USING DIGITAL TOOLS FOR MONITORING AND ANALYSING SPATIAL VARIATIONS OF POPULATION DISTRIBUTION IN THE CITY OF AL-MADINAH AL-MUNAWARAH, KINGDOM OF SAUDI ARABIA, 2004-2020

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ABSTRACT:
This article combines demographic and spatial data to investigate and analyse spatial variations in population distribution in Al-Madinah Al-Munawarah in the Kingdom of Saudi Arabia. Drawing on multiple data sources, it applies a straightforward rationalisation-based methodology based on combining demographic indicators with spatial data using geographic information systems and remote sensing. The findings show that Al-Madinah's population was estimated at 1,500,000 people in 2020; the Lorenz curve and the Gini ratio reveal that the population is unevenly distributed geographically since 95% of the population lives in 18% of the city's total area. The central area is densely populated: about half of the population lives within a 5-kilometre radius. Location quotient values reflect variations between concentrations of Saudis and non-Saudis. Due to the expansion of the city's built-up area, net population density fell from 46 to 32 p/ha between 2004 and 2020; Saudis are more mobile than non-Saudis as their mean centres recently shifted 1,337 and 665 meters south, respectively. The study concluded that Al-Madinah's residents, especially Saudis, are gradually moving from the central business district to the periphery.

Key-words: *GIS, Remote Sensing, City, Net population density, Gini ratio, Mean centre of the population, Standard distance, Location quotient, Al-Madinah Al-Munawarah.*

1. INTRODUCTION

Urban areas are expanding rapidly, with many cities becoming increasingly compact due to population growth (Tungnung & Anand, 2017). Cities are growing in both population and footprint at double previous rates (Angel et al., 2011). These considerable geographical changes, especially the dramatic global increase in urban populations, are affecting natural and man-made systems. Worsening overcrowding, housing shortages, and insufficient infrastructure all require effective city planning and management (Herold et al., 2005): managing the repercussions of urban expansion is a contemporary global challenge. Furthermore, future urban growth and the concomitant appropriation of natural resources has significant consequences for sustainable development plans (United Nations Population Division, 2019).

Geographic inequality is a primary driver of development, suggesting that governments often fail to equitably distribute economic resources (World Bank, 2009). Moreover, many countries face an increasing severity of socio-economic inequalities between or within urban areas due to the interrelationship between spatial population concentration and economic development (Portnov & Pearlmutter, 1999). Population and economic activities, therefore, tend to be concentrated in the central business districts (CBD) of many cities, while the peripheries are characterised by diminishing populations and slower economic development.

The Kingdom of Saudi Arabia (KSA) has undergone rapid urbanisation since the 1950s. The proportion of the population living in urban areas of the KSA increased from 21% in 1950 to 84% by 2018; the urban population is projected to reach 86% by 2030 and 90.4% by 2050 (Alahmadi & Atkinson, 2019; United Nations Population Division, 2019). Therefore, to examine this issue in the context of the KSA, this paper takes Al-Madinah Al-Munwarah, the capital of Al-Madinah Province

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and a place of great religious significance to Muslims as it houses the Prophet's Holy Mosque in its centre, as a case study. The Prophet's Mosque is the city's centrepiece and has contributed several times to changes in Al-Madinah's morphology.

The KSA conducted four reliable nationwide censuses in 1974, 1992, 2004, and 2010; a fifth census was intended to take place in 2020, with the planning phase starting on January 10, 2018. However, on March 13, 2020, GAS announced a suspension of the enumeration phase due to the COVID-19 pandemic. Al-Madinah is the fourth most populous city in the KSA. According to the Saudi census conducted by the General Authority for Statistics (GAS), between 1974–2010, Al-Madinah's population increased from 198,000 to 1,100,000. The Ministry of Municipal and Rural Affairs (MMRA) recently estimated the population of Al-Madinah at 1,400,000 and projected an expansion to 2,000,000 by 2030 (MMRA, 2019a). Moreover, the city has experienced high population growth in recent decades (above 3%). Importantly, most of Al-Madinah's inhabitants inhabit the 5,000-hectare area surrounding the Prophet's Mosque at the city's centre. This area is cramped, especially during peak visiting seasons, as around 90% of those performing Hajj and Umrah visit the Prophet's Mosque after their journey to Makkah (Islam's holiest city) (MMRA, 2019a). In 2019, Al-Madinah received almost all of those performing Hajj and Umrah: 2,489,406 visitors during Hajj (GAS, 2019a), and 11,700,368 during Umrah (GAS, 2019b). Furthermore, the morphology of the city, especially its CBD, has changed due to the numerous enlargements to the Prophet's Mosque that could contribute to alleviating the population density in this area.

Accurate mapping of population distribution is essential for policymaking, urban planning (Mossoux et al., 2018), and identifying any dimensions of imbalance between a particular population and the area it occupies. Although spatio-temporal data on population and its determinants are important for understanding and responding to population problems, such long-term data are often difficult to obtain (Wang & Chen, 2016). New tools, however, such as geographic information systems (GIS), remote sensing (RS), and geospatial tools can produce accurate maps that allow data retrieval for customised geographic areas and are not limited to administrative units like censuses (Long et al., 2001; Stewart, 2004; Yang et al., 2009). Combining RS data with GIS technology for population studies is crucial in order to maximise the respective strengths of each approach in analysing certain population aspects (Yagoub, 2006; Benomar et al., 2006; Yang et al., 2009; Weerakoon, 2017).

Al-Madinah's high population density in its central area has led to many problems: overcrowding, traffic congestion, poor infrastructure, and old or dilapidated housing stock. The government has sought to moderate the population density in the CBD and redistribute the population to the periphery. Therefore, to manage the population-related issues effectively, it is necessary to monitor and analyse the changes in the population distribution in Al-Madinah through accurate mapping.

The use of GIS and RS techniques to analyse and model environmental issues has received considerable attention in the critical literature across recent decades. Such techniques have furthered the study of population-related issues such as urban sprawl, urban land use change or land cover, and urban planning (Ibrahim & Sarvestani, 2009; Tungnung & Anand, 2017). Furthermore, these approaches provide effective tools for spatialising population census data; integrating geodemography with GIS capabilities allows researchers to examine and query the spatial components of population data (Yang et al., 2009). The use of GIS in demographic analysis ranges from creating maps to modelling the relationships between population variables (Baudot, 2001). Stewart et al. (2004) used GIS and RS to examine urbanisation in Greater Cairo based on the built-up area identified from census data, finding that population densities tend to decrease in the centre and increase at the periphery. Other scholars have used a dasymetric method to improve the representation of population distribution, obtaining a high-resolution dataset of population distribution, and analysing the accessibility to population centres (Linard et al., 2012; Amaral et al., 2012).

Estimating the number of residents at the neighbourhood level by combining fieldwork data with high-resolution RS offers a solution to systematically mapping population distribution in areas where reliable census data are not regularly available (Mossoux et al., 2018). Benomar et al. (2006) used GIS to estimate the population growth of the Libyan city of Zwarah and found that the population growth rate was 7.2%, with the city's footprint increasing from 355 to 4,270 hectares between 1980–2000. Ramzi (2012) used RS to predict the future urban growth of the Egyptian city Ras Sudr and found that the city's expansion was due to population growth. Furthermore, Wang and Chen (2016) produced a dataset on China's population distribution and its driving factors using GIS and RS: China's population was densest in the southeastern regions, with availability of water being the primary factor influencing population distribution. Long et al. (2001) proposed a GIS-based measurement of urban population density for China, India, and the USA, providing insight into the ecological impacts of urbanisation. Marti-Henneberg et al. (2016) used digital tools to investigate population density trends in Spain, finding that the population was unevenly distributed across the nation. Yagoub (2006) examined the population distribution in Al Ain city in UAE using GIS and RS: the average difference between the population recorded in 2001 and the estimated population from images was 5% and that the population density decreased further from the CBD.

Al-Madinah's CBD has a relatively long history of being densely populated due to its religious significance and being home to many sectors serving residents and visitors (Ragab, 1979; Makki, 1989; Mohamed, 2011; Al-Mahdy, 2013; Mohamed et al., 2016; Tayan et al., 2017). Ragab (1979) revealed that Al-Madinah's densely populated CBD forms a semi-circle with a radius of 500-metres with the Prophet's Mosque at its centre. In the late twentieth century, Al-Madinah underwent a series of urban expansions due to external and internal migration (Mohamed, 2011). Abdou (2017) reported that between 2000–2016, the overall trend of Al-Madinah's residential mobility was towards its outer zones, motivated by increase in family size, change in marital, rental rates in the centre, or proximity to family, friends, and the workplace.

Previous literature has predominantly focused on the services and urban expansion of Al-Madinah, while overlooking the city's population distribution trends. This study addresses this gap, being (to the best of our knowledge) the first attempt to monitor and analyse the spatial variations in Al-Madinah's population distribution by integrating demographic and spatial data using GIS and RS. The built-up area was calculated for each district in the city, providing a much more comprehensive overview of its population distribution and possibilities for detailed geographical analysis (Marti-Henneberg et al., 2016). The methodology involved combining census data with spatial data to visualise Al-Madinah's population distribution. The 2004 and 2010 censuses by district were used to estimate the population in 2020 in order to provide the demographic data needed for monitoring Al-Madinah's recent population distribution. This study aims to accurately analyse various aspects of the geographical distribution of Al-Madinah's population in 2004 and 2010 in order to predict them in 2020. Additionally, it endeavoured to examine the evolution of Al-Madinah's mean centre of population, standard distance, and location quotient over the past two decades.

