Developing the desert: The pace and process of urban growth in Dubai

Ahmed K. NASSAR
Lancaster Environment Centre, Lancaster University, Lancaster;
e-mail: a.nassar@lancaster.ac.uk

G. Alan BLACKBURN
Lancaster Environment Centre, Lancaster University,
Lancaster; e-mail: alan.blackburn@lancaster.ac.uk

J. Duncan WHYATT
Lancaster Environment Centre, Lancaster University,
Lancaster; e-mail: d.whyatt@lancaster.ac.uk

Corresponding author
Ahmed K. NASSAR
Postal address: Lancaster Environment Centre, Lancaster University, Lancaster, LA1 4YQ, UK. Tel.: +441524 510237
Fax: +441524 593985

HIGHLIGHTS

- Dubai grew rapidly between 1972-2011 with the rate of urban growth and associated sprawl dependent on local and global drivers.
- Urbanization has resulted in an increase in vegetation cover and inland water bodies in this hyper arid environment.
- Offshore islands demonstrate that development has not been constrained by physical barriers or land ownership.
- Landscape metrics reveal rapidly oscillating phases of urban diffusion and coalescence.
- The sequence of these phases and the spatial patterns of development are unique to the Dubai landscape.

1. Introduction

Over the last decade Dubai Emirate has witnessed great economic growth resulting from rapid urbanization which has turned the desert into residential, commercial, sports and tourism projects. In addition, the offshore environment has been developed with artificial islands, such as Palm Jumairah, Palm Deira and the World Islands. Cities within a city are a particular characteristic of this Emirate, and a number of mini cities have been developed in Dubai including Dubai Festival City, Sports City, Media City, Internet City and Healthcare City. The scale of development in recent years is evidenced by the estimate that 25% of the world"s construction cranes operate in Dubai (Badouri, 2007). Indeed, the rapid pace of urban growth in Dubai has attracted the attention of economists, environmentalists and urban planners. However, there is no publicly accessible information on the expansion of Dubai, likely due to a paucity of data overall and governmental restrictions on data that do exist. Therefore, the present research presents us with the opportunity to develop and apply an accurate and objective method for quantifying urban growth in order to understand the spatiotemporal characteristics of the development process in this rapidly changing landscape.

Urban development often takes place as a consequence of factors such as industrial expansion, economic prosperity and population growth (Li, Sato, & Zhu, 2003; Yin, Stewart, Bullard, & MacLachlan, 2005). Conversely, urban growth can be constrained by a range of factors including differential patterns of land ownership and physical barriers such as coastlines (e.g. Taubenböck, Wegmann, Roth, Mehl, & Dech, 2009). In Dubai, the main driver for recent urban development has been a political strategy to diversify the basis of the economy via inward investment in real estate, in the face of diminishing oil reserves. This policy has resulted in a ten-fold increase in the population of Dubai since 1975 (National Bureau of Statistics [NBS], 2010;

Dubai Statistical Centre [DSC], 2011) mainly due to the increase in expatriate workers with locals forming only 8.8% of the total population in 2010 (NBS, 2011). Moreover, in Dubai, urban growth has not been constrained by physical boundaries such as the desertified terrestrial environment or the Gulf coast, or by issues of land ownership. Hence, this makes Dubai an interesting and important site for investigating the characteristics of urban development under a unique combination of drivers and apparent lack of constraints.

Satellite remote sensing has been widely used in studies of urban growth and offers a cost effective and time saving alternative to other conventional methods such as surveying (Patino & Duque, 2013). Over the last 40 years there have been significant advances in sensor technologies as well as digital image processing methods and analytical tools. The spatial, spectral and temporal resolution and coverage of satellite imagery has improved considerably, however there are often operational trade-offs between these parameters which can limit the applicability of the data for studying urban growth. For example, Gamba, Dell'Acqua, Stasolla, Trianni, and Lisini (2011) discussed the limitations of using high spatial resolution images to monitor urban growth due to their relatively low spectral resolution and coverage, in addition to their high financial cost and lack of a sufficiently long archive of imagery. The timescale over which urban growth has been investigated using remotely sensed imagery also varies considerably between studies; some researchers study urban growth over short time periods, for example, Moeller and Blaschke (2006) tested the feasibility of using Quickbird imagery to monitor Phoenix, USA from 2003 to 2005, while Rajendran, Arumugam, and Chandras (2002) used IRS-1A & 1C imagery in combination with old aerial photographs and topographic maps to study urban growth in Tiruchirapalli, India between 1928 and 1998. However, the most appropriate timescale is likely to be determined by achieving a balance between the known period and pace of urban development in an area and the availability of remotely sensed data of suitable temporal and spatial coverage and resolution for that area.

Data from the Landsat satellite series, considered medium-high spatial resolution, is available at no cost, with near-global coverage from 1972 to the present date. The higher spatial and spectral resolutions of the later Landsat TM and ETM+ sensors make them very useful for detecting urban areas and other forms of land cover. The earlier Landsat MSS sensor has lower spatial and spectral resolutions, but is the only accessible source of imagery for the period 1972-1984. The three sensors combined provide the longest time series of images with a relatively short revisit time (nominally 16 days) over the period in which Dubai has grown most rapidly, and therefore represent a potentially valuable source of information for understanding the process of development in the emirate. Previous researchers using remotely sensed data to study urban growth in arid environments have faced considerable challenges in discriminating urban areas from sand using multispectral imagery and a range of different techniques have been proposed. For example, Stewart, Yin, Bullard, and MacLachlan (2004) used an automated relative reflectance enhancement technique to aid discrimination, while Yagoub (2004) and Yin et al. (2005) used manual classification, but no universal solution has emerged. Hence, an appropriate method needs to be applied in order to achieve adequate levels of discrimination for Dubai using the Landsat data.

There has been a long-standing interest in the study of urban form and the analysis of urban growth in relation to demography and economy. Early urban growth theories included the Concentric Zone Theory (Burgess, 1924), the Sector Theory (Hoyt, 1939), the Multiple Nuclei Theory (Harris & Ullman, 1945) and the Wave Theory Analog Approach (Boyce, 1966). Increased computing power enabled the development of urban growth simulation models such as

SLEUTH (Clarke, Hoppen, & Gaydos, 1997) to account for the key drivers of urbanization. More recently, empirically based models of growth have been developed as a result of advances in monitoring capabilities offered by remote sensing and analytical tools to quantify urban development (Dietzel, Herold, Hemphill, & Clarke, 2005; Dietzel, Oguz, Hemphill, Clarke, & Gazulis, 2005). In particular, there has been a growing interest in the use of landscape metrics to study urban structures and patterns of urban evolution (Aguilera, Valenzuela, & Leitão, 2011; Araya & Cabral, 2010; Taubenböck et al., 2009; Wu, Jenerette, Buyantuyev, & Redman, 2011). These metrics have been developed to analyse spatial configuration and pattern within landscapes in addition to the dynamics of landscape structure and heterogeneity (e.g., Alberti, 2008; Leitão, Miller, Ahern, & McGarigal, 2006; Yeh & Huang, 2009). In the context of the present study, landscape metrics provide a means of quantifying specific spatial characteristics of landscape patches, classes of patches of particular land cover types, or entire landscape mosaics and therefore have value in helping to understand the process of urban development at a range of scales.

The outputs from remotely sensed mapping exercises have been analysed using landscape metrics for a number of cities in order to inform models of urban growth (Dietzel, Herold, et al., 2005; Dietzel, Oguz, et al., 2005; Martellozzo & Clarke, 2011). These studies suggest that cities are developed through harmonic oscillation of two phases, diffusion and coalescence, with each phase consisting of multiple waves over different time periods. Dietzel, Oguz, et al. (2005) indicate that this harmonic behaviour can be reflected by landscape metrics such as number of patches and Euclidian nearest neighbour distance for urban patches, but other metrics may not exhibit any harmonic behaviour. The oscillation of phases has been measured over different periods of time, such as the 11 oscillations over a 100 year period evidenced in Central Valley cities of California (Dietzel, Herold, et al., 2005) or the 3 oscillations over 28 years found in Houston (Dietzel, Oguz, et al., 2005). Given the distinctive drivers and styles of development found in Dubai, this city provides us with an interesting opportunity to examine the extent to which these existing models of urban growth are applicable in a rapidly developing coastal landscape that is typical of a number of cities that are emerging in the Middle East.

