# EVALUATING THE POTENTIAL OF EARTH OBSERVATION FOR SUPPORTING SUSTAINABLE URBAN LAND USE PLANNING

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# DECLARATION

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# DECLARATION: PUBLICATIONS

| Chapter | Publications |
|---|---|
| Chapter 3 | Musakwa W and Van Niekerk A (2013). A review of earth observation applications in urban planning. |
| Chapter 5 | Musakwa W and Van Niekerk A (2013). Implications of land use change on the sustainability of urban centres: A case study of Stellenbosch, South Africa. *Cities*, http://dx.doi.org/10.1016/j.cities.2013.01.004, |
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| Chapter 7 | Musakwa W and Van Niekerk A (2013). Monitoring sustainable urban development using built-up area indicators. A case study of Stellenbosch, South Africa. *Computers Environment and Urban Systems*. Article in Review. |

The conceptual development, analysis, and write up of the above publications was completely accomplished by the author of this dissertation. My supervisor, Prof A Van Niekerk, provided direction and guidance throughout.

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# ABSTRACT

In many developing countries, rapid urbanisation continues to substantially transform land from agricultural and rural land uses, as well as natural landscapes into urban areas. This leads to significant changes to the socio-economic fabric and nature of the natural environment. Data to monitor such transformation is often out of date, unreliable, in unstandardised format, cumbersome and expensive to collect or simply unavailable in urban centres of many developing countries. These characteristics inhibit local authorities' and other stakeholders' capacity to monitor and leverage resources toward sustainable urban development. Sustainable urban land use planning is a major objective of urban planning, but it is difficult to put into practice. This study investigates the efficacy of earth observation (EO) for collecting information required for sustainable urban land use planning and proposes the use of decision consequence analysis (DCA) as a simple and structured way to put sustainable urban development into practice. The study focuses on three central determinants of sustainable urban land use, namely (1) land use change and land use mix, (2) urban sprawl and (3) the urban built-up area. Consequently, urban sustainability indicators of these three components were identified. EO data for Stellenbosch, a town in the Western Cape province of South Africa, was gathered and used to perform spatio-temporal analyses of the indicators in a geographic information system (GIS). This enabled the establishing of the positive or negative trajectory made toward achieving sustainable urban land use planning. The study demonstrates how the use of EO data, DCA, urban sustainability indicators and GIS can enhance local authorities' capacities for monitoring urban sustainability. EO data and urban sustainability indicators were used to develop an urban sustainability toolbox which facilitates evidence-based decision making. The results also show that urban sustainability indicators derived from EO are valuable in providing synoptic, up-to-date, standardised and normalised information on urban areas. Such information would be expensive and cumbersome to collect without the use of EO and GIS. As a result, earth observation will continue to play a key role in monitoring urban sustainability, particularly in developing countries.

**Keywords**: Built-up areas, decision consequence analysis, earth observation, geographic information system, indicators, sustainable land use, sustainable urban development, land use, urban sprawl

# OPSOMMING

Die volgehoue en versnelde verstedeliking wat in baie ontwikkelende lande voorkom is voortdurend besig om landbougrond, plattelandse gebiede en natuurlike landskappe na stedelike areas om te skakel. Dit bring ʼn noemenswaardige verandering in die sosiaal-ekonomiese struktuur en aard van die natuurlike omgewing te wee. Data om hierdie veranderinge te monitor, is dikwels verouderd, onbetroubaar, nie in ʼn standaard formaat nie, omslagtig, te duur om te in te samel of net eenvoudig nie beskikbaar vir baie stedelike sentra van ontwikkelende lande nie. Hierdie faktore beperk plaaslike owerhede en ander belanghebbendes se moniteringskapasiteit en verhinder die beskikbaarstelling van hulpbronne vir volhoubare stedelike ontwikkeling. Beplanning vir volhoubare stedelike grondgebruik is ʼn belanrike doelwit, maar is moeilik om in die praktyk toe te pas. Hierdie studie ondersoek die doeltreffendheid van aardwaarneming (AW) vir die insamel van inligting wat vir volhoubare grondgebruik beplanning nodig is. Die studie stel die gebruik van analise van besluitnemingsgevolge (ABG) as ʼn eenvoudige en gestruktureerde manier voor om volhoubare stedelike ontwikkeling in die praktyk toe te pas. Die ondersoek fokus op drie hoof bepalende faktore van volhoubare stedelike grondgebruik, naamlik (1) verandering en vermenging van grondgebruik, (2) stedelike kruip, en (3) die beboude stedelike gebied. Gevolglik is aanwysers van die stedelike volhoubaarheid van hierdie drie komponente geïdentifiseer. AW-data vir Stellenbosch, ‘n dorp in die Wes-Kaap provinsie van Suid-Afria, is ingesamel om met behulp van ʼn geografiese inligtingstelsel (GIS) die aanwysers tyd-ruimtelik te analiseer. Dit het dit moontlik gemaak om die positiewe of negatiewe trajekte vir die bereiking van volhoubare stedelike grondgebruiksbeplanning vas te stel. Die studie demonstreer hoe AW-data, ABG, aanwysers van stedelike volhoubaarheid en GIS plaaslike owerhede se kapasiteit vir die monitering van volhoubaarheid in stede kan bevorder. AW-data en stedelike volhoubaarheidsaanwysers is gebruik om ‘n stedelike volhoubaarheidsgereedskapkis te ontwikkel wat bewysgebaseerde besluitneming fasiliteer. Die resultate wys ook dat volhoubare stedelike aanwysers afgelei uit AW, nuttig is om sinoptiese, gestandardiseerde en genormaliseerde inligting oor stedelike gebiede te voorsien. Hierdie tipe inligting is duur en omslagtig om in te samel sonder die gebruik van AW en GIS. Gevolglik sal AW voortaan steeds ‘n sleutelrol speel in die monitering van stedelike volhoubaarheid, veral in ontwikellende lande.

**Sleutelwoorde:** Beboude gebiede, analise van besluitnemingsgevolge, aardwaarneming, geografiese inligtingstelsel, aanwysers, volhoubare grondgebruik, volhoubare stedelike ontwikkeling, grondgebruik, stedelike kruip

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# ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| ASTER | Advanced space-borne thermal emission and reflection radiometer |
| CBD | Central business district |
| CCRS | Canada Centre for Remote Sensing |
| CGA | Centre for Geographical Analysis |
| CIESIN | Center for International Earth Science Information Network |
| COT | Cluster outlier analysis |
| CUO | Cape Urban Observatory |
| CSIR | Council for Scientific and Industrial Research |
| CUrLUS | Canadian urban land use survey |
| DCA | Decision consequence analysis |
| DLR | German Aerospace Centre (des Deutschen Zentrums für Luft- und Raumfahrt) |
| DSM | Digital surface model |
| DSS | Decision support system |
| DTM | Digital terrain model |
| EB | Empirical Bayesian |
| EO | Earth observation |
| EO-1 | Earth observing mission satellite |
| ESDA | Exploratory spatial data analysis |
| ESKOM | Electricity Supply Commission |
| ESRI | Environmental Systems Research Institute |
| EU | European Union |
| FAO | Food and Agriculture Organization |
| FESLM | Framework for evaluating sustainable land management |
| GEOBIA | Geographic object-based image analysis |
| GHG | Greenhouse gasses |
| GME | Geospatial modelling environment |
| GIS | Geographic information system |
| GLUM | Global land use mix index |
| GNSS | Global navigation satellite systems |
| GOUNet | Global Urban Observatory Network |
| HDI | Human development index |

