USING VHR SATELLITE IMAGERY TO ESTIMATE POPULATIONS IN INFORMAL SETTLEMENTS

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ABSTRACT:

In order to generate appropriate data quickly enough for it to assist local policies and their controlling actions we need effective methods of monitoring informal settlements. In this respect remote sensing data is especially powerful since it helps to link the geographic location with accurate socio-economic data. Due to the microstructure, merged/overlapping rooftops and irregular buildings shapes in slums the detection of informal residential settlement structures from satellite imagery represents an especially challenging task. Our research focuses on Kibera (on the edge of Nairobi), which is the largest informal settlement in Kenya, and one of the largest in Africa. In our study we used the density per area method in order to estimate the population in the Kibera informal settlement and object-based classification methodology from GeoEye and QuickBird satellite imagery to accurately determine the residential areas. The area is composed of various size houses and a mostly unpaved road and path network which produces a hard to interpret spectral response on satellite imagery. The results of the object-based analysis based on morphological attributes were further explored in order to analyse the settlement growth and changes between 2006 and 2009.

1. INTRODUCTION

1.1 Motivation

Informal settlements represent an extremely dynamic phenomenon through space and time and the number of people living in these areas is on the increase worldwide. These areas often lack any kind of data that would enable monitoring systems and lead to an accurate estimation of the population numbers. The collection of population data depends mainly on the census, which is labour-intensive, time-consuming and demands substantial financial resources. The population estimates of our study area of Kibera (Nairobi, Kenya) vary between 170,000 and 1 million and are as such highly debatable. What is certain is that the area covering 2,5 km^2 is informal and self-organized, stricken by poverty, disease, population increase, environmental degradation, corruption, lack of security and lack of information, all of which contribute to the lack of basic services.

Monitoring systems joining spatial (location) and social data can be used for monitoring, planning and management purposes. New monitoring methods are required if we wish to generate adequate data that will help link the location and socioeconomic data in urban systems to local policies and controlling actions. In situations when we lack accurate maps of informal settlements and relevant census data, answers can be found using satellite or aerial technologies. A census is a complex undertaking; it requires significant human, technological, and financial resources to plan and execute (Hardin et al., 2007). Although it is impossible to measure the population on remote sensing images, remote sensing technology and measuring the visible variables may provide for a relatively accurate population estimate.

1.2 Aims of the study

This paper focuses on the ability to acquire basic spatial data and apply it to the informal settlement of the Kibera slum (Nairobi, Kenya), using high-resolution satellite imagery. The American Association for the Advancement of Science (AAAS), which supports the operation initiatives of MapKibera Project/Trust (MKP/T) and other NGO activities, has donated satellite images of the studied area. The MKP activities (MKP, 2011) include activities that cover various types of mapping the actual physical and socio-demographic features of the Kibera informal settlement. The aim of the study was to assist MKP in its processing of satellite data and first mapping of the entire slum. The various studies of the Kibera informal settlement had two goals: first, to derive a detailed land use/cover map that could further supply the population estimation, and second, to analyse the potential of VHR imagery for detecting changes and settlement growth in the recent past. Since object-based classification of VHR satellite data has been argued as the most appropriate method for obtaining information from urban remote sensing applications, this approach was used to derive an accurate land cover map.

1.3 Overview

A generically applicable and rapid operational land cover mapping of informal settlements has generally proven difficult (Netzband & Rahman, 2010). In order to establish a detailed urban structure and delimitate residential objects from open areas, and potentially obtain an informal settlement structure on the micro-structural level (distinguishing individual houses), we have implemented an object-based approach. For this research we used software that does not support multilevel segmentation. Since the segmentation parameters were selected for a particular land use (buildings), others were expected to be under- or over-segmented. Nine land cover classes were extracted during the segmentation and these included four types of residential

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housing. Our results would have improved if we chose residential sub-classes rather than use a single general class. Some urban elements (e.g. rooftops) were created using a combination of numerous surface materials, which produced a spectral response that was difficult to interpret with the use of automated (routine) procedures.

Considering the fact that we lack detailed socio-geographic data for Kibera, we decided to assess the population on residential land cover class information using solely the density per area method. The total built-up area was calculated and different settlement scenarios (i.e. persons/living area) that were obtained from the sample census capture were tested (through which we wished to observe the range of the possible population fluctuation).

