Analysis of urban sprawl at mega city Cairo, Egypt using multisensoral remote sensing data, landscape metrics and gradient analysis

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Abstract – This paper is intended to highlight the capabilities of synergistic usage of remote sensing, landscape metrics and gradient analysis. We aim to improve the understanding of spatial characteristics and effects of urbanization on city level. Multisensoral and multitemporal remotely sensed data sets from the Landsat and TerraSAR-X sensor enable monitoring a long time period with area-wide information on the spatial urban expansion over time. Landscape metrics aim to quantify patterns on urban footprint level complemented by gradient analysis giving insight into the spatial developing of spatial parameters from the urban center to the periphery. The results paint a characteristic picture of the emerging spatial urban patterns at mega city Cairo, Egypt since the 1970s.

Keywords: Urban Remote Sensing, change detection, landscape metrics, gradient analysis, urban sprawl, megacity, TerraSAR-X, Landsat

1. INTRODUCTION

With the words 'The world has entered the urban millennium' Kofi Annan, the former General Secretary of the United Nations, emphasized in 2001 that the highly dynamic process of urbanization throughout the world has an irreversible impact on the earth's system. Innovative strategies and techniques are needed to recognize, measure, analyze and understand the process of urban sprawl.

However, there is no uniform definition of the term 'urban sprawl'. In literature five different groups of definitions are identified (Siedentop, 2005). According to this the term 'urban sprawl' defines (1) deconcentration of urban functions in combination with spatial expansion of urban settlements into rural areas (Pumain 2003) (2) dominance of low density settlement structures (Gläser & Kahn, 2003) (3) transformation of formerly monocentric compact cities into discontinuous, polycentric, disperse urban pattern (Torrens & Alberti, 2000) (4) relevant effects on society by the new spatial pattern, like traffic overload (Ewing, 1994) (5) splinter development contradicting to aims of spatial planning ideas and concepts. Thus, the analysis of the urban sprawl phenomenon must be highlighted from multidimensional perspectives.

Remote sensing is one scientific field to provide insight into the multidimensional urban sprawl phenomenon. The techniques show their value predominantly in space-oriented questions regarding the various definition of urban sprawl. Remote sensing provides spatially consistent data sets that cover large areas with both high spatial detail and high temporal frequency. Recent research has used remotely sensed images to quantitatively describe the physical spatial structure of urban environments and characterize patterns of urban morphology. Studies vary from general views on city level (Sudhira et al, 2003, Taubenböck et al, 2008a) to highly detailed analysis of urban morphology on building / block level (Barr et al, 2004; Taubenböck, 2008).

In this study we monitored and analysed effects of the enormous population pressure on spatiotemporal urbanization at megacity Cairo in Egypt, Africa. We used multisensoral and multitemporal data sets from the optical sensor Landsat as well as from the German radar sensor TerraSAR-X. Using these sensors we classified -using object-oriented hierarchical classification methodologies- urban footprints from 1972 until 2008. Subsequently we conducted change detection to quantify urban sprawl and identify directions of growth on city level.

Furthermore, we used a combination of landscape metrics and gradient analysis to describe and analyze the physical urban appearance on urban footprint level. Landscape metrics can be defined as quantitative and aggregate measurements derived from digital analysis of thematic categorical maps showing spatial heterogeneity at a specific scale and resolution (McGarigal, et al, 2002; Herold et al, 2003). Gradient analysis illuminates the developing of spatial parameters with respect to location (Taubenböck et al 2008b). The combination of remote sensing, landscape metrics and gradient analysis aims to highlight spatiotemporal perspectives on urban sprawl.

2. STUDY SITE AND DATA

Already a "million city" by the early years of the twentieth century, Cairo has grown particularly rapidly since the Second World War (Sutton & Fahmi, 2001). The population of todays' mega city officially grew since 1950 to 2.4 million, until 1975 to 6.4 million and to 12.5 million inhabitants in 2007 (metropolitan area 17.8 million) (UN, 2007). Cairo today is not only the capital of Egypt but also its economic, social, service, and administrative centre. The city's size and rapid growth have resulted in serious problems in most aspects of the life of its population. The government has attempted both to decentralize population and activities from Cairo and to reorganize and manage its growth at the national, regional, and local levels (Yousry & Atta 1997).