| | |
|---|---|
| HH | High-high |
| HL | High-low |
| IUCN | International Union for Conservation of Nature |
| LH | Low-high |
| LIDAR | Light detection ranging |
| LISA | Local indicator of spatial autorelation |
| LL | Low-low |
| LLUM | Local land use mix index |
| LUDB | Land use database |
| LUC | Land use change |
| LUF | Land use frequency |
| LWC | Leaf water content |
| MCDA | Multi-criteria decision analysis |
| MODIS | Moderate resolution imaging spectroradiometer |
| NAS | National Academy of Science |
| NASA | National Aeronautics and Space Administration |
| NASARDA | Nigerian National Space Research and Development Agency |
| nDSM | Normalised digital surface model |
| NDVI | Normalised difference vegetation index |
| NGO | Non-governmental organisation |
| NMT | Non-motorised transport |
| PSS | Planning support system |
| PROPOLIS | Planning and research of policies for land use and transport for increasing urban sustainability |
| PSIR | Pressure state impact response |
| PSR | Pressure state response |
| SA | South Africa |
| SANSA | South African National Space Agency |
| SBC | SPOT building count |
| SDSS | Spatial decision support system |
| SMURF | System for monitoring urban functionalities |
| SPOT | Système pour l'observation de la terre |
| STIAS | Stellenbosch Institute of Advanced Studies |

| | |
|---|---|
| SWMs | Spatial weight matrixes |
| UAV | Unmanned aerial vehicle |
| UHI | Urban heat island |
| UN | United Nations |
| UNDP | United Nations Development Programme |
| UNEP | United Nations Environment Programme |
| UNESCO | United Nations Educational, Scientific, Cultural Organization |
| UN-HABITAT | United Nations Human Settlements Programme |
| USA | United States of America |
| VMT | Vehicle miles travelled |
| WCED | World Commission on Environment and Development |
| WHO | World Health Organization |
| WSSD | World Summit on Sustainable Development |

# CHAPTER 1: FOSTERING SUSTAINABLE DEVELOPMENT IN A RAPIDLY URBANISING WORLD

Developing countries are experiencing unprecedented urbanisation rates, resulting in the growth of large cities and the associated problems of unemployment, urban poverty, inadequate healthcare, poor sanitation, urban slums, urban sprawl, unsuitable land use planning, traffic congestion and environmental degradation (Barredo & Demicheli 2003; UN 2012; UN-HABITAT 2009). Rapid urban growth often leads to unsustainable land use development, particularly when decision makers and managers lack the necessary capacities to leverage resources for implementing sustainable urban development policies (Hicken 2009; Klosterman 1995; Repetti, Soutter & Musy 2005; Taubenböck & Esch 2011). In this chapter the application of sustainable development in urban land use planning is critically overviewed. The chapter sets out the research problem statement, the aim and objectives, research methodology and agenda.

## 1.1 SUSTAINABLE DEVELOPMENT

The concept of sustainable development and its applicability has been widely discussed in the literature (Breheny & Batey 1992; Dur, Yigitcanlar & Bunker 2009; Nijkamp, Lasschuit & Soetmaan 1992; UN 2012). Sustainable development is a prescriptive concept on how to address the dilemma of advancing economic development, while protecting the environment and enriching the quality of life of human beings (WCED 1987). Sustainable development comprises ethical norms of welfare, distribution and democracy, while recognising that nature's ability to absorb human-made encroachments and pollution is limited (Seghezzo 2009; Sustainable Seattle 2010; WCED 1987). Sustainable development is primarily about ensuring that everybody, both in rich and poor countries, can have their basic needs met, today as well as tomorrow. This must be achieved in a way that does not jeopardise the natural systems on which life on earth is dependent (Ness 2001). Sustainable development therefore implies intergenerational and intragenerational equity (Breheny & Batty 1992). It has been repeatedly noted that the definition of sustainable development is abstract (Farrow & Winograd 2001; Rees 1992) but, despite its vagueness it is an appealing concept which has lead many countries to commit to fostering sustainable development. This commitment is evidenced by the Bruntland Commission (WCED 1987) and the follow-up 2000 World Summit on Sustainable Development in Johannesburg (UN 2000) as well as the 2012 Rio+20 held in Rio de Janeiro (UN 2012). The main obstacles experienced in implementing sustainable development policies are first, how the loosely-defined principles of sustainable development can be employed in setting up policies and projects, and second, how to gauge the efficiencies of these policies in terms of reaching the designated sustainability goals (Dur, Yigitcanlar & Bunker 2009; Ness 2001). The main challenge is to transform the principles of sustainable development into operational models (Halla, Kennedy & Adams 2005).

An associated challenge of sustainable development is the reconciliation of society's development goals with the planet's environmental limits over the long term (Clark & Dickson 2003). The coinage 'the theory and rhetoric practice gap' by Ness (2001) describes this predicament (Hall 2004). Consequently, the discipline of sustainability science which seeks to use science and technology to aid in achieving sustainability has emerged during the past two (1990s and 2000s) decades (Clark 2007; UN 2012). Sustainability science is problem-driven, with the goal of creating and applying knowledge in support of decision making for sustainable development. Sustainability science is grounded in the belief that for such knowledge to be truly useful, it generally needs to be 'coproduced' through close collaboration between scholars and practitioners (Clark 2007). This has prompted the development of programmes which integrate the use of technologies such as geographical information systems (GIS) (Wolf & Meyer 2010), spatial decision support systems (SDSS) (Volk et al. 2010) and planning support systems (PSS) (Moore 2008) to advance sustainable urban land use (Göcmen & Ventura 2010) for urban planning.

Sustainable land use is a notion generated from sustainable development (Sustainable Seattle 2010) and combines technologies, policies and activities that integrate socio-economic principles with environmental concerns to simultaneously maintain five goals, namely productivity, security, viability, acceptability and protection (Dumanski 1997). For a land use to be sustainable it has to sustain productivity which can take the form of industrial, commercial, residential or any other type of land use services (Cornforth 1999). Security implies reducing the level of production risks that may destabilise local relationships. For example, establishing a nuclear plant that produces radioactive waste can cause concern within nearby communities. Viability means that a particular land use has to be economically viable to survive, whereas acceptability means that a particular land use has to be embraced by society. Protection entails safeguarding the quantity as well as quality of soil and water resources for equitable use by future generations. There may be additional local conservation priorities such as the need to maintain genetic diversity or preserve individual plant or animal species. The competing interests amongst stakeholders make the achievement of these five goals of sustainable land use a complex task. A consequence of this complexity is that urban planners find it difficult to evaluate land use sustainability in urban areas, especially for large areas. In many land use sustainability evaluations, the area to be assessed has to be small enough to ensure that the physical, biological, economic and social influences are almost uniform (Dumanski 1997; FAO 1976, 1993). However, planners often require estimates of sustainability relating to larger areas such as cities or regions. Such estimates are generally based on selected, simplified conceptualisations of the more complex reality of cities (FAO 1995). These estimates are required for modelling sustainable development in cities.

## 1.2 MODELLING SUSTAINABLE DEVELOPMENT IN CITIES

Attempts have been made to address the complexity of evaluating sustainable land use in urban areas through the use of urban models. The first models date back to Von Thünen's classic agricultural model (Dumanski 1997; FAO 1993). Computer models have been used to assist in decisions relating to urban transportation, urban form and urban economics since the 1950s (Liu 2009). These models, however, had unsatisfactory explanatory outcomes as they focused on techniques and not the underlying theory of the urban forms that affect sustainable land use (Dur, Yigitcanlar & Bunker 2009; Liu 2009). Consequently, planners developed new approaches using disaggregated data in novel urban models such as choice models and cellular automata (Barredo & Demicheli 2003; Feng & Liu 2012). GIS, PSS and SDSS enable planners to easily implement and visualise models, hence spawning a growing interest in model development (Volk et al. 2010). Such models can be traced to the Food and Agricultural Organization's (FAO) framework for land evaluation (FAO 1976) which subsequently led to the development of the framework to evaluate sustainable land management (FESLM) (FAO 1993). The FAO has also been instrumental in the development of automated land use evaluation tools using GIS (Dumanski 1997). Among these are the land use data base (LUDB) and the agricultural land use correlation system (FAO 1999). However, because the FAO models are mainly designed and applied in rural contexts, there is a growing need for models that can deal with contested space in urban environments.