We were also interested in locating the step-wise expansion of the informal residential areas through comparing the images taken through time. Despite the use of the VHR satellite image time series may provide a reliable approach in detecting dense urban growth in detail (Hofmann et al., 2006), a pixel-based multi-level technique (Veljanovski, 2008) for urban expansion was employed.

1.4 References to related work

Even though remote sensing images offer a well suited data source and there is a strong need for obtaining spatial information on informal settlements (in order to improve the living conditions of their residents), studies of informal settlements with VHR data are rare. Nevertheless, Hoffman (2001) presented the first results of detecting informal settlements from IKONOS data in Cape Town and through this showed the main feasibilities when using object-oriented approach. The results were promising but seemed to be very data dependent. Later on Hoffman et al. (2006) showed that several adaptations were necessary in order to improve the OBIA algorithm when applying its extraction methods to the QuickBird scene. The automatic image analysis procedures for a rapid and reliable identification of refugee tents from IKONOS imagery over the Lukole refugee camp in Tanzania was created by Giada et al. (2002). Sliuzas and Kuffer (2008) analysed the spatial heterogeneity of informal settlements using selected high resolution remote sensing based spatial indicators such as roof coverage densities and the lack of a proper road network characterized by the irregular layout of settlements. The cooperation between KeyObs, UNOSAT, OCHA and Metria resulted in the digitalization of the 2009 VHR GeoEye satellite image of the Afgooye corridor (Somalia), in which all temporary shelters were identified (UNHCR, 2010). The various methods used to detect and monitor spatial behaviour of informal settlements were also presented by Lemma et al. (2005), Radnaabazar et al. (2004), Kuffer (2003), Sartori et al. (2002), Dare & Fraser (2001) and Mason et al. (1998).

2. STUDY AREA AND DATA

Kibera is located in Kenya, southwest of Nairobi's city centre, and covers an area of 2,5 km^2, which represents less than 1 percent of Nairobi's total area while containing over 25 % of its population. It is the largest informal settlement in Nairobi, and the second largest urban slum in Africa, with the population numbers varying through the seasons. The settlement is divided into a number of villages, including Kianda, Soweto West, Raila, Gatwekera, Kisumu Ndogo, Lindi, Laini Saba, Siranga, Kamdi Muru, Makina, Mashimoni and Soweto East (Figure 1).

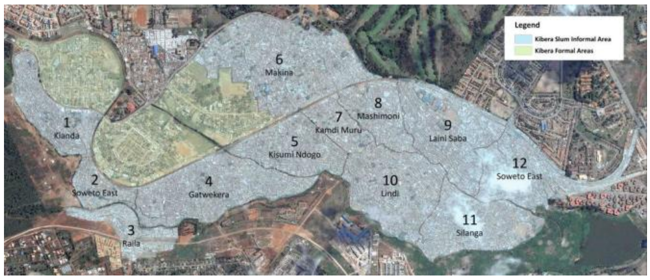

Figure 1. The slum of Kibera is divided into three formal and twelve informal villages.

High spatial resolution satellite images allow for the identification of detailed geographical features on the Earth's surface. This study involved one GeoEye and two QuickBird satellite images acquired between 2006 and 2009. Satellite images obtained from AAAS were already processed to a degree. The main characteristics of these images are described in Table 1.

Sensor	**Band used**	**Spatial resolution** (panshar-pened)	**Cloud coverage over Kibera**	**Acquisition Date**
GeoEye	R-G-B	0.5 m	Minor	25-07-2009
QuickBird	R-G-B	0.6 m	Free	10-08-2008
QuickBird	R-G-B	0.6 m	Free	27-03-2006

Table 1. List of satellite images used in the study and their main characteristics.

Besides the inherent different spatial resolutions the main differences between GeoEye and QuickBird images were found in the sensor viewing angles, which caused the shadows of higher objects to show differently on the images. As the Kibera informal settlement is positioned on a hilly terrain, the positional accuracy fit for geographical entities could not be reached through image geo-registration because much of the distortion is a result of the terrain. No digital elevation model was available for the study, thus ortorectification was not possible. Finally QuickBird images were registered to the GeoEye image with the rubber sheeting method based on over one thousand manually selected control points.

