4 Population density estimation at sub-national scale – the case of Zimbabwe

4.1 Introduction

Data quality and up-to-dateness is one of the major drawbacks of the risk estimation methodology described in section 3 and this concerns all three major underlying factors: hazard risk, vulnerability and exposure. Contrary to common presumption, reliable data on population numbers and spatial distribution, as source for the exposure part of the risk equation, is rarely available for non-industrialised countries. The lack of recent population data at fine spatial resolution hampers the work in all steps of crisis management, namely early warning systems and emergency actions.

In developing countries censuses are typically carried out every ten years. In less prosperous countries they are often supported by donor institutions. Censuses are usually carried out by national statistical offices and the results are made available to the public in aggregated form as national statistical yearbooks. Aggregated demographic information at country level is also provided by international organisations and commercial yearbook atlases. In developing countries population figures are also recorded within the scope of development projects and in the aftermath of disasters in order to determine dimension and type of assistance needed. The spatial extent of these surveys is usually limited due to the area selected for a project or affected by a hazardous event. They aim at generating information regarding certain aspects of population and lack the spatial and temporal continuity and coverage of traditional censuses. Due to the surveys' specific application there is no strategy to (1) update the information or (2) make it available to wider user groups (SCHNEIDERBAUER & EHRLICH 2005).

For the integration of population datasets into spatial analysis such as agriculture, environment, disasters or communities' vulnerability/poverty estimations, the data need to match two requirements:

- Availability at finer scale units than those resulting from usual censuses.
- Storage in raster format in order to ease computation and modelling.

The research community has developed techniques to transform population vector data based on censuses into raster data, with a population number per grid cell (see chapter 4.2). The raster format containing population counts is also referred to as population density representation and is increasingly used for disaster management, early warning and rapid response to crises. Current research is attempting to improve the accuracy and to increase the resolution of data on population distribution. Future work will increasingly focus on the development of attribute information determining populations' characteristics such as their vulnerability.

The work within this chapter focuses on the improvement of the spatial resolution of population datasets available at district levels covering Zimbabwe. It (1) uses country specific information layers, (2) evaluates the use of medium resolution satellite imagery and map based data for a population density estimation made available at a grid size of 150 meters. The methodology developed covers a region in Zimbabwe that includes the capital Harare.

4.2 Background

Population data from censuses are commonly made available per administrative / political unit. The datum includes the spatial representation of the administrative unit as vector polygon and the associated attribute reporting the total population value. Countries are subdivided in a hierarchical system of administrative units up to 4 levels deep: country, regions / provinces, counties / districts, and municipalities / communes. Administrative borderlines are not usually drawn to represent geographical phenomena. Therefore, on vector data based choropleth population maps, the populations seem to be homogenously distributed over the area of the administrative unit, despite possibly significant variations in real population densities. The dasymetric mapping approach aims to delimit regions with similar population densities by applying ancillary data (MENNIS 2003; LANGFORD & UNWIN 1994). Dasymetric mapping of populations at large and medium scale has been successfully applied in developed countries by using land use / land cover information stemming from earth observation data (LANGFORD et al. 1991; HOLLOWAY 1999; CHEN 2002; MENNIS 2003; LO 2003; LIU 2004).

Population data associated with vector boundaries are difficult to compute or integrate into spatial models. These data are therefore often disaggregated into grid cells of finer spatial unit since:

- Raster data format provides uniform scale, even if the original administrative units cover different areas.
- Raster cells are easy to process, which is of particular importance for GIS analysis. Grid cells are particularly useful in a number of decision support applications implemented when population estimations have to be computed for areas that intersect the administrative units for which population data are made available. In fact, raster data can be re-aggregated to accommodate any aerial arrangement, making population counts particularly easy to carry out.

Converting point values or polygon values into grid format is referred to as surface modelling. A commonly used technique in population modelling is smart interpolation. Smart interpolation for population density estimation is based on two major steps:

(1) the calculation of a grid-based population potential and

(2) the allocation of population numbers, usually available at a certain administrative level, to the gridded population potential.

The population potential estimation may rely on a series of variables including the location and size of urban settlements, as well as thematic data layers such as those depicting national parks, protected areas and inaccessible areas that are supposedly not populated. A model based on these input layers and transformed into algorithm for automatic computation helps to generate population raster datasets over large areas.

The first global population density estimation in raster format was initially developed under requests from international agricultural research institutes (DEICHMANN 1996). Since then other raster based global population densities have been produced (SUTTON et al. 2003), of which the 'Global Population of the World' (GPW) from the Center for International Earth Science Information Network (CIESIN) at the Columbia University (BALK & YETMAN 2004) and Landscan (DOBSON et al. 2000) (see chap 3.3) have received the most attention due to their accessibility and frequent update. Landscan was developed by allocating census counts at 30" X 30" cells through a 'smart' interpolation based on the relative likelihood of population occurrence. The allocation to cell is based on weighting computed from slope categories, distance from major roads, and land cover (MIRELLA et al. 2005).

The global population density datasets are lacking accuracy information but they are invaluable. They are used to provide preliminary estimates of casualties in the aftermath of natural disasters such as earthquakes, tropical storms or large floods. Also, in the absence of better population figures, these datasets are used in the assessment of slow onset disasters, namely droughts or epidemics, which are typically geographically specific. However, the demand for more precise population density data at a finer scale remains unmatched.