A number of studies have focused on the development of systems to support decisions relating to sustainable urban land use. One example is the Sustainable Seattle project that has led Seattle to be labelled the 'green and clean' city of the USA (Sustainable Seattle 2010). However, the developers suggested that biodiversity indicators can be improved by synthesising existing indicators through ongoing research. Another study, the Canadian urban land use survey (CUrLUS) used satellite remote sensing to monitor urban sustainability by quantifying transport-related energy sustainability indicators, e.g. density, urban compactness and urban land use mix (Guindon & Zhang 2005). While CUrLUS combines land cover, land and demographic as well as socio-economic information to estimate sustainability, Burton (2002) used urban compactness as an indicator of sustainability. It is clear from the literature that there is a lack of consensus on how urban sustainability indicators can be quantified and that there is a concomitant need to develop standardised methodological tools which can be used universally (Aneja et al. 2011; Burton 2002). To address this, the European Union (EU) embarked on the planning and research of policies for land use and transport for increasing urban sustainability (PROPOLIS) project to assess urban land use strategies and to demonstrate their effect on the sustainability of EU cities in seven regions. The PROPOLIS system is unique in that it not only monitors sustainability but also makes forecasts of sustainability (Spiekermann & Wegener 2003).

Many studies have focused on the development of dedicated SDSSs and PSSs for sustainable urban land use management (Keenan 2006). These systems include the development of scenario-based systems for finding alternative housing sites (Wolf & Meyer 2010), the What if? software (Klosterman 2008), sustainable settlement development using socio-ecological multicriteria decision analysis (MCDA) (Schetke, Haase & Kotter 2010), and a system for sustainable land use modelling (Renetzeder et al. 2010; Sattler et al. 2010; Wiggering et al. 2006). Other examples of such studies include Ludin & Yakup (2006), who employed GIS and decision support systems (DSS) software to select development alternatives based on a specific procedure, and Farrow & Winograd (2001) who developed a set of sustainability indicators for land use modelling to monitor land use sustainability and support decision-making on a regional scale.

Despite the numerous attempts to use SDSS and other technologies for solving urban sustainability problems, several aspects still need to be addressed. These include the improvement of knowledge acquisition methods; the development of protocols to elaborate, facilitate, share and reuse knowledge; and the integration of several sources of data and knowledge in such systems. Very few full-featured SDSSs and PSSs that employ MCDA have been developed, implemented and evaluated (Ascough et al. 2002; Poch et al. 2004; Repetti, Soutter & Musy 2005; Sattler et al. 2010). The growing acceptance of graphical, user-friendly operating systems and software has paved the way for decision makers to play a more hands-on role in using SDSSs and PSSs. This trend is likely to continue and it will set the focus on the formulation of SDSSs and PSSs which are responsive to the needs of decision makers (Malczewski 2006; 1999).

The adoption of urban planning tools has been hampered in developing countries by shortages of resources, lack of skills and the low quality of available information (Repetti, Soutter & Musy 2005; Timmermans 2008). Timmermans (2008) argues that many of these geospatial systems are 'toy' enterprises developed as stand-alone projects not suited for real-world applications. The existing systems are, in many cases, too expensive to implement or too sophisticated to maintain (Göcmen & Ventura 2010). Many systems are suited for particular locations, so that they can only be applied in a specific setting, whereas the need is for place-independent models which can be applied universally (Moore 2008). In addition, a major constraint to implementing existing systems in developing counties is that they rely on data that is often not routinely collected by authorities (Brömmelstroet 2012). Planning tools are required which suit developing countries' needs, conventions and conditions (Klosterman 2001; UN-HABITAT 2009). In response to this need, a system for monitoring urban functionalities (SMURF) was developed and applied in Theis (Senegal) to support urban management and to provide expertise about land realities (Repetti, Soutter & Musy 2005). However, SMURF only facilitates participatory land management and is consequently not a comprehensive tool for assessing and supporting sustainable land use.

Earth observation (EO) has the potential to address many of the data-availability problems experienced in developing countries (Sherbinin et al. 2002). Through remote sensing, critical physical properties which are prohibitively expensive or impossible to obtain in situ can be described, classified and measured (Taubenböck & Esch 2011; Yuan 2008). EO data is also available at regular intervals and can be used to effectively monitor the high urbanisation rates and informal developments with which municipal records are often unable to keep pace (CIESIN 2009; Skidmore et al. 1997). Another important feature of EO is its capacity for routine, periodic and unobtrusive updating through common algorithms (Jensen & Cowen 1999; Miller & Small 2003; Patino & Duque 2012). This makes cross-country city comparisons possible and enables the development of methods for evaluating sustainable land use for cities in developing countries, which would be difficult if not impossible to do using existing municipal data sets (Gatrell & Jensen 2008; Skidmore et al. 1997; Toure et al. 2012).

The application of EO in urban planning shows promise as processing techniques shifted from pixel-based approaches to geographic object-based image analysis (GEOBIA). GEOBIA is well suited for urban areas because it allows the extraction of detail on urban structure such as size, shape and legend classes (Addink, Van Coillie & De Jong 2012). This ensures extensive information which enhances decision making (Addink et al. 2012; Hay & Castilla 2008). Storage of EO data has also improved with the shift from analogue to digital, culminating in the development of data warehouses which has increased the accessibility of such data for making decisions (Liu & Weng 2012). Nichol et al. (2007) point out that EO practitioners use a multitude of superlatives (multispectral, hyperspectral, GEOBIA), thus showing that EO is maturing and gaining importance in decision making, particularly for urban planning in a hyperchanging environment. Importantly, the focus of EO must shift from purely science-driven approaches to precisely defined user-orientated applications for monitoring urban sustainability. This shift must entail a move from data collection to information extraction applicable to day-to-day decision making.

EO has been applied in urban areas for land use and land cover classification (Dewan & Yamaguchi 2009; Erener 2012; Esch et al. 2010; Forster 1983; Guindon & Zhang 2005; Keita & Zhang 2010; NASA 2009; Stefanov, Ramsey & Christensen 2001); measuring attributes of the physical environment (Lai & Cheng 2010; Lo & Faber 1997; Vintrou et al. 2012); transportation studies (Jin & Davis 2005; Yuan et al. 2009); estimating population sizes (Almedia et al. 2011; Ural, Hussain & Shan 2011) and monitoring urban sprawl (Bhatta, Saraswati & Bandyopadhyay 2010; Pozzi & Small 2002; Zhang 2003). Patino & Duque (2012) reviewed the applications of satellite remote sensing in urban areas with an emphasis on social problems, while Cowen & Jensen (1998) concentrated on the technical requirements of EO sensors for urban environments. Miller & Small (2003) evaluated the potential of EO in environmental research and policy. These studies testify that remote sensing has great potential to provide useful information, not available from other sources, to monitor sustainable land use, particularly in developing countries.

Three key issues of the application of EO data in urban planning emerge from literature. First, despite extensive research on land use and land cover classification, little research has been carried out on deriving measures of land use mix which are essential for monitoring urban land use sustainability (Guindon & Zhang 2005; Song & Rodriguez 2005). Second, more research on spatial statistics and metrics that goes beyond the urban extent is required for monitoring urban sprawl (Anselin 2012; Gerundo & Grimaldi 2011; Le Néchet 2011). Third, EO is crucial in updating or developing indicators for built-up areas, for monitoring sustainable land use planning and urban growth (Taubenböck & Esch 2011; Taubenböck et al. 2010). These key issues are critical in monitoring and achieving sustainable land use.

## 1.3 PROBLEM STATEMENT

The increasing rate of urbanisation, industrialisation, and population growth in developing countries over the last decade has forced society to consider whether human beings are changing the very conditions that are essential to life on earth (UN 2012; UN-HABITAT 2011). This disturbing trend has led to more calls on cities to advance sustainable land use to make cities and the world a better place to live in. Unfortunately, there is a deficiency of planning tools for monitoring and supporting decisions regarding sustainable urban land use in developing countries. Fortunately, EO has the potential to monitor and support decisions concerning sustainable land use planning because it offers a solution to the non-availability of data. However, research is required to determine which information is needed to support sustainable land use planning in the cities and towns of developing countries and whether such information can be successfully obtained through EO. The following research questions emerge from this problem statement:

1. What information is needed to support sustainable urban land use?
2. To what extent can such information and the underlying data be obtained through EO methods?
3. How can such EO based information be used to support decision making pertaining to sustainable urban land use planning in developing countries?

