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Detection of Urban Growth in Taiz City, Yemen, Between 1981 and 2022 by Using Google Earth™ and Geographical Information System Data

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Abstract - Rapid urbanization brought serious socio-economic and environmental problems in many cities around the world, particularly in developing countries like Yemen. Urban "sprawl", a synonym of rapid and unplanned urban growth, is considered an obstacle for sustainable development, which causes serious long- and short-term problems, such as extreme infrastructure expenses, economic inefficiency, environmental destruction, and social instability. This is the case of Taiz City, the third largest city in Yemen, which is facing a huge challenge to manage the spatial extension of its built-up area at the expense of the reduction of natural resources and environment. This study aims to investigate urban growth process in Taiz City, focusing on urban sprawl and agricultural land-use change during 1981–2022. The data used are high resolution geospatial data, which are the topographic map for 1981 and Google Earth (GE) images for 2003, 2012, and 2022. The methodology adopted was manual digitizing using Geographic Information System (GIS) software to extract urban land use features from the images of the different dates. Four land-use maps were produced and used for calculation the urban sprawl and land-use changes. The urban expansion rate and patterns were also identified in three phases: 1981–2003, 2003–2012, and 2012–2022. The results show that the built-up area increased six times from 6.2 km^2 in 1981 to 34 km^2 in 2022, while the agriculture area decreased by 77% from 18 km^2 in 1981 to 4.2 km^2 in 2022. The urban sprawl in Taiz covered about 75% of its municipal area and extended to the agricultural and rural areas. The sprawl index (USI) is measured to be 5.4%, indicating a high degree of sprawl in Taiz. There is no open space left for future development, and the water resources are at risk of population and depletion. The study demonstrated that informal and haphazard expansion must be controlled, a development strategy should be prepared, so that sustainable urban growth can be achieved. The results of this study could be used as a decision support tool for urban management activities. The vector layers produced by this study could provide the required input data for the future urban modeling of the city.

Keywords: urban growth, sprawl, spatial patterns, Taiz, Yemen

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Introduction

Background

Urban growth is a phenomenon inherent to human civilization, and present in various forms in different stages of human history (Mantelas *et al*. 2010). Urban growth had earlier been considered as urbanization, but soon the rapid and uncontrolled urban growth changed to that of urban sprawl (Basawaraja *et al*., 2011). Urban sprawl is defined as the spreading out of a city over rural land at the periphery of the urban areas (European Environmental Agency, 2000). Rapid urbanization, or urban "sprawl", led to the change of land use and land cover, causing loss of productive agricultural land, deterioration of water quality, water distribution and sewage treatment problems (Malarvizhia *et al*., 2016). Urban sprawl is by no means a phenomenon restricted to developed countries (Jaeger *et al*., 2010). As it is one of developing countries, Yemen witnessed rapid urbanization and the impacts it brings.

Yemen has rich urban heritage and tradition, spanning several thousand years. Its cities were homes of unique built environment (HUB website https://population-hub.com/en/ye/population-of-taiz-7111.html). Presently, the structure of Yemen cities developed through growth of ancient urban cores encroaching into the rural fringe areas. During the last five decades, the urban population of Yemen has increased by more than thirteen times from 0.9 million to 12 million (Yemen National Report, 2016). In Yemen, the development is uncontrolled, and planning is haphazard, lacking any clear vision about the future. Yemen large cities have expanded rapidly as a result of population growth and economic development. For that reason, cities have many socio-economic, infrastructural, and management problems (Al-Shalabi *et al*., 2013). Taiz is one of such cities that have most affected by rapid urbanization in term of severity (HUB website https://population-hub.com/en/ye/population-of-taiz-7111.html).

Taiz was a small town surrounded by green landscape and agricultural lands from all sides. During the last four decades, it has experienced both a high rate of population growth and human-induced land changes. The population of Taiz has increased by more than six times (Yemen National Report, 2016). As a result, there are instances of unplanned urban spatial expansion as evidenced by dramatic land-use changes that observed in the city and its environs. Thus, detection of urban growth in Taiz is an essential component in urban development. Identification and analysis of urban patterns helps in the effective planning of infrastructure in the urban areas. In addition, understanding the behaviour of urban sprawls could assist in achieving sound environmental planning and resource management (Al-Darwish *et al*., 2018).

Generally, change detection is the process of identifying differences in the state of an object by remotely sensed it at different times (Singh, 1989). The physical expressions and patterns of urban growth (sprawl) can be detected, mapped, and analyzed using remote sensing data and geographical information system (Barnes *et al*., 2001). Extensive research efforts have been made towards urban change detection and urban sprawl for nearly four decades (Feng and Li, 2012). Most of previous research involved the use of open-sourced satellite images and running a pixel-based classification using GIS software (Hu *et al*., 2013; Isnain and Mokthar, 2022; Isnain and Musta, 2022). However, the free satellite images are insufficient for detailed land cover mapping for those areas with complex and high heterogeneous landscapes, such as the urban environment (Zhou *et al*., 2008; Laliberte *et al*., 2012). Furthermore, classifications of medium resolution satellite images have lower accuracies in urban areas located in arid or semi-arid climates because of the spectral confusion occurring between bare soil and built-up elements (Rasul *et al*., 2018; Zhang *et al*., 2015). Alternatively, the researchers tend to use high resolution satellite images to detect and analyze detailed changes in an urban environment (Batista and Haertel, 2010). However, the high cost and narrow spatial coverage limit the use of such images, especially by scientists in developing countries (Lu and Weng, 2007; Reddy, 2008).

In this context, use of Google Earth images, which are freely accessible and have higher resolution, has become a better alternative (Mering and Upegui, 2010). The advantage of using Google Earth is that it provides a continuous series of images with less than 0.5 m resolution (Malarvizhia *et al*., 2016), which are very useful in spatiotemporal change detections (Mering and Upegui, 2010). However, Google Earth images have poor spectral information, as they contain only red, green, and blue bands (Yu and Gong, 2011), and hence pixel-based classification cannot be carried out (Malarvizhia *et al*., 2016). To overcome this drawback (Malarvizhia *et al*., 2016; Mering and Upegui, 2010; Madarasinghe *et al*., 2020;) and others, practicing on-screen digitization in place of pixel classification have been recommended. The use of on-screen digitization method on Google Earth imagery is recommended as a cost-effective and high accuracy method for land-use mapping of smaller urban areas, particularly in developing countries. It has, therefore, been used in detecting and monitoring urban changes on various scales with useful results (Al Mashagbah *et al*., 2012; Tapulu *et al*., 2014; Abdelaty, 2016; Silva and Li, 2017; Al-Ruzouq *et al*., 2017). Manual digitization of topographic maps and aerial photographs have also been used for long-term LULC changes in many areas (Lieskovsky, 2018; Drummond *et al*., 2019; Osgouei *et al*., 2022).

As yet, however, no study in Taiz and Yemen in general has used Google Earth as a data source for urban growth analysis. Only one old land-use and hydrological study has been carried out in 1996 by Dar El-Yemen (National Water Resource Authority, 1997). Another recent one was conducted by United Nations, Human Settlement Programme (UN-Habitat), but focused on assessment the impact of the current war on Taiz City infrastructure (Taiz City Profile- United Nations, Human Settelement Programme in Yemen). Therefore, there is dearth of information on the rate of arable land loss due to urbanization in the studied area, particularly using Remote Sensing (RS) and Geographic Information System (GIS) techniques. It is for such reasons that Taiz City has been chosen as the researched area for studying the spatial patterns of urban growth and its impact on the environment. The period of focus is from 1981 to 2022. The aims of this study are to produce a land-use/land-cover maps for Taiz City in Yemen at different years in order to detect changes that have taken place in the built-up land, and subsequently to analyze the urban sprawl of different time periods and to explore the effect of urban area growth on the agriculture land and environment in Taiz City. The results of this study will show the spatial, temporal evolution of Taiz City and its vicinity. Hopefully, the results of this study will provide policy makers and city planners with useful information for sustainable urban development and planning.