The objectives of this study are firstly to quantify land cover change in Dubai by conducting a spatiotemporal analysis of remotely sensed data and relate this to the economic, population and political drivers; secondly, to quantify changes in the spatial structure of the emirate through the use of landscape metrics; finally, to evaluate the extent to which the process of urban growth in Dubai conforms with the diffusion-coalescence theory (Dietzel, Herold, et al., 2005; Dietzel, Oguz, et al., 2005).

2. Materials and methods

2.1. Study area

Dubai is one of seven emirates forming the United Arab Emirates, being the second largest after Abu Dhabi in terms of population and area (Figure 1). The total area of the emirate before the development of the islands was 3885 km^2 excluding Hatta which is an exclave city that has no boundary with Dubai Emirate (Department of Finance, 2009). Dubai Creek runs south from the Arabian Gulf for 13km, dividing the city into Deira to the east and Bur Dubai to the west. Dubai is considered as hyperarid with an annual average rainfall of approximately 8mm falling mostly in winter and late autumn (Dubai Airport, 2010).

Some historians date the origins of Dubai to 1833 when around 800 people settled in the creek area (Pacione, 2005). In this early period the economy was heavily reliant upon fishing and pearling, and Dubai was the transit point for overland trading convoys traveling from Iraq to the Sultanate of Oman and a strategic sea port for trading ships travelling between Asia, Africa and the Gulf region. Population growth accelerated in the 1970‟s after the discovery of large oil reserves in the emirate which attracted a large labour force, primarily from overseas countries. The Dubai government used the oil revenue to develop infrastructure and industrial projects such as Dubai international airport, Port Rashid, the dry docks and an aluminium smelter (Pacione, 2005). These developments initiated the urbanization process that is the focus of the present investigation.

2.2 Data used

A time series of Landsat images was acquired from the U.S. Geological Survey (Table 1). Our target was to quantify urban growth at 5 year intervals over the period of the Landsat archive and this was achieved apart from in the 1990‟s when the interval was larger due to lack of available scenes. However, following a preliminary analysis of imagery over the last decade, additional scenes were utilised after the year 2000 in order to provide a better representation of the faster pace of land cover and coastal change during this period. To cover the whole emirate two Landsat MSS scenes were required (see Table 1) while individual TM and ETM+ scenes were sufficient. The images were cloud free and were chosen to be as close as possible to the same Julian day in order to minimise the effects of variations in solar geometry (see Ji, et al., 2001). Supporting data were collected from Dubai municipality, Dubai Statistical Survey Department and the Emirates Institution of Advanced Science and Technology.

2.3 Data preparation and pre-processing

All images were pre-processed to remove radiometric, atmospheric and geometric distortions. All Landsat bands (1 to 7 covering visible, near and shortwave infrared) were used in subsequent stages, apart from the thermal band because it has coarse spatial resolution and failed to provide useful information for land cover discrimination in the context of this study. The two MSS scenes were mosaicked together to cover the study area for 1972, 1976 and 1980. Landsat images were co-registered precisely with existing map data using a WGS 84 datum/Dubai Local Transverse Mercator projection. This was achieved using 57 ground control points which were collected from road intersections delimited on existing digital maps and these were distributed across the images to provide maximum accuracy (Jensen, 2005). Registered Landsat images were then used to co-register other Landsat images where reference data was unavailable. In all corrections, a 3rd order polynomial transform was employed and overall RMS errors for all cases were less than half a pixel as recommended by Jensen (2005). The nearest neighbour method was used for image resampling in order to preserve the original pixel digital number values.

2.4 Classification

The spectral clusters inherent within the imagery were examined in order to determine which land cover classes could be distinguished that would be of value for addressing the aims of the research. Anderson"s Level 2 land cover classification schema (Anderson, Hardy, Roach, & Witmer, 1976) has been used in some previous studies that have investigated urban growth using Landsat imagery. However, our preliminary investigations revealed that for Dubai it was not possible to derive such a detailed classification, in particular the discrimination of urban sub classes (residential, commercial etc.), without the use of supporting data such as aerial photography or ground survey data collected at the same time as each Landsat image. Given the limited availability of such supporting data for Dubai, a modified Level 1 Anderson classification schema was adopted and this was suitable for fulfilling our objective of quantifying the historical trajectory of urban growth. Four land cover classes were mapped: urban, vegetation, water and sand, as seen in Table 2.

A hybrid method of classification using unsupervised and supervised algorithms was adopted in this study. Unsupervised classification techniques were used to aid the selection of the training areas required for the subsequent supervised classification of each image, as this provided the most effective spectral separability of different land covers. Using unsupervised classification in this way can reduce the time required for manual selection of adequate training classes and can reduce the subjectivity of the process (King, Lee, & Singh, 1989). This „hybrid" approach therefore attempts to combine the advantages of both methods and overcome their limitations (Lo & Choi, 2004). The Iterative Self Organizing Data (ISODATA) clustering algorithm was firstly used as it provided maximum separability of different land cover classes. The most important parameters in ISODATA are: number of clusters, convergence threshold and maximum number of iterations. Given the distinctive coastal desert environment of our study site, we conducted trials using a sample image from each Landsat sensor to identify the optimal clustering parameters for achieving maximum land cover separability for each sensor. It was found that 30 clusters and 50 iterations were optimal for TM and ETM+ images and 20 clusters with 40 iterations were optimal for MSS, with a 0.95 convergence threshold for both. All other images in the time series were then classified using the appropriate optimal parameters for the sensor type.

The second step was to apply a maximum likelihood algorithm using spectral signatures derived from training areas within the image to be classified. Training areas should be accurately and carefully selected for all the required output classes to reduce errors of omission and commission and signature extension problems (King et al., 1989). At this stage the output from the unsupervised classification was used to guide the selection of the training areas to improve the efficiency of the selection process and increase the accuracy and representativeness of training areas for the 4 land cover types. Approximately 280 training areas were selected for TM and ETM+ images and 100 for MSS images. Finally, a 3 x 3 kernel size smoothing filter was used to remove “salt and pepper” effects created from classification to minimise errors in areas of mixed land cover (Masek, Lindsay, & Goward, 2000).

2.5 Classification Accuracy Assessment

Accuracy assessment was undertaken for the classifications of Landsat images acquired in the four years for which reference data were available. For each of these years, a total of 60 stratified random samples (image and reference pairs) were collected for each class and these samples were independent from the data used for training in order to avoid the risk of bias (Verbyla & Hammond, 1995). The reference sample classes were identified through manual interpretation of a Dubai Sat1 image for the 2011 Landsat image classification, IKONOS images for 2005 and 2000 and aerial photography for 1998.

The classification accuracy of the 4 images tested was consistently high (Table 3). The overall accuracies exceeded the minimum 85% accuracy acceptable for the Level 1 Anderson classification scheme (Anderson et al., 1976) and the kappa coefficients exceeded the values recommended by Janssen and Van Der Wel (1994). These results compare favourably with previous studies in desert cities using different classification techniques where overall accuracies range between 84 and 88% (Stewart et al., 2004; Yagoub, 2004; Yin, et al., 2005). Confusion matrices were produced for the 4 years and the producer and user accuracies were calculated.

Detailed definitions and use of these accuracy measures have been discussed extensively (e.g., Congalton & Green, 2009). The matrices showed that there were no constantly high levels of confusion between different land cover types (Table 4 is an example matrix for the 2011 classification). The consistency of these results confirms the transferability of the classification technique across the Landsat image time series and gives us confidence that the land cover maps produced were sufficiently reliable for subsequent analysis and interpretation.

2.6 Urban growth rate and landscape metrics

The pace of change in the areal coverage of urban land cover was quantified using the compound annual growth rate formula:

$$\textit{Compound Annual Growth Rate}\left(t_0, t_n\right) = \left(\left(\frac{A\left(t_n\right)}{A(t_0)} \right)^{\frac{1}{t_n - t_0}} - 1 \right) \times 100 \qquad \text{(Equation 1)}$$

Where $A(t_0)$ is the initial area of urban land cover, $A(t_n)$ is the area at the end of the analysis period and $t_n - t_0$ is the number of years covered by the analysis period. Hence, this approach could be used to characterise the pace of urban growth over the entire Landsat time series or particular periods within this. The same formula was also used to characterise changes in the other land cover types.