Our study aims to monitor and analyze the spatial urbanization processes on city level since 1972. To maximize the period of time for monitoring urbanization Landsat data –available since 1972– have been chosen. With its field of view of about 185 km, the satellite can survey the large metropolitan area of the study site. The chosen level of spatial resolution with Landsat features does not deliver microscopic detail, but enables to classify the urban footprint in its correct dimension. Due to technical problems of Landsat ETM 7, continuously monitoring of urbanization processes to date needs new data sources.

For continuative monitoring we choose the German TerraSAR-X radar sensor, which is capable of acquiring data at day and night, independent of weather or environmental conditions. Hence, SAR data is more reliably available than optical imagery. Moreover, urban environments feature a more constant and specific behavior and appearance in radar data compared to the spectral characteristics of built-up areas in optical images. In SAR data settlements appear as clusters of direct backscattering centers -

forming bright signal returns - and dark shadow regions. TerraSAR-X provides different modes and incidence angles to scan the earths' surface. The stripmap mode incorporates a swath width of 30 km and a spatial resolution of 3 meters. Thus, the technical specifications enable coverage of the metropolitan areas as well as the capability for classification of urban footprints. Therefore, the combination of both systems lets us analyze extended time series on city level.

3. METHODOLOGY

1.1 Classification of multisensoral and multi-temporal remote sensing data and change detection

The classification procedure of the various data sets basically consists of three main steps: (1) a specific pre-processing of the particular data set, (2) the segmentation of the images, (3) the classification in order to identify and extract the urbanized areas.

(1) Both optical and SAR data require several steps of pre-processing. The optical Landsat data have been prepared by an atmospheric correction reducing atmospheric perturbations like dust, smog, and sparse clouds. The quality of SAR data, however, usually suffers from speckle noise. Hence, the TerraSAR-X SM data is prepared by the so-called 'SelectiveMean Filter' (Esch, 2006). The tool is designed as an adaptive moving window filter with filtering based on the local statistics of the central pixel and its surrounding pixels. By this method, the filter tool is able to detect highly and sparsely structured areas in the imagery and reduce the speckle noise in less structured areas. During the filtering, speckle noise in homogeneous non-built-up areas is reduced. Instead, bright and highly structured parts remain unfiltered as reliable indicators for urban areas.

(2) (3) The image analysis is performed - including segmentation and classification – using an object-oriented approach. A land cover classification extracting the classes urbanized areas, non-urbanized areas and water was performed separately on all individual images. The main goal is to identify the urban built-up areas to measure the changes of extent, directions, speed and pattern of the urban extension over the time interval. For that purpose the classification methodology is based on an object-oriented hierarchical approach (Taubenböck, 2008; Thiel et al 2008). The object-oriented, fuzzy-based methodology was implemented to combine spectral features with shape, neighbourhood, context and texture features. The classification methodology of Landsat data is mainly based on the spectral capabilities of the sensor. The seven spectral bands as well as indices like NDVI are involved to separate water bodies or vegetation areas from urbanized space. SAR data, however, only provide a single wave length. Consequently, spectral information is rare compared to optical data and it is more difficult to extract precise information from SAR data (Esch et al 2009). Settlement areas are characterized by numerous bright scatterers in the intensity image. In order to create a SAR-based settlement mask the classification of urban area starts with the identification of sure urban structures indicated by the high backscattering of corner reflectors. The first classification step aims at the identification of distinct urban point scatterers (UPS) which are characterized by a very high intensity and a very high speckle divergence - features which almost exclusively appear in the context of backscatter from man-made structures. These reflectors are used as seed points (Thiel et al 2008). Assuming that all settlements feature clusters of UPS the analysis is subsequently focused on the neighbourhood of the UPS. Subsequently, region-growing is implemented for a detection of ambiguous built-up areas. An accuracy assessment has been performed by a randomization of 150 checkpoints and a visual verification process for every individual classification result. The accuracy assessment resulted in 89 to 95 %.