Studied Area

Taiz City is the capital of Taiz Governorate which is located in the southwest of Yemen on both the Red Sea and Gulf of Aden (Figure 1). The city is considered as the third most important city in Yemen, and it is also the culture capital of the country. It owns its importance form of geostrategic location and also its historical, political, economic roles. The location of Taiz is vital crossroads between the northern and southern parts of Yemen, and access to Bab Al Mandab that represents one of the most important straits in the world. The city of Taiz is established in the 12^{th} century, and has been taken as the capital of Yemen for many periods of time. It was a small town enclosed within an area of about 1 km^2, surrounded by an ancient wall and large tracts of agricultural lands. After the revolution of 1962, the city was a thriving commercial hub and had been developing into a centre of industry since the 1970s. The population of Taiz was 39,665 in 1962. It grew to 137,889 in 1982, and 424,767 in 2002, and is estimated to be 907,739 in 2022 (Yemen National Report, 2016). The municipality of Taiz consists of three districts, those are Al Mudhaffar, Al Qahirah, and Salah, with an area of 43 km^2, but it has expanded beyond the administrative city boundary through seizing the adjacent rural areas. Generally, Taiz possesses significant features of urban fringe, ranging from urban areas to rural/agricultural areas. Therefore, "Taiz City and its vicinity" have been taken under this study.

The studied area covers about 90 km^2, and lies between longitudes 43° 55’ - 44° 06’ E and latitudes 13° 33’ - 13° 38’ N. The area is part of mountainous region that comprises the west of Yemen. It is located at the foot of a 3,000 m high mountain, known as Jabal Sabir. The elevation of

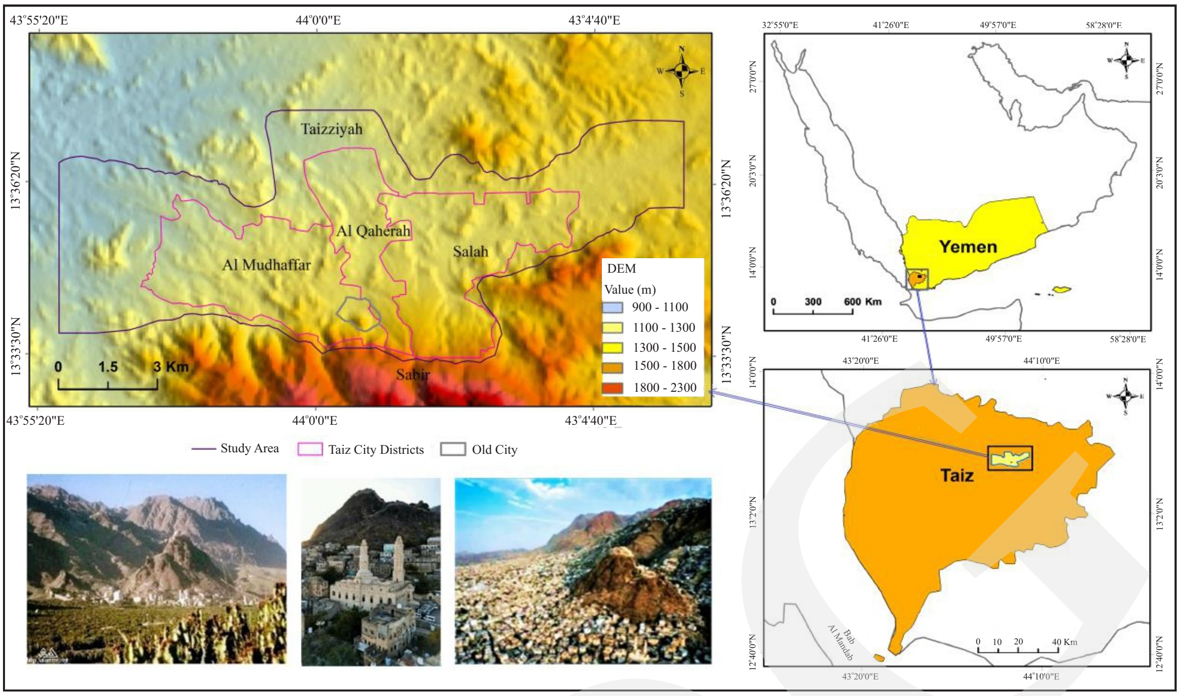

Figure 1. Geographic location, digital elevation model of the studied area, and overview of Taiz City.

the area ranges between 1,100 to 1,600 m above sea level. Around 60% of the area is hilly and consists of dissected terrain with steep slopes, and the remaining 40% has an undulated topography with gentle slopes. The surface of the area is covered mainly by two rock types, granitic rocks in the south and basaltic rocks in the northern part of the city. The climate of the region in general is semi-arid, but the studied area has a moderate climate all the year. The average daily temperature is 24°C and the average humidity of 50%. The rainfall in Taiz occurs in two seasons of the year (spring and summer) with an average of 560 mm per year. Agriculture is the most important land resource in Taiz. For a long time, agriculture has been the pillar of its economy. The rains and groundwater are the sources of the water supply for the area population, irrigation, and industries. However, urban growth is considered as one of the main problems that reduced the natural resources in the area. Figure 1 shows the location of Taiz in Yemen and in Arabian Peninsula, the boundary of the studied area, the boundaries of Taiz City districts and the topography of the area in the DEM map at the background.

Data and Methodology

This section describes the data used and methods adopted in this study to achieve the objectives. Given that the main objective of this study is to produce urban land-use maps for a long time (1981 to 2022), and because unavailability of time series data in digital format, very high-resolution data have to be used from different sources, and to perform manual digitization method to produce vector data and LU maps. The primary data required for the present study comprised small scale topographic maps and very high-resolution Google Earth images. The topographic maps of Taiz produced in 1981 on scale 1:50,000 were used for mapping the extent of the urban area as it stood at the 1981 level. The historical satellite images were downloaded for the span of twenty years from 2003 to 2022 with a duration of ten years. Specifically, the very high-resolution satellite data was collected from Google Earth for the years of 2003, 2012, and 2022 to study the change in the land use of the area. Thus, the urban spatial feature extraction was investigated in urban areas using topographic maps of 1981 and Google Earth images of 2003, 2012, and 2022. As ancillary data, the Digital Elevation Shuttle Radar Topography Mission (SRTM) data and the available local information related to the studied area were collected from different sources and were used to support the analysis. Table 1 shows the information of the collected data. All datasets used in this study were individually processed and analyzed in GIS environment. The topographic maps and Google Earth images were converted into digital land-use maps through manual digitization process. A manual digitization approach was performed here as it is found more accurate than the other classification methods, particularly for the heterogeneous and fragment areas like the studied area. In general, the methodology consists of three stages: 1) data preparation; 2) data processing which includes digitization process and land use mapping, and 3) change detection analysis. Figure 2 shows the

Table 1. Data Information

Data Type	Date/Year	Resolution (m)/scale	Source
Topographic maps	1981	1:50000, 5 m	Yemen Survey Authority
Google Earth	3/9/2003	1 m	http://www.google earth.com
Google Earth	8/12/2012	1 m	http://www.google earth.com
Google Earth	9/3/2022	1 m	http://www.google earth.com
SRTM	6/11/2009	30 m	(USGS) https://earthexplorer.usgs.gov/
Administrative maps			Old sketch maps