The patterns of urban land cover in Dubai were quantified by analyzing binary grids of urban and non-urban pixels using landscape metrics in Fragstats 3.4 (McGarigal, Cushman, Neel, & Ene, 2002). Although many metrics can be generated, many are highly correlated or unrelated to the objectives of this study. Hence, based on the findings of previous research using landscape metrics for urban studies, five metrics were carefully selected for this study (Table 5). These metrics were generated for each of the years for which land cover had been mapped from Landsat data in order to quantify the dynamics of urban growth.

2.7. Population analysis and drivers of urban growth

The population density for urban areas was calculated for each sampling period by combining annual total population data together with the percentage of population in urban/rural areas and the area of urban land cover determined from the Landsat data. The rate of change in urban population density was calculated using Equation 1 in subsection 2.6. The changes in urban area and urban population density have been found to be good indicators of the processes of urbanization and urban sprawl (Angel, Parent, Civco, & Blei, 2010; United Nations, 2012; Yin, et al., 2005). Political and local/global economic factors were also compiled and integrated with the urban land cover time series in order to further understand and interpret the various phases of urban development.

3. Results and discussion

3.1 Land cover changes

Figure 2 illustrates the changes in land cover across Dubai between 1972 and 2011, with an increase in urban, vegetation and water at the expense of sand. There has been a dramatic increase in the area of urban land cover over 39 years (561km^2), which represents a compound annual growth rate of 10.03%. The majority of this urban growth occurred after 2000, with the period 2003-2005 experiencing a peak compound annual growth rate of 13.02%. In comparison, Guangzhou city in China had a compound annual growth rate of 7.72% between 1979 and 2002 according to data published in Ma and Xu (2010). Furthermore, according to estimates by the City Mayors Foundation (n.d.) the fastest growing city in the world is Beihai in China with a compound annual growth rate of 10.58% between 2006-2020 (observed and forecast). Such comparisons confirm that Dubai was one of the fastest growing cities in the world throughout the time period covered in this study, and particularly during the first decade of the 21st century.

Figure 2 also illustrates that vegetated areas increased substantially from 0.85km^2 in 1972 to 41.31km^2 in 2011, a compound annual growth rate of 10.47%. This occurred in response to government policies to increase the green spaces in Dubai by developing farms, parks, gardens and mangrove forest (Al Marashi & Bhinder, 2008). Likewise the amount of inland water increased from 3.88km^2 to 18.30km^2, a compound annual growth rate of 4.06%. This increase was due to creek dredging and expansion, port construction and the development of recreational water bodies. Such large changes in vegetation and water bodies are likely to have ecological and environmental impacts. Maintaining such land covers in a hyperarid region requires continual inputs of energy, water and chemicals and this may have negative environmental consequences. However, these land covers may promote biodiversity and improve microclimate and air quality in a way which mitigates some of the impacts of the urban development. Therefore, it is important that the environmental costs and benefits of these patterns of land cover change are investigated in future research.

3.2 Spatiotemporal characteristics of urban growth

Figure 3 illustrates how the size and shape of the urban area has changed over time. The majority of the urbanization between 1972 and 1990 was concentrated around Dubai Creek. During this period, the central urban area expanded east of the creek from 2.3km in 1972 to 8km in 1990 and west of the creek from 0.7km in 1972 to 11km in 1990. The rulers ensured that Dubai's oil revenues were directed to implement major infrastructure projects such as Rashid port, Jebel Ali port, Dubai International Airport and Jebel Ali free zone. These developments acted as seeds for subsequent urban growth in the west of the emirate detected in the present study (Figure 3). During this period, the urban area expanded at an annual rate of 11% while the population experienced an annual growth rate of 7%. This meant that urban population density decreased at an annual rate of 5% indicating that a process of urban sprawl was initiated during this period.

During the 1990‟s the urban area expanded in the east of Dubai towards Sharjah Emirate and along the gulf coast, particularly for residential purposes. However, leapfrog developments also occurred towards the west of the emirate (Fig. 3). Within this period there were similar annual rates of urban growth (6.2%) and population growth (5.5%) resulting in a much smaller rate of decrease in urban population density (0.7% per annum) than in the previous period. Some context for these findings is provided by the study of Angel et al. (2010) who used a global sample of 120 cities and found an average annual increase in urban area of 3.66% and a population increase of 1.66% between 1990 and 2000. It was also found that urban population density decreased by 1.7% per annum in developing countries and 2.2% in developed countries, indicating a more intense process of urban sprawl in developed countries (Angel et al., 2005). Therefore, during this period Dubai experienced substantially higher rates of growth in urban area and population than the global sample used by Angel et al. (2010) but the intensity of urban sprawl was below that of other countries.

After the collapse of oil prices in 1997, a strategic decision was made by the government to diversify the economy of the emirate to avoid over reliance on the fragile petroleum industry, by building new infrastructure, stimulating real estate marketing and developing tourism. As a result, oil revenue fell from 46% of total income in 1974 to less than 5% in 2005 (Dubai

Government, 2007) and less than 2% in 2010 (DSC, 2010). The Dubai government implemented a number of policies to attract foreign businesses, for example, allowing full ownership and 0% corporate and income taxes for up to 25 years in free zones. These initiatives help explain the dramatic increase in the number of urban areas including arterial roads that were detected in the present study between 2000 and 2005 (Figure 3) with the construction of major highways and roads such as Emirates Road (E311) which is 68km long and extends from the east to the west of the emirate. Furthermore, huge ribbon urban developments were observed between 2000 and 2005 along a 5km wide zone along the coast in the west of the Emirate, in addition to the palm development which will be discussed later. In this rapid phase of development, the annual rate of urban growth increased to 12% and while population growth remained very high (7.4% per annum) the declining urban population density (2% per annum) demonstrates that the process of urban sprawl intensified during this period.

In 2002 the ruler of Dubai issued a decree to allow foreign ownership of properties in Dubai which resulted in a boom in the real estate market. Accordingly, the results of this study demonstrate further construction of arterial roads between 2005 and 2008 including the 71km long Bypass Outer road (E611), with associated ribbon and infill urban developments. During this period, the annual rates of urban and population growth remained high (7.9% and 7.6%, respectively) but this was followed by decline in urban and population growth (to 4.7% and 6.8% per annum, respectively) during 2008-2011. This was the first time since the start of the period covered by this study when an increase in urban population density was observed (2% per annum), indicating a deceleration of urban sprawl. This decline in urban growth may be a consequence of the global economic recession which developed towards the end of 2007. Nevertheless, there was still a large expansion of urban area of 74km^2 during this latter period.

The urban areas continued to expand primarily towards Jebel Ali port to the west, towards the newly constructed Al Maktoum International Airport (DWC) and Dubai Industrial City (DIC) to the southwest and towards Sharjah in the north east of the emirate (Figure 3).

By 2011, urban areas covered 15% of the total land area of the emirate, a substantially higher proportion than the 5%-10% coverage found in European countries (Milanović, 2007). Alongside this, the percentage of population living in urban areas is very high and has remained so since the 1970s (95-98%). This compares with Europe and China where 74% and 51%, respectively, live in urban areas (United Nations, 2012). Therefore, the high rates of growth in urban area and population and the high proportions of urban land cover and urban population are notable characteristics of Dubai emirate, while the observed process of urban sprawl is common to most cities globally.

3.3 Coastal change in Dubai

Our results also show a considerable alteration to the form of the coastline of Dubai since 1972 due to both offshore and onshore construction. Using the land cover classes generated from Landsat data, it was possible to define the offshore developments as either completed urban developments (the urban class) or developments under construction (the sand class). Figure 4 shows the extent of coastal development that had taken place by 2011, with considerable areas of completed urban development and even larger areas under construction. The first major coastal developments were observed between 1972 and 1976 with the dredging and filling operations to extend Rashid Port and its dry docks. This was followed during the period 1976-1985 by the excavation of Jebel Ali which is now recognised as the largest inland artificial harbour in the world (Pacione, 2005). Offshore construction for real estate and tourism purposes began during

1992-1998 with the Jumairah beach extension and Burj Al Arab hotel. However, a significant increase in the pace and scale of offshore development took place during 2000-2003, with the construction of Jumairah Palm Island. Even more extensive changes in the coastline appeared between 2003-2011 where 68km^2 was added to the total terrestrial area of Dubai Emirate by offshore reclamation projects in the Arabian Gulf. By 2011 approximately 11km^2 of the marine environment had been converted to urban areas (artificial islands) while approximately 57km^2 were converted to sand where four islands are still under development (Palm Deira, World Islands, Palm Jebel Ali and Dubai Waterfront). This transformation of the form of the coastal landscape is likely to have implications for the aquatic environment, with potential changes in the dynamics of currents, sediments, biogeochemicals and ecosystem functions. Further work is now required to understand the environmental impacts of this coastal change, in order to define environmental management strategies and guide future coastal development.