2. STUDY AREA

Al-Madinah lies on the western part of the Arabian Shield and extends from 24° 21' 00" to 24° 36' 00"N and 39° 36' 00" to 39° 24' 36"E. It is located on the northwestern side of Saudi Arabia and occupies an almost flat basin surrounded by lava plateaus and hills**.** The surrounding mountains are 800–1500 meters high, with Wairah being the highest, followed by Uhud (MMRA, 2019a; Matsah & Hossain, 1993). Five valleys pass through Al-Madinah: Al-Aqiq, Al-Aqoul, Bathan, Mahzoor, and Ranounaa. Administratively, Al-Madinah is divided into seven municipalities (see **Fig. 1**).

Al-Madinah has 107 districts and is served by both ring and radial roads; its ring roads include King Faisal Road (the innermost ring road), King Abdullah Road (the second ring road), and King Khalid Road (the third ring road). For the purpose of analysis, the city was divided into four geographic zones:

(i) Zone 1 contains the CBD, is encircled by the innermost ring road and covers 186.5 hectares. Zone 1 contains six districts, with El-Harm at its centre. It is extremely crowded, especially during visiting season, due to its religious significance and the associated concentration of commerce, accommodation, and service industries.

Fig. 1. Location of the study area (*source: Al-Madinah Regional Municipality (ARM), 2020*).

(ii) Zone 2 forms a ring-shaped area extending from the innermost ring road to the second ring road. This zone covers 5,360 hectares. Zone 2 comprises 25 districts, forms the main residential area, and contains a significant concentration of commercial activities.

(iii) Zone 3 is a ring-shaped area which stretches from the second ring road to the third ring road, covering 45,947 hectares. Zone 3 comprises 56 districts and is mainly residential. Much of Zone 3 has only recently become residential.

(iv) Zone 4 comprises the periphery, extending from the third ring road to the city's outer administrative boundary, occupying 177,937 hectares. It includes 20 districts, most of which are uninhabited (see **Fig. 2**).

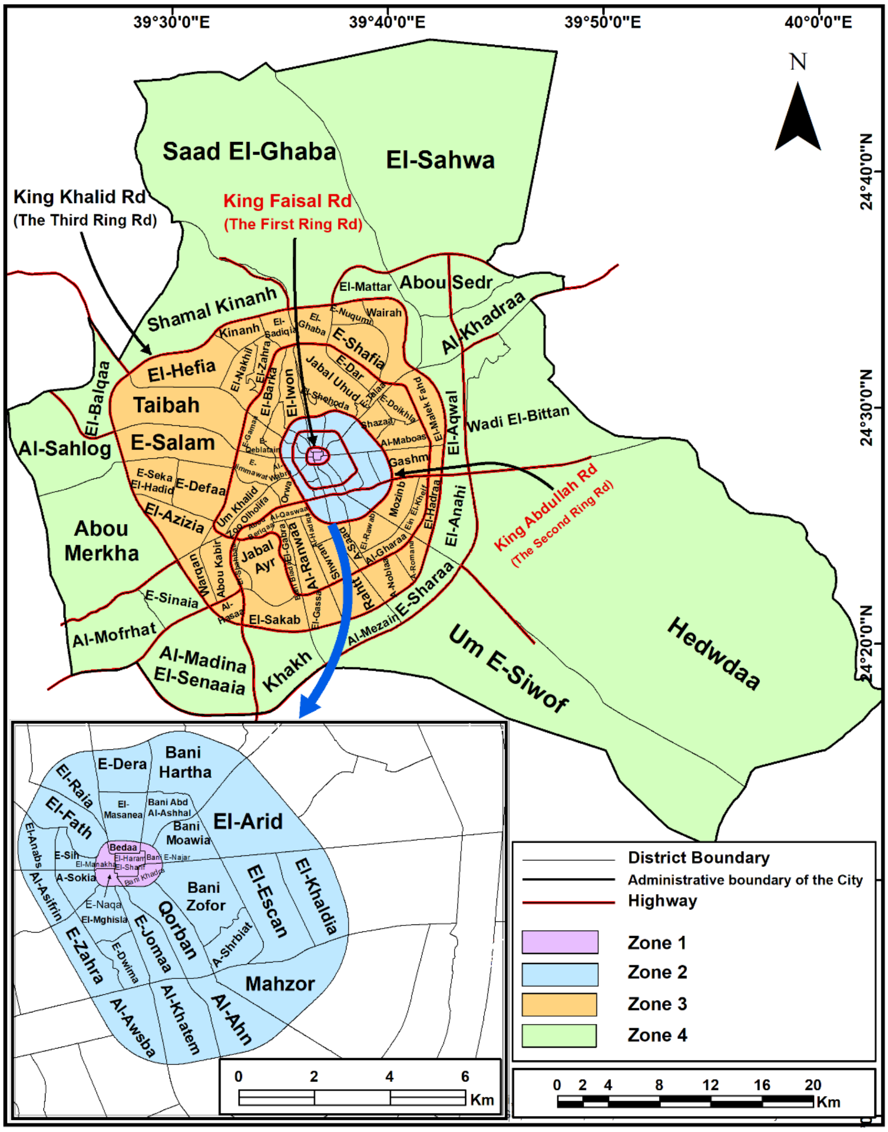

Fig. 2. Administrative map and the four geographic zones of Al-Madinah (*source: As Figure 1*).

3. METHODS AND MATERIALS

The dynamics of spatial population distribution have long attracted academic interest and combined various disciplinary approaches (Voss, 2007). The recent increase in interest in the population sciences has been driven by the increased availability of geospatial data and the emergence of GIScience tools for their analysis, including GIS, spatial analysis, and spatial statistics (Matthews et al., 2019; de Smith et al., 2018). Therefore, in order to analyse and visualise aspects of population distribution in Al-Madinah, the research methodology involved integrating demographic data with spatial data derived from GIS and RS based on district-level information from the 2004 and 2010 censuses. Spatio-temporal demographic data are essential for understanding and responding to population issues. Unfortunately, it is often difficult to obtain such data in Al-Madinah at the district scale and over an extended period. Beyond the 2004 and 2010 censuses, no data are available on Al-Madinah's population by district. Therefore, the work relied heavily on both censuses, using them to estimate the city's population in 2020. The population estimation approach involved using an equation to determine Al-Madinah's likely population by district on February 2, 2020. Evaluation studies show that mathematical methods may be necessary for the absence of symptomatic data for the postcensal period (Bryan 2004). This approach assumes that population growth occurs in a linear manner and that the rate of change remains consistent: by calculating the growth rate during a baseline period, this same growth rate can be applied to a future, target period (George et al., 2004; Khoiyangbam & Gupta 2015). Initially, the population growth rate of a district was calculated in the baseline period (2004–2010) using the following equation:

$$r = \frac{P_t - P_0}{t * P_0}$$

where r is the population growth rate during the base period (2004–2010), P_t is the population in the launch year, P_0 is the population in the base year, and t is the number of years in the base period. Then, a projection, using this method, was computed using the following:

$$P_t = P_0 * (1 + rt)$$

where P_t is the population in the target year (2/2/2020), P_0 is the population in the launch year, t is the number of years in the projection horizon, and r is the calculated population growth rate for the base period (Khoiyangbam & Gupta, 2015).

Furthermore, the study adopted two assumptions to match Al-Madinah's population structure by nationality and account for recent transformations in socioeconomic and political conditions in the KSA. The first assumption concerned Saudis: it was assumed that the growth rate of each district, shifted from uninhabited by Saudis to inhabited between 2004–2010, was equal to the growth rate of the total number of Saudis in Al-Madinah (0.02091967), and remained stable during the target period (2010–2020). The growth rate of any of the remaining districts in the target period was assumed to be equal to that of the baseline period. The second assumption concerned non-Saudis: it was assumed that the growth rate of each district, changed from uninhabited by non-Saudis to inhabited between 2004–2010, was equal to the growth rate of total non-Saudis in Al-Madinah (0.06674985), and remained constant over the target period. For any of the remaining districts, the target period growth rate was assumed to be lower than the baseline period with a percentage ranging between 0.1–0.7. This expected reduction was grounded in the introduction of new costs attached to foreign employees and dependents: fees for foreigners sponsoring dependents in KSA were introduced in July 2017 and gradually increased over the following three years. These new financial demands forced thousands of migrants (accompanied by family members) to leave the KSA, especially in 2018 and 2019.