Post classification comparison was found to be the most accurate procedure and presented the advantage of indicating the nature of the changes. Pixelwise change detection was implemented checking the land cover classes individually of the available years. Figure 1 shows the evolving urban footprint and its sprawling expansion in Cairo over time.

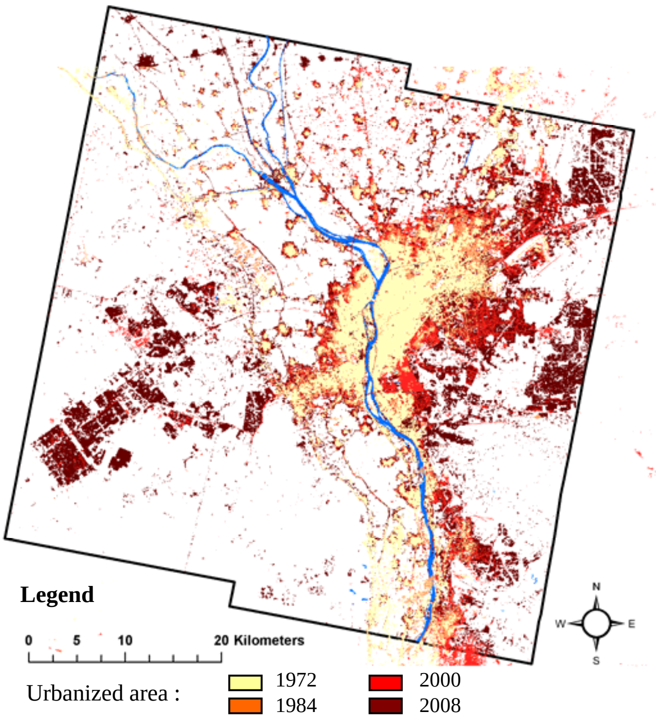

Figure 1. Change detection from1972 until 2008 for megacity Cairo

1.2 Urban sprawl analysis using landscape metrics

Landscape metrics enable to quantify a landscape (here: urbanized area) with respect to spatial dimension, alignment and pattern at a specific scale and resolution. We included in our analysis landscape metrics from the following different categories: 'area metrics', 'patch density, patch size and variability metrics', 'shape metrics' and 'nearest neighbour metrics' (MacGarigal et al, 2002). 'Area metrics' quantify landscape composition, not landscape configuration. 'Class area' (CA) defines the spatial dimension of the urbanized areas as first parameter to monitor urbanization over time. In addition we use the largest patch index (LPI) at the landscape level to quantify the percentage of total landscape area occupied by the largest patch (Luck & Wu, 2002).

From the category 'Patch Density, Size and Variability metrics' we use the number of patches and the mean patch size to quantify landscape configuration. 'Shape metrics' quantify landscape configuration by complexity of patch shape. The 'Landscape Shape Index' (LSI) provides the corrected perimeter-to-area ratio for the landscape as a mean. Hence, it is a measure of aggregation or clumpiness: if the urbanized area comprises one single compact area, the LSI will be small, approaching 1.0. If the landscape contains dispersed patches with complex and convoluted shapes the LSI will be large. Thus, this parameter is used as a measure of complexity of urban growth (Taubenböck et al., 2008a). Nearest neighbor metrics quantify landscape configuration. We use ‘nearest neighbor standard deviation’ (NNSD) as a measure of dispersion; a small standard deviation relative to the mean implies a fairly uniform or regular distribution of patches across landscapes, whereas a large standard deviation relative to the mean implies a more irregular or uneven distribution of patches.