3. METHODOLOGY

Extracting urban land use structure data from remote sensing imagery requires methods that are able to provide an appropriate level of observed details. The tendency of mapping informal areas is that the resulting data can be linked to the socio-economic data from the informal settlement. In order to obtain relevant information from complex urban systems it is therefore necessary to use new, complex data processing methods that are adapted to the characteristics of high-resolution images. Higher resolution also reveals much greater surface details, and the used methodology should be able to detect and evaluate whether it is dealing with essential data (an important feature of a geographic object) or not. Due to the heterogeneous microstructure of these settlements (joined or overlapping roofs, irregular building shapes and related spectral properties of geographical objects in such environments) it is hard to detect the structural and morphological characteristics of informal settlements on satellite images. Rooftops are covered by different materials, ranging from new to rusty sheets, bricks and other materials, each of them with its own specific reflectance characteristics (spectral representation) on the satellite image (Figure 2).

Figure 2. Detailed urban structure of Kibera.

For the population estimation study we need to clearly distinguish between the rooftops, unpaved roads and non-built-up land, i.e. distinguish between residential areas and open soils. Object based segmentation automatically divides the satellite image into homogeneous elements (segments), in which close correspondence to the real (geographical) objects on the Earth's surface is expected. The use of image elements (segments) obtained in this way has a number of benefits; one of them is the ability to incorporate spatial and contextual information such as size, shape, texture and topological relationships into the contextual classification (Blaschke et al., 2004; Benz et al., 2004). In the classification stage all of these segments are classified according to their attributes into the most appropriate classes (representing various geographical objects under study consideration), while obtaining detailed classification of urban area land cover/use.

With the object-based analysis on rooftop morphology attributes we expected to improve the assessment of the potential population in slum areas. Since no complete and relevant field survey (official census) has been performed recently, different density parameters were tested in order to approach the potential population and these were compared to other sample population assessments.

3.1 Land cover classification

Since the analysis of the total area of the Kibera informal settlement, with its vast amounts of details, would be too demanding in terms of computer processing, we divided the GeoEye image of Kibera into 12 smaller parts (according to 12 informal villages). Thus we obtained 12 regional classification outputs, which were merged in the final stage. In order to avoid erroneous classification on the edges, we applied a 30 meter buffer zone when masking the village fragments from the entire GeoEye image.
Because of GeoEye image characteristics (close to the nadir viewing angle, good spatial resolution, and fine contrast) we used the object-based classification methodology for land cover classification, at which we used ENVI EX software that consists of two user driven stages (segmentation and classification). The supervised segmentation within the used software is defined by two segmentation parameters that influence the average segment sizes: segmentation and merging. Setting different values for these two parameters causes a change in the size of the segments, allowing for the image to be segmented at a number of different scales so that both parameter values influence the classification results. Since the surface structure is similar throughout the settlement, the same general segmentation parameters were used for each of the 12 villages. In the classification process the informal settlement segmentation parameters that have proven to be the best in extracting the shapes of individual buildings were adapted. Since the segmentation parameters were adequate merely for a single particular land use (i.e. buildings), others were expected to be under- or over-segmented. There is no single "optimal" scale for analysing remote sensing images, instead there are numerous optimal scales that are specific to the image-objects that exist within a scale (Hay et al., 2003) and this is why using a multi-scale approach may often be preferable (Johnson and Xie, 2011). All spectral bands were used and given equal weight for image segmentation and all available attributes were calculated for all of the segments. The objects extracted during the segmentation were classified using the Support Vector Machine (SVM) classification algorithm in an object-oriented framework along with training sets, selected by an experienced user. Nine land cover classes were used in total (Table 2).

Land use/cover classes	**Description**
Buildings_blue	Residential houses with "blue" rooftop spectral representation.
Buildings_light	Residential houses with "white" (bright) spectral representation.
Buildings_ brown	Residential houses with "brown" (dark) spectral representation.
Buildings_red	Residential houses with "red" spectral representation.
Roads	Traffic connections between villages, usually unpaved.
Shadows	Shadowed areas around high vegetation and buildings.
Soil	Un-vegetated soil and muddy ground.
Vegetation 1	Green vegetated areas (trees, shrubs), low vegetation (grass).