Improvement of the smart interpolation techniques relies on the availability of country specific fine scale data and Earth Observation data. Aerial photography and satellite imagery were already tested for population density mapping in the 1980's. Remote sensing techniques have been applied in order to improve or overcome census shortcomings in developing countries' censuses (ADENIYI 1983; OLORUNFEMI 1984). Coarse resolution imagery has been used in improving global population density assessments (ELDVIGE et al. 1997), and medium resolution for zone based estimations (LO 2003). HARVEY (2002) specifically tested estimations of population numbers from satellite imagery. With the availability of very high resolution imagery, formal settlements such as cities and informal settlements such as refugee camps can be assessed for population density (GIADA et al. 2003a; GIADA et al. 2003b). A recent overview of techniques used for counting population in cities is provided by MESEV (2003).

This study addresses the use of medium resolution imagery for zone based estimates of population densities. It aims at further developing methodologies that allow the relatively rapid generation of information on population distribution at a fine scale that is required for improved disaster management.

The study area extends over 185 x 185 km, coinciding with the coverage Landsat TM scene path 170 and row 72 (Figure 19). It includes the economic centre and capital Harare, and makes up part of the most productive agri-ecological zone of intensive farming in Zimbabwean's Highveld and Middleveld (VINCENT & THOMAS 1960). The study area covers commercial private farmland as well as government owned land, referred to as communal land[10]. The study is therefore representative of the land cover and land use diversity in Zimbabwe. Within the study area are three million people, accounting for 25% of the overall Zimbabwean population, living on an area of 33206 km^2, which is 12% of the total land cover.

[10] In southern Africa 'communal land' generally refers to an area of land owned by the State, which confers certain use rights (for cultivation, livestock grazing, timber harvesting, settlement, etc.) to rural populations that do not hold individual proprietary deeds. Many such areas in Zimbabwe are used for traditional agro-pastoral farming activities.

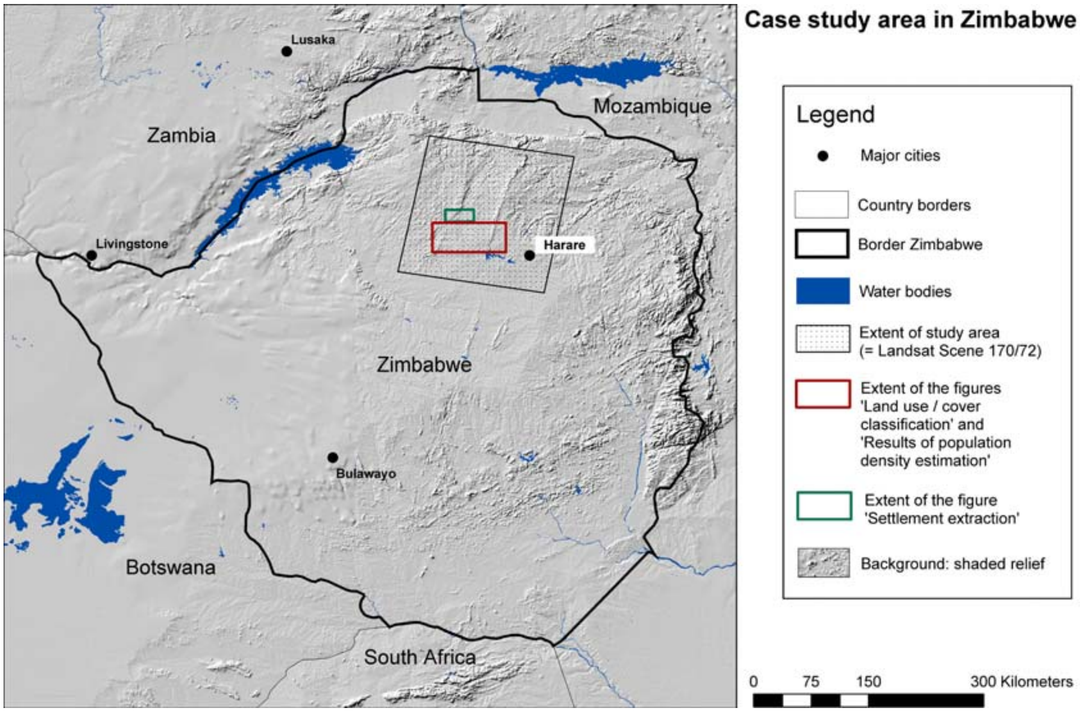


Figure 19: Case study area in Zimbabwe including the extents of Figure 20 “Processing stages of the extraction of human settlements from the scanned maps” (green box), Figure 21 “Landsat imagery classification” and Figure 23 “Results of population density model” (both red box) (source: author).

4.3 Methodology

The distribution of population within each district of the study area in Zimbabwe was modelled by creating a continuous surface of population density at a grid cell size of 150 m. The methodology for surface modelling of population data relies on combining information from a number of information layers listed in Table 14.

The input data were available as explicit digital information, with a spatial and attribute component, and data layers that required information extraction to provide delineation of spatial units and associated attributes. The ready-to-use information layers included the administrative borders of Zimbabwe at district level with associated population counts, protected areas, urban areas available as polygons, the road network available as lines, and towns available as point data. The raster information layers included the 1 km land cover and the digital elevation model derived from the Shuttle Radar Topography Mission (SRTM) elevation dataset. Two data sources required information extraction: Satellite imagery that needed to be classified into fine resolution land cover / land use classes and maps that were processed to extract specific features such as village location.