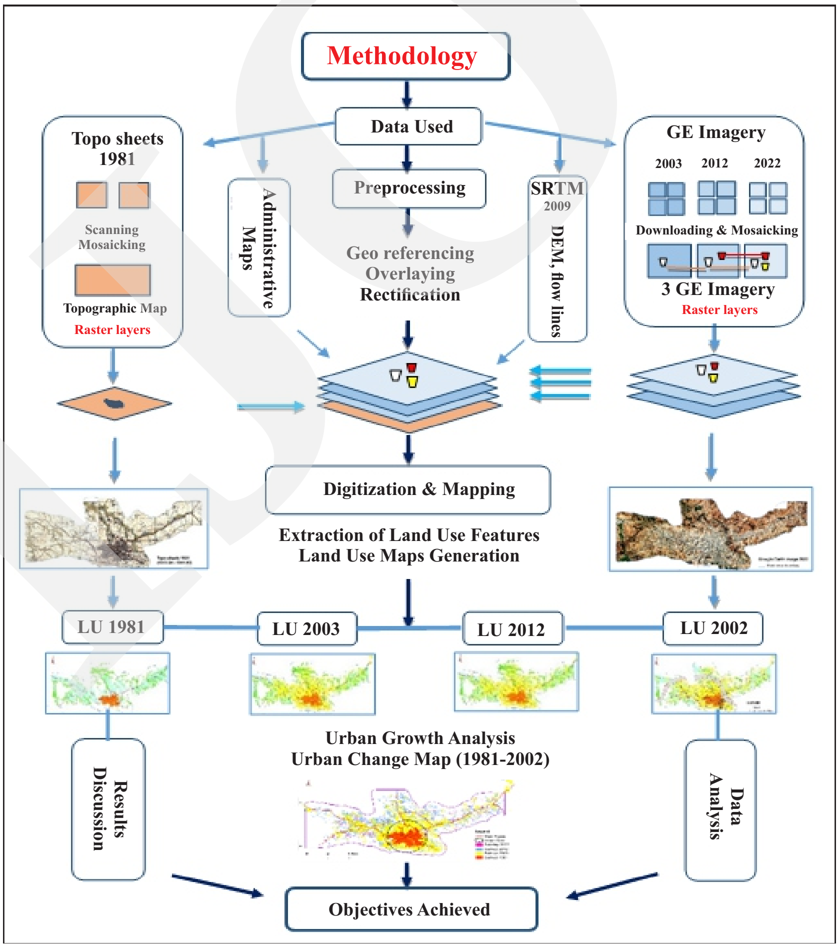

Figure 2. Flowchart describing the procedure followed to detect urban changes and land use configuration over the last four decades in the urban area of Taiz City.

flowchart of methodology steps followed in this study, while the details for each step taken will be presented in the following sections.

Pre-processing of Datasets

The preparation steps include downloading, mosaicking, geo-referencing, rectification, and clipping of the datasets to the borders of the studied area. The topo sheets of Taiz City (No. 1343B4 and 1344A3, scale 1:50,000) which were prepared in 1981 based on aerial photographic maps, were scanned and geo-referenced using their lat/long in Arc GIS 10.8, then they were mosaicked, and the boundary of the studied area was cropped. The resulting raster topographic map has spatial resolution of 5 m (Figure 3a). The Shuttle Radar Topography Mission (SRTM) of 30 m resolution were downloaded and geo-referenced, and then used to derive the digital elevation model (DEM) and the surface water hydrology map. Hence, the drainage patterns of the studied area and the old sketch administration maps of Taiz City were scanned and geometrically registered to the same coordinate system of the other datasets. The boundary of the city as seen in Figure 1 is digitized and has been saved as shape file format (.shp) in ArcGIS database.

Prepration of Google Earth images was started by their downloading from Google Earth pro 7.2 (Lefebvre *et al*., 2006) by using Elshayal smart (Lotfi *et al*., 2010) software. The advantage of Google Earth is that it allows the user to download images at any preferred eye altitude. The user can decide the relevant eye altitude to take the total area to be covered, and also the required resolution for image processing. Lower eye altitudes may cover a small area, but resulting in high image resolution when the obtained images are geo-referenced and vice versa (Tapulu *et al*., 2014). The advantage of Elshayal is that it downloads the images along with their coordinate information, so the images can be directly utilized for any kind of GIS analysis without the need for geo-referencing (Yemen National Report, 2016).

Based on their availability and also their accuracy, the three Google Earth images (2003, 2012, and 2022) were chosen to download. For each image, a total of thirty slides were required to cover the whole studied area. The earliest image

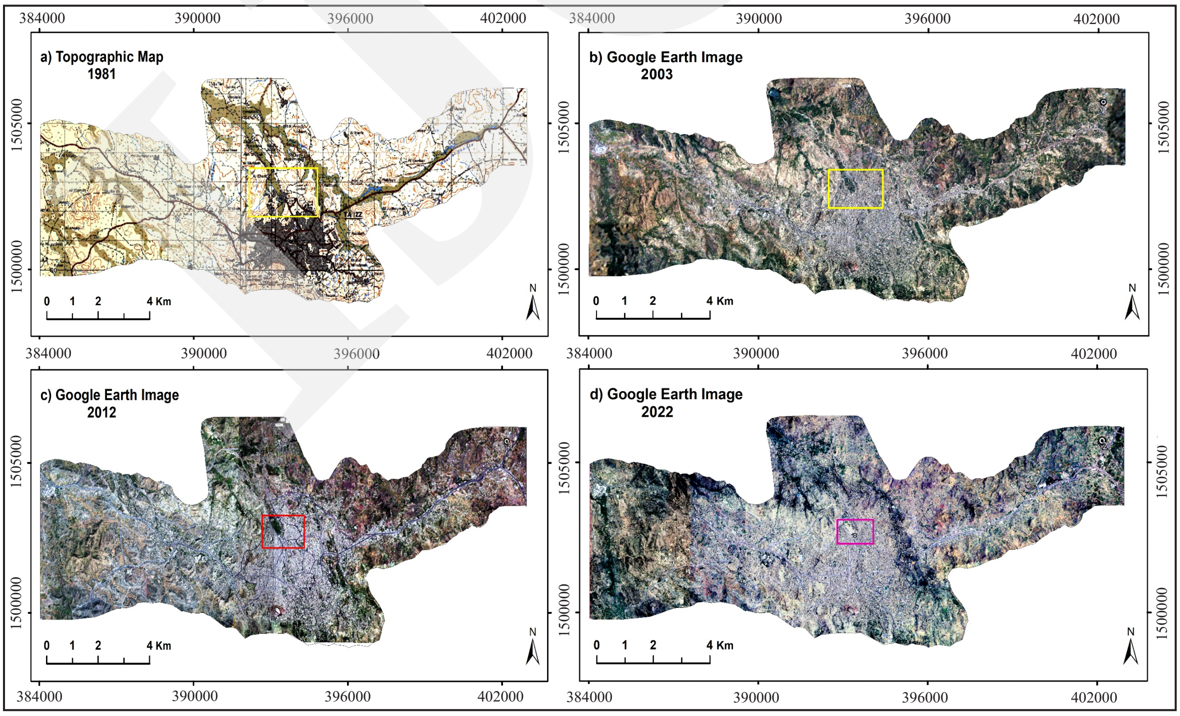

Figure 3. Datasets of the studied area: (a). Topographic map 1981, and (b-d). Google earth image 2003, 2012 and 2022: respectively.

was started to download which dated 3rd September 2003. The thirty slides were downloaded and then mosaicked by using Elshayal to form one big image covering the entire part of the studied area. The mosaicked image was then exported from Elshayal to ArcGIS, in which the image is converted from geographic coordinate system (Lat/long) into WGS84 projection system UTM zone 38 northern hemispheres. The geo-referenced image was cut only for the studied area boundary to be easier for analysis and less load in the software. The images of 2012 and that for 2022 were downloaded and prepared in the same way as explained before. Figure 3 shows the primary datasets used in this study. After downloading, the three images were then overlaid on each other in order to rectify them. Rectification is a very important step in this stage as it is necessary to correct their scales, minimize any displacement between the different images in order to produce spatially correct maps. The three images were rectified by using several GCPs located at the corners of the images. Then they saved with same scale (1:1), which resulted in a spatial resolution of approximately 1 m. Figure 4 displays samples of rectified Google Earth images and topographic map overlaid on each other. The figure shows that all features in the different images are practically laying on each other indicating excellent alignment. Finally, all the prepared datasets (raster layers of topographic, GE images, and DEM) were opened in the same work station to be ready for digitization process.