Table 2. Land cover classes obtained with object-based analysis.

These nine urban land use/cover classes included four types of residential housing. Sub-classes were selected due to the different spectral signature properties within the same land cover class (e.g. instead of selecting only class "buildings" we selected four subclasses "buildings_blue", "buildings_light", „buildings_brown" and "buildings_red"). This way we obtained better results than we would if we would have used a single general class.

Classification results were obtained as a raster image and vector file. Vectors were exported to a single layer and later processed for the need of post-classification with ESRI ArcMap software. Polygons smaller than 2 m^2 were merged with larger neighbouring polygons.

3.2 Urban growth of the informal settlement

The Kibera informal settlement is very limited in terms of spatial expansion. In our study we were interested in detecting urban growth on available satellite data. In general, change detection techniques can be grouped into two main types (Singh, 1989): image differencing techniques and post-classification comparison techniques. Since determining land use with object-based classification is an extremely time consuming and demanding task, we decided to use an older, but

faster method. A multi-level change detection approach, which was primarily developed for medium-resolution images, was applied (Veljanovski, 2008). This method starts off by finding significant deviations in a slightly reduced spatial scale (3 x 3 pixel window or 1,5 m spatial resolution in the given case), based on specific neighbourhood mean value annotation. The identified locations of changes are then examined for differences in the original scale image (0,5 m resolution). This way the greater share of apparent changes, which are a consequence of radiometric differences between datasets and do not represent real changes, can be avoided. This method requires radiometric standardisation between the images acquired at different dates (radiometric standardization with linear regression was used) and effectively resolves local radiometric discrepancies between images.
For the entire Kibera informal settlement changes were obtained by comparing GeoEye 2009-07-25 and QuickBird 2006-03-27 images. The change patches smaller than 5 m^2 were eliminated for the purpose of this example, mainly in order to reduce the impact of the change artefacts belonging to small patches, which were a result of minor rooftop renovations. The results were visually examined and the evaluation of the change pattern characteristics (over- and under-estimations) was performed throughout the area with the use of complementary comparison of the used satellite images.

3.3 Population estimation

Estimating the population of small areas using various scales through space and time is a difficult demographic task. Although population is not directly measurable on remote sensing images this technology may provide a good approximation of population estimation with the use of visible variables, e.g. the number of residential buildings and/or the area of the built-up zone (Zhang, 2003). Several estimation methodologies have been developed for remotely sensed data (Hardin et al., 2007): 1.) use of allometric population growth models, 2.) use of dwelling unit type, 3.) use of land type zones, 4.) pixel/object based approach as a function of spectral reflectance or texture on satellite images. The process of estimating the population via the dwelling identification is conceptually simple, however it depends on the successful identification of various dwelling types from high-resolution imagery.
Considering the fact that it is hard to perform a census in Kibera (due to the high crime levels and therefore inferior access, seasonal variability of the numbers of residents, distrust of the inhabitants to tell actual data, non-uniform instructions for data collection...), we decided to assess the population solely through residential land cover class information obtained from object-based classification with density per area method. For each village a total area of buildings was calculated and different occupation scenarios (i.e. persons/living area) were applied in order to observe the range of possible population fluctuation. The used sample population densities were collected from different parts of Kibera and represent sample census data.

4. RESULTS

4.1 Land cover classification and urban growth in Kibera

Detailed mapping of the informal settlement has proven to be difficult due to the complex microstructure of the roofs (a combination of various roof materials, renovations and shadows). It was impossible to determine the boundaries of individual buildings, since these were often combined into larger objects. Consequently, it was impossible to count the individual houses and impossible to determine the exact number. In order to obtain individual residential objects two approaches were considered: 1.) manual correction of the shapes of obtained polygons, however a small test showed that this approach is extremely time consuming (correction took more time than it would take if one would manually digitize the area) and 2.) use of additional attributes that are automatically created in the ENVI EX segmentation phase. Investigation showed that there is no functional relation within the additional attributes of all building sub-classes. Therefore additional attributes could not assist the semi-automatic reclassification of some segments that would lead to improved shapes of individual objects in built-up zones.