## 1.4 AIM AND OBJECTIVES

The aim of this research is to evaluate the potential of EO to model, monitor and inform sustainable urban land use, particularly for urban settlements in developing countries. The objectives are to:

1. Conduct a literature study to review the use of EO in urban planning.
2. Compile a list of indicators that can be used to model sustainable urban land use for developing countries.
3. Develop EO and GIS techniques for monitoring sustainable urban land use.
4. Demonstrate how the techniques can be applied in a case study of Stellenbosch.
5. Describe how the techniques can be used to support decision making.
6. Evaluate the potential of EO for monitoring and supporting sustainable urban land use planning in developing countries.

## 1.5 RESEARCH METHODOLOGY

A model-building approach was used in this study to develop and evaluate a procedural framework for sustainable urban land use planning in urban settlements. Consequently, the research followed a quantitative approach where spatial indicators of sustainable urban land use were applied. As highlighted in Section 1.1 sustainable development and sustainable land use planning are noble concepts but are difficult to put into practice to support day-to-day decision making. Accordingly, decision consequence analysis (DCA) (Hall WL 2010) was applied as a structured approach for developing a framework for evaluating sustainable land use in developing countries using EO and GIS analysis.

The research agenda is shown in Figure 1.1. The initial stage of the research involved problem identification and formulation as well as setting the aims and objectives (Chapter 1). The second step in the research was to conduct a literature review, which spans two chapters. Chapter 2 provides a brief background on sustainable development, the indicator frameworks of sustainable development and DCA. Chapter 3, reviews the application of EO in urban planning and concludes that more research is required on land use change and land use mix indicators, spatial statistics on urban sprawl and built-up area indicators that have a strong bearing on assessing sustainable urban land use. This sets the context for Chapter 4, which focuses on thematic selection and overall indicator development for evaluating the potential of EO in supporting sustainable urban land use planning. Data collection, preparation and analysis and the study area are also discussed in Chapter 4. The framework to develop an urban sustainability toolbox for evaluating the potential of EO in supporting sustainable urban land use planning is also discussed in Chapter 4.

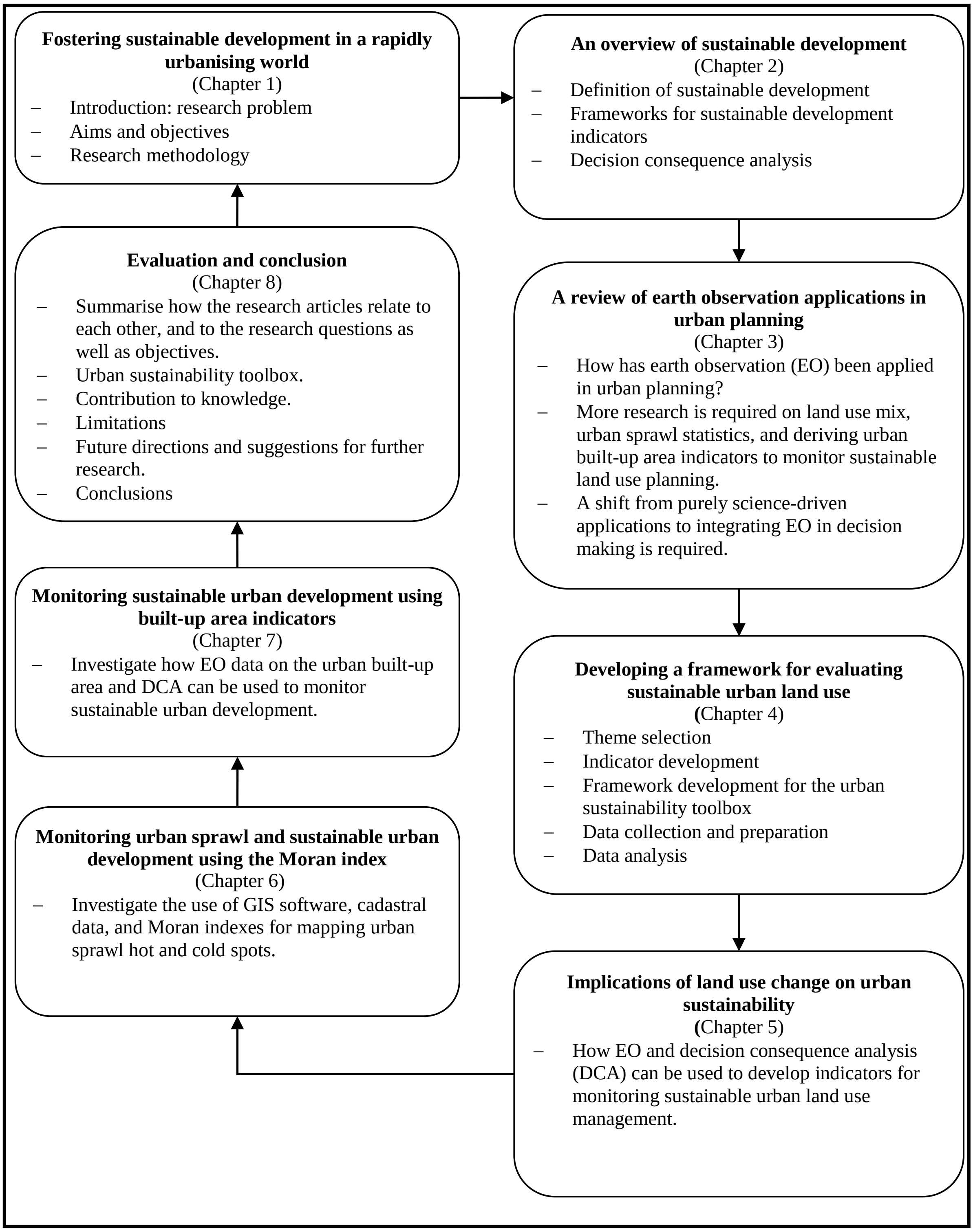



Figure 1.1: Research agenda for evaluating earth observation for supporting sustainable land use planning

Chapter 5 reports on how land use maps, derived through EO data and DCA, can be used to develop land use mix indicators for monitoring sustainable urban land use. Similarly, Chapter 6 describes the measuring of urban sprawl using spatial statistics (Moran indexes) to identify wasteful forms of urban sprawl which presage unsustainable urban land use management. Chapter 7 details how built-up area sustainability indicators derived from EO and DCA add value to sustainable land use planning. Chapter 8 synthesises and concludes the study by providing an application of the urban sustainability toolbox and comments on the study's contribution to knowledge, its limitations and makes recommendations on future research directions. The dissertation comprises eight chapters, four of which (Chapters 3, 5, 6 and 7) were prepared as articles for submission to peer-reviewed journals for publication.

## 1.6 STUDY AREA

Stellenbosch, a university town in the Western Cape province of South Africa, is located approximately 55 km east of Cape Town's CBD (Figure 1.2). The N1 and N2 freeways link Stellenbosch and Cape Town via R44. The town is located between latitude -33.9333° (33°55'59.88") South and longitude 18.8500° (18°51') East.