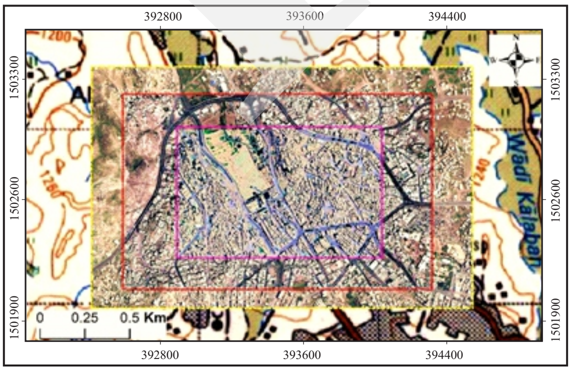

Figure 4. Samples of Google Earth image representing subsets of different datasets rectified and overlaid on each other.

Digitization and Mapping

There are several methods available for mapping of remote sensing data, which include digital classification (supervised and unsupervised), semi-digital (NADVI and NADBI), and manual digitization. However, the most accurate method is certainly manual digitization from high resolution data as mentioned by Lefebvre *et al*. (2006) and Lotfi *et al.* (2010) and also tested by Madarasinghe *et al*. (2020) who found it more accurate (by 26%) than digital classification methods. Digitizing in GIS is simply defined as the process of tracing the geographic features either from a hardcopy or a scanned image into vector data. In other words, it is the conversion of raster data to vector data (Al-Ruzouq *et al.*, 2017).

The manual digitization method by using ArcGIS is a proven technique and produces reliable results. Although it consumes very much time, it has more close results as the real feature forms (Alkan *et al*., 2010). It is, therefore, has been used in this study in order to get more accurate results, and also to maintain vector data to be used by researchers for future studies.

The land use/cover features that were considered to be digitized in the present study were grouped under three major classes, which are; urban, non-urban, and agriculture lands. The urban lands (built-up) include all buildings and roads, building layouts and others; non-urban (open lands) includes all land cover features such as exposed rocks (hills and scrubs) and barren lands (bare soil areas). Agricultural area comprises only cultivated fields. Almost all features in the built-up class were digitized from the Google Earth images, but the other features were digitized for completeness and to compute the percentage of development and growth of various features with respect to each other and to the total area of the city. The digitization procedure was carried out first on topographic maps of 1981, and then on Google Earth images of 2003, 2012, and 2022, respectively.

For the topographic map, the prepared raster layer of topographic map (Table 1) was used as a time reference for delineation the extent of the urban area and agriculture lands as they stood in 1981. From this map, the boundary of Taiz urban area was digitized, the main roads and agriculture features were digitized also and saved as polygons in shape file format (.shp) in GIS data base. Some agriculture features, such as small agricultural areas and short drainage lines, are not presented in the topographic map. Therefore, the digitized features were cross-checked by visual inspection of the data of the DEM and drainage lines. Then agriculture area polygons were modified to represent their accurate widths. Afterwards, polygons detected in aerial photos were extracted to classify land cover/use units of each year. Transforming generated polygons to vector format using ESRI-ArcGIS 10 software, types of land use/cover, and their area were determined. Figure 5b presents the selected extent of the vectorized topographic map with DEM and drainage pattern in the background.

After geometric correction of Google Earth satellite images, the digitization process was performed. For mapping the Google Earth of 2003, four layers under which the various features to be digitized were created. Each layer was given a unique colour to distinguish it from the other layers. From this image, every individual feature of each land-use class was digitized while using ‘snapping’ tool to ensure interconnecting lines are actually joined together to form a closed area (polygon). Since the Google Earth image is of a high spatial resolution, it provides clear and detailed features which make it easier for digitization activities. Hence, an accurate digitization was carried out to classify each and every feature into assigned class names. At this stage, visual interpretation was done all over the studied area to confirm every digitized feature is categorized into corresponding classes. The polygons of the same class were aggregated into a single vector layer, and later similar layers were merged to

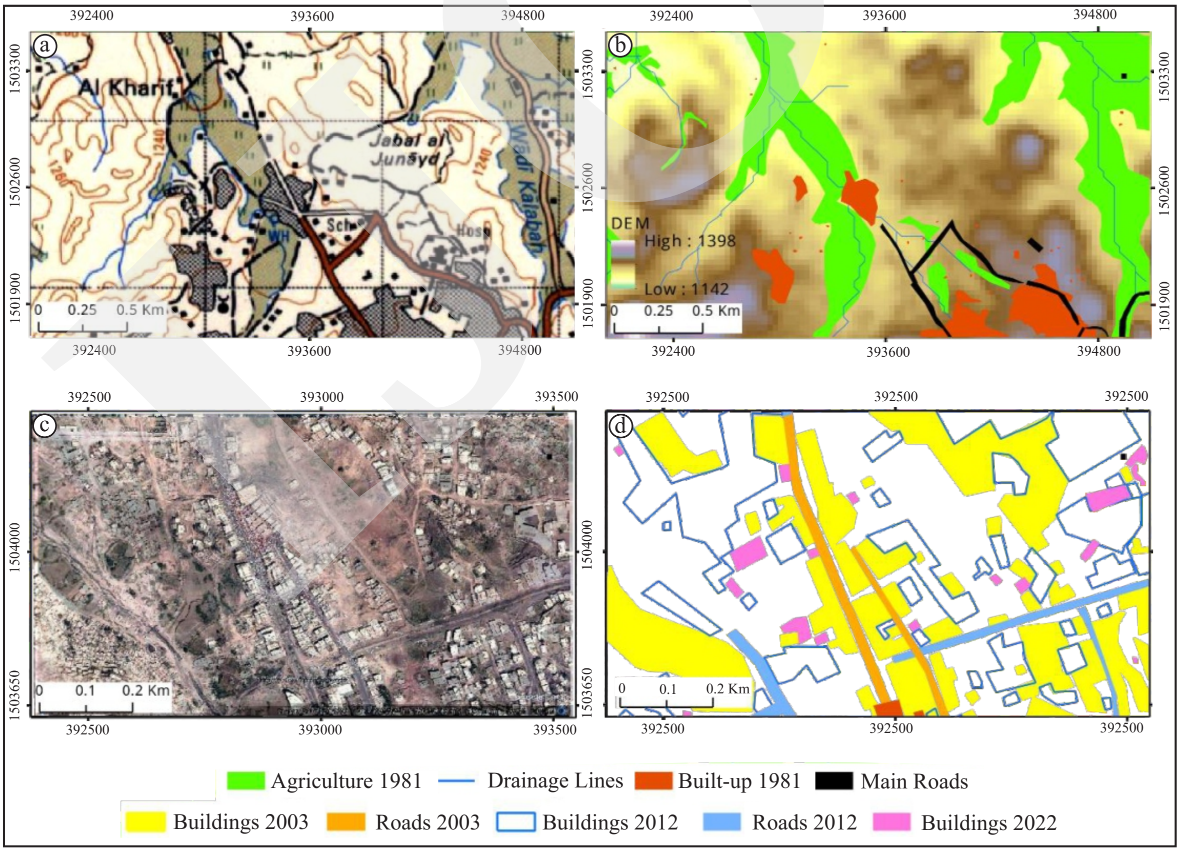

Figure 5. Subset of (a). Topographic map of 1981 and (b). Its digitized features with DEM at the background, (c). Samples of Google Earth images overlaid on each other, and (d). Final digitizing features from all samples.