RS data were required to accurately analyse the population distribution of Al-Madinah. Due to its ability to provide multi-temporal analysis, RS offers a unique perspective on the evolution of population distribution in cities (Canada Centre for Remote Sensing, 2003; Ramzi, 2012). Combining land cover data with detailed settlement data can redistribute aggregate census counts to enhance the accuracy of gridded population data (Linard et al., 2011). Therefore, the research methodology relied on three RS images that were selected to identify Al-Madinah's built-up areas in 2004, 2010, and 2020, respectively. These three images share the same satellite system, path, row, and spatial and temporal resolution, but have different remote sensor names and identifiers. They were geometrically corrected by the provider on the Universal Transverse Mercator (UTM) projection system, the zone of 37N, and on the World Geodetic Survey of the year 1984 (WGS_84) spheroid and datum (see **Table 1**). These three datasets were carefully selected to match as closely as possible the dates of Saudi censuses and the author's estimate, as only two days separate the image obtained on 17 September 2004 and the third Saudi census on 15 September 2004; seventy-one days separate the image obtained on 14 February 2010, and the fourth Saudi census on 17 April 2010; the image obtained on 2 February 2020 corresponds to the date the author estimates the postponed 2020 census would have taken place. Thus, these three datasets accurately reflect the built-up area of each district in Al-Madinah in 2004, 2010, and 2020, respectively.

Table 1.

Technical details of the Landsat dataset used in the study.

Sensor Name	**Landsat-5-TM**	**Landsat-7-ETM+**	**Landsat 8**
Acquisition Date	17-SEP-2004	14-FEB-2010	2-FEB-2020
Sensor Identifier	Thematic Mapper (TM)	the Enhanced Thematic Mapper Plus (ETM+)	Landsat Operational Land Imager (OLI) And Thermal Infrared Sensor (TIRS)
Path / Row	170/43	170/43	170/43
Spatial Resolution	30 * 30	30 * 30	30 * 30
Spectral Resolution	7	6	8
Pixel Depth	8 Bit	8 Bit	16 Bit
Cloud Cover (%)	0.00	0.00	0.00
Spatial Reference	WGS_1984_UTM_zone_37N	WGS_1984_UTM_zone_37N	WGS_1984_UTM_zone_37N

Source: The United States Geological Survey USGS's Earth Explorer web browser.

The satellite images were then processed, enhanced, and classified using ArcGIS. They were subjected to supervised classification, since classification of RS images is commonly used as a source of supplementary data. A land cover map is a valuable GIS layer and is essential for disaggregating demographic data (Linard et al., 2011). Supervised classification was conducted for three land-use classes: (i) built-up areas (housing, government offices, educational and health institutions, and recreational and accommodation facilities); (ii) agricultural land (palm groves and green spaces); (iii) uninhabited areas (mountains, hills, and stony plains) (see **Fig. 3**).

The supervised classification started with a training phase by assigning pixel samples belonging to the three aforementioned classes in each image, followed by a decision-making phase where the computer assigned each class label to other, similar pixels in the image. The supervised classification identified the expansion of the built-up area of each district in 2004, 2010, and 2020. Next, the built-up area of each district in the three images was digitized and linked to its population size using GIS tools. This method provides more accurate dot-density maps than methods based on administrative boundaries alone. Dot-density maps were used to represent the actual locations of populations in each district of Al-Madinah: they clearly show where specific data occur, especially in demonstrating how a population is distributed across a given area (Allen, 2022; Gomes, 2017; Newbold; 2010). To summarise, this approach aimed to estimate the population in the built-up area of each district, as GIS and census data were combined to link the population data with particular locations to create population density maps (Ramzi, 2012). Moreover, this method provided accurate maps of population distribution using dot density symbology to represent the population density within a district's built-up area and monitor the spatiotemporal variations of different aspects of population distribution.

While population census data are rarely available at a high spatial resolution (Mossoux et al., 2018), satellite imagery provides a good indication of population density (Rai Technology University, n.d), as a land cover map is perhaps the best single indicator of population density (Dobson et al., 2000). Therefore, the area of built-up area in each district in the three datasets was computed and linked to the population size using GIS tools to obtain the net residential population density.

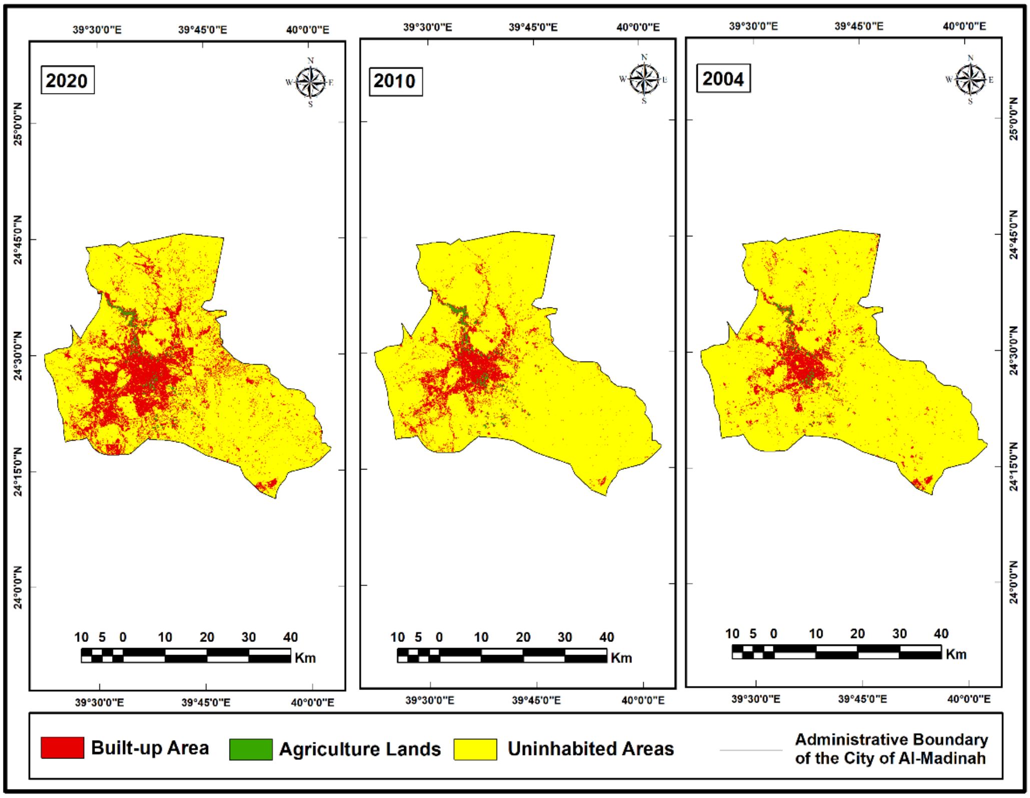

Fig. 3. Supervised classification results for the satellite images of Al-Madinah in 2004, 2010, and 2020, respectively (*source: USGS's Earth Explorer web browser; ARM, 2020*).

Briefly, the population density was calculated for built-up areas covered by Al-Madinah's census units, as calculating net residential densities gives a more accurate representation of population densities and helps planners to analyse urban land use (Long et al., 2001; Weerakoon, 2017).

Overall, the calculation of area of the built-up area of each district in Al-Madinah led to precise calculations for population distribution, net population density, mean centre of population (MCP), and standard distance (SD). Furthermore, the spatial statistics tools provided by the GIS programme were used to determine the MCP and SD for Al-Madinah in 2004, 2010, and 2020, respectively. However, calculations of other indicators of population distribution such as the concentration index (CI), the Lorenz curve, and the Gini Ratio (GR), were based on the administrative boundaries to show clearly the imbalance between the population and available space in Al-Madinah.

The methodology also involved calculating CI and location quotients (LQ). CI is the maximum of the set of values of the difference between the cumulative percentages of population and areas of the geographical units of a region. Algebraically, it is given as:

$$\mathrm{CI} = \frac{1}{2}\sum |\mathrm{xi} - \mathrm{yi}|$$

where *xi* is the percentage of the population and *yi* is the percentage of the area.

LQ compares a population characteristic with the total population in terms of its regional distribution. Mathematically, LQ is written as:

$$\mathrm{LQ} = \frac{\mathrm{xi}}{\mathrm{pi}} \Big/ \frac{\mathrm{X}}{\mathrm{P}}$$

where *xi* is the population of district i with characteristic x, pi is the total population of district i, X is the city's total population with characteristic x, and P is the city's total population.

4. RESULTS AND DISCUSSION

The four reliable Saudi censuses in 1974, 1992, 2004, and 2010 reveal a substantial increase in Al-Madinah's population over the census years: 198,000; 609,000; 920,000; and 1,100,000 people, respectively. The number and proportion of non-Saudis also increased: 43,000 (22%), 176,000 (29%), 280,000 (30%), and 385,000 people (35%), respectively (GAS, 1974-2010). The Madinah Urban Observatory estimated Al-Madinah's population at 1,301,322 people in 2018; the current study estimated the population to be 1,500,308 people in 2020, 20.3% of whom were non-Saudis. Accordingly, the number and percentage of non-Saudis decreased in 2020, reflecting the impact of the previously mentioned new legislation introducing new costs for foreigners.