Final classification results are shown in Figure 3. Ratio of residential land use to all land uses for every village is shown in Table 3.

Figure 3. Merged final classification results of the GeoEye image for land cover classes for all 12 Kibera villages.

Land use [m^2] / village	**Residential**	**Total**
Kianda	117,710	170,145
Soweto West	49,620	81,343
Raila	45,657	108,583
Gatwekera	234,609	307,520
Kisumi Ndogo	111,472	164,717
Makina	303,599	444,710
Kamdi Muru	51,248	81,412
Mashimoni	96,287	128,355
Laini Saba	181,211	277,786
Lindi	159,112	271,668
Silanga	150,058	243,733
Soweto East	174,200	248,181
SUM [m^2]	**1.674,784**	**2.528,152**
SUM (%)	**66.25**	**100**

Table 3. Area of residential land use for 12 informal villages and the total village land use sum in Kibera.

All (semi)automatic classification methods display certain errors, but as an approximate solution object-based classification on VHR data yielded excellent results when proper segmentation parameter values were selected. Accuracy assessment was performed through the comparison of supervised classification results with manually digitalized objects. The comparison was performed on an area covering 200 x 300 m in the village of Lindi. Since the outline of individual residential objects could not be extracted we compared only the total sums of areas classified as *residential*. The different shapes and colours in informal settlements determine a complex urban formation, which is difficult to differentiate from other land cover types, especially from bare soil and unpaved streets.
Object-based classification and land use mapping of the Kibera settlement on a GeoEye image highlighted some typical

problems for object delineation in slum-like areas that can be corrected only with substantial manual work. The main difficulties are associated with informal area outer-homogenity (due to the domination of rooftops in urban agglomeration) but inner-heterogenity (rooftops micro structure due to the use of various materials within one rooftop). Object-based classification is thus very demanding in terms of methodology adaptation to informal residential area specifics, especially when accounting for their direct relation to their representation on different satellite data sources.

The change detection applied to Kibera informal settlements aimed to obtain an outline of the distribution and extent of major urbanisation processes. The chosen method has proven to be suitable for monitoring changes related to multiple processes (buildings construction, buildings collapse or disappearance, rooftop renovation, increase/decrease in vegetation) and/or of the coincident description of their trends. Although a quantitative assessment of changes was not performed due to the lack of independent reference data, a detailed visual control was performed through the comparison of the before and after images.
The informal settlement is extremely limited in terms of spatial extensions; the river channel cuts it off in the south and the golf course in the north. Therefore the area did not expand drastically over the last few decades, however it is clear that the informal settlement has progressively became denser.

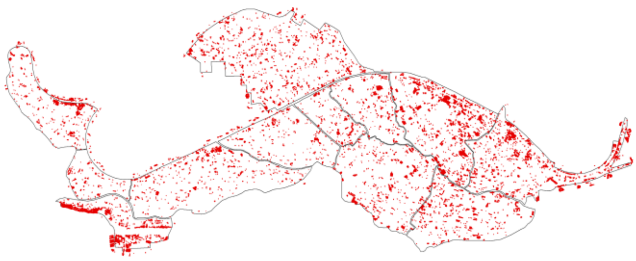

Figure 4. Identified changes between 2006 and 2009.

The main changes in the Kibera slum are a consequence of new building constructions, roof renovations and less of building destruction. The identified change pattern (Figure 4) clearly draws attention to the spots where the urbanisation was most intensive between 2006 and 2009: Kianda northeast, Raila southern border, Mashimoni and Laini Saba northern border and Soweto East eastern tail. According to the density of the change pattern elements, in addition to the edges of the Kibera informal settlement, several changes also occurred in the eastern part of Kibera, mainly due to large new building constructions or complete rooftop renovations.