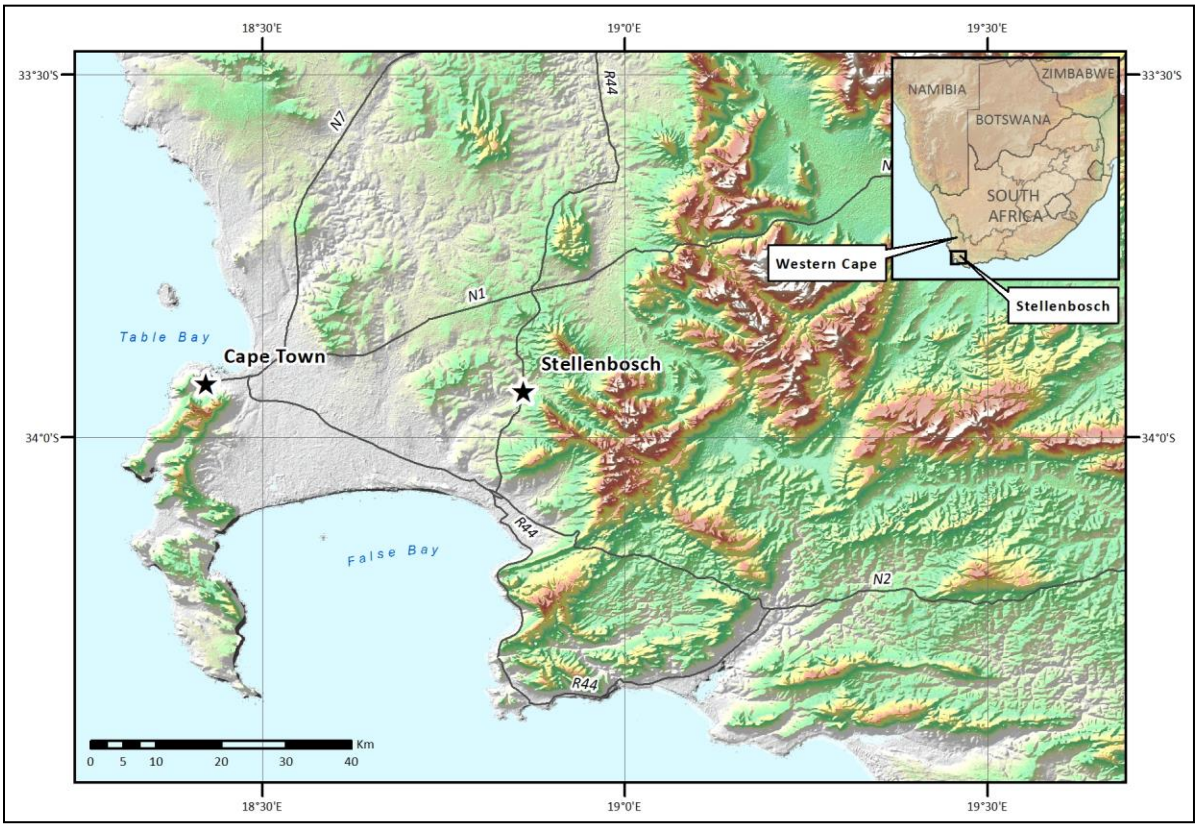



Figure 1.2 Location of Stellenbosch within the South-Western Cape

Stellenbosch is the second oldest town (after Cape Town) in South Africa. Stellenbosch was founded in 1669 and it quickly became an independent local authority in 1682. Stellenbosch is commonly referred to as the Eikestad (City of Oaks) due to its oak lined streets. The town is internationally renowned for its beautiful environment, many places of interest, wine farms, street cafes, restaurants and quality wines. Stellenbosch is also renowned for its various architectural types such as, Dutch, Georgian, and Victorian which reflects its heritage as well as divisive past. It is also the home of the world class Stellenbosch University and a strong business centre which include major South African corporations, technology start-ups, small enterprises and home businesses (Stellenbosch Municipality 2012).

The population of Stellenbosch increased from 60 000 in 2001 to 90 000 in 2010 at a mean annual growth rate of 8.5%. This growth was mainly due to in-migration (InterStudy 2009; SA Statistics 2001; Stellenbosch University 2010). In terms of ethnicity, the community is dominated by Coloureds (56.4%), followed by Whites (22.7%), Africans (20.6%) and Asians (0.22%) (Stellenbosch Municipality 2010). From 1996 to 2009, the White population increased by only 3% (with negative growth since 2005), while the number of Asians increased by 12%. The largest increase was seen in Africans (44%) over this period. Gender ratios are fairly even with 50.8% female and 49.2% male (Stellenbosch Municipality 2012).

As stipulated in the Municipal Systems Act, Stellenbosch like all local municipalities, is governed by a strategic plan called the Integrated Development Plan (IDP) (Stellenbosch Municipality 2010). The IDP sets out what the municipality aims to accomplish over a five-year period and how it will do this. It is a management tool that provides municipalities with a framework for strategic decision making. The IDP is developed in consultation with community stakeholders, as well as provincial and national governments. Essentially, the IDP outlines the general vision of a town or municipality. Stellenbosch’s vision is to become a world class university town which delivers excellent services to its community.

# CHAPTER 2: AN OVERVIEW OF SUSTAINABLE DEVELOPMENT

The notion of sustainable development has permeated almost every discipline. It is a guiding principle for many national, international and non-governmental organisations. Sustainable development now also guides urban land use planning. For nearly half a century, there have been conferences on and commitments to sustainable development. Various frameworks have been advanced to measure and simplify sustainable development. This chapter briefly outlines sustainable development, and indicator frameworks to measure sustainable development are discussed.

## 2.1 TIMELINE OF SUSTAINABLE DEVELOPMENT

Sustainable development is a process of exchange that allows current human needs to be satisfied without compromising the possibilities of future generations (WCED 1987). This is achieved through the use and conservation of the natural resource base, the maintenance and expansion of diverse social, technological and production options (UN-HABITAT 2011; Winograd 1995). Development implies progress or growth whereas the notion of sustainability implies capacity or viability (Winograd & Farrow 2007). The word sustain, and the derivate sustainability originates from the Latin *sustenere* which means to hold from below (Jacques, Dunlap & Freeman 2008). Sustain therefore means to maintain, to support or to endure (Becker 1997). The word sustainable has its contemporary meaning of maintaining an ecological balance rooted in the late nineteenth century in sustained forestry yields in Germany (Wheeler 2000).

Table 2.1 provides a timeline of sustainable development in contemporary literature. The term ‘sustainable’ first appeared in a human development context in 1972 in Meadows et al’s. (1972) book on the limits to growth. The term gained international recognition at the 1972 UN Conference on Human Environment in Stockholm (Becker 1997; Wheeler 2000). The Stockholm conference resulted in a strong environmental action-orientated approach to sustainable development with the needs of the developing nations getting less attention (De Wit & Verheye 2007). In 1980, another milestone was reached with the publication of the World Conservation Strategy, an initiative of the International Union for Conservation of Nature (IUCN), the Food and Agricultural Organization (FAO), the United Nations Environmental Programme (UNEP) and the United Nations Educational, Scientific, and

Cultural Organization (UNESCO) (Becker 1997). The strategy argued that development must be compatible with conservation. Another landmark is the 1987 publication of the World Commission on Environment and Development's *Our common future* which emphasised the present generation's responsibility to safeguard future generations' options and opportunities for development by protecting the planet's environment and natural resources (De Wit & Verheye 2007; WCED 1987; Wheeler 2000). This was followed by the 1992 Earth Summit on Environment and Development where the international community formally embraced sustainable development as the cornerstone of development objectives in both developed and developing nations (Breheny & Batey 1992; De Roo 2003; Gunder 2006; Freeman 2004; Halla, Kennedy & Adams 2005; Rees 1992; UN 2000). The summit culminated in Agenda 21, an action plan to achieve sustainable development. Agenda 21 also spotlighted the importance of land, both in rural and urban areas, in achieving sustainable development. The HABITAT Agenda II of 1996 concentrated on how to achieve sustainable cities in an urbanising world (UN-HABITAT 2011).