Regarding the population distribution of Al-Madinah visualised using dot-density maps, **Figure 4** shows the demonstrably uneven distribution of Al-Madinah's populations. The most populous districts are located around the Prophet's Mosque in the CBD, with the population density gradually decreasing towards the periphery. The cities of Al-Madinah and Makkah are similar in urban sprawl as they each expand radially from a central holy site which can be seen to catalyse their population distribution. Looking at the zonal analysis, most residents were concentrated in the two innermost zones (zones 1 and 2), while many parts of zone 3 and most of zone 4 contained large areas which were uninhabited. Zone 1 was the most highly populated, particularly during visiting season; for Al-Mahdy (2013), it represents a 'town inside a city' with 300,000 inhabitants, 80% of whom are temporary residents. The current study reveals that almost 63%, 60%, and 50% of Al-Madinah's population were contained within a five-kilometre circle in 2004, 2010, and 2020, respectively. Al-Madinah's population concentration in the CBD dates back to the early 1970s. A quarter of Al-Madinah's population in 1971 (137,000 people) was estimated to be within a one-kilometre circle of the centre (Ragab 1979). The past two decades have seen spatio-temporal variations in the city's population distribution as inhabitants relocated widely in 2020 due to recent settlement projects. Two new directions of population spread emerged in 2020. The first was to the south, as people became concentrated in districts covered by zone 3, such as north of Mozinb, southwest of El-Gharaa, south of A-Saad, Shwran, Al-Ranwaa, and Al-Hadiqa. This population shift was due to housing plans approved by Al-Madinah for the period 2010–2028 which intended to relocate 80% of the city's population to its southern districts (Mohamed, 2011). The second population spread was to the west, as people started concentrating in the western districts of zone 3 in 2010, a trend that had increased by 2020. Between 1965–1989, Al-Madinah expanded to the west and southeast, beyond the second ring road, avoiding the mountains and expanding into the valleys (MMRA, 2019a). This was to accommodate a wealthy Saudi elite who chose to settle in villas outside the CBD in the 1970s (Ragab 1979) because they could afford private alternatives to public services (Stewart et al., 2004).

Over the past two decades, Al-Madinah has seen increased residential mobility from its two inner zones to the southern, southwestern, and western districts of zone 3. Broadly, Al-Madinah's residential mobility is from the centre to the periphery which is consistent with the most populous city in the KSA in the late 1980s (Riyadh) (Al-Kharif, 1994). Between 2000–2016, some zone 2 districts (such as El-Arid, E-Jomaa, and El-Raia) experienced residential mobility to zone 3 districts located to the south, the southwest, and the west (Abdou, 2017). Saudis and non-Saudis were (and remain) concentrated in the central area within the second ring road in more densely populated unplanned settlements (MMRA, 2019a).

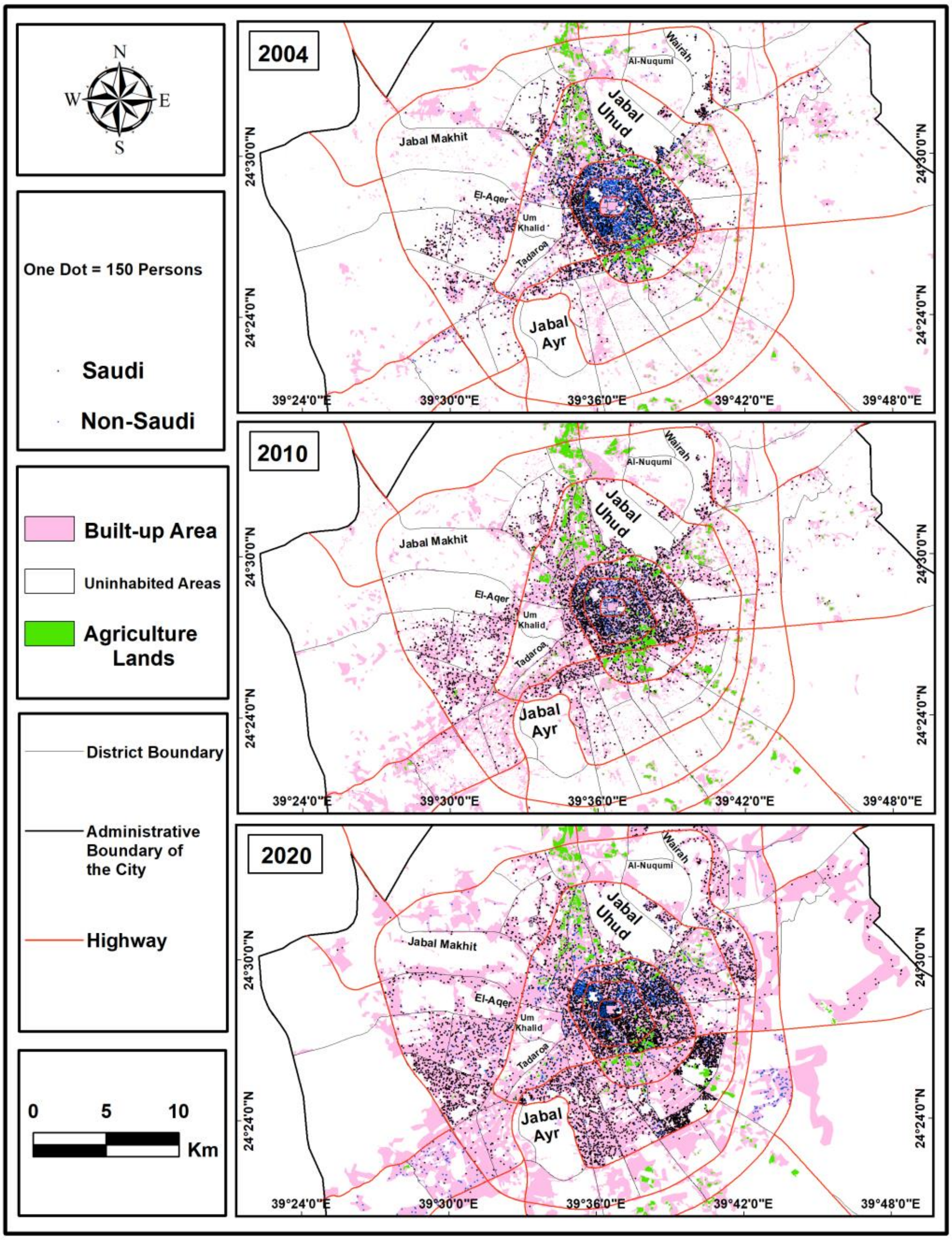

Fig. 4. The evolution of Al-Madinah's population distribution (2004–2020) (*source: GAS 1974-2010; USGS's Earth Explorer web browser; ARM, 2020*).

The 2010 map reflects an increase in the concentration of Saudi inhabitants in the western districts of zone 3. The 2020 map reveals that the concentration of Saudis increased in the southern, southwestern, and western districts of zone 3, especially in Mozinb and Al-Gharaa. However, the vast majority of non-Saudis resided in the two inner zones between 2004-2020, due to proximity to their places of employment in the CBD. In the central area within the second ring road, foreign workers represent the largest population (MMRA, 2019a). This finding is consistent with the case of Al-Ain city, as the majority of non-citizens were largely clustered near the CBD (Yagoub, 2006). In summary, Saudis have relocated further from the CBD than non-Saudis over the past decade: while many Saudis moved from zone 2 to zone 3, non-Saudis have instead moved between districts within the same zone. Additionally, Al-Madinah's mountains have long served as natural barriers that have curbed urban expansion and subsequently led to the spread of settlements to the north, south, and west. That said, the city has recently expanded north, south, and east along the valleys (MMRA, 2019a), leading to changes in the population distribution map.

Regarding gross population density, continued population growth in a city causes widening administrative boundaries and changes in land cover. Therefore, naturally vegetated land and agricultural land are converted into residential areas characterised by high population density. As Al-Madinah covers a large administrative area (229,430 ha), the city's gross population density is low and slowly increasing, from 4 to 6.5 p/ha between 2004–2020. By comparison, Makkah had a low density of 2.3 p/ha in 2013 (El-Abd, 2018), while the Libyan city of Zwarah had a high gross population density of 39 p/ha in 2000 (Benomar et al., 2006). Al-Madinah's two inner zones recorded the highest densities (see **Table 2**). The significant increase in population density in zone 1 versus a slight decrease in zone 2 between 2004–2020 was due to non-Saudis relocating from zone 2 to zone 1. Conversely, the density of Saudis increased in zones 2 and 3 because many Saudis wished to avoid the overcrowded city centre. These findings are consistent with the case of the city of Riyadh, as it has experienced a decline in population density at an exponential rate from the city centre, with variations between its sectors and zones (Al-Gabbani 1991).

Table 2.

Gross and net residential population densities of Al-Madinah by nationality and zone (2004–2020).