show the combined area of each class for a specific year. This process enabled to calculate the area of each layer, which in turn was used for area comparison. The final product of this process is the thematic map or land-use map representing the year of 2003. Subsequently, the procedure of interpretation and detection of land use/cover is conducted based on upgrading results obtained from previous period (2003) in order to provide land-use/cover map of 2012. To minimize the time of digitization, the thematic vector layers of 2003 were overlaid on the raster image of 2012, and then were manually digitized forward in time, and as a result, the new features were obtained that were observed in the image of 2012 and that of 2022. As an example, Figures 5c and d show samples of geo-referenced Google Earth images overlaid on each other and the digitized LU features for the 2003, 2012, and 2022. Finally, the entire digitized work was thematic maps (*i.e.* LU maps for 1981, 2003, 2012, and 2022) which were saved in ArcGIS database for subsequent analysis.

Change Detection Analysis

Change detection analyses describe and quantify differences between images of the same scene at different times (Hegazy and Kaloop, 2015). In this study, the vector data of the four land use maps that generated through the digitization process were statistically analyzed in order to quantify the change that took place in the studied area over the study periods. The statistical analyses were done using ArcGIS 10.8 (convert vector to graph, calculate area, and attribute table). Change detection was then carried out by comparing the areas under each LU class of the respective years. The post classification (digitization) comparison is used here, which was found to be an accurate procedure for land-use/cover change detection. The land-use map of 1981 was used as a reference for comparison with the land-use situation in 2003, 2012, and 2022. Furthermore, by applying vector analyses, urban sprawl over the study period (2003–2022) was determined by computing the area of the city core in 2003 (*i.e.* 22 km^2), and comparing it with that obtained from the digitized images for the building theme of 2012 and 2022. The final results of this analysis were represented in terms of maps and graphs, and also summarized in terms of tables. Finally, the spatiotemporal evolution of Taiz urban area was highlighted and the urban expansion rate, patterns, and types, as well as urban sprawl characters are discussed in the next section.

Results and Discussions

This section presents a summary of the resulting maps and quantification that took place over the course of this research for the Taiz urban area. This section includes four subsections: the first subsection discusses the land-use maps and urban changes in the area; the second shows the urban expansion rate and pattern; the third presents the characteristics of the urban sprawl and its relationship with population growth, and the fourth subsection gives some light on environmental situation in the studied area.

Urban Growth and LU/LC Change Maps

Urban growth can be greatly emphasized or explained if a closer look at other land-use covers is taken (Alharthi and El-Damaty, 2022). LU/LC maps, in general, depict the geographical distribution of various land covers across the researched area. Land use is all of arrangements, activities, and inputs that people are implementing it in land cover type (UNFAO, 2006). The researched area containing three land-use types were obtained from classified images in different periods, including the built-up area, agriculture area, and open lands (bare soils and rock exposed which are covered by natural vegetation). The three land-use classes were extracted from the different datasets by using manual digitization process and the final outcome was four land use/cover maps (*i.e.* 1981, 2003, 2012, and 2022) which were presented in Figure 6. The geometric area of each class of each map was calculated and compared, and the results for individual classes of four generated output maps were shown in Table 2. Separate

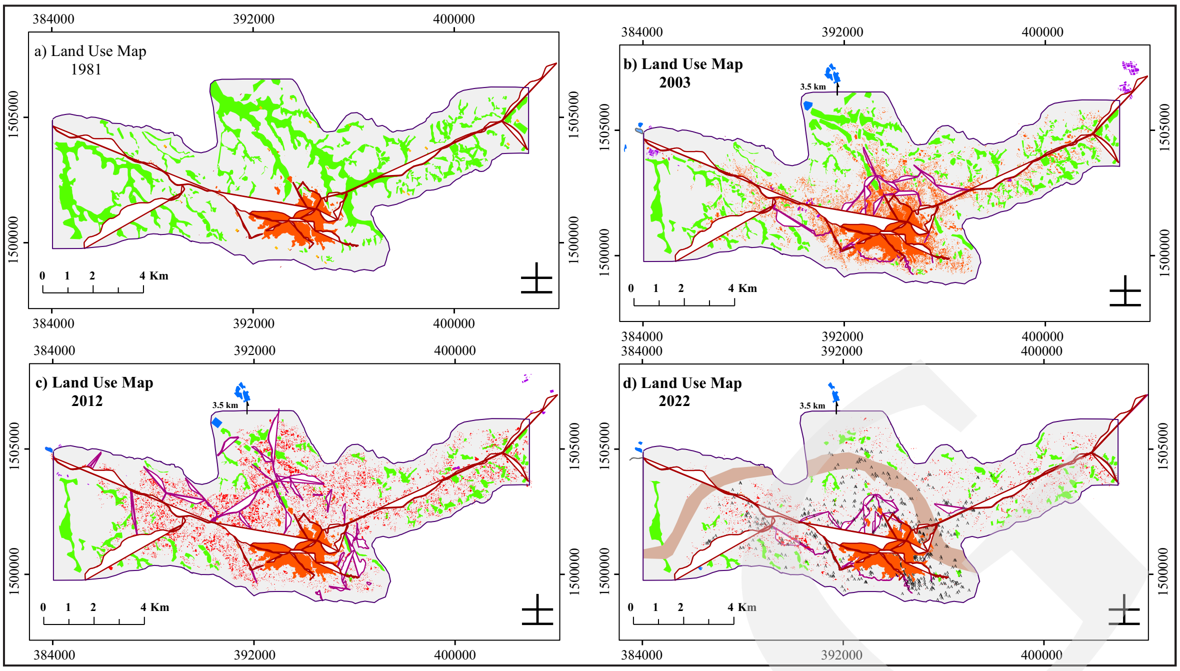

Figure 6. Land use maps showing built-up area and agriculture areas of Taiz City derived by the manual digitization of topographic map 1981, and Google earth image of 2003, 2012, and 2022.

Table 2. Analysis of Built-up Area Expansion Based on Total Area Calculation between the Time Intervals

Class Name	1981		2003		2012		2022		Difference (1981-2022)	
	km²	%	km²	%	km²	%	km²	%	km²	%
Urban	6.2	7	24.4	27	35.5	39	36.8	40	+30.6	+490
Agriculture	18	20	10.5	12	6.7	7	4.2	5	-13.8	-77
Open Lands	66	73	54	60	48	53	49	54	-17	-26
Total Area	90	100	90	100	90	100	90	100		

growth rates for the main urban elements (buildings and roads) and that for agriculture land have been calculated based on digitized features and represented in bar graphs as shown in Figure 7.

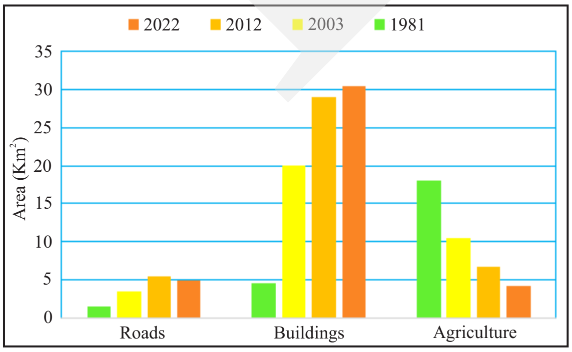

Figure 7. Development of urban areas (buildings and roads) and their relation to the agriculture area over the years.