Dataset	Format / Resolution / Scale	Date	Coverage / Size	Theme extracted	Source
Population Census data	District level	2002	Countrywide	Population per district	Central Statistical Office Zimbabwe
Administrative subdivision of the country	Polygon	2002	60 Districts	District boundaries	Survey-General Zimbabwe
Urban areas	Polygon	NA	Areas of 8 main cities	City area boundaries	Humanitarian Information Centre
Protected areas	Polygon	NA	Countrywide	Protected area boundaries	Survey-General Zimbabwe
Road network	Line	2002	Countrywide		Humanitarian Information Centre
Settlements	Point	NA	Countrywide	Towns	DCW
Elevation	Raster / approx. 90 m (3 arc seconds)	2002	Countrywide	Slope	SRTM, United States Geological Survey
GLC 2000	Raster / 1 km	2000	Countrywide	Selected land cover classes	JRC
Landsat ETM	Raster / 15 m & 30 m	2002 / 2003	24 scenes	Land cover / Land use	LANDSAT
Topographic Maps	1:250,000	1973-1995	34 maps	Village locations	Survey-General Zimbabwe
Woody cover map	Analogue map (Printed version) 1:1 000,000	1998	Countrywide	Woodland (Photointerpreation)	Zimbabwe Forestry Commission

Table 14: Data layers used for modelling population densities within the study area (source: author).

All data layers required pre-processing that included the standardised transformation into a common geodetic projection. A selection of significant data layers was processed in order to allow their input into the smart interpolation model.

The modelling procedure produced a weighting value for each pixel in the study area according to the relative probability of population numbers living within the pixel area. The weighting values permitted the redistribution of one population value per district to a number of grid cells within this district.

4.3.1 Pre-processing and information extraction

Pre-processing consisted of scanning maps, geo-coding all information layers in a common geodetic projection, and the conversion of the data into raster format. Zimbabwe is covered by two UTM zones, making standard UTM difficult to use. The national projection and the most common projection for mapping Zimbabwe as a whole country, is the

Transverse Mercator projection, based on the modified Clarke 1880 spheroid (MUGNIER 2003). Therefore, all the data were projected into this coordinate system. The projection of the satellite images was carried out after the classification in order to avoid information loss. After the projection, all vector layers were transferred into raster layers of 15 m pixel size, fitting with the panchromatic band of Landsat ETM. Information extraction was performed on scanned maps in order to extract the location of villages and on satellite images in order to produce a land cover map for the area.

4.3.2 Processing map data

The scanned topographic maps at a scale of 1:250,000 were processed in order to extract the location of small settlements. Villages and buildings such as schools and hospitals indicating the centres of settlements are represented within these maps as black dots and rectangles of slightly different size (see legend of Figure 20). A combination of feature recognition and image processing algorithms allowed for the extraction of these objects. Figure 20 shows the working step results for a cut-out of the study area, where mining symbols printed in the same colour as the village dots hampered the extraction procedure. Figure 20 a represents the scan of the original map. In a first process step black features of a defined size were identified within the scanned maps by applying the mathematical morphological methods of erosion and dilation, resulting in the production of a binary file (Figure 20 b). Following, the erroneously selected objects, such as fragments of black labelling, were separated based on their shape and shape / size combinations (Figure 20 c). Figure 20 d shows the final result superimposed on the original scanned map. This extraction process resulted in the identification of 6823 settlements within the whole study area.