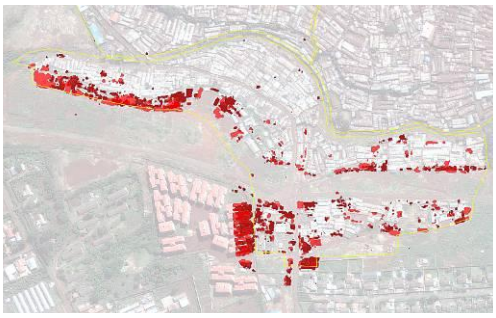

Figure 5. Urban expansion in the village of Raila in 2006, 2008 and 2009.

Additional socio-economic data or information on major events (such as flooding) would be welcomed if we wished to associate the rate of more intense rooftops renovations at some Kibera villages compared to the other parts of the settlement. Figure 5 represents the urban growth pattern in the village of Raila in 2006, 2008 and 2009. Light red corresponds to 2006-2008 and dark red to 2008-2009.

4.2 Kibera population estimation in 2009

According to the total residential area in Kibera, obtained from object-based classification, the population estimate was calculated using various density per area parameters (Table 4). Additionally we illustrated this information in terms of typical house sizes in the example of the Raila village (Figure 6). The total surface of Kibera was calculated from the vector results of housing areas obtained through object-based classification as a sum of all 12 villages. All of the vectorized structures have been computed using ArcGIS software and we assumed that all structures are used for habitation purposes.
The sum of the residential areas shows that the total residential area of Kibera amounts to 1.646,883 m^2, which is more than 20 % of the total surface in 1993 as given by Sartori et al. (2002). Due to the denser housing, which has appeared within the informal settlement through the years, the population has increased since 1993.
As we can see in Table 4 the population estimation of Kibera can vary between 150 thousand and 650 thousand people, depending on the different sample census sources.

Source	Density [people/m^2]	No. of population in Kibera
MapKibera Project (2008)	0.0951	156,652
IRIN (2006)	0.2000	329,377
AHI US (2005)	0.3000	494,065
Sartori et al. 1 (2002)	0.3300	543,471
Sartori et al. 2 (2002)	0.3900	642,284

Table 4. The estimation of population according to the density acquired from different sample censuses. The housing area of Kibera was calculated from the results obtained from object-based classification of the GeoEye image from 2009.

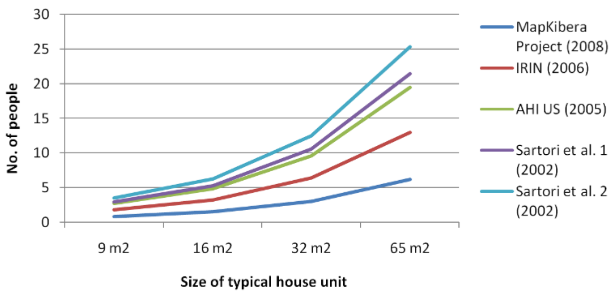

Figure 6. Density of people according to different sample censuses per typical house size in the Raila village example.

We are aware that the adopted area of residential land use can be overestimated, since it does not take into account that certain objects (presumably those close to the main road network) can be used for other land use (shops, services). In order to obtain this information we would need to conduct sociological recognition in the field itself. Such indications cannot be reliably defined merely from rooftop characteristics.

5. DISCUSSION

The roofs and unpaved ground in the informal settlement of Kibera have a similar spectral response in the visible spectrum. This made the strategy for distinguishing and classifying segments into correct thematic classes weaker and increased the amount of post classification work. The described situation favours the use of multispectral images, which include infrared band(s), whenever we want to map urban microsystems. Nevertheless, we can state that the object-oriented methodology used in the analysis of dense urban areas shows great promise. Both - the mapping of the spatial structure of the Kibera slum settlements and the urban expansion, and the estimation of the number of inhabitants in Kibera - lead to satisfactory results. The study confirmed that satellite imagery could provide important complementary information to the traditional methodologies for population estimation. Data obtained from high-resolution imagery is essential for planning informal settlements (e.g. infrastructure construction and management), especially if the spatial data is related to socio-economic data collected in the same area. Although the presented methodology for population estimation (e.g. the delineation of individual buildings within the slum) still shows numerous unsolved problems, the solutions are already being developed. The object-based analysis of remote sensing data thus represents a great potential for assessing the number of residents in informal settlements. By fostering a commitment to human rights with water and sanitation access the living conditions of the world's population can be improved.

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