperature analyses showed a significant annual rise of 0.0469°C, with land surface temperature increasing from 29.24°C to 30.15°C, confirming a pronounced urban heat island pattern concentrated in central and northern districts. Unlike prior regional studies that analyzed climate variability in isolation, this study linked temperature change directly to population density and land-cover transformation, revealing that areas with higher urban development exhibited the greatest thermal increase.

Rainfall trends added a new layer of insight by identifying spatial variability, where northern and coastal areas experienced a decline, while central and southwest zones recorded modest increases. Moreover, the Sequential Mann–Kendall analysis detected statistically significant drought periods between 2008 and 2016, aligning with extreme drought years (1991, 1997, 2009, 2012, 2017, and 2021).

4. Discussion and recommendations

The study has shown that Dar es Salaam has undergone extensive demographic and environmental transformation over the past three decades. The city's population increased by 295.61%. Built-up areas expanded rapidly, replacing 35.57% of natural vegetation, including forests, bushlands and grasslands. Although agricultural areas generally retained their extent, urban expansion pushed them outward city centres. These patterns are consistent with urbanization trends observed in other African cities, where high population growth and informal development have accelerated land conversion [50, 51].

Climatic observations during the same period revealed a consistent rise in temperature. The mean temperature increased by 0.93°C, with a statistically significant upward trend during long dry seasons ($R^2 = 0.7514$). Built-up areas recorded the highest temperature increases, indicating the emergence and intensification of urban heat islands (UHI). This finding aligns with documented UHI effects in Dar es Salaam [52] and other urban centers in East Africa [53-55]. In contrast, rainfall showed a non-significant but slightly declining trend ($R^2 = 0.0219$), with considerable variability across years and seasons. These climatic shifts contributed to a series of prolonged drought events observed significantly between 2008 and 2016.

To substantiate these results, the study analyzed vegetation health using the Normalized Difference Vegetation Index (NDVI). A comparative assessment reveals a visible decline in NDVI values across most parts of the region (Figure 23). In 2019, large areas particularly in the southern and peripheral zones recorded NDVI values as high as 0.60, indicating healthy vegetation. By 2022, these values had decreased, with the maximum NDVI dropping to 0.51. Simultaneously, central urban zones show expansion of lower NDVI values (ranging from -0.10 to 0.07), indicating progressive vegetation degradation due to built-up expansion.

A statistical analysis using paired sample t-tests on NDVI values between 2019 and 2022 confirmed a significant mean difference at the 95% confidence level ($p < 0.05$), highlighting that the vegetation decline is not due to natural variability but is instead driven by anthropogenic land-use change. This observation coincides with the rapid population growth and urban sprawl documented in Dar es

Salaam during this period, which resulted in the transformation of vegetated and agricultural lands into impervious surfaces, such as roads and buildings [24, 56]. Although 2022 experienced reduced drought intensity as supported by the SPI trends and Sequential Mann-Kendall test results (Figures 17 and 18), the overall vegetation health did not recover. This suggests that the primary driver of vegetation loss during this period was not climatic stress but human-induced land conversion. The consequences of this finding, together with the persistence of drought conditions, indicate significant impacts on the local community in Dar es Salaam, including reduced agricultural productivity, declining surface water availability, and intensification of urban heat island (UHI) effects. These outcomes highlight the urgent need to adopt sustainable urban planning practices, expand green and blue infrastructure, and strengthen climate adaptation and water resource management strategies to enhance the city's resilience and ensure its long-term sustainability. To realize these, the study recommends the following:

a) Promote solar energy in informal settlements

Informal settlements in Dar es Salaam rely heavily on charcoal and firewood for cooking, contributing to deforestation and degraded air quality. Regional pilot programs have demonstrated that solar energy adoption in such communities can reduce charcoal use by up to 14% % [57]. By scaling up access to affordable solar technologies, including solar cookers, lanterns, and rooftop photovoltaic systems, the city can reduce pressure on natural forests and bushlands.

b) Develop, update and enforce land use master plans

The conversion of natural land to built-up areas highlights the failure of preparing and enforcing land use frameworks. Authorities should in advance prepare, revise and strictly enforce land use master plans to regulate urban expansion, protect green corridors, and guide infrastructure development. Urban zones should include designated green belts and ecological buffers to preserve forest, grassland and bushland areas essential for climate regulation and biodiversity.

c) Develop real-time spatially-based digital platforms for climate monitoring and drought early warning

Adverse climatic trends are caused by many factors, including arbitrary land cover modifications, and, as determined in the study, they could be identified in advance through predictions of meteorological and environmental data (e.g., from TMA). Authorities should adopt and integrate such systems with real-time climatic indicators like SPI and Mann Kendal Test. Part of this recommendation is already implemented in this study by developing a spatially based GIS dashboard containing population, land cover and climatic trends with remote sensing dataset.

5. Conclusion

This study investigated the effects of population and land cover changes on climatic trends, including rainfall, temperature and drought from 1990 to 2022, and it used Dar es Salaam, Tanzania, as a case study to realize its objectives. Additionally, it aimed to develop a web-based GIS dashboard that integrates ICT to facilitate interactive sharing and in-depth exploration of the key findings.