Zones			Zone 1	Zone 2	Zone 3	Zone 4	Al-Madinah
Gross density (people/ha)	2004	SA	6.1	66.6	5.8	0.1	2.8
		Non-SA	30.8	40.8	1.1	0.0	1.2
		Total	36.9	107.3	6.8	0.1	4.0
	2010	SA	24.6	71.2	6.7	0.1	3.1
		Non-SA	140.1	49.1	1.6	0.1	1.7
		Total	164.7	120.2	8.3	0.2	4.8
	2020	SA	348.4	85.4	13.9	0.2	5.2
		Non-SA	280.5	25.3	1.8	0.2	1.3
		Total	628.8	110.7	15.7	0.4	6.5
Net residential density (people/ha)	2004	SA	7.2	90.7	31.1	2.3	31.9
		Non-SA	36.6	55.6	5.8	0.8	13.9
		Total	43.8	146.3	36.9	3.1	45.8
	2010	SA	32.1	90.2	25.3	2.9	29.8
		Non-SA	182.3	62.2	6.1	2.9	16.0
		Total	214.3	152.3	31.4	5.9	45.9
	2020	SA	418.1	95.8	28.4	1.7	25.4
		Non-SA	336.7	28.4	3.6	1.8	6.5
		Total	754.8	124.1	32.0	3.5	31.9

Source: Author's calculation based on: GAS 1974-2010; USGS's Earth Explorer web browser; ARM. (2020).

Considering the entire population of Al-Madinah, **Figure 5** shows that the closer the proximity to the Prophet's Mosque in the CBD, the greater the gross population density; conversely, the further away from the CBD toward the periphery, the lower the gross population density. Therefore, the pattern of population density in Al-Madinah is consistent with location theory, as population density declines in relation to the distance from the CBD. A large area of Al-Madinah's periphery remains underdeveloped and has potential for further residential expansion. Furthermore, the highest population densities (100 p/ha <) were concentrated in many districts of the two inner zones, particularly those districts proximate to the Prophet's Mosque in 2004 and 2010, while the lowest densities (< 50 p/ha) were found in most districts in zones 3 and 4.

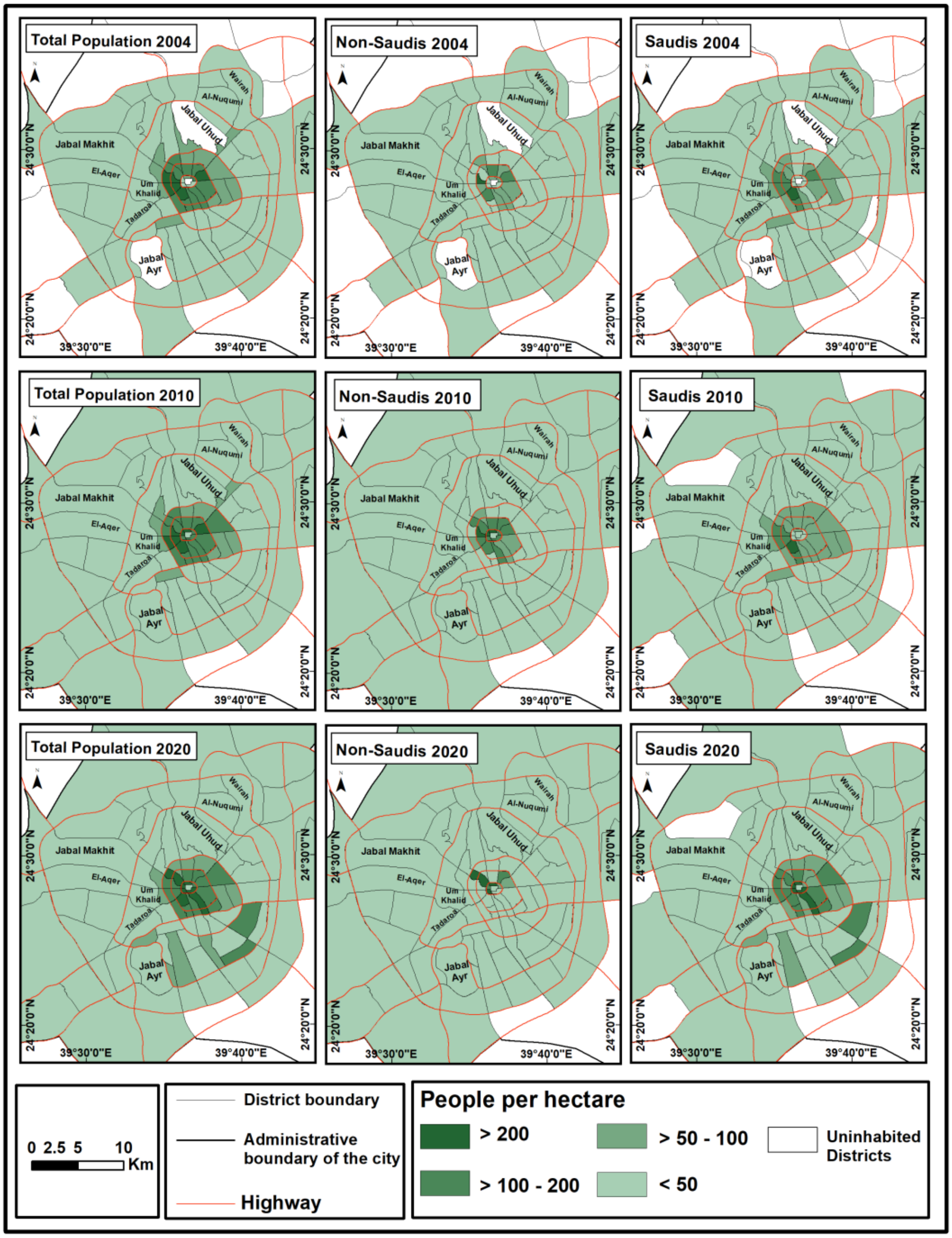

Fig. 5. Evolution of population gross density of Al-Madinah (2004–2020).
(Source: GAS 1974-2010; ARM, 2020).

By 2020, population density had increased in eight districts of zone 3, such as Al-Gharaa, Mozinb, and Al-Wabra due to the relocation of Saudis from the CBD to the southern and western districts of zone 3.

Net residential density in Al-Madinah rose from 13 to 46 p/ha between 1962–1978 (Makki, 1985) before falling from 46 to 32 p/ha between 2004–2020, while Al-Madinah's residential area increased from 20,098 to 47,022 hectares. Therefore, Al-Madinah had a net density lower than the UN-Habitat recommended population density of 150 p/ha (UN-Habitat, 2014), in common with many other Saudi cities in 2016, such as Jeddah (55 p/ha), Dammam (70 p/ha), Riyadh (48 p/ha), and Makkah (46 p/ha) (MMRA, 2019a). The central area of Al-Madinah within the second ring road has remained the most densely populated, with 142, 154, and 144 p/ha in 2004, 2010, and 2020, respectively. These densities almost fit the UN-Habitat recommended density. Zone 1 is more densely populated than zone 2, with a net density of 214 vs 152 p/ha in 2010, and 755 vs 124 p/ha in 2020, respectively.

Variations in population densities provide guidelines for interpreting the geographical distribution of economic activities (Marti-Henneberg et al., 2016). Therefore, the concentration of businesses catering to visitors in the CBD has created an imbalance in the distribution of services and facilities between the CBD and the periphery of Al-Madinah. Most visitors elect to stay in the CBD to be near the Prophet's Mosque and accessibility services and facilities (Makki, 1989). Moreover, both Saudi and non-Saudi residents seek to live in the centre as both a desirable location and for proximity to the mosque where they perform their five daily prayers. In 2020, the net population density in zone 3 was twice the gross population density, reflecting population mobility into zone 3, primarily by Saudis. For the entire population of Al-Madinah, **Figure 6** shows that districts with high net density are spread over a larger area compared to gross density. Aligning with the findings from the gross density maps, most of these districts are in the two inner zones. Conversely, some of these districts are in zone 3. Moreover, the net population density in these districts was extremely high, peaking with E-Sih in 2004 (541 p/ha), Bedaa in 2010 (410 p/ha), and E-Naqa in 2020 (2,243 p/ha). By 2020, six districts had a population density of > 500 p/ha, two of which were located in zone 3. Recently, relatively high population densities have been recorded in zone 3, with the number of districts with > 50 p/ha increasing from 9 to 15 between 2010–2020. **Figure 6** indicates an important distinction in the population density patterns of Saudis and non-Saudis: districts with high non-Saudi populations were confined to the two inner zones in 2004 and 2010, but in 2020 were limited to the eight districts north and west of the Prophet's Mosque (likely due to thousands of accompanying migrants departed the KSA after the declaration of the new fees). Meanwhile, high population densities of Saudis expanded to Zone 3 within the research timeframe. In 2020, relatively high densities of non-Saudis (50 p/ha) were concentrated in a narrow circle less than two kilometres in radius around the CBD, while high densities of Saudis occupied a ring-shaped area over ten kilometres in radius.

Statistically, Al-Madinah's net and gross densities differed during the research timeframe. The proportion of the difference between both densities for each district varied widely between 5–99%, 2–99%, and 1–96%, with means of 59%, 55%, and 39%, and standard deviations of 32%, 33%, and 29% in 2004, 2010, and 2020, respectively. This difference is because some districts have more non-residential areas than others. There are also variations between the four zones, with the differences ranging from 1–33%, 1–30%, 3–96%, and 30–97%, with means of 16%, 10%, 43%, and 75%, and standard deviations of 10%, 8%, 23%, and 17% in zones 1, 2, 3, and 4, respectively in 2020. The high proportion of the differences and means in zone 3 or 4 is due to many districts having non-residential areas such as mountainous, agricultural, and open areas. Therefore, planning for Al-Madinah's population redistribution or resource allocation based solely on gross density would lead to poor decision-making.