1.3 Urban sprawl analysis using gradient analysis

In contrast with the urban analysis using the complete urban footprints of the cities, gradient analysis illuminates the developing of spatial parameters with respect to location. The following urban structure analysis is two fold: Firstly, based on the individual classifications of the four time steps histogram analysis of built-up areas identifies mono- or polycentric growth types and their temporal evolution. Therefore a scan algorithm counts the percentage of built-up areas in comparison to non-built-up areas for every row and every column of the classification results (Taubenböck et al. 2008b). With respect to location the two plots in x and y directions are added to integrate the spatial information of urbanized gradients into one diagram. The result of the scan is displayed as continuous graph over the particular spatial location for every individual time step. The peaks reflect the physical focal points of urbanised areas and thus enable to assess the physical spatial pattern as mono- or polycentric and its developing over time.

Secondly, built-up density is a measure to characterise spatial urban pattern and structure. Densities vary substantially from city to city and from the urban center (ring 1) to peripheral areas (Taubenböck et al., 2008). Using artificial concentric rings with a constant radius of 10km, the built-up density with respect to location is calculated for various spatial zones.

4. RESULTS

Cairo is an explosively spatially growing mega city (cp. Fig. 1). The result of the change detection displays stark transformations of the urban footprint over time. With regard to the definition of ‘urban sprawl’ in the introduction, the study monitored and revealed some of these multidimensional spatial processes: Analyzing the landscape metrics we observe a constant increasing spatial urbanization over time from 1972 until 2000. Since the millennium spatial urban sprawl becomes more extensive. This also affects the impact of the largest patch index, decreasing since