Table 2.1: Timeline of sustainable development

| **Conference** | **Year** | **Theme and focus** |
|---|---|---|
| UN Conference on Human Environment | 1972 | Environmental approach to sustainable development |
| World Conservation Strategy | 1980 | Emphasis on development having to be compatible with conservation strategies |
| World Commission on Environment and Development | 1987 | WCED is a major milestone where sustainable development is defined as development that does not jeopardise future generations' needs. Sustainable development has social, economic and environmental implications. |
| Earth Summit on Environment and Development | 1992 | Adoption of Agenda 21 |
| HABITAT Agenda II | 1996 | Sustainable cities and human settlements |
| Johannesburg Earth Summit | 2002 | Focus on implementation of old agreements through partnerships, rather than a new declaration |
| Rio+ 20 Summit | 2012 | Assessment of progress of previous commitments and garnering political support to achieve sustainable development. |

Sources: UN (2012); UN-HABITAT (2011)

At the Johannesburg World Summit on Sustainable Development (WSSD) in 2002, it was agreed that partnerships are an essential component in achieving sustainable development. Furthermore, the summit concluded that achieving sustainable development in developing countries is being hampered, inter alia, by insufficient investment and political instability (Sachs 2002). At the Rio+20 conference, a follow-up to the 1992 Earth Summit, the accent was on assessing progress with previous commitments and on securing political commitment to achieve sustainable development (UN 2012). There was also a recommitment to pay attention to the urban dimension of sustainable development. Cities were recognised as hubs of production, science, socialisation and commerce. The Rio+20 conference concluded that the challenges cities face can be overcome in ways that allow them to continue to thrive and grow, while improving resource use and reducing pollution and poverty.

Despite the various commitments made to achieving sustainable development in cities, little mention is made of targets, delivery dates and how sustainable development in cities can be measured and monitored. Despite a multiplicity of commitments and targets, the spatial element is also missing.

## 2.2 INDICATOR FRAMEWORKS FOR SUSTAINABLE DEVELOPMENT

Since the formulation of the Bruntland Commission’s abstract definition of sustainable development in 1987, various frameworks have been proposed for developing sustainability indicators. Indicator frameworks seek to translate natural and social science phenomena into manageable information units that can be used in decision making (Haberl & Schandl 1998; Jozsa & Brown 2005; Mannis 2002; Nathan & Reddy 2008; Opschoor & Reijnders 1991). These frameworks are important for communicating and measuring progress in sustainable development (Pinter, Hardi & Bartelmus 2005). Examples of such frameworks include the pressure state response model (Adriaanse 1993), the basic orientors model (Bossel 1999), barometer of sustainability (Prescott-Allen 1999), project-based training (World Bank 2008), problems and components (Sustainable Seattle 2010), and aggregate frameworks (Moldan & Billharz 1997; Wackernagel & Rees 1996). These frameworks are discussed in more detail in the following subsections.

### 2.2.1 The pressure state response model

The pressure state response (PSR) model organises information at a macro level by implying an overall causal progression of human activities that exert pressure on the environment and natural resources, leading to changes in the environment and society (Winograd & Farrow 2007). These changes prompt the generation of measures and actions to reduce their negative impacts (Adriaanse 1993). The PSR framework has been modified to the pressure state impact response (PSIR) which is used to define and organise a series of indicators in response to problems. The PSIR model identifies the impact of human activities on the environment and the impact of the environment on human activities. The PSIR and PSR models are simple and easy to use for defining and assessing performance indicators (Sustainable Seattle 2010). However, the frameworks assume linear cause-and-effect relationships which may not always be the case. Furthermore, depending on the context, how a problem is defined and considering judgement of the user, any given indicator can be considered an indicator of pressure, state or impact. This hinders the harmonisation and applicability of the decision-making model (Adriaanse 1993).

### 2.2.2 The basic orientors model

The basic orientors model takes a systems approach to sustainable development (Bossel 1999). This system consists of six orientors, namely: existence, effectiveness, freedom of action, security, adaptability and co-existence (Table 2.2).

Table 2.2: The basic orientors model

| Orientor | Definition | Indicators |
|---|---|---|
| Existence | The basic requirements for survival | Availability of shelter, clothing, food, water, sanitation and life expectancy |
| Effectiveness | The ability to use limited resources. | Work hours necessary for life support and efficiency of resource use |
| Freedom of action | The ability to cope with variations within one’s surroundings. | Income level, job opportunities, health and mobility |
| Security | The ability to withstand change. | Safe neighbourhood, savings, insurance and social security scheme |
| Adaptability | The ability to evolve. | Education and training, flexibility as well as cultural norms |
| Co-existence | The ability to survive and thrive among other competing and/or cooperating systems. | Social skills, compatibility of language and culture |

Source: Adapted from Bossel (1999)

Because orientors are not directly measurable, indicators for each orientor have to be identified. These indicators are used to evaluate the viability and performance of the human, support systems and natural systems of the orientors. The basic orientors model is useful because both assessment and performance indicators can be defined and used (Bossel 1999). Use of orientors is also valuable in describing and evaluating the development of ecosystems as well as determining the sustainability trajectory of the ecosystem. However, some of the orientors, such as co-existence, are difficult to define, measure and manage (Farrow &

Winograd 2001). Moreover, the basic orientors model is complex which makes it difficult to implement.

### 2.2.3 Barometer of sustainability

The barometer of sustainability employs a performance scale which assesses development as desirable, acceptable or unacceptable regarding human or ecosystem well-being (Prescott-Allen 1999). The barometer has two axes, one for human well-being, and the other for ecosystem well-being. Each axis is divided into five sections which rate overall sustainability as bad, poor, medium, ok and good. The intersection of the two axes (human and ecosystem well-being) provides an overall reading of the well-being and progress toward sustainability (Winograd & Farrow 2007). This enables users to obtain a clear overview of well-being and sustainability (IUCN 2002). The barometer also assists in drawing broad conclusions from an array of often confusing and contradictory signals. However, the barometer was mainly designed to rank countries and regions, thus limiting its use in spatial decision making. Because it is difficult to integrate the spatial dimensions, it impossible to explore geographical patterns (Prescott-Allen 1999).

### 2.2.4 Project-based framework

The project-based model is a simple pragmatic approach applied on a project-to-project basis (World Bank 2008). The project cycle is used as a framework for classifying variables as input, output, outcome and impact indicators (World Bank 1994; 2008). Input indicators monitor project-specific resources while output indicators measure the goods and services provided by the project. Outcome indicators measure the immediate short-term results of the project, whereas impact indicators monitor the long-term or more pervasive results of the project (Bartik & Bingham 1997; Rossi & Friedman 1990). While the project model attempts to distinguish between indicators, in many practical situations distinctions are unclear. The model is most useful in institutions that work on a project basis and its use is mainly confined to sectoral problems such as housing and access to water. In addition, the replicability of the model is often difficult (Bartik & Bingham 1997).

### 2.2.5 The problems and components model

Owing to the shortcomings of the frameworks described above, many researchers have developed pragmatic ways to define their own set of indicators according to specific problems and components that call for attention (Nathan & Reddy 2008; UNDP 2010, 2011;

World Bank 2008). The model identifies problems that are to be measured, for example. inadequate housing, and it defines a set of indicators. Although this approach is useful for assessing and monitoring development efforts, it often does not have defined goals and reference values. The model lacks a systematic conceptual framework and it usually reflects the orientation of experts and institutions (Farrow & Winograd 2001). As a result, sets of indicators may be detailed for some problems while being non-existent for others (Winograd & Farrow 2007)