3.4 Engines of economic, population and urban growth in Dubai

In Dubai, it can be seen that in response to internal and external factors, changing government policy has provided a series of engines of economic and population growth that have promoted the urban development that has been quantified in the present study. The first trigger for urban expansion in the early 1970‟s was the discovery of oil which initiated rapid economic development and the central urban area expanded in order to provide accommodation and facilities for the growing population of workers in the oil industry. With the decision of the government to establish Jebel Ali port and its industrial area after 1976 and Jebel Ali free zone in 1985 to the west of the city, the urban area evolved from the agglomeration around the creek into several satellites of commercial and residential developments. The free zone legalization system allowed foreign companies to take advantage of low wage non-unionized workers (Pacione,

2005) which, in turn, led to a further increase in the demand for accommodation and facilities during this period. The political instability caused by the second Gulf War in 1990 had a negative impact on business activity and international trade which hindered the economic development of Dubai and this resulted in the years 1990-1992 having the lowest annual rate of urban expansion (4%) of the whole study period. The trigger for the modern era in the development of Dubai was the sharp decline of oil prices in 1997 (International Monetary Fund, 2000). This event led to a strategic decision by the government to diversify the economy of the emirate to avoid over reliance on the fragile petroleum industry, by building new infrastructure, stimulating real estate marketing and developing tourism. As a result, the activity of non-governmental establishments and international commercial organisations increased by 41% between 1993 and 2000 (DSC, 2000). This led to the recruitment of a large international labour force, with consequent demand for residences and facilities leading to rapid urban growth.

Following the 2002 decree by the ruler of Dubai to allow foreign ownership of properties in areas designated by the government, a boom in the real estate market occurred and many „mega" construction projects took place including Jebel Ali Free Zone extension, Dubai metro, the offshore islands and some developments distant from the city, deep in the desert. These projects reinforced the urban expansion process and demonstrated that the spatial evolution of Dubai was not hindered by the natural geographic barriers presented by the waters of the Gulf or desert sand dunes. However, the global financial recession which began in 2007, led to a decline in economic, population and urban growth rates in Dubai. Total Gross Domestic Product (GDP) decreased by 2.7% between 2008-2009 with greatest declines in the productivity of the construction, real estate and business services sectors (DSC, 2009), but by 2011 productivity and consequently population and urban growth had recovered. Hence, this sequence of phases in the evolution of Dubai demonstrate the interactions between government policy and economic drivers and consequences, the resultant fluctuations in the rate of population growth and the associated variations in urban expansion and form.

3.5 Urban growth patterns in Dubai in the context of existing urban growth theory

Previous studies of urban growth by Dietzel, Herold, et al. (2005) and Dietzel, Oguz, et al. (2005) suggest development can take place in oscillating phases of diffusion and coalescence in urban form, and that these phases can be detected using landscape metrics based on the number of urban patches and distance between them (NP and MNN, respectively). Figure 5 illustrates the historical changes in landscape metrics for urban areas in Dubai over the study period. Based on the NP plots, the study period can be divided into recognisable phases of coalescence, when NP is decreasing, and diffusion, when NP is increasing (denoted using vertical shading). The MNN metric is able to confirm these phases, as it also decreases during coalescence and increases during diffusion. There is only one departure from this in the period 1985 to 1990 where MNN decreases during a period of diffusion (as indicated by increasing NP). This indicates that new, separate urban patches were being developed in this phase, but they tended to be in close proximity to existing patches. In all other phases of diffusion, MNN increased, indicating the dispersion of urban development across the emirate. The LPI also provides supporting evidence for the oscillating phases of growth, as it consistently increases during coalescence, when development is concentrated around the historical urban core, and decreases during diffusion, as more distant urban centres start to develop. There is only one departure from this in the period 2008 to 2011, where the decreasing LPI during a phase of coalescence indicates that more extensive urban areas have coalesced away from the historical urban core. The LSI metric (AWMPFD is not shown in Fig 5. as it had the same behaviour) demonstrates that the shape complexity of urban areas increases during diffusion phases and decreases or remains fairly constant during coalescence phases. However, there is a tendency towards a continual increase in shape complexity throughout the latter part of the study period and the effects of coalescence and diffusion on urban shape become less apparent. The complexity of urban shape results from the mixed commercial and residential development that has come to dominate Dubai in recent years. Such mixed developments are characterised by a fairly low density of buildings interspersed with sizeable proportions of vegetation and water bodies.

Therefore, the landscape metrics demonstrate that the development of Dubai has taken place via alternating stages of coalescence and diffusion, in accordance with the model of Dietzel, Herold, et al. (2005) and Dietzel, Oguz, et al. (2005). However, the oscillation between these phases occurred over shorter periods of time than Houston and the Central Valley of California cities observed by Dietzel, Oguz, et al. (2005) and Dietzel, Herold, et al. (2005). These shorter periods may be due to the fast planning process and rapid pace of development in Dubai, especially after 2000, as opposed to the planning process in the US which results in longer time periods for significant development to occur (Dietzel, Oguz, et al., 2005). Furthermore, there is evidence in Figure 5 that the oscillation between coalescence and diffusion has become more frequent in Dubai over the course of the study period. This demonstrates that it is important to acquire frequent data on the patterns of urban land cover, which is likely only to be retrieved from satellite data, in order to fully characterise the process of urban growth in rapidly developing cities, such as Dubai. Indeed, it could be argued that because some of the latter phases of coalescence and diffusion begin and end between consecutive image acquisition dates (i.e. consecutive data points on Figure 5), there may be a case for using more frequent images than those used in the present research. However, as all available/useable scenes from the

Landsat archive were used in this study, to increase the frequency would necessitate the use of images from other satellite systems, which could introduce a series of difficulties around comparability issues.

By comparing Figure 5 (metrics) with Figure 3 (maps of change in urban extent), it is possible to suggest that superimposed upon the basic oscillations between coalescence and diffusion there are particular spatial patterns of development that have taken place within each phase. The correspondence between these phases and patterns is summarised in Figure 6 (which also depicts the engines of urban growth discussed in section 3.4). The first phase of coalescence is characterised by a compact bi-central urban growth pattern on each side of the creek throughout the 1970‟s. The following stage of diffusion throughout the 1980‟s largely took of the form of a satellite development pattern, occurring mainly to the west towards Sharjah Emirate and South East of Dubai towards Jebel Ali port. A period of coalescence throughout most of the 1990‟s was characterised by a ribbon pattern of development along the coastal strip of the Arabian Gulf. A short period of diffusion then ensued where satellite developments arose at various points inland of the coastal strip and in the western side of the emirate. As Figure 3 shows, between 2003 and 2008 the road network expanded rapidly and urban development patterns followed this network. The profusion of road networks into previously non-urban territory which triggers the spatial evolution of the urbanization front has recently been described as the „exploration‟ process (Strano, Nicosia, Latora, Porta, & Barthélemy, 2012). The final coalescence phase is characterised by infill development throughout the emirate, with a „densification‟ process (Strano et al., 2012) corresponding to an increase in the local density of roads around existing urban centres.

It is important to acknowledge that the methods used in the present study are only able to offer a two dimensional representation of the process of urban growth in Dubai. This does not account for an important aspect of the urbanization of Dubai where several zones within this city have expanded vertically as well as horizontally, with the construction of high rise buildings. According to the Skyscraper Center (2012), 19 skyscrapers in Dubai are among the highest 100 buildings in the world. In terms of magnitude, such vertical expansion is negligible in comparison with the increase in horizontal area of Dubai, nevertheless, quantifying the contribution of high rise construction to the total volume of expansion could be important for further understanding the process and pattern of urbanization. While there is a paucity of remote sensing data to support such analyses over an extended time series, the increasing availability of stereo imagery and LiDAR derived surface models should facilitate future investigations and enable the refinement of spatiotemporal models of urbanization to incorporate the third dimension. Likewise, combining three dimensional information together with the enhanced abilities of the future generation of hyperspectral satellite systems (Committee on Earth Observation Satellites, 2012), should enable greater discrimination of the subclasses of urban land cover. Hence, further improvements in the thematic resolution of land cover mapping in urban environments will allow more effective monitoring and modelling of the process of urbanization and its environmental impacts in rapidly growing cities such as Dubai.