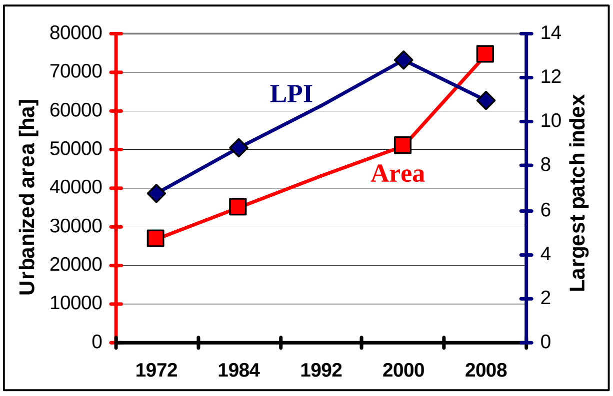

Figure 2. Area metrics: Total urbanized area and LPI

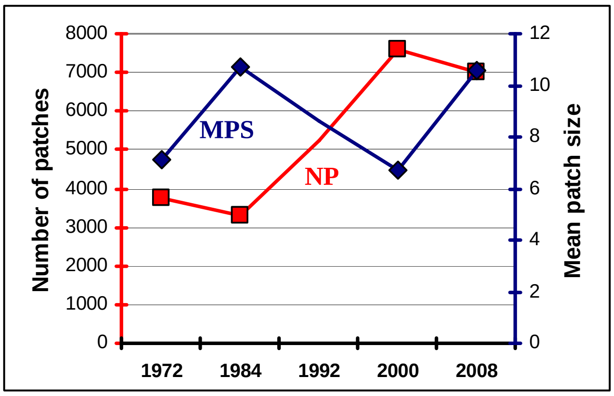

Figure 3. Mean patch size and number of patches

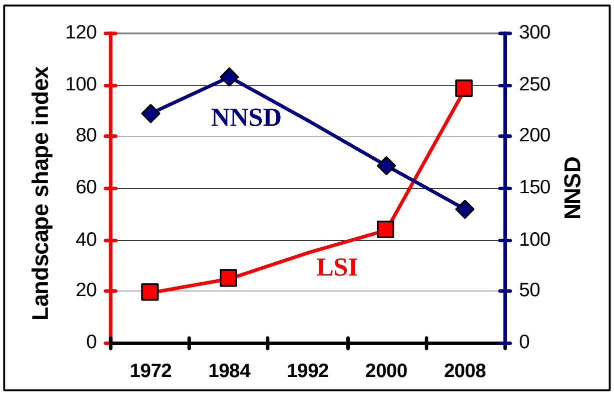

Figure 4. LSI and nearest neighbor standard deviation patch

2000, due to the developing of large planned satellite towns disconnected from Cairos’ main urban footprint (cp. Fig. 2). The number of patches shows rapid growth from the 1980s until 2000. This is reflected in disperse, patchy spatial growth, which led to sprawling splinter development (leapfrogging). The leapfrogging until 2000 took place with very small patches showing a decrease in MPS (cp. Fig. 3). Since 2000 coalescence of the prior punctual growth leads to a decrease in NP and at the same time an increase in MPS. Punctual growth with small patches and laminar spatial expansion adjacent to the compact urban core resulted in a constantly increasing complexity of the urban footprint. Only since the millennium the complexity shows abrupt rise. Responsible for this is the developing of large satellite towns, and thus deconcentration respectively transformation of formerly monocentric compact cities into discontinuous, polycentric,

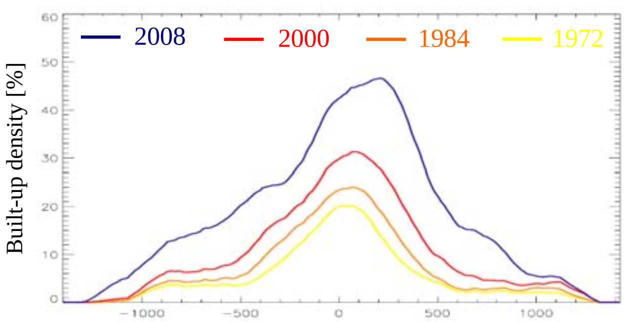

Figure 5. Histogram analysis for Cairo

disperse urban pattern. The disperse settlements and the large spatial urbanization leads to a strong decreasing of NNSD (cp. Fig. 4).

For location-based gradient analysis we use the parameter 'built-up density' and its development from the urban core to the periphery for various approaches. Histogram analysis clearly displays the transformation of a monocentric urban structure in the 1970s to a polycentric metropolitan area of Cairo in 2008. Results show only marginal changes from the 1970s until 2000 with one spatial peak. Thus, the compact city predominantly grew by densification and adjacent expansion to the former urban footprint. Only recently extensive development to multiple peaks for a polycentric metropolitan area is observed. In addition we also observe a saturation effect of urbanization in the urban core since 2000 and relocation of sprawl and densification to the rings 2-5 (cp. Fig. 6).

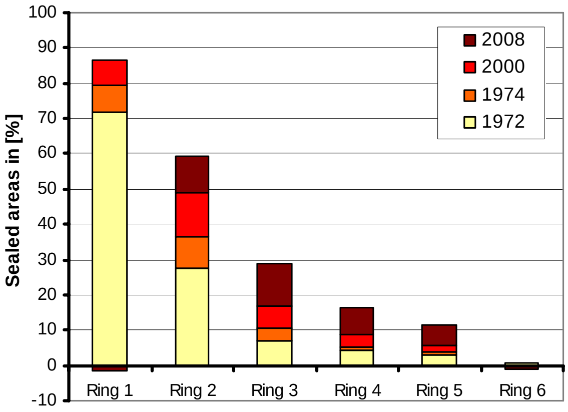

Figure 6. Temporal gradient analysis of urbanized areas

5. CONCLUSION

The study has demonstrated that urbanization and its spatiotemporal form, pattern and structure can be described, quantified and monitored using a combination of remote sensing, landscape metrics and gradient analysis. Landsat in combination with TerraSAR-X data proved to be independent, area-wide, and – with respect to the limited geometric resolution– adequate data sources for consistent long-term analysis on city level of the large and fast-changing area of mega city Cairo, Egypt. The combination of remote sensing, landscape metrics and gradient analysis gives insight into the multidimensional phenomenon of urban sprawl and lets us indirectly even include and interpret causes and consequences of dynamic growth processes.

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