From Figure 6 and Table 2, the expansion of urban areas is clearly visible. The urban area was mainly located in the inner part of Taiz until 1981. However, over time the urban (built-up) area increased, and the other lands decreased. While analyzing the land cover map for 1981, it can be seen that the investigated area has a total area of 90 Km² of the total area, the urban area class comprised of 7%, agriculture areas are composed of 20%, and space area class is composed 73% of the studied area. In 1981, the urban area was concentrated in the inner part of Taiz, whereas agriculture land was spread all over the area, and most of the wadis were being cultivated. The 2003 land-cover map indicated an increase in the urban areas which reaches to 28%

of the total area, and a reduction in agriculture areas and open space areas of 12 % and 60 %, respectively. In 2003, the urban area expanded out of the city core, particularly in the northern part of the city and along the main roads. Significant increase in the roads, industrial, and disposal sites were observed in the area. Furthermore, the digitization result for the 2012 map showed an increase of urban areas of 38%, and a reduction in the other land covers.

The urban area has spread all over the area, new patches of settlements were produced in the city peripheral. A remarkable increase in the roads is observed especially in the northern part of the studied area. However, based on 2022 land-use map (Figure 6d), the region as whole has completely changed. As can be seen in Figure 6d, the studied area has divided in two parts separated by what so called "war-barrier zone" which is measured to cover about 9 km^2 (10 % of total area). In this zone, the buildings are sparse, the roads are cut down or destroyed. The area calculation of the new buildings that constructed in the period between 2012 and 2022 (Table 2) indicates that the building area expanded by only 1.3 km^2, from 35.5 km^2 in 2012 to 36.8 km^2. On the other hand, the agriculture area is 5 %, but the open lands have slightly increased by 1 % (Table 2).

Figure 7 explains the development of urban elements (building and roads) in relation to the agriculture land over the study periods. As can be seen in this figure, there is an upward trend in the urban elements over the years. While the building area was covered about 5 % (4.5 km^2) in 1981, it increased to cover 20 % (18.5 km^2) in 2003, and then 28.5 km^2 (32 %) in 2012, and 30.2 km^2 (34 % of total area) in 2022. Similarly, the roads area increased from 1.5 km^2 (1.3 %) in 1981 to 3.5 km^2 (3.5 %) in 2003, and 5.5 km^2 (6 %) in 2012, but decreased to 5 km^2 in 2022. On the other hand, there is a downward trend in agriculture over the years. The agricultural land decreased from 18 km2 (20 %) in 1981 to 10.5 km^2 in 2003, and then to 4.2 km^2 (5 %) in 2022. Hence, there is a strong relationship between the urban growth and agriculture lands. This is an inverse relationship whereby the increase in urban growth leads to a decrease in agriculture lands. A steeper increase in growth of buildings, compared to the growth in the roads indicates that there was sprawling expansion whereby building development has taken place without the development in transportation system. Sprawling areas are the areas in which the decrease of the agricultural land and increase of new construction are at their peak (Eryilmaz *et al*., 2008). Similar results have been reported by many researchers such as Hegazy and Kaloop (2015), Ahmed (2011), and Nzoiwu *et al.* (2017).

Thus, from the comparison as stated above, it can be concluded that there was a drastic change in Taiz urban between year 1981 and 2022. How much each LU/LC increased or decreased has been summarized in Table 2. In general, the urban area has expanded by 600 %, from 6 km^2 (7%) in 1981 to 36.8 km^2 (40 %) in 2022 with a net increase of 31 km^2 and an annual rate of 0.7 km^2/year. On the other hand, the area of agricultural zones is reduced from 18 km^2 (20 %) in 1981 to 4.2 km^2 (5 %) in 2022, with a total decrease of 13.8 km^2 and an annual rate of 0.34 km^2/year. The area of open lands (bare soils and rugged land) was 66 km^2 (73 %) in 1981 and it is reduced to 49 km^2 (54 %) in 2022 (Table 2). As it is clearly seen in Figures 1 and 6, Taiz City cannot be developed so much as a result of natural limitations (high altitude regions) in the south and northeast. This fact has caused lands located in the north and southwest of the city (which are mostly agricultural lands) to be occupied by urban constructions. In general, the increase of the urban area can be attributed to the continuous development due to high demand for houses over the years, coincided with a series of development in the city such as noticeable migration from rural to urban areas, and development decisions for industrial/ infrastructural investment. The decrease of agricultural area may be explained by the urban expansion and also due to the continuous deterioration in its productivity for reasons related to increasing soil salinity and pollution of water resources as well as environmental conditions.

Urban Expansion Rate And Pattern

As the main theme of this study was to investigate the urban land-use dynamics; thus, more attention was given to analyze the rate and pattern of built-up areas over the different study periods. Therefore, the study period (1981 - 2022) was divided into three stages (1981 - 2003, 2003 - 2012, and 2012 - 2022). Analysis the rate of urban growth between the three periods is summarized in Table 3. The graphical maps of the urban area of 1981, 2003, 2012, and 2022 were overlaid for visual comparison (Figure 8). This map enables a direct visual comparison of urban patterns in different time limits.

Table 3 and Figure 8 show that the rate and pattern of urban areas have changed between the different time intervals. At the beginning of the first period 1981, the spatial distribution of the urban built-up in Taiz was concentrated in the city centre. The core of Taiz City was spread within a radius of 1 km. No patches of settlements in the periphery were observed in the studied area. During the first period (1981 - 2003), urban areas expanded by 18.4 km^2 (or 0.8 km^2 yearly), the annual urban growth rate reached 14 %. The core of Taiz City was spread within a radius of 2 km (Figure 8). New patches of settlements were observed in the periphery of the urban core. Horizontal urban expansion was dominant in this period and urban growth in Taiz occurred mainly along transport routes, especially in the northern, eastern, and western parts of the city where industrial and economic zones were constructed there. While in the southern part of the city, less expansion is observed due to the rugged mountains.

During the second period (2003–2012), urban areas have increased by 11 km^2, from 24.5 km^2 in 2003 to 35.5 km^2 in 2012 given an annual rate of 1.2 km^2/year within nine years (Table 3), which is one and a half times more than the rate of the previous period (1981 - 2003). In this period, the

Table 3. Analysis of Built-up Area Expansion Based on Total Area Calculation between the Time Intervals

Period	Change (km^2)	Change (%)	Time Span (Years)	Annual Growth Rate (km^2/Y)
1981-2003	18.4	307	22	0.8
2003-2012	11.1	45.5	9	1.2
2012-2022	1.5	4.2	10	0.15

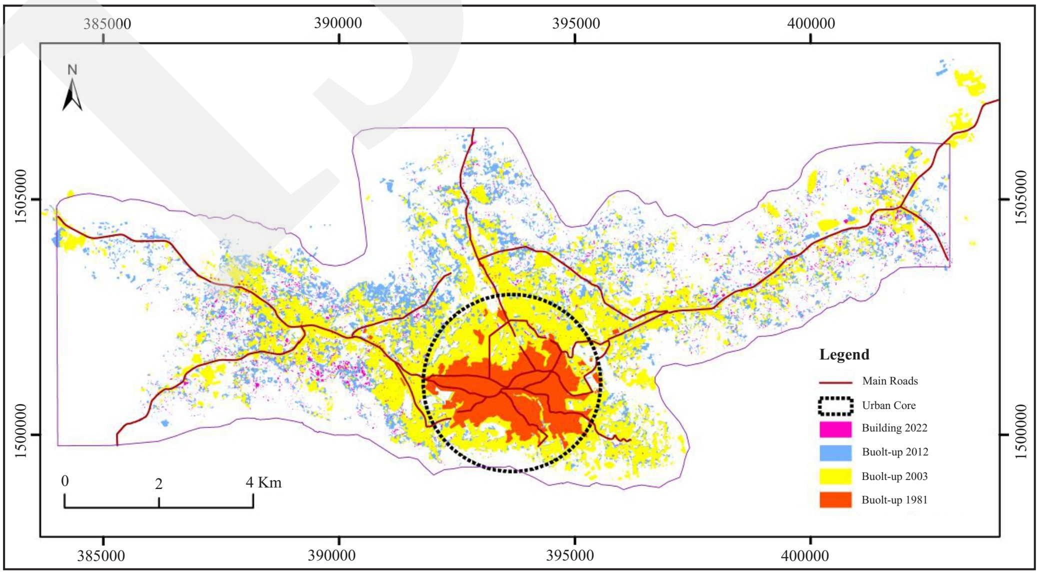

Figure 8. Spatiotemporal development of Taiz urban area between 1981 and 2022.