3.6 Comparing Dubai to other rapidly growing cities

In order to provide some context for our observations on urban growth in Dubai, it is useful to provide a comparison with other cities. However, such comparisons can be difficult because the data related to urban growth is produced by studies that have widely varying objectives and methodologies for monitoring urbanization; in particular, the length of the study period and sampling interval varies substantially. Although several rapidly growing cities have been documented (e.g. City Mayors Foundation, n.d.), detailed long term studies have not been carried out on many of these cities. Therefore, here we discuss only studies that have presented sufficiently detailed information over an extended time period.

The high rates of growth in urban land cover that we have observed in Dubai are comparable to those of the fastest growing cities in the world. For example Angel et al. (2005) reported that the cities with the highest growth rates of urban land cover were Yiyang, China between 1994-1999 and Bacolod, Philippines between 1992-2000, with annual growth rates of 14.67% and 12.25%, respectively. Schneider and Woodcock (2008) studied the growth of 25 cities between 1990-2000 and revealed that the highest annual growth rates were in Dongguan and Guangzhou, China with rates of 14.25% and 11.68%, respectively, while the remaining cities had annual growth rates of less than 5%. The major form of development in Dongguan and Guangzhou was of fragmented patches of urban areas with large amounts of expansion in the fringe and hinterland areas with a decline in population density over the study period. Schneider, Seto, & Webster (2005) showed that Chengdu, China had annual growth rate of 7% between 1978-2002, which comprised of three phases of development. Firstly, prior to 1990, urban expansion occurred in all directions, especially around the core which resulted in unattached urban areas becoming agglomerated; secondly, after 1990, urban areas expanded along road corridors and as satellite patches around the airport; thirdly, there was an infilling process which connected the satellite patches in the late 1990‟s to 2002. These findings indicate a cycle of diffusion and coalescence during the study period. A similar process of urban evolution to Chengdu has been observed in Guangzhou, China which experienced an annual growth rate of 7.72% between 1979 and 2002 (Ma and Xu, 2010). In Guangzhou growth initially radiated outward from the historic core then became focused along major transport links before shifting from the historic centre to a new city centre. Hence, the basic forms of spatial evolution in Chengdu and Guangzhou are similar to those in Dubai but Dubai possesses some more complex forms of development such as onshore and offshore satellites, ribbon and gradual infill, which are superimposed on the basic growth forms. However, a major difference between Dubai and most other fast growing cities is that its spatial evolution is linked to increases the area of both vegetation and water. For example, Seto et al. (2002) reported the high growth rates of the Pearl River Delta cities in China and found substantial decreases in vegetation cover as 1376km^2 of urban area was converted from farmland. Likewise, Pune in India experienced a high annual growth rate of urban land cover of 10% at the expense of water bodies and vegetated lands (Bhailume, 2012).

In comparison to other cities that have developed in desert environments, Dubai shows some similarities and some differences in growth characteristics. Greater Muscat in Oman, situated in a coastal desert in the Gulf region, experienced a rapid urban growth with an annual compound rate of 8.11% between 1960-2003 (Al-Awadhi, 2007) which is only slightly lower than that observed for Dubai. However, unlike Dubai which has grown in all directions, Muscat has grown mostly in the coastal strip with three major urban forms: firstly a very narrow urban expansion between major old urban areas; second an accelerated urban expansion along the coastal strip, and finally an infilling urbanization between urban patches. In Muscat vegetation cover decreased over the study period, in contrast to Dubai, but there was a small increase in inland water cover. Doha in Qatar is another desert city along the Gulf coast which was studied over the period 1972- 2002 and found to experience a decrease in vegetation cover, in contrast to Dubai, but did show an increase in total area of 10km^2 due to land reclamation in a similar, but smaller scale process to that observed in Dubai (Al-Manni, Abdu, Mohammed, & Al-Sheeb; 2007). Las

Vegas in the desert environment of Nevada is the fastest growing city in the United States (City Mayors Foundation, n.d.). Xian, Crane, & McMahon (2005) studied urban expansion in Las Vegas from 1984-2002 and demonstrated an annual growth rate of 4.31%. As in Dubai, urban areas in Las Vegas have sprawled in almost all directions where several roads and transportation systems were built to serve the city. However, the growth of Las Vegas has been constrained by surrounding mountains whilst the development of Dubai has not been impeded by such restrictions.

4. Conclusions

This has been the first study to quantify the rapid process of urbanization in Dubai Emirate, which was achieved using a time series of Landsat imagery to capture the key phases of development from 1972 to 2011. Indeed, without satellite remote sensing it is difficult if not impossible to document such large scale changes in land cover, as other sources of information are restricted or non-existent for this region. A hybrid unsupervised and supervised classification method was able to provide an accurate discrimination between urban and other land cover types, even in this challenging desert environment.

There was a rapid rate of development over the entire study period and this was particularly intense after 2000, making Dubai one of the fastest growing cities in the world during this period, but growth has slowed recently. The observed spatiotemporal dynamics of urban growth were closely associated with prevailing local and global economic conditions and the ambitious development strategies implemented by the government of Dubai. The high rates of urban growth have resulted in a notably high proportion of the emirate now being urban land cover and a particularly high proportion of the total population has occupied urban areas throughout the development period. While the population growth rate has been high, this has been outpaced by the rate of increase in urban area and the declining population density is indicative of a process of urban sprawl that has been observed in most cities globally.

A substantial increase in vegetation and inland water bodies was observed and the ecological and environmental impacts of maintaining such land covers in a hyperarid region are worthy of further investigation. While offshore constructions and land reclamation are not unique to Dubai, the pace, scale and complexity of the coastal urban developments observed in this study are unprecedented. Again, it is important that the impacts of such developments on the coastal environment are now investigated.

This study tested the applicability of the diffusion-coalescence model of urban development in a physical and socioeconomic environment that is substantially different from where the model was developed and previously applied (Dietzel, Herold, et al., 2005; Dietzel, Oguz, et al., 2005). The analysis of landscape metrics provided evidence that Dubai generally conformed to the model of oscillating phases of urban diffusion and coalescence, albeit with much more rapid transitions between these phases than has been observed in other cities. While coalescence and diffusion provided a useful overall description of the urbanization process, each of these basic phases was characterised by specific spatial patterns of development. Earlier phases were dominated by bicentral, satellite and ribbon patterns, while latter stages comprised infill, „exploration‟ and „densification‟ (Strano et al., 2012).

This study has provided a new insight into the pace and process of urban growth in Dubai. While there are several characteristics in common with the development of other cities, there are many unique spatiotemporal features of urbanization in Dubai. It is now important to evaluate the consequences of this form of rapid urban development on the environment.

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Figure captions

Figure 1. Study area, Dubai Emirate, United Arab Emirates. The map of Dubai Emirate shows the major roads that exist at the time of writing.

Figure 2. The trend of land cover changes in Dubai (1972–2011). Urban area on primary Y-axis, vegetation and water on secondary Y-axis.