**2.2.6 Aggregate models**

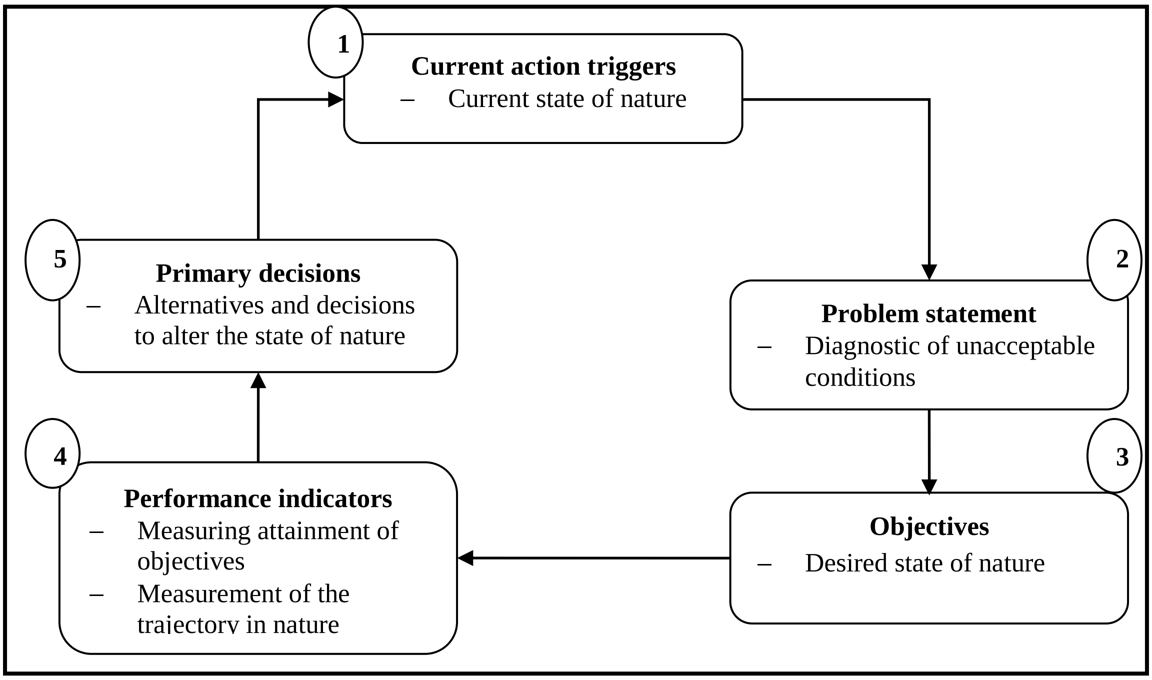
Aggregate models combine multiple indicators into one index to measure sustainable development. They are a cross-summation of various indicators. These include the index of sustainable welfare, the wealth of nations indicators (World Bank 1994), the human development index (HDI) (UNDP 2010; 2011) and the ecological footprint (Moldan & Billharz 1997; Wackernagel & Rees 1996). The index of sustainable welfare measures the portion of economic activity which delivers genuine increases in the quality of life (World Bank 1994). In contrast, the wealth of nations indicator provides country-level data on comprehensive wealth, adjusted net savings and non-renewable resource rents. Conversely, the HDI measures the average progress of a country or locality in achieving a long and healthy life, decent education and a decent standard of living (UNDP 2010). Meanwhile, the ecological footprint model "documents the extent to which human economies stay within the regenerative capacity of the biosphere" (Wackernagel & Rees 1996: 104). The ecological footprint is useful for determining the environmental impact of human activity at various scales (e.g. city, region, public company, NGO).

Aggregate models have serious deficiencies in scope, for example the HDI neglects the environment (UNDP 2011), while the ecological footprint does not take cognisance of the social aspects of development (Moldan & Billharz 1997). Aggregate models also do not explore meaningful relationships. Consequently, simple stand-alone indicators that better explore problems and relationships should be used. As a result, information pertaining to sustainability is best provided by the 'complete picture' as shown by the entire set of stand-alone indicators, not just by aggregates (Bossel 1999; Farrow & Winograd 2001). The use of separate indicators assists in showing various patterns and relationships that would be masked if one aggregate indicator were used. Moreover, decision makers or the public may not necessarily be interested in an aggregate or unable to fully comprehend aggregate indicators

(Winograd & Farrow 2007). This makes it necessary to provide information as separate indicators.

### 2.2.7 Decision consequence analysis

Sustainable development is a noble concept that is difficult to put into practice to support day-to-day decision making. Decision consequence analysis (DCA) (Hall WL 2010) is an emerging method which has been put forward as a structured approach and framework for developing sustainable development indicators. DCA formalises the decision-making process by using decision theory, probability and statistics (Hall WL 2010). The process breaks down complicated problems, such as sustainable development and sustainable land use, into increasingly smaller units until the particular component can be accurately analysed and understood within the context of the overall problem. DCA flows from 'triggers' that establish a set of conditions that create the need for decisions (Figure 2.1). Consequently, DCA identifies a network of actions that provide a balanced response to the triggers. To achieve a transition between the current action triggers and a desired state, data needs to be collected and indicators developed as well as analysed.




Source: Adapted from Hall WL (2010)

Figure 2.1: Elements of decision consequence analysis

The development of performance metrics or indicators in a DCA framework is fundamental. Indicators measure the degree of success or failure of a choice and guide the modification of alternatives and pathways for moving between two states. In DCA the indicators are scaled to replace traditional advocacy-based indicators which currently dominate the sustainability debate. The scaling of indicators can be either quantitative or qualitative and involves identifying threshold conditions that set conceptual boundaries of performance. Scaling and thresholds determine whether progress has been made toward achieving sustainable development.

DCA has been used in many applications. For instance, it has been used to solve traffic congestion in Atlanta, Georgia. High commuting times were identified as the action trigger while reduced traffic flow was the desired state (Hall WL 2010). To assess progress toward reaching the desired state, performance indicators (carbon emissions, travel time, traffic queues) where indentified and analysed. Analysis of this data influenced further decisions where various alternatives, such as construction of a new road and redirecting traffic, were formulated to solve the congestion problem. Similarly, DCA was applied to monitor greenhouse gas (GHG) emissions at Barksdale Air Force Base in the USA (Heilmann & Tillman 2010). The action trigger of the Barksdale study was to offset fund reductions in 2008 by developing a better understanding of natural infrastructure assets. The objective was to quantify GHG exchange at the base. To achieve this, land cover classification was done on satellite imagery to determine the spatial and temporal GHG flux variation at the base. A map was produced to facilitate decisions regarding carbon sequestration.

DCA is a useful approach to assessing sustainable development because it can be applied in qualitative, quantitative and spatial contexts. Moreover, it can be applied in various disciplines and settings. It is an objective process that replaces the ubiquitous advocacy-based frameworks which dominate the sustainability debate. Decision makers found DCA to be a useful method for putting the concept of sustainable development into practice in day-to-day decision making (Hall WL 2010; Heilmann & Tillman 2010). Though DCA is useful, it is not a simple, magic answer to the conundrum of sound sustainable decision making and policy formulation (Hall WL 2010). It is a “disciplined approach for identifying, acknowledging, and measuring uncertainty and for creating the opportunity for feedback mechanisms to function” (Hall WL 2010: 485). DCA offers an outline for capable decision makers at varying levels of technical competence in the relevant disciplines to align measures of success with core objectives (Heilmann & Tillman 2010). After decision makers implement this framework in developing, implementing and evaluating policy, they can help to create and encourage sustainable systems that function as intended.

This section discussed various indicator frameworks. However, it is how the indicators are analysed and presented which determines their practical use for decision-making.

## 2.3 INDICATOR ANALYSIS AND PRESENTATION

Sustainability indicators derived from the frameworks described in the previous section, can be analysed and displayed in various ways (Nathan & Reddy 2008). A major challenge is to translate these indicator frameworks into quantifiable measures (Guindon & Zhang 2007; Mannis 2002). This can be done by presenting indicators in formats such as tables and numerical and spatial data (Farrow & Winograd 2001; Winograd & Farrow 2007). Tables and numerical data are useful to show trends and trajectories of sustainability over time, for example tables showing the change in hectarage for particular land uses over a period of analysis. But, the presentation of indicators in tables and or as numerical data is not adequate because changes in sustainable development occur in both time and space. Land use change calls for spatial representations in the form of georeferenced maps which visualise the location of the changes. This enables decision makers, particularly planners, to identify problem areas where change is taking place and apply best practices. EO data analysed in a geographic information system facilitate spatial, quantitative and temporal analyses of sustainable development (Esch et al. 2010). Moreover, spatial analysis of sustainability indicators aids the discernment of the causes and consequences of development problems (Lo & Faber 1997). Graphical representations of the spatial heterogeneity and variability of territorial phenomena such as sustainable land use enhances information making it more comprehensible to a larger audience (Repetti & Desthieux 2006). The use of EO and GIS is consequently a logical response to the need for spatial indicators in urban planning.