The results obtained show a rapid increase in population in both urban and peripheral areas. Land cover changed significantly, marked by a loss of vegetation. Agricultural areas largely maintained their extent, while built-up areas expanded considerably. Spatial analysis revealed a systematic shift in agricultural zones due to urban expansion. Climatically, the findings indicated a decrease in rainfall, although the trend was not statistically significant. In contrast, temperature increased, with a significant trend observed during long dry seasons.

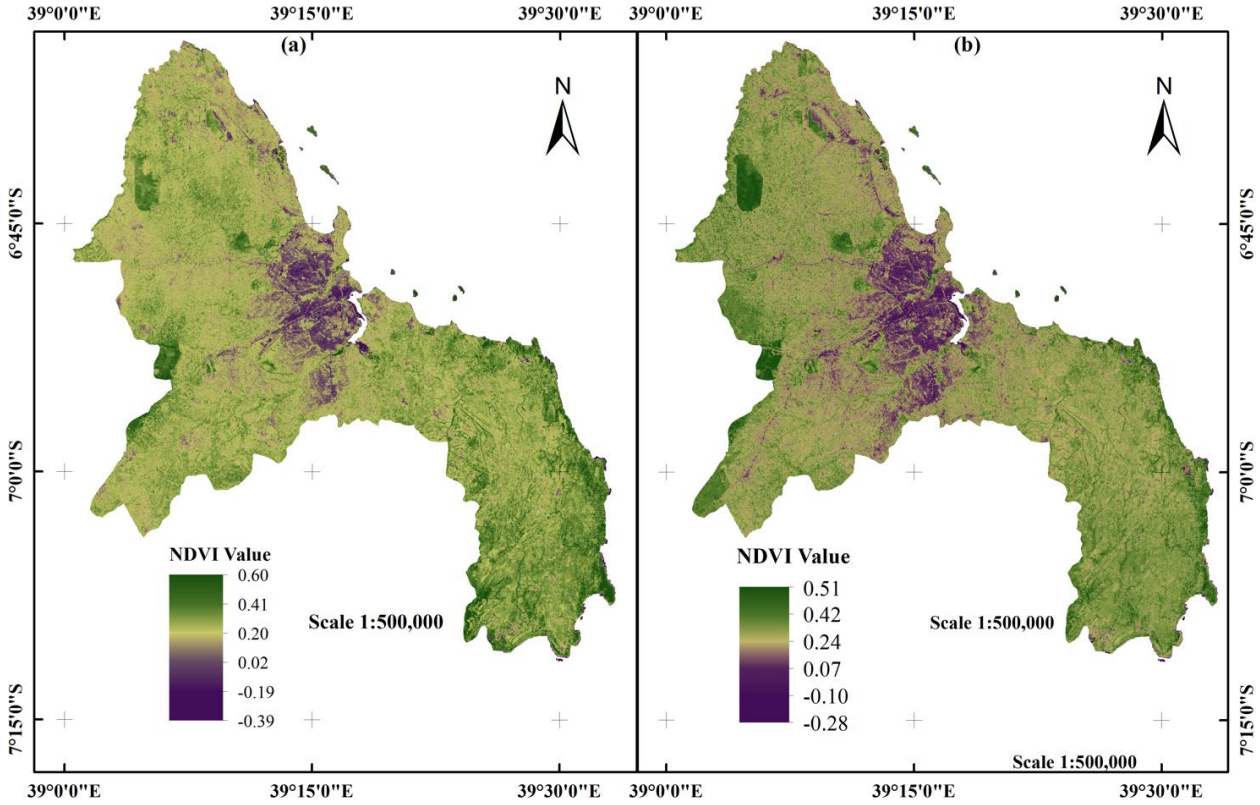


Figure 23. Spatiotemporal distribution of NDVI in Dar es Salaam in 1990 (a) and 2022 (b).

The increase in temperature contributed to severe droughts between 2008 and 2016.

Part of these results was successfully integrated into the dashboard (https://ilvjosem02.github.io/CoICT-Paper2/). A functionality test of the dashboard retrieved temperature data and allowed users to search and resize other information as needed. This finding provides a way of deploying a dynamic and an interactive platform to effectively analyze and monitor population and land cover dynamics in urban areas. Additionally, integrating ICT, GIS and climate insights provides a foundation to critically elaborate the effects of uncontrolled human activities in the environment.

Future research should address the following limitations:

i. Our study relied on population data from the 1988 national census. The use of this data may have introduced a slight discrepancy in the estimation of parameters at the start of the study period.
ii. The information planned for the designed dashboard was not fully loaded. The web map platforms accepted lightweight files only for the display on the dashboard.
iii. The designed dashboard does not incorporate predictive models to forecast future scenarios related to population growth, land cover changes and climate trends. Additionally, it lacks big data insights and scaling factors to increase its use with other mobile/web ICT platforms.

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