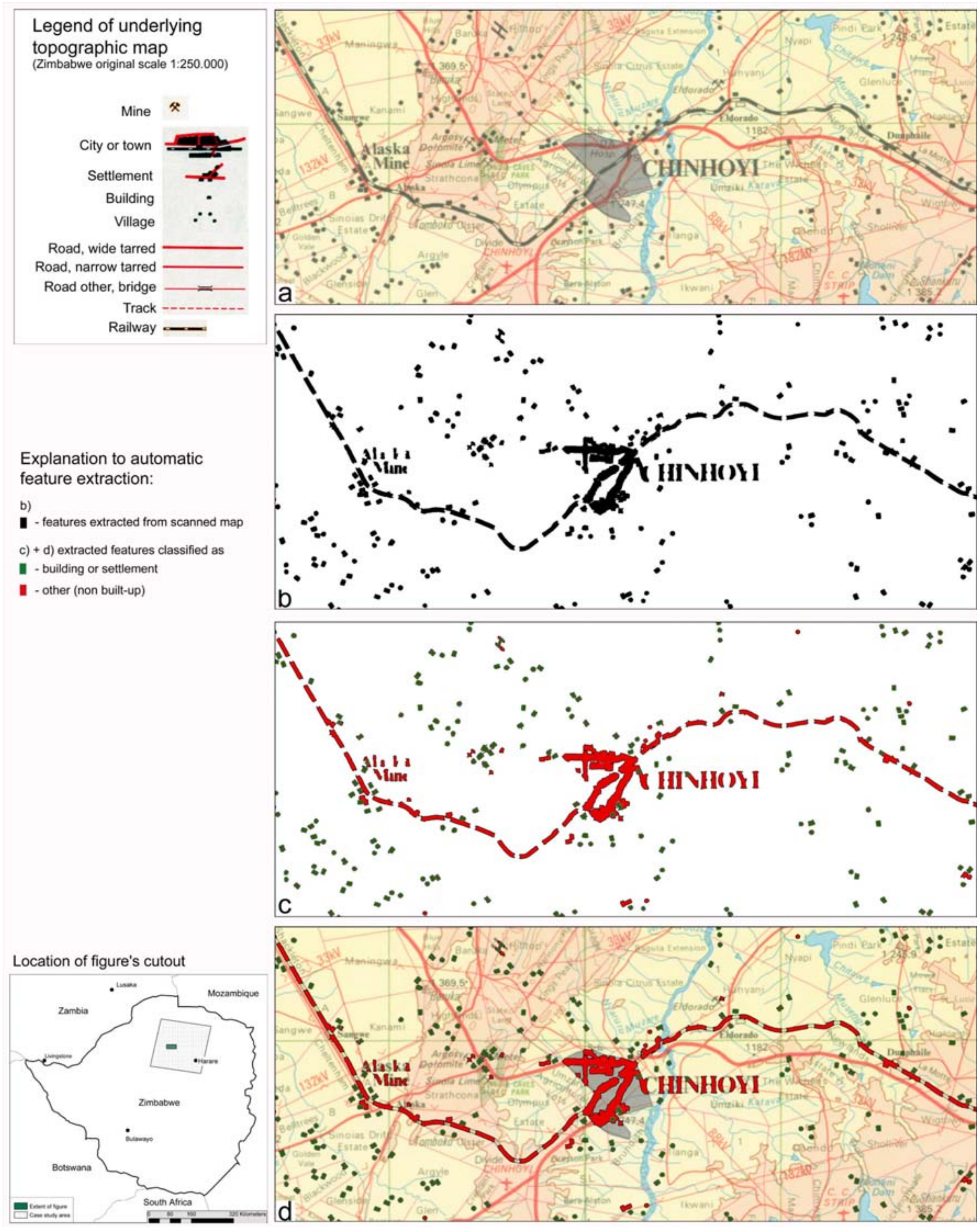


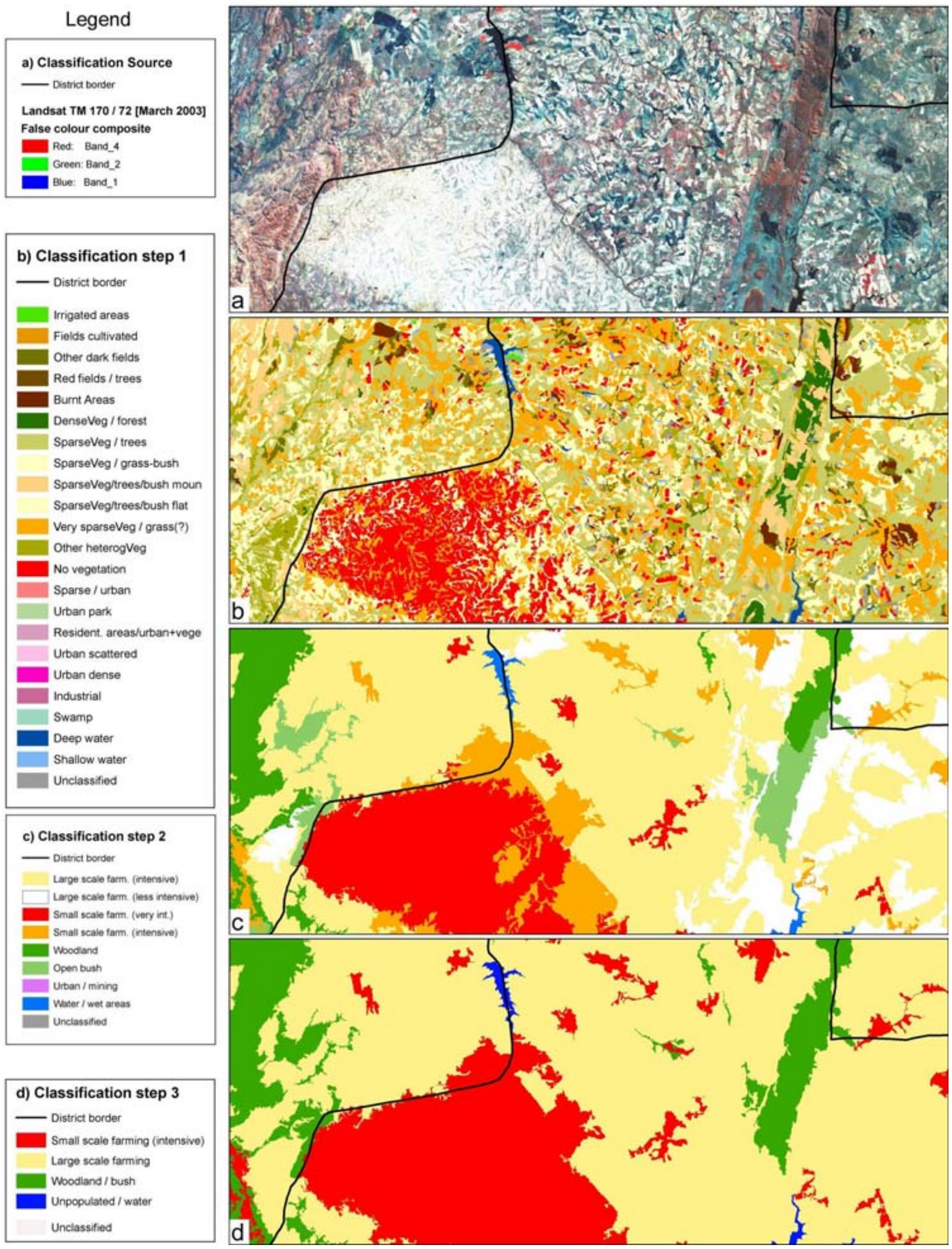
Figure 20: Processing stages of the extraction of human settlements from scanned maps