Al-Madinah's concentration index (CI) has fallen slightly, being 85.3%, 82.6%, and 81.6% in 2004, 2010, and 2020, respectively. However, all of these figures show a high population concentration in certain districts, as the higher the CI, the more concentrated the population. Approximately 81% of the city's population would have to be redistributed to more peripheral districts to achieve an exact correspondence between population and area. CI in Al-Madinah shows a greater population concentration than the Gulf city of Al-Ain (55%) (Yagoub, 2006). The CI of Al-Madinah has been gradually declining over the past two decades, reflecting a modicum of success of government efforts to alleviate population concentration in the CBD.

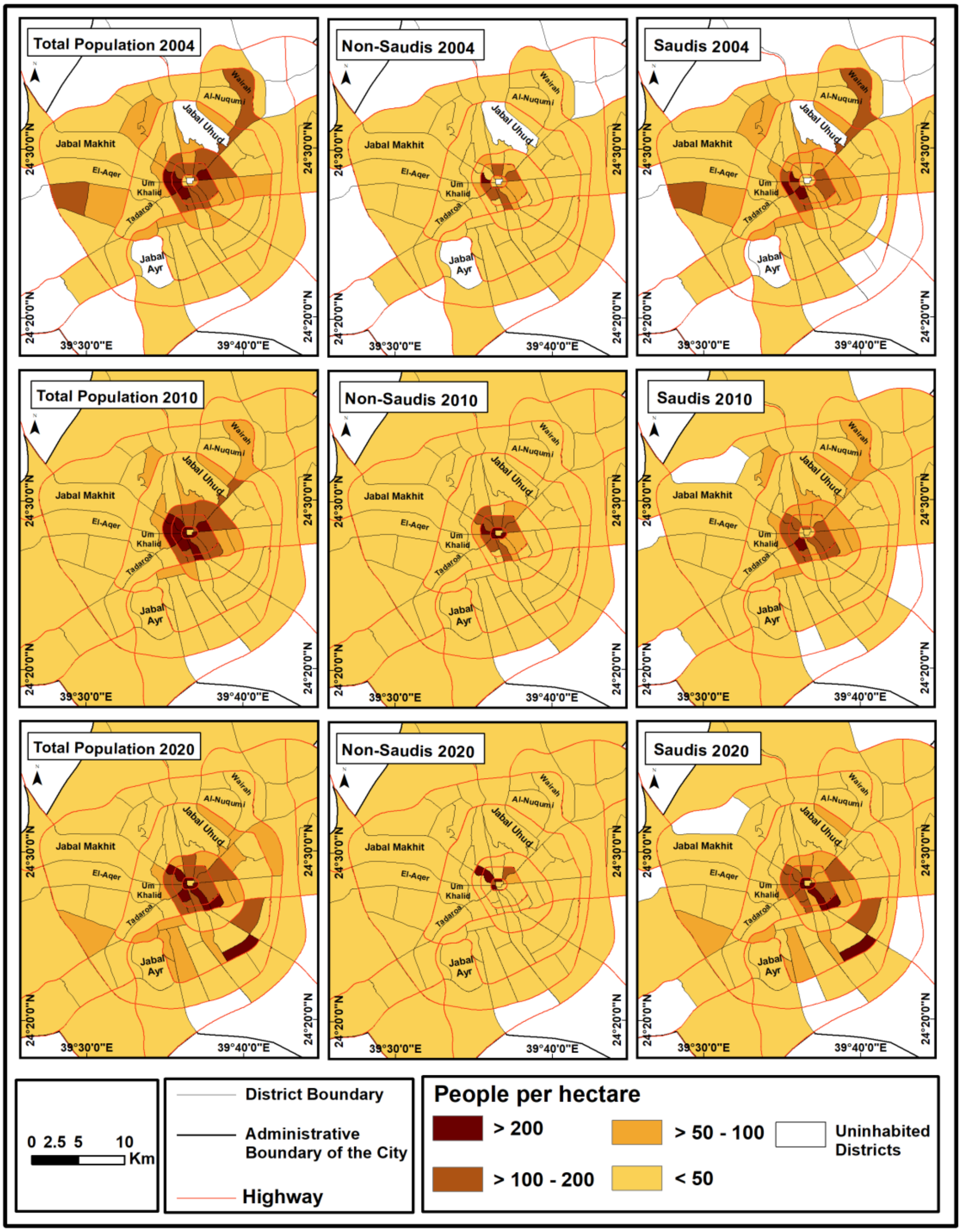

Fig. 6. Evolution of Al-Madinah's net residential population density (2004–2020). *(Source: GAS 1974-2010; USGS's Earth Explorer web browser; ARM, 2020).*

Furthermore, Al-Madinah's population was (and remains) unevenly distributed geographically: 95% of the population lived within 11%, 13%, and 18% of the city's total area in 2004, 2010, and 2020, respectively. However, the area occupied by the population is gradually increasing in the twenty-first century (see **Table 3**).

Table 3.

Evolution of the relationship between the proportion of the population and land area occupied in Al-Madinah (2004-2020).

% of population	% of land area		
	2004	2010	2020
95	11	13	18
75	3	4	8
50	1	1	3

Source: Author's calculation based on: GAS. (1974-2010); Al-Madinah Regional Municipality. (2020).

Similarly, the Lorenz curves (**Fig. 7**) show an imbalance between population and area: there is a significant deviation from the perfect equality line of even distribution. Based on the Lorenz curve, the Gini Ratio (GR) can be calculated. Al-Madinah's GR was 0.946, 0.936, and 0.892 in 2004, 2010, and 2020, respectively. This was higher than in Al-Ain (0.732) (Yagoub, 2006). Al-Madinah's GR is close to 1, indicating an almost complete inequality between population and area, with the vast majority of the population located in the central area. Although Al-Madinah's GR is decreasing, there remain large swathes of land which could accommodate a significant proportion of the population.

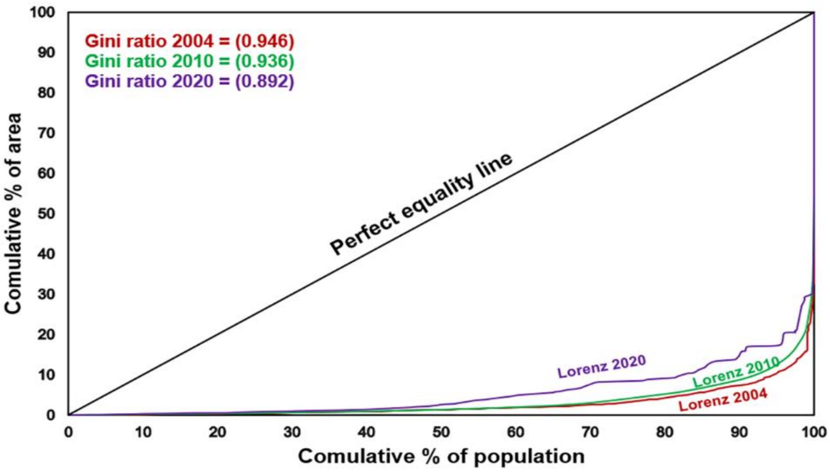

Fig. 7. The Lorenz curves for measuring population concentration in Al-Madinah (2004–2020). *(Source: GAS 1974-2010; ARM, 2020).*

The calculation of the MCPs for Al-Madinah, shown in **Figure 8** and **Table 4**, is based on the population distribution over the inhabited area. Although the MCPs were typically close to El-Haram district between 2004–2020, they shifted from west to south, indicating movement from the centre to the south, as Al-Madinah's current urban sprawl follows its major transport routes radiating outwards from the CBD to valleys like Al-Aqiq in the south. Moreover, the south of Al-Madinah is free of topographical constraints and is a preferred residential location for religious considerations: it symbolises the direction from which the Prophet Muhammad (PBUH) first entered Al-Madinah, migrating from Makkah. Regarding the total population, the MCP moved from El-Manakha district in 2004 and 2010 to E-Jomaa in 2020, 746 meters south of El-Haram district. The MCP for Saudis moved from El-Manakha district in 2004 to E-Naqa in 2010, then to E-Jomaa in 2020, 894 meters south of El-Haram. However, the MCP for non-Saudis shifted a short distance from El-Haram district in 2004 to El-Manakha in 2010, then to Bani Khadra in 2020, 173 meters south of El-Haram. Saudis are more mobile than non-Saudis: the MCP for Saudis shifted 1,337 meters south between 2010–2020 while that of non-Saudis moved just 665 meters south. The likely explanation for this is that housing in the south of Al-Madinah, especially outside the second ring road, is expensive for most non-Saudis but suitable for many Saudis as there are many new residential developments such as Al-Alia, Awali-Quba, and Jawhrat Al-Madinah, which predominantly consist of villas.