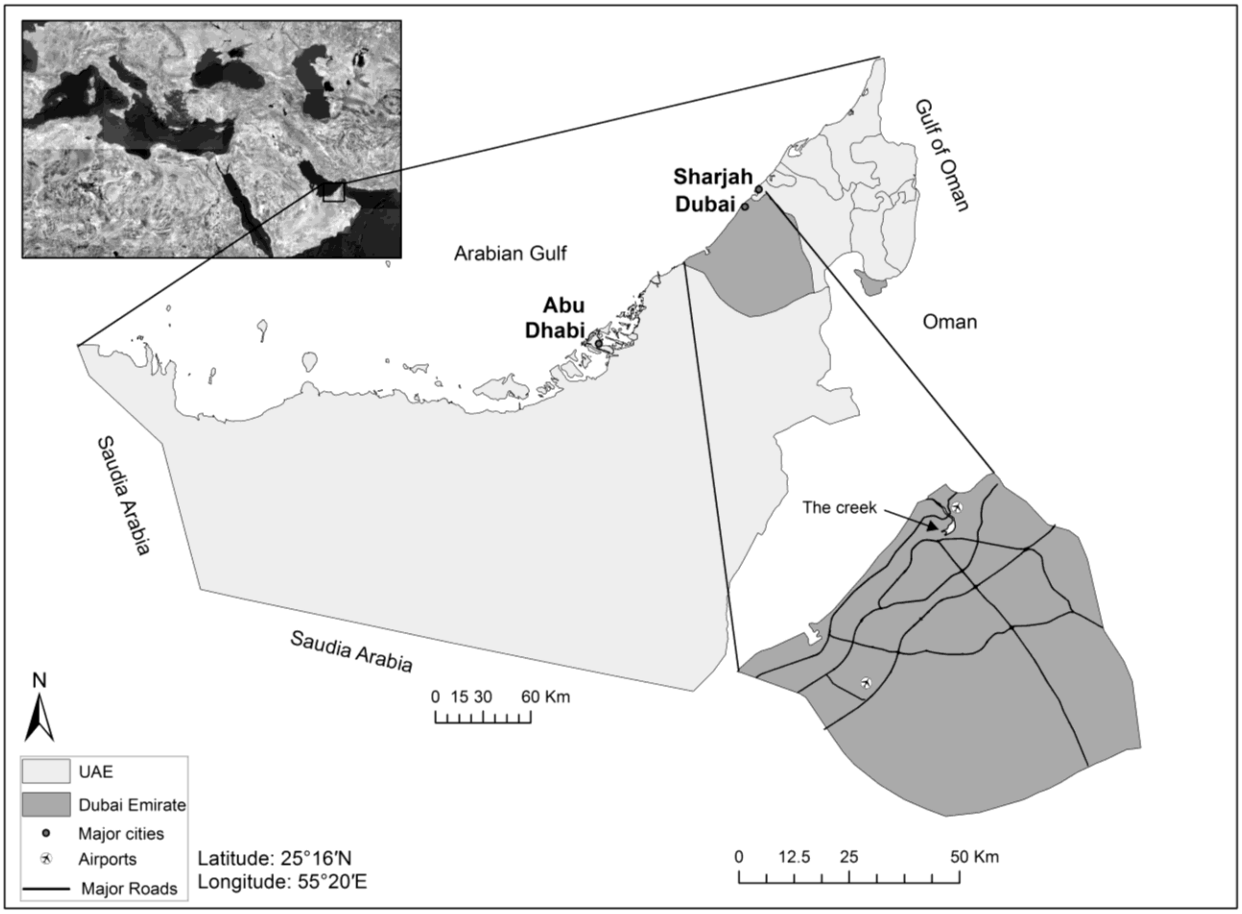
Figure 3. Change in urban extent in Dubai Emirate (1972-2011). Emirates road (E311); bypass outer road (E611); Dubai industrial city (DIC); Al Maktoum international airport (DWC).

Figure 4. Dubai's coastal development by 2011.

Figure 5. Historical changes of the landscape metrics for urban areas in Dubai: Number of Patches (NP); Mean Nearest Neighbour distance (MNN); Largest Patch Index (LPI); Landscape Shape Index (LSI). Differences in vertical shading indicate phases of coalescence (Coal.) and diffusion (Diff.) as interpreted from the NP plot.

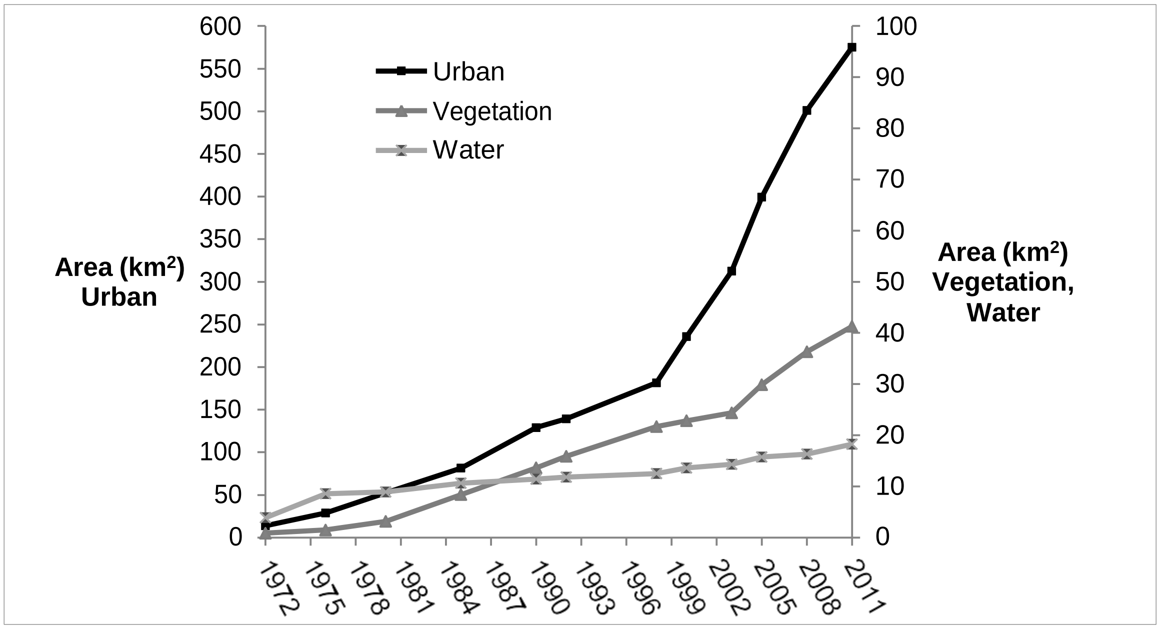
Figure 6. Correspondence between phases of coalescence and diffusion and spatial patterns of urban development for Dubai over the study period. The engines of urban growth (as discussed in section 3.4) are also depicted in this figure.

Figure 1



Gulf of Oman
Sharjah
Dubai
Arabian Gulf
Abu
Dhabi
Oman
The creek
Saudia Arabia
Saudia Arabia
N
0 15 30 60 Km
UAE
Dubai Emirate
Major cities
Airports
Major Roads
Latitude: 25°16′N
Longitude: 55°20′E
0 12.5 25 50 Km

Figure 2



600
550
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450
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350
300
250
200
150
100
50
0
Urban
Vegetation
Water
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90
80
70
60
50
40
30
20
10
0
Area (km²) Urban
Area (km²) Vegetation, Water
1972
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1978
1981
1984
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1990
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1996
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2002
2005
2008
2011