a: Original scanned map (top),
b: Features extracted from the map (second from top)
c: Classification of extracted features (second from bottom)
d: Classified extracted features superimposed on the original map (bottom)
(source: author).

4.3.3 Processing satellite imagery

Two Landsat ETM scenes were used in the scope of this work. The dry season image (Aug 03, 2002) was processed for the classification process, whilst the scene recorded at the end of the wet season (May 02, 2003) was selected for validation purposes. Four major land use classes were produced that included intensive small scale farming on communal land, large scale commercial farming, woodland, and land unsuitable for population. The classification process used object oriented image analysis tools available in the software package e-cognition of the company Definiens. The classification process was based on data from the Landsat ETM multi spectral band with 30m and the panchromatic band 8 at 15m resolution (Figure 21a). The NDVI calculated from the TM band 4 and TM band 3 was used as an additional band. The image was first segmented at two different levels. The first level was used to identify relatively small objects of similar spectral characteristics such as large fields in commercial farm areas (Figure 21b). Typical feature characteristics for object differentiation are shape, mean reflection values in a certain band or their standard deviations. The second segmentation level was used to identify larger regions with similar general land cover patterns (Figure 21c). Each object at this level included a number of sub-objects stemming from the first segmentation level. The differentiation process at level 2 is predominantly based on the type and characteristics of the sub-objects included, combined with the sum of the area covered by sub-objects of the same class. The classification procedure required frequent verification and supervision supported by the Landsat image of the wet season and the woody classification map. 23 land cover classes based on segmentation level 1 were identified, which were converted into eight land use classes derived from segmentation level 2. For integration into the model these eight classes needed to be aggregated resulting in four final land use types (Figure 21d).

The results of the satellite image classification are very satisfactory. The spatial and spectral resolution of the TM Landsat scenes is sufficient for a division into main land cover classes. The quality of the analysis was significantly increased by the additional available scene and geo-datasets. The allocation of land use classes to classified groups of pixels relied on local and expert knowledge in particular regarding the main variances in population densities that exist between intensive small scale subsistence agriculture, large scale commercial farming, bush and woodland, and non-populated areas.



a: Original Landsat image

b: Level 1 segmentation resulting in 23 classes

c: Level 2 segmentation and aggregation of level 1 into eight classes

d: Aggregation of classification results into four classes for integration into the model

Figure 21: Landsat imagery classification, extract of study area including commercial farms and communal land (source: author)

4.3.4 Geo-processing

Geo-processing consisted of geometric correction and in some cases merging the input layers into information layers to be used in the smart interpolation modelling exercise. Four final input layers were derived comprising land use, human settlements, road network, and slope classes.

Land use

The classification of different land use types is based on medium resolution satellite imagery (Landsat ETM) of the dry season in 2002, enhanced by ancillary information stemming from medium satellite imagery from the end of the wet season in 2003 (Landsat ETM), a woody cover map from 1998 and the GLC2000[11]. The classification of the study area resulted in four main rural land use classes, each accounting for a specific average population density:

(1) intensive subsistence small scale farming, which is the predominant use of communal land,
(2) large scale commercial farming,
(3) bush and woodland not (recently) used for agricultural purposes and
(4) areas not suitable for human settlements.

Human settlements

The human settlements layer merged information from three data sources that have been allocated to four hierarchy levels:

(1) A polygon vector file - that includes the eight most important Zimbabwean urban areas. This layer provided information on the urban extent of the cities Harare and Chitungwiza for the study area, classified as hierarchy level 1.
(2) The settlements from the Digital Chart of the World (DCW), coded as point information and classified as level 2 when large or district capitals (only two present in the study area) and
(3) coded as level 3 when towns.
(4) Smaller settlements, typically villages that were not available from DCW, were derived from the 1:250,000 topographic maps and coded as level 4.

The settlements available as single pixel (level 2, 3 and 4) were buffered to produce an associated area corresponding in size to the relevant hierarchical level. Towns of level 2 were buffered with a 1500m radius, those of level 3 with 600m and the villages extracted from the map with 100m.

Road Network

Information on the road network is based on a dataset from the Humanitarian Information Centre of the UN in Zimbabwe, last updated in 2002. The roads were classified into two groups, primary and secondary roads. The class allocation was carried out by considering tarmac quality, which is included in the dataset, and level of road traffic. All roads missing attribute information were classified as secondary roads. The primary and secondary roads were buffered by 300m and 150m respectively, based on the assumption that population

[11] Global Land Cover 2000 database. European Commission, Joint Research Centre, 2003, http://www.gvm.jrc.it/glc2000 based on SPOT VEGETATION satellite images <viewed December 2006>.

density close to roads increases and the extension of the concerned area is correlated with road importance.