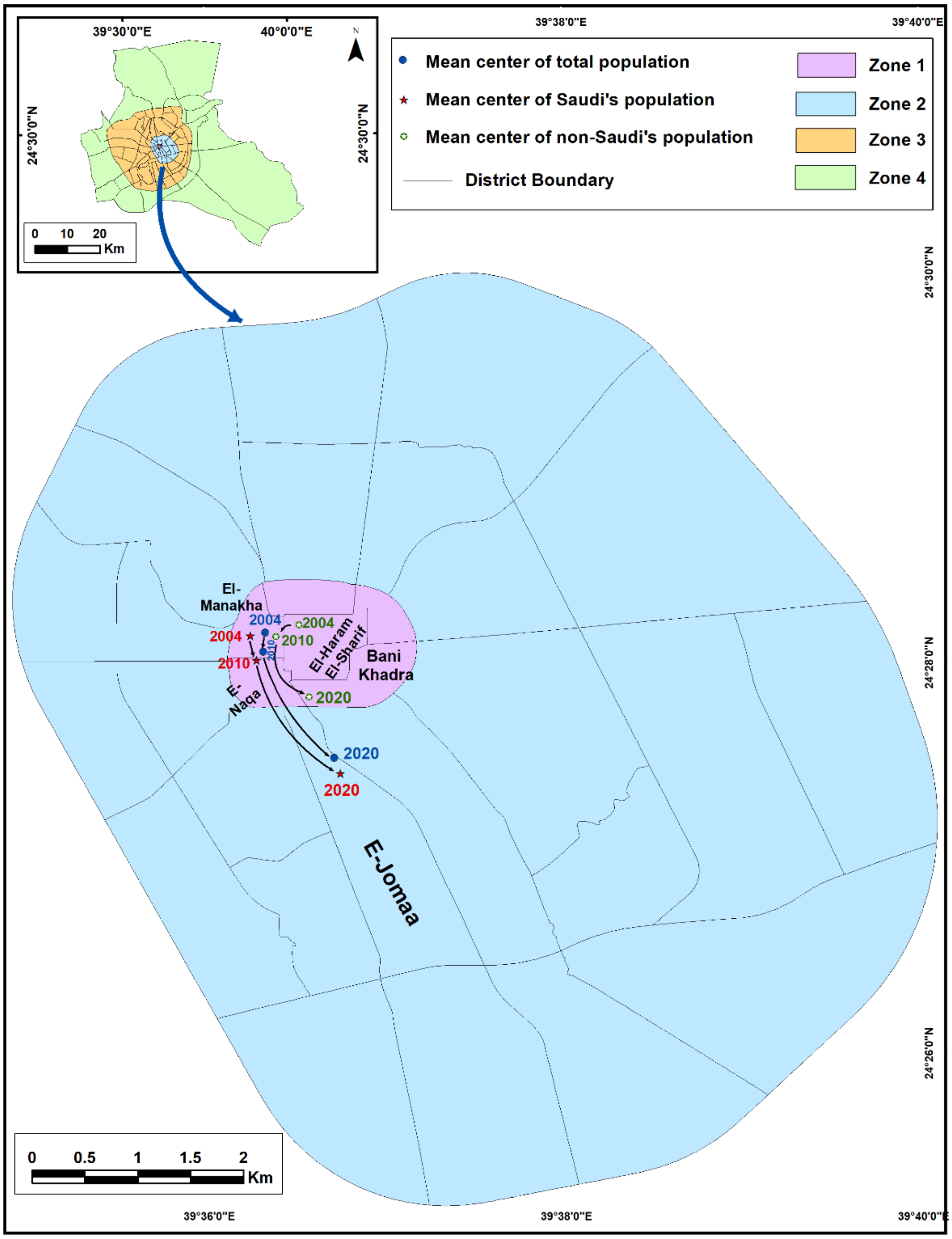

Fig. 8. Mean centre of population for Al-Madinah: 2004–2020.
(Source: GAS 1974-2010; USGS's Earth Explorer web browser; ARM, 2020).

Table 4.

Mean centre of population for Al-Madinah: 2004-2020.

Nationality	Year	North Latitude	East Longitude	Location	
				Zone	District
Saudis	2004	24° 28' 9"	39° 36' 14"	1	El-Monakha, 323 meters west of El-Haram.
	2010	24° 28' 2"	39° 36' 16"	1	E-Naqa, 253 meters southwest of El-Haram.
	2020	24° 27' 27"	39° 36' 44"	2	El-Jomaa, 894 meters south of El-Haram.
non-Saudis	2004	24° 28' 12"	39° 36' 31"	1	Northwest of El-Haram.
	2010	24° 28' 8"	39° 36' 23"	1	El-Monakha, 83 meters west of El-Haram.
	2020	24° 27' 50"	39° 36' 34"	1	Bani Khadra, 173 meters south of El-Haram.
Total population	2004	24° 28' 10"	39° 36' 20"	1	El-Monakha, 184 meters west of El-Haram.
	2010	24° 28' 4"	39° 36' 19"	1	El-Monakha, 199 meters southwest of El-Haram.
	2020	24° 27' 32"	39° 36' 42"	2	El-Jomaa, 746 meters south of El-Haram.

Source: Identified by the author using ArcGis 10.2, based on: GAS. (1974-2010); ARM. (2020).

SD is a measure of inhabitants' dispersion from their mean centre. **Figure 9** confirms Al-Madinah's population concentration as approximately two-thirds of the total population, Saudis, and non-Saudis were concentrated inside small circular areas with radii of 5.2, 5.7, and 3.7 kilometres in 2004 compared to 6.7, 6.8, and 6.5 kilometres in 2020, respectively. This reveals an abnormal population distribution pattern, as the population is confined to a small area surrounding the Prophet's Mosque. This small area, though, is a locus of business, accommodation and services. **Figure 9**, however, shows the wide distribution of Saudis and non-Saudis in 2020 compared to 2004.

This article provides an accurate examination of Al-Madinah's population distribution, net population density, MCP, and SD by identifying and calculating the area of the built-up area of each district using GIS and RS. However, this data has limitations: for example, the built-up area of each district identified comprises buildings not only for residential purposes but also for commercial, industrial, educational, and health activities. Fortunately, these non-residential purposes occupy a small amount of the built-up area. Additionally, the mismatch in dates between the datasets and the Saudi censuses of 2004 and 2010 may have slightly reduced the accuracy of the built-up area calculation.

LQ is widely used as a geographic index to compare the relative population concentrations of a subregion with those of an entire region. In this research, it is used to measure the distribution of Saudis and non-Saudis within a district compared to the total population. There was significant variation in LQs for Saudis (see **Figure 10a**) and non-Saudis (see **Figure 10b**). The local concentrations of Saudis were higher than expected (above 1) in many districts of zones 2 and 3, revealing an over-representation of Saudi citizens, while Saudis were under-represented (below 1) in all districts of zone 1, except Bani Khedra, and many districts of zone 4.

However, the local concentrations of non-Saudis were higher than expected in all districts of zone 1 and many of zone 2. Non-Saudis were most prevalent (above 2) in all districts of zone 1, except Bani Khedra, and some districts of zones 3 and 4. This is likely because zone 1 is characterised by older housing stock (Mohamed et al., 2016; MMRA, 2019a) with more reasonable rents which may be preferable for foreign workers.