spatial urban expansion of the city occurred in all directions, in the core as well as the fringes. Haphazard urban expansion was dominant in this period (Figure 6c). This figure shows the growth patterns are spread all over the lands, *i.e.* the growth has filled spaces, and has merged many clusters together around existing built-up areas. There was also expansion in the hills and in the main valleys. This can be clearly observed if the pattern of urban expansion is compared in Figure 8 with the DEM map in Figure 1. It is evident that the settlements have spread towards the lower areas in elevation in the northern part of the city. While in the southern part, most of the building was on the hills and mountains. Land shortage and lack of proper management of urban lands have resulted in the use of rugged lands which are not suitable for urban use and construction.

During the third period (2012–2022) that coincided with the war period, urban growth was at the lowest rate. It occurred at approximately 0.15 km^2/year, as 0.1 % the rate of the previous period (2003–2012). In this period, the spread of urban area has nearly stopped in Taiz, with the exception of safer areas in the east (Al Hawban-Aden Road) and in the southwest (Taiz-Al Dabab Road). A decrease of urban growth is expected due to the armed conflict in Taiz where many buildings and roads have been damaged or cut. According to UN-Habitat (M. Elsyayal Smart GIS Map Editor software, ver. 21. 02. http://freesmartgis.blogspot.com.), about 7,000 buildings have been damaged in the city, and widespread destruction in residential areas and wide scale infrastructure damage is visible in Taiz City.

Overall, the results of the above analysis confirmed that the massive expansion of Taiz City had occurred during 1990s and 2000s. In this period, Taiz City has expanded by 30 km^2 in thirty-one years, with an annual rate of increase of 1 km^2 per year. Two urbanization indexes were observed: middle growth rate (0.8 km^2/y) is observed during the first period of urbanization (1981–2003) and higher rate of urban growth (1.2 km^2/y) is observed during the second period (2003 to 2012). This is followed by the lowest rate (0.15 km^2/y) during the war period. The urban expansion being experienced in Taiz can be described as horizontal and scattered in the first period and haphazard in the second period, since the urban spread occurs in all directions, spreading farther from the city centre, but mostly biased along the main roads and towards the lower areas in elevation. The variation in both rate and pattern can be attributed to the variation in the political and socio-economic situations in Taiz and Yemen in general.

Characteristics of Urban (Sprawl) in Taiz

Urban sprawl is characterized by unplanned, uneven utilization and increase in the built-up area along the urban and rural fringe, or that it can be defined as “peripheral growth that expands in an unlimited and non-contiguous way outward from the solid built-up (Feng and Li, 2012), and this attribute gives considerable information for understanding the behaviour of such phenomenon. Earlier studies carried out in parts of the world highlight and confirm that the built-up area could be used as a fairly accurate parameter for urban sprawl analyses. The proportion of the total population in a region to the total built-up of the region is a measure of quantifying sprawl. In this study, the spatial distribution of built-up areas that extracted from Google Earth images were used to characterize the urban sprawl of Taiz City. Furthermore, the population in the region also influences sprawl.

In Figure 8, the development of urban sprawl in Taiz is clearly observed. From this figure, three types of urban sprawl can be distinguished: leapfrog, filling, and extension. Leapfrog sprawl is that the expansion took place in the form of leaps separated over the area, which area unattached to any existing urban cluster (Wilson *et al.*, 2003). The buildings took place in empty spaces of the urbanized area and suburbanized area. Extension is the areas extending an existing urban cluster in a contiguous way (Basudeb, 2010).

To measure the degree of sprawl in Taiz, the urban sprawl index (USI) was calculated as the ratio of urban expansion to population increase

(OECD, 2013). The index is equal to zero when both population and urban area are stable over time. It is larger than zero when the growth of the urban area is greater than the growth of population, *i.e.* the density of the metropolitan area has decreased. The USI is computed as Formula 1:

$$USI = \frac{Ug}{Pg}, \quad \text{...(1)}$$

where:

USI is the urban sprawl index,

Ug is the annual urban growth (%) and

Pg is the annual population growth (%).

The annual urban growth rate (UG) is calculated by Yue *et al*. (2013) as:

$$Ug = \left(\frac{Ub - Ua}{Ua} \times \frac{1}{T}\right) \times 100\% \quad \text{......................(2)}$$

where:

Ug is the annual urban growth percentage rate,

Ua and Ub represent the urban area at the beginning and end of the monitoring period, respectively, and

T is the period of time from a to b time.

The population in the studied area is estimated for the years 1981, 2003, 2012, and 2022 based on the available data from the world pop project (University of Southampton, 2016). The results of this analysis (Table 4) show that the average annual growth in Taiz urban area as determined from change detection maps was 5.4 % from 1981 to 2022, compared to an annual population growth rate of approximately 4.1 % from 1981 to 2022. Hence, the USI= 5.4/4.1= 1.3. It is slightly higher than zero, so there is a high degree of sprawl in Taiz City. As the result, population density has decreased from approximately 21,600 inhabitants per square km in 1981 to 17,600 inhabitants per square km in 2012, and decreased to be 1,900 people per square km in 2022. The built-up density within the studied area (the ratio between the built-up to the total area) is calculated to be 75 % in the city core and 13 % in the urban periphery.

Some features of sprawl in Taiz have been detected by visual interpretation of Google Earth imageries as shown in Figure 9 in 2003. The urban sprawl in Taiz was especially digitized at the city periphery with the appearance of some scattered patches (yellow circle) on the north side. However, in 2022 the built-up (red circle) became denser, and new patches of settlements were observed in the northern part of the city. The appearance of black areas (war barrier zone) is more important with a dense vegetation cover oriented towards the northwestern side.

Based on the visual interpretation of Google images and field observations as shown in Figure 9, the sprawl in Taiz in addition to that it is rapid, uncontrolled, haphazard, leapfrog, informal, *etc*. There are many other characters that could be found in Taiz. These are: the low densities at periphery areas compared to the city centre; the spreading of slum housing in the city centre; the scattered development of roads; the random construction of homes; the loss of vegetation cover; the lack of public spaces, gardens and play grounds, the abandonment of vegetation cover; the lack of public or green spaces; the housing is characterized by detached, individual houses, and the surplus of housing units.