Slope

Slope information was calculated from the SRTM elevation dataset. This dataset is produced at 90 m resolution. For this study the CGIAR-CSI (Consortium for Spatial Information) SRTM data product was used on which a number of processing steps have been applied in order to represent the elevation values as continuous surfaces. The SRTM dataset served as the foundation for computing the slope, based on a 3 by 3 neighbourhood around each pixel. The results were divided into three classes of slopes with < 10 degree, 10 – 20 degree and > 20 degree. The resulting land use classification was available at 15m grid cells, corresponding to the resolution of 15m of the panchromatic band 8 of the Landsat ETM scene.

4.3.5 Smart interpolation

Modelling of the population density was carried out by allocating weighting factors to the pixels of each input layer by using GIS technology, according to a number of decision rules. The process of weight allocation is summarised in the decision tree diagram of Figure 22. The first rule relies on the land use class input layers. The weight 0 was allocated to all pixels within the land cover class representing areas unsuitable for hosting populations. All other pixels, unless they are in the vicinity of the buffered areas of roads or human settlements, were allocated weight 1 for bush and woodland, weight 2 for large scale farming and weight 8 for small scale intensive farming (see Figure 22).

In the second decision step, weighting values for all pixels lying within the defined vicinity of roads and human settlements were assigned. If the pixel was close to transport infrastructure, then it obtained the weight 5 or 20 respectively, according to whether the transport line crossed a wooded area or farm land. The weighting values allocated to pixels within or close to settlements depend on the hierarchy class of the settlement. Pixels associated with class 2 (small cities) and class 3 (towns) received a weighting of 60, while those related to class 1 (villages) received a weighting of 20[12]. All weights allocated to pixels concerning their vicinity to a road network and human settlements were overlaid and summed up.

The last decision rule took into account the interrelation between population density and terrain. It has been applied to all pixels lying within areas of a certain degree of slope. If the slope value is between 10 and 20 degrees the pixel weighting value was halved. If the slope was steeper than 20 degrees then it was halved again. After giving consideration to the degree of slope, each pixel received its final weighting value. For example, a pixel lying within the land use class 'large scale farming' in the vicinity of a road and close to a village, located on a slope of 13 degrees, would have received the value: (20 + 20) / 2 = 20.

Following this allocation procedure, the population counts at district level available from the Zimbabwean Census of 2002 were distributed according to the weighting value pw of each pixel according to Equation 8.

[12] Large cities corresponding to human settlements class 1 obtain a unique population density value that is based on the average population of the entire city. Population density estimations within cities require a different model.

(Equation 8)

$$pop\ (i,j)\ [D] = a_D * pw\ (i,j)$$

In Equation 8 pop(i,j) [D] is the number of estimated people living within the area of pixel (i,j) that is lying within district D, a_D is a constant, computed for district D, and pw (i,j) is the weighting factor of pixel (i,j) received from the model (Figure 22). The constant a_D is computed by dividing the overall population number of district D by the sum of the weighting values of all pixels within district (Equation 9).

(Equation 9)

$$a_D = \frac{pop\ [D]}{\sum \{pw(i,j)\ \forall\ (i,j) \in [D]\}}$$

In Equation 9 pop [D] is the census population of district D and pw (i,j) is the weighting value of pixel (i,j). Hence, the sum of the estimated population values for all pixels within a district area is equal to the census value of the same district. For those districts of which only part of the area is overlapping with the study area the population figure considered in the model (pop [D]) was computed according to the proportion of the area lying within the study area, assuming a homogeneous population distribution.

Following the modelling process, the pixels were aggregated to a raster layer with 150m resolution. A lowpass filter was applied to smooth differences between adjacent pixel values.