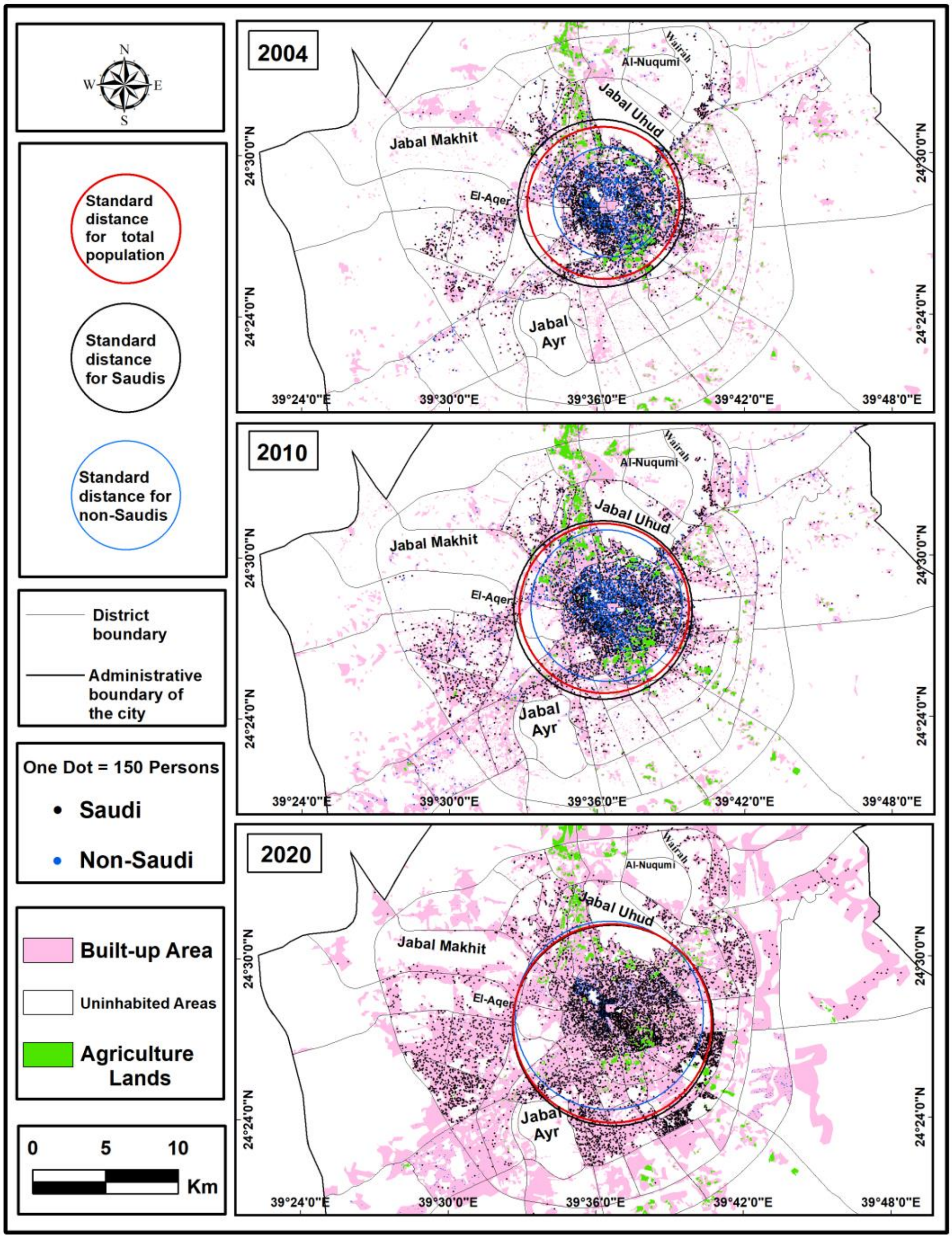

Fig. 9. Standard distance for the population of Al-Madinah: 2004–2020. *(Source: As Figure 8).*

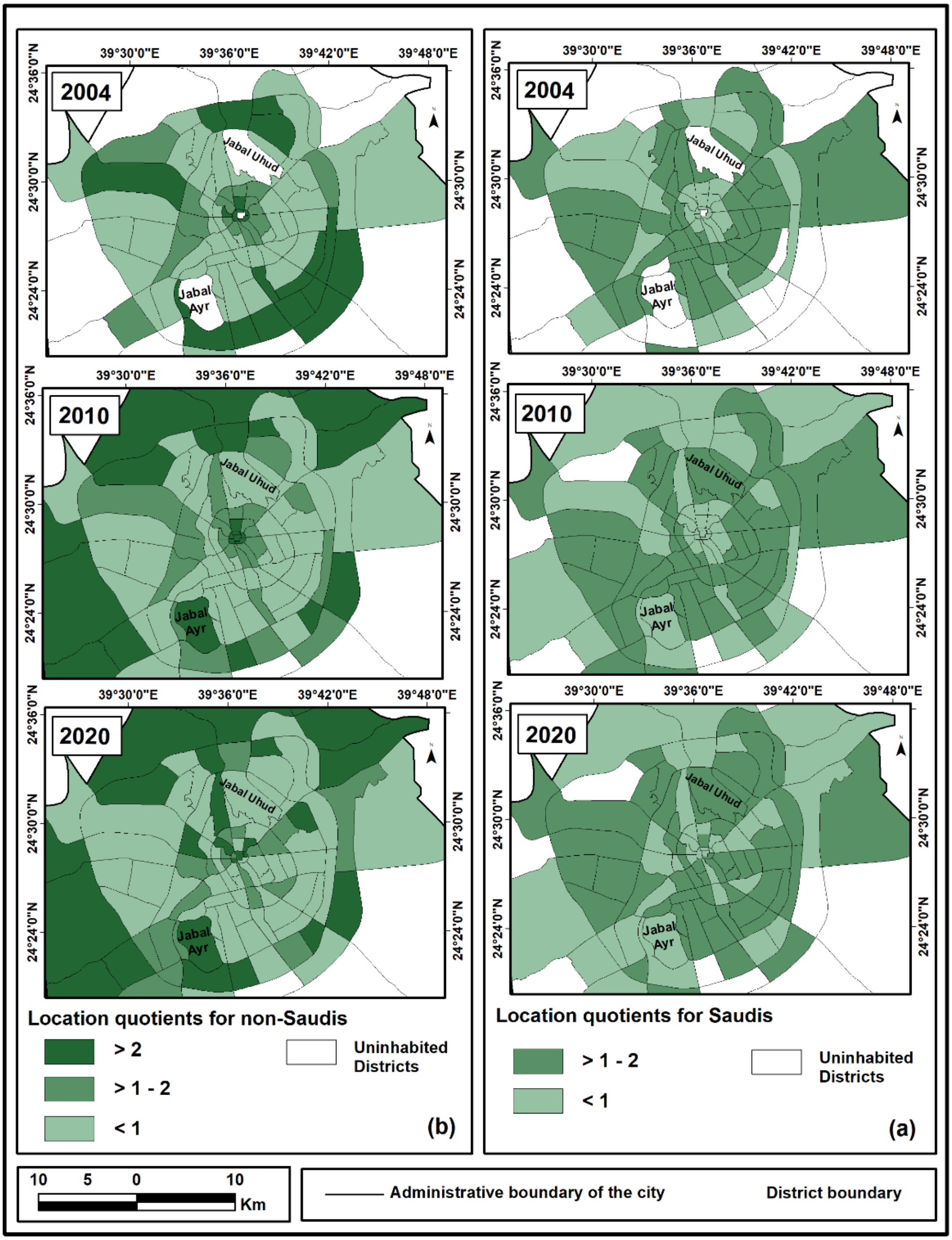

Fig. 10. Location quotients for Saudis and non-Saudis in Al-Madinah: 2004–2020.
(*Source: GAS 1974-2010; ARM, 2020*).

5. CONCLUSION

Al-Madinah is the fourth most populous city in the Kingdom of Saudi Arabia, with 1,500,000 inhabitants. Most residents have settled in the central area, putting pressure on infrastructure. The current study analysed the population distribution of Al-Madinah by combining demographic data with spatial data using GIS and RS. The findings reveal that the diverse populations living in Al-Madinah are unevenly distributed geographically. While there is a concentration in the centre around the Prophet's Mosque in the CBD, the population density gradually decreases towards the periphery. Like the city of Riyadh in the late 1980s (Al-Kharif, 1994), Al-Madinah has recently experienced residential mobility from the central area to the periphery, especially to the southern, southwestern, and western districts. At least half of the city's population resides in a small circular area with a radius of 5 kilometres surrounding the CBD. Recently, the city has witnessed significant population mobility, especially to the south and west. In line with many cities, Saudi citizens form the bulk of the relocating population, who are financially secure enough to avoid the congested CBD (Yagoub, 2006; Stewart et al., 2004).

The second half of the twentieth century saw an increase in Al-Madinah's net population density, while the last two decades have seen a decline from 46 to 32 p/ha due to the expansion of its built-up areas. The central area within the second ring road is densely populated (144 p/ha in 2020). Most high-density districts are in the central area within the second ring road; however, recently, districts outside the second ring road are also becoming densely populated. Variations in the population densities of Al-Madinah's zones or districts are due to the geographical distribution of different economic sectors (Marti-Henneberg et al., 2016). In 2020, population density increased in some districts between the first and third ring roads due to the relocation of Saudis from the CBD to these districts. High population densities were concentrated within a radius of ten kilometres of the CBD for Saudis, but within two kilometres of the CBD for non-Saudis. Furthermore, this study found that the percentage difference between the net and gross population densities for each district in Al-Madinah varied considerably between 1–96%: the CI (81%) showed a higher population concentration than many other Gulf cities; the Lorenz curves and GR values confirm the imbalance between population density and area in Al-Madinah over the past two decades; almost 95% of the population now lives in 18% of the city. The mean centre of population (MCP) is close to the district of El-Haram and has recently shifted from the west to south of the Prophet's Mosque because the south is free of topographical constraints and is a preferred residential area for religious reasons. Saudis are more mobile than non-Saudis: their MCPs have recently shifted 1,337 and 665 meters southward, respectively. Although the SD confirms the population concentrations in Al-Madinah, it reflects their recent spread over a large area. Moreover, the LQ values show variations between the local concentration of Saudis and non-Saudis. They were higher than expected for Saudis in many districts between the first and third ring roads, while they were most prevalent for non-Saudis in almost all districts within the first ring road. This likely reflects the impromptu residential areas characterised by older housing stock with more reasonable rents which may be preferable for foreign workers.

Overall, Al-Madinah's residents, especially Saudis, are gradually moving from the CBD to the periphery. Based on the results of this study, the city's authorities should implement further residential projects, especially in the periphery of Al-Madinah, allocating some areas specifically to non-Saudi citizens. Finally, city officials should give more consideration to economic growth and service development in the periphery of Al-Madinah and seek to improve quality of life for those residing in the CBD.

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