Figure 3

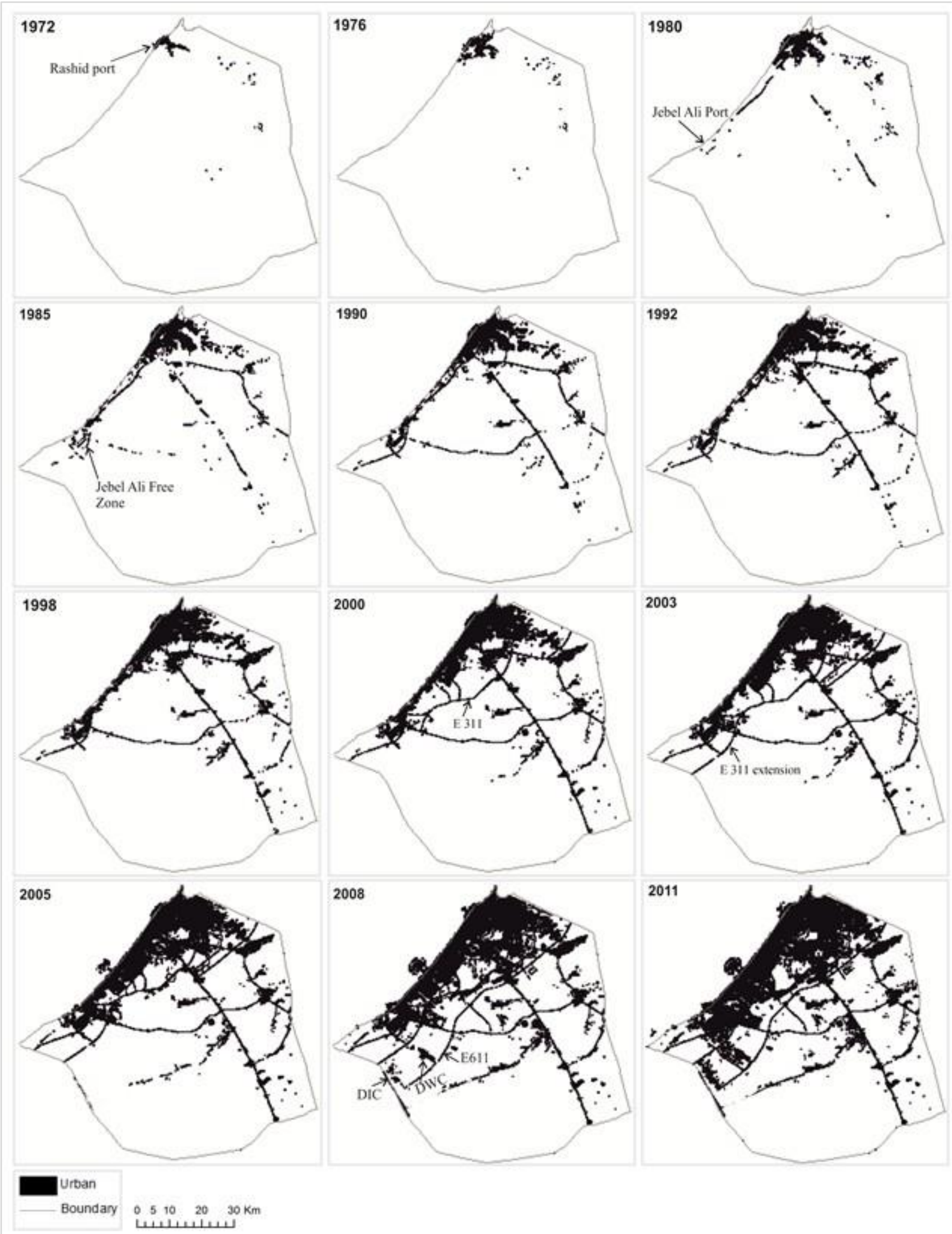

1972
Rashid port
1976
1980
Jebel Ali Port
1985
Jebel Ali Free Zone
1990
1992
1998
2000
E 311
2003
E 311 extension
2005
2008
E611
DIC
DWC
2011
Urban
Boundary
0 5 10 20 30 Km

Figure 4

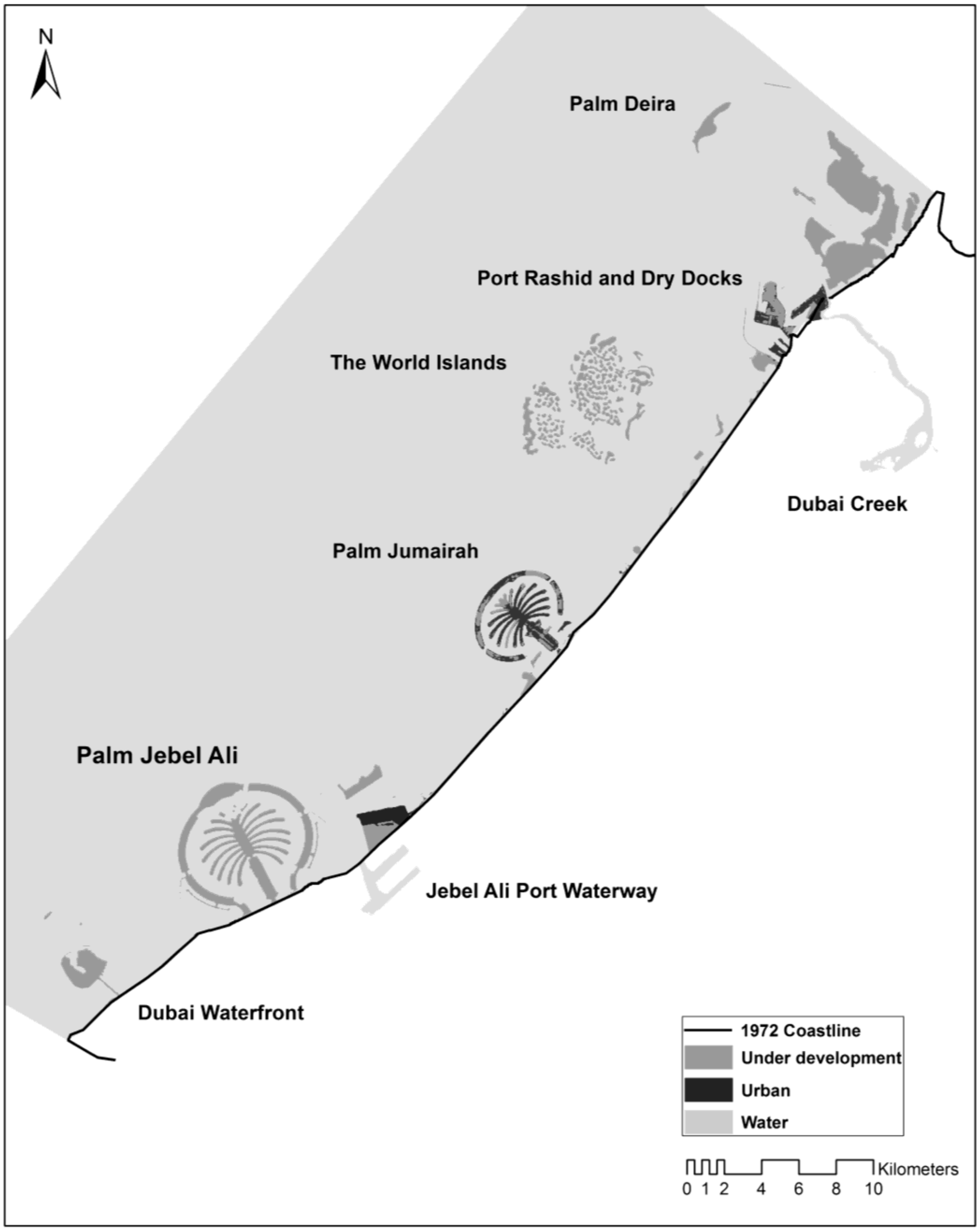
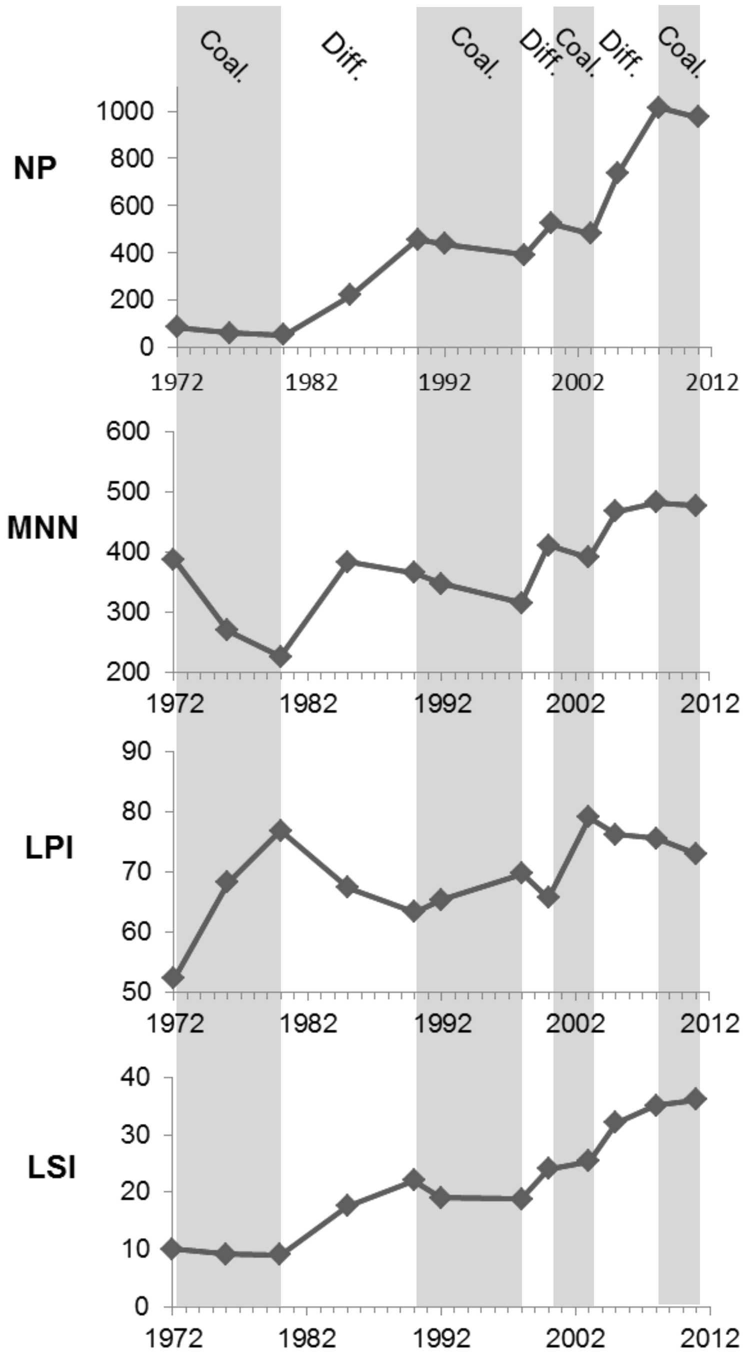
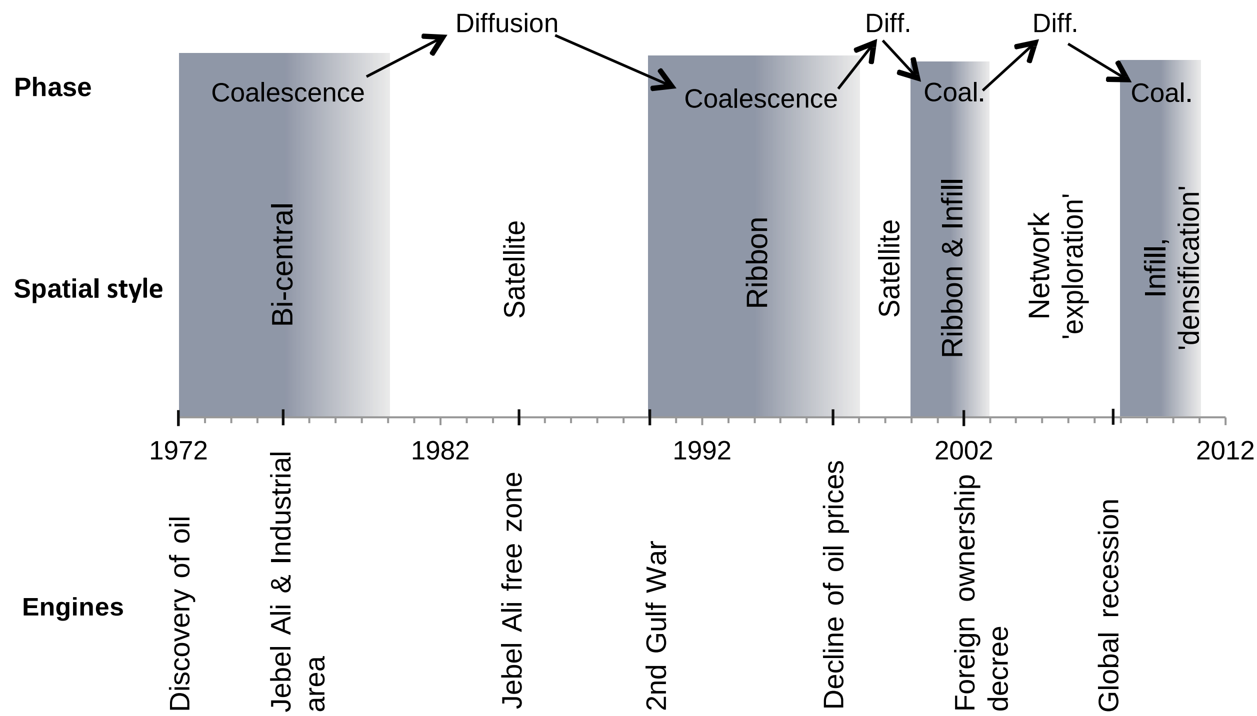