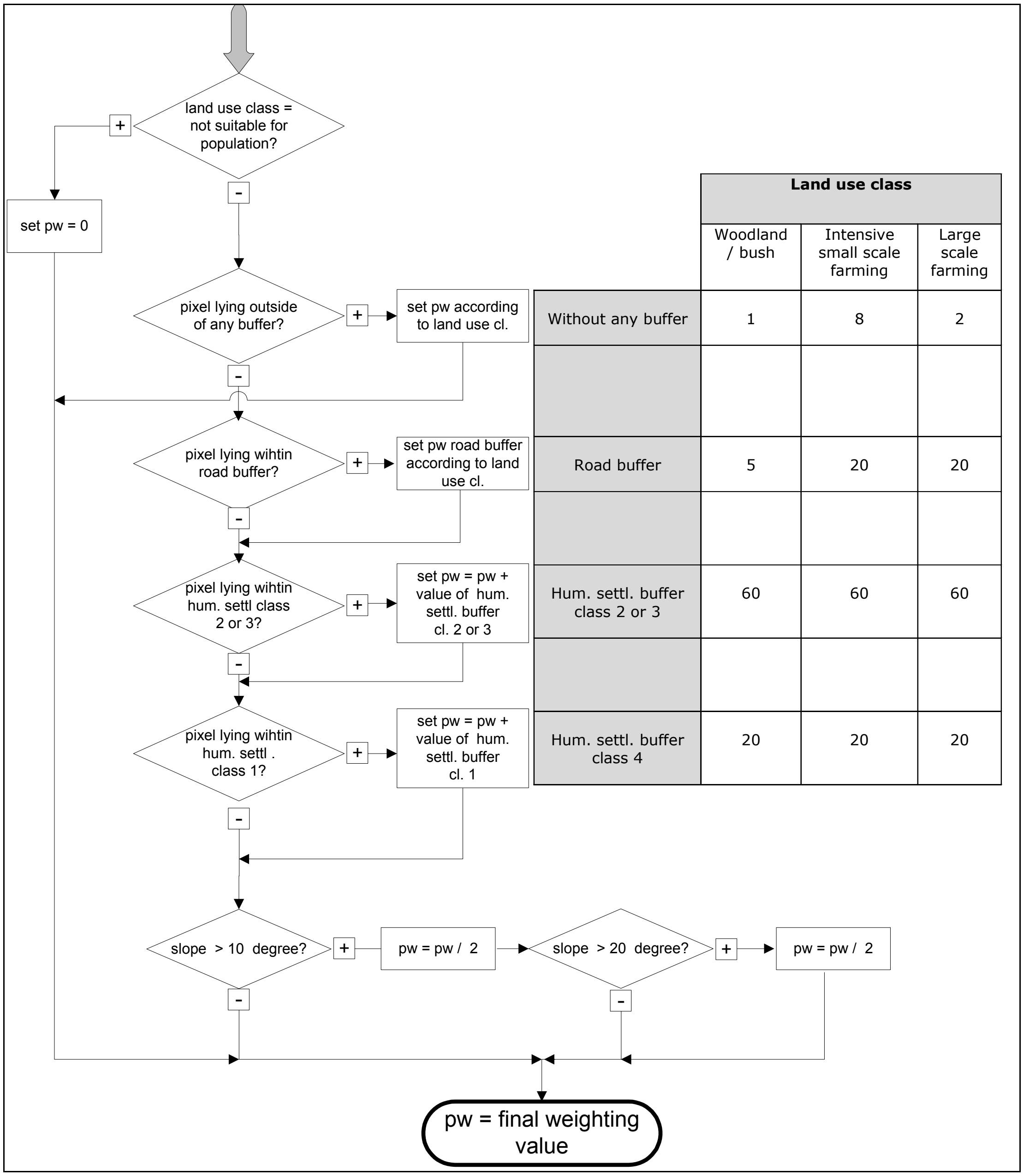


Figure 22: Decision tree diagram used to assign weighting values to pixels (pw) (source: author)

4.4 Results and Discussion

The resulting population density estimation for a part of the study area is shown in Figure 23 as original dataset and after lowpass filtering. The figure also shows the equivalent area as a choropleth map representing population counts at district level, and as the Landscan 2002 population dataset. Pixel in yellow represent low and red pixel represent high population densities values. The figure highlights the advantage of having population densities in grid format and at finer resolution. The choropleth map provides single counts for large areas, thus averaging areas with high and low population densities. Landscan inevitably provides coarse results. The outcome of the population modelling exercise at the fine resolution of 150 m reflects typical population density patterns in Zimbabwe, for example communal land with high densities and commercial farm land with low population densities.

Combining different sources of input data to provide weighting for population assessment is an empirical and error prone exercise. The input datasets are of different quality and the errors accumulate when merging the dataset. Errors introduced into the model applied for this study can be linked with a number of sources. First, the location accuracy of human settlements within the DCW is probably low. The DCW are in fact derived from 1:1,000,000 maps. The quality of the topographic maps and the density of mapped villages vary with different years that they have been updated. The automatic dot detection allows for false hits and inevitably misses some villages. The location of some villages may also have changed since the production of the map.

Medium resolution Landsat imagery provides valuable information to identify land cover. The pixel size is in general sufficiently small for distinction to be made between fragmented communal land used intensively by subsistence agriculture and large scale commercial farm areas. The combination of satellite images recorded during dry and wet seasons assists in the identification of irrigation schemes and regions with little vegetation, thus accounting for areas with the likelihood of high population pressure.

The object oriented classification procedure proved effective and efficient in processing large datasets, such as a full Landsat ETM scene. The image segmentation at two different levels as a base for a land use classification of eight classes proved to be most appropriate and allowed a clear discrimination of the main Zimbabwean land use systems.

Additionally the ETM imagery with a 15m panchromatic band can be used to identify the spatial outline of larger towns. Densities within urban areas will have to be addressed with very high resolution imagery.

The global availability of the Landsat imagery makes it a unique dataset for use in population density studies in developing countries. In moist tropics however, the use of active sensors has to be considered in order to solve the problem of permanent cloud coverage.

The availability of a 90 meter resolution digital elevation model is critical for at least two reasons. It allows computation of the slope gradient, which is strongly correlated with population densities, and thus identifies areas that are not suitable for hosting any population. Also, population density may vary with the elevation. For example, in Zimbabwe, the highlands are favoured areas of settlement due to climate and geological conditions.