Table 4. Taiz Population and Urban Growth Percentage, Rate, and Density (1981–2022)

Year	Population	Population Growth (%)	Urban Area (km^2)	Annual Urban Growth (%)	Population Density
1981	129,561	---	6.00	—	21600
2003	441,438	6	24.5	14	18000
2012	624,232	3.9	35.5	5	17600
2022	700,000	1.5	36.8	0.37	19000
Average		4.1		5.4	19000

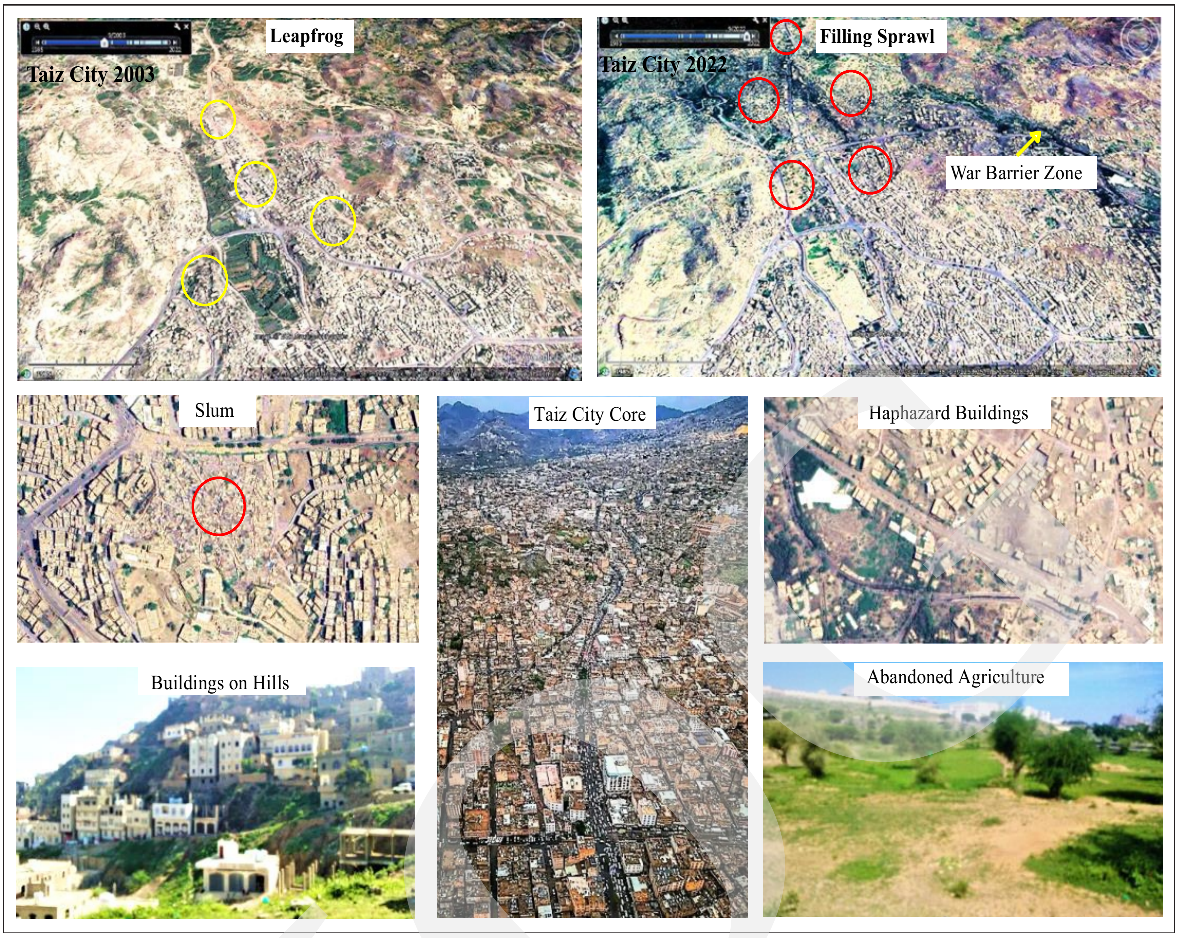

Figure 9. Urban sprawl detected in the north of Taiz from 2003 to 2022 based on Google Earth images with pictures showing some sprawling features observed in the studied area.

Effect of Urban Sprawl on the Environment of Taiz

In addition to the fact that urban growth was at the expense of agricultural lands, it caused many other problems such as water supply, sewage disposal, soil salinity, and desertification, *etc.* (Al-Darwish *et al.*, 2018). The water supply is the most pressing problem in Taiz. The increase in urban population has exhausted the existing water supply sources that exist in three well fields at the city periphery. According to governmental reports, the average urban domestic per capita decreased from about 85 l/d per person in 1986 to about 23 l/d by the year 2010. The significant shortages of water supply is caused by the depletion of existing water resources. Furthermore, the water supply network is rarely extended to new users (only 57 % of the population are covered). Sanitation is another daunting problem. The increase in the populated area within Taiz City has put more pressure on the existing wastewater treatment plant that exists in Al Borayhi area, 8 km to the north of the city centre. The sewerage network covers only 44 % of the population. In several unsewered areas to the north, east, and west of the city, raw sewage is disposed of directly into wadis, which causes the health hazard and threatens to contaminate groundwater resources. The average salinity of the groundwater in these areas was about 3,000 mg/l, and increased to about 4,000 mg/l in 2002 (Google earth Pro ver.7.1. https://www.google.com. 2020. The third problem is the abandonment of vegetation covers. The vegetation in the urban area of Taiz was cut by man to build. As mentioned before, about 0.35 km^2 of agricultural land has been converted to urban use per year in the last forty years. Thus, it can be concluded that the environmental problems in Taiz are caused by the lack of planning, the over-exploitation of water resources, and uncontrolled housing. To face these problems, the present study highlighted the need to focus on the development of alternative strategies to conserve natural resources and slow down the pace of land cover changes. The strategies that should be adopted by the local authorities include ensuring environmental sustainability, good governance, and enhanced urban development. In this work, the necessary data and information were tried to be produced for adaptation and implementation of these strategies in Taiz context.

Conclusions

In Taiz City, no study on urban growth change detection has been carried out until now. Thus, this study attempted to identify such urban growth change for the last four decades (1981−2022). The data used for this study were multiseries high resolution satellite images and topographic maps. As a new tool in remote sensing technology providing positional data with suitable accuracy and free of cost, Google Earth was used as a source for the data in this study. Three Google Earth images for the years of 2003, 2012, and 2022 and the topographic map of Taiz for the year 1981 were individually processed in GIS environment. A manual digitization method was performed to extract the urban land-use features from the different datasets. Three land-use classes have been identified as urban built-up, agricultural, and open lands, and four land-use maps in vector format were generated to represent the four mentioned dates (*i.e.* 1981, 2003, 2012, and 2022). The spatial distribution of the built-up area in each map was analyzed, and the major land-cover changes were highlighted by using vector area comparison approach in ArcGIS software. The results show that the urban area in Taiz had rapidly expanded during the last forty years. This has resulted in drastic shrinking in agricultural lands and environmental degradation. During the study period, the urban area has expanded by 600 % from1981 to 2022. The increase in settlements has caused a decrease in the agriculture area by 77 % during the same period. The city has grown rapidly between 1981 and 2012. After 2012, the city has experienced different changes in its land use, which represented by slowdown urban growth. In terms of urban patterns, the major change, and urban expansion were found to occur in the northern, western, and eastern parts of the city along the main roads and towards the low laying areas with less expansion on the hills and mountains in the southern part. Three sprawling patterns are recognized in the studied area: leapfrog along the main roads filling in the urban core and haphazard at the urban fringes. A correlation between the urban growth, population growth, and the environmental status of Taiz City shows that the growth rate of the built-up area outpaced the population growth rate, and there is no vegetation and green area left in the city. Due to the haphazard urban development in Taiz, the city faces many problems such as drinking water shortages, sewerage disposal issues, traffic congestion, and other environmental and socio-economic issues that cannot be solved without addressing issues related to urban development. Thus, further environmental impact such as water pollution, air pollution, and ecological imbalance should be studied in response to the growth of urban in Taiz. The results of this study can assist the decision-makers and urban planners to reconsider the strategy of the city future expansion. The spatial and temporal analyses of urban expansion and the vector data provided by this study could be used as the required input data for future urban modeling of Taiz City.

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