N
Palm Deira
Port Rashid and Dry Docks
The World Islands
Dubai Creek
Palm Jumairah
Palm Jebel Ali
Jebel Ali Port Waterway
Dubai Waterfront
1972 Coastline
Under development
Urban
Water
Kilometers
0 1 2 4 6 8 10

Figure 5



Coal.
Diff.
Coal.
Diff.
Coal.
Diff.
Coal.
NP
MNN
LPI
LSI
1000
800
600
400
200
0
600
500
400
300
200
90
80
70
60
50
40
30
20
10
0
1972
1982
1992
2002
2012

Figure 6


Phase
Spatial style
Engines
Diffusion
Diff.
Diff.
Coalescence
Coalescence
Coal.
Coal.
Bi-central
Satellite
Ribbon
Satellite
Ribbon & Infill
Network 'exploration'
Infill, 'densification'
1972
1982
1992
2002
2012
Discovery of oil
Jebel Ali & Industrial area
Jebel Ali free zone
2nd Gulf War
Decline of oil prices
Foreign ownership decree
Global recession

Tables

1

Table 1
Data used in the study

Data type	Spatial Resolution	Path/Raw	Acquisition date YYYY/MM/DD
Landsat (MSS)	60m	172/042	1972/11/11
Landsat (MSS)	60m	172/043	1972/11/11
Landsat (MSS)	60m	172/042	1976/08/06
Landsat (MSS)	60m	172/043	1976/08/06
Landsat (MSS)	60m	172/042	1980/08/25
Landsat (MSS)	60m	172/043	1980/08/25
Landsat (TM)	30m	160/043	1985/02/11
Landsat (TM)	30m	160/043	1990/08/28
Landsat (TM)	30m	160/043	1992/06/14
Landsat (TM)	30m	160/043	1998/10/13
Landsat (ETM+)	30m	160/043	2000/08/23
Landsat (ETM+)	30m	160/043	2003/08/16
Landsat (ETM+)	30m	160/043	2005/07/22
Landsat (ETM+)	30m	160/043	2008/08/29
Landsat (ETM+)	30m	160/043	2011/08/22
DubaiSat-1	5m	-	2011
IKONOS	1m (Pansharpened)	-	2001, 2005
Aerial photo	1: 50,000	-	1997
Roads	(vector)	-	2008, 2011
Dubai boundary	(vector)	-	2008

Table 2
Land cover classification schema used in the study

Land cover	Subclass description
Urban	All manmade (built up) surfaces, including roads, commercial, industrial, pavements, etc.
Vegetation	Farms, parks, gardens, mangroves, palm trees, golf courses, etc.
Water	Inland open water and recreational water bodies
Sand	Sand dunes, coastal sands and rock outcrops

Table 3
Land cover classification accuracy

Year	Overall accuracy%	Kappa coefficient
1998	88.75	0.85
2000	87.08	0.83
2005	91.67	0.89
2011	93.33	0.91

Table 4
Confusion matrix, users and producers accuracy for the land cover classification for 2011

	Class	Reference pixels: Vegetation	Urban	Sand	Water	Total	Users Accuracy%
Classified pixels	Vegetation	58	0	2	0	60	96.67
	Urban	1	54	5	0	60	90.00
	Sand	1	3	56	0	60	93.33
	Water	0	0	4	56	60	93.33
	Total	60	57	67	56	240	
	Producers Accuracy%	96.67	94.74	83.58	100.00		

Table 5
Landscape metrics used in this study with related authors who used these metrics in their work

Landscape Metric	Explanation	Range	Recent research focusing on urban pattern
Number of patches (NP)	Number of spatially distinct patches for the urban class	NP ≥1, without limit.	Aguilera et al., 2011; Araya & Cabral, 2010; Dietzel, Oguz, et al., 2005; Taubenböck et al., 2009; Tian, Jiang, Yang, & Zhang, 2011
Largest patch index (LPI)	Percent of the total landscape covered by the largest patch.	0 < LPI ≤ 100	Araya & Cabral, 2010; Dietzel, Herold, et al., 2005; Dietzel, Oguz, et al., 2005; Taubenböck et al., 2009
Mean Nearest Neighbour distance (MNN)	Average of the shortest distance (m) from one urban patch to another.	MNN > 0, without limit	Aguilera et al., 2011; Araya & Cabral, 2010; Dietzel, Herold, et al., 2005; Dietzel, Oguz, et al., 2005; Tian et al., 2011
Landscape Shape Index (LSI)	Total length of urban edges divided by the square root of the total landscape area (square metres).	LSI ≥ 1, without limit	Dietzel, Oguz, et al., 2005; Taubenböck et al., 2009; Wu et al., 2011; Yue, Liu, & Fan, 2010
Area Weighted Mean Patch Fractal Dimension (AWMPFD)	Average fractal dimension of patches in the landscape, weighted by patch area	1 ≤ AWMPFD ≥2	Araya & Cabral, 2010; Dietzel, Herold, et al., 2005; Dietzel, Oguz, et al., 2005; Tian et al., 2011; Zhang, Ban, Liu, & Hu, 2011