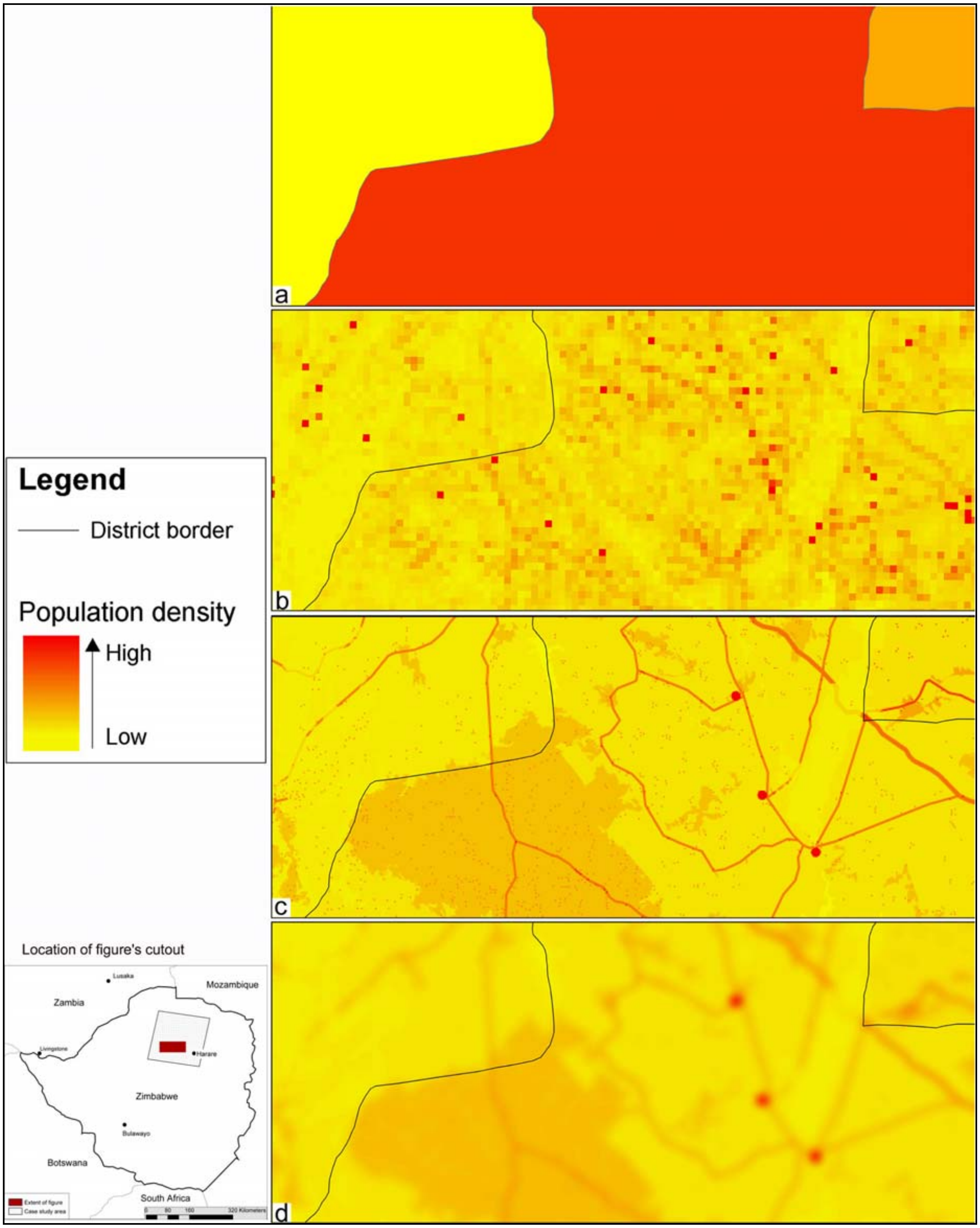


Figure 23: Results of population density model in comparison with other population data
a: Population distribution as choropleth map (top, source: Zimbabwe census data)
b: Population density as grid with 1 km resolution (second from top, source: Landscan)
c: Modelling result of this study with 150m grid resolution (second from bottom)
d: same as c but after lowpass filtering (c and d source: author).

Finally, the selection of weighting factors allocated in the modelling process is based on subjective local and expert knowledge. The modelling result, the final population density estimation, remains very difficult to evaluate. Research findings related to the creation of continuous population surfaces in developed countries are often cross-checked with small enumeration units (LANGFORD et al. 1991; EICHER & BREWER 2001). In Zimbabwe, population data for the smallest administrative unit, the 'ward', are available but they are often incorrect and the ward borders are continuously being changed for political reasons. An alternative method of evaluation could be to get the census' population counts before the data are aggregated into administrative units. This would require the cooperation of the relevant statistical institution and their willingness to provide the data for research purposes.

In most developing countries recent data about land use, infrastructure and population at fine scale are poor. The method applied for this study is a relatively quick way to extract information from and add value to datasets that are normally also available for developing countries. The methodology elaborated and the tools implemented are therefore of general importance for population density estimations at fine resolution in those countries. The results can feed into early warning or alert systems and support decision making in order to enhance disaster management and humanitarian aid activities. Finally, land use information and population data can also be linked to vulnerability and food insecurity. Therefore, mapping land use and population data is essential in order to come up with needs assessments in the case of drought or other disasters.

However, population distributions are determined by physical, socio-economic and historical factors that are country specific. Therefore, in order to be transferred to other countries, the modelling procedure needs to be adapted to case-specific characteristics, the determination of which requires a certain level of local / expert knowledge. In addition, passive sensors might not provide sufficient cloud free satellite data for regions lying within the moist tropics.