## 2.4 SUMMARY AND CONCLUSION

The contemporary sustainable development discourse has its origins at the 1972 UN Conference on the Environment. The WCED’s definition of sustainable development in 1987 signifies the beginning of widespread adoption of sustainable development as a guiding principle in development efforts. The urban dimension of sustainable development started to gain momentum at the 1996 Habitat II conference. All these conferences, advocated sustainable development and its associated components (sustainable urban land use) as noble and worthwhile goals to pursue. Useful frameworks have been proposed for generating sustainable development indicators to measure and put sustainable development into practice for day-to-day decision making. DCA is useful in this respect because it integrates sustainable development into routine decision making. Sustainable development indicators can be presented in dimensions like numerical data and spatial data, the former to show temporal trends while the latter exposes locational changes. EO and GIS provide both numerical and spatial indicators of sustainable development, which explains why they have been applied in urban planning. Accordingly, the following chapter reviews how these technologies have been applied in urban planning

# CHAPTER 3: A REVIEW OF THE APPLICATION OF EARTH OBSERVATION FOR URBAN PLANNING

Musakwa, W and Van Niekerk, A. (2012). The application of earth observation for urban planning: Trends and future directions.

**Abstract**

Cities are constantly changing and city authorities face immense challenges in obtaining accurate and timely data to effectively manage urban areas. This is particularly problematic in the developing world where municipal records are often not updated or even available. Spaceborne earth observation (EO) has shown great potential for providing up-to-date spatial information about urban areas. This paper reviews the application of EO for supporting urban planning. In particular, the study overviews case studies where EO was used to derive products and indicators required by urban planners. The investigation found that EO is currently being used mainly for land cover mapping and building extraction, but that it is underused for deriving important urban indicators such as land use mix measures, urban sprawl statistics, impervious surfaces, population estimates and urban built-up area analysis. A shift from purely science-driven EO applications to the provision of useful information for day-to-day decision making and urban sustainability monitoring is clearly needed.

**Keywords:** Earth observation (EO), urban planning, sustainable urban development, rapid urbanisation

## 3.1 INTRODUCTION

Cities are places of industrial and economic growth as well as wealth creation (UNEP 2011). Cities are also places of poverty and inequality, often characterised by pollution and harm to the environment (UN-HABITAT 2009). These challenges hinder the achievement of sustainable development and the mitigation of climate change (Heldens, Esch and Taubenböck 2012). By 2030, cities in the southern hemisphere are expected to have more people living in their urban areas than in rural areas which will put pressure on the carrying capacity of cities (UN-HABITAT 2010; Taubenböck and Esch 2011). In many developing nations, urbanisation is largely a result of rural-urban migration (WCED 1987) often leading to poor urban planning characterised by poor governance (Klosterman 1995; 2001) and poor access to essential services (UN-HABITAT 2009). Cities are constantly changing, thereby exerting immense pressure on city managers to make urban areas more liveable. Local authorities have a responsibility to provide accurate and timely spatial information for the monitoring and management of urban areas (Nichol et al. 2007). The synoptic view of earth observation (EO) has been advocated as a solution for providing timely and accurate spatial data for monitoring cities (Hall 2010; Santos et al. 2011).

Patino and Duque (2012) reviewed the application of satellite remote sensing in regional science research in urban areas. They focussed on social problems with a spatial dimension, whereas Cowen and Jensen (1998) concentrated on the technical requirements of EO sensors for urban environments. Miller and Small (2003) paid attention to the potential of EO in environmental research and policy. These studies demonstrate the vast potential of EO in supporting urban research and policy development. Meanwhile, Hoalst-Pullen and Patterson (2011) emphasise that there is a disconnection between academic research on EO applications in urban planning and the actual adoption and use of remote sensing technologies as well as data by professional urban planners. This paper gives a general overview on EO applications in urban planning with the spotlight on urban sustainability. The potential of EO and its future directions in monitoring urban sustainability are also discussed.

## 3.2 HISTORY OF EO

Earth observation refers to the collection, processing, modelling and dissemination of data about the status as well as changes in the earth's natural and built environments (Kooistra 2012). EO gained importance due to the dramatic impact that modern human civilization is having on the earth, the need to minimise the negative impacts, and the opportunities EO provides to improve human well-being (Taubenböck and Esch 2011). Common EO instruments include remote sensing satellites, global positioning system (GPS) stations, cameras mounted on aeroplanes (Campbell 2011) and other in-situ measurements and instruments such as weather stations (Kooistra 2012). EO has its modern beginnings with the discovery of infrared light and photography in the early eighteenth century (Bayhan 2011). In the early 1800's, the first aerial photographs were taken from aeroplanes and this practice was taken further in World War I for military reconnaissance (Campbell 2011). In the 1960s and 1970s there was a shift from aerial photography to earth-orbiting satellites culminating in the launch of Landsat 1, the first earth-orbiting satellite specifically designed for the observation of the earth's surface land areas (Hall 2010). Subsequent EO satellites include Spot-1 (1986), IKONOS (1999), Quickbird (2001), SPOT-5 (2008), RapidEye and GeoEye (2008). Google's launch of Keyhole for Google Earth in 2005 sparked a geospatial revolution, significantly increasing the public's awareness of satellite imagery.

The proliferation of EO data has also been aided by improvements in image-processing techniques to extract useful information (Schaepman 2007; Whiteside, Boggs and Maier 2011). There are many methodologies for extracting information from images, including statistical, neural and fuzzy classifiers (Weng 2012). Processing techniques have also shifted from pixel-based approaches to geographic object-based image analysis (GEOBIA) (Hay and Castilla 2008; Addink, Van Coillie and De Jong 2012). Storage of EO data has changed from analogue to digital, culminating in the development of data warehouses that have increased public access to such data (Liu and Weng 2012). Nichol et al. (2007) point out that the practice of EO now has a multitude of superlatives (multispectral, hyperspectral, GEOBIA) showing that it is maturing and gaining importance and significance in decision making, particularly for planning in hyperchanging environments.

## 3.3 WHY APPLY EO?

EO data is increasingly being used in research owing to its advantages over in-situ data collection methods such as field surveys (Barr and Ford 2010; Vintrou et al. 2012). EO provides a unique synoptic view from space or air, thereby enabling scientists and planners alike to customise the spatial boundaries of their studies (Miller and Small 2003; Hall 2010). The Centre for International Earth Science Information Network (CIESIN) maintains that EO uses a common algorithm, resulting in consistent and objective data (CIESIN 2010). This enables intercountry comparisons that would be difficult, if not impossible, with national or city data sets (Skidmore et al. 1997). Hence, it is possible to draw conclusions by comparing the same phenomena in different countries, cities, regions or even continents during the same period (Liu et al. 2012). Another feature of EO data is its capacity for routine, periodic and unobtrusive updating (Esch et al. 2010). Moreover, EO has the capability to describe, classify and measure critical physical properties that would be prohibitively expensive (Cowen and Jensen 1998), time-consuming (Sherbinin et al. 2010) or impossible to obtain in-situ or from aggregating other sources (Barr and Ford 2010). EO consequently provides a quick way of developing spatial databases (Miller and Small 2003). These distinctive characteristics of EO have led to the establishment of international research institutes such as CIESIN, the National Aeronautics and Space Administration (NASA) (CIESIN 2010), the German Aerospace Centre (Esch et al. 2010) and the Canada Centre for Remote Sensing (CCRS) (Guindon and Zhang 2005), among others, to advance the use of EO by identifying new urban remote sensing applications for policy development and management.

In most developing countries, municipal records are often unable to keep pace with the high rate of urbanisation and informal urban development (Repetti, Soutter and Musy 2005). EO not only provides a quick synoptic view of urban areas, but it allows planners to cross-check or complement other sources such as censuses or field surveys, thereby improving the validity and reliability of research results (Baud et al. 2010). This has increased the use of EO and related geographic information systems (GIS), spatial decision support systems (SDSS) and planning support systems (PSS) for urban planning (Klosterman 2008). EO data also makes these systems more effective through the provision of multitemporal data which enables manifold spatio-temporal analyses (Esch et al. 2010). Various independent layers of information can be derived from EO data, making it a one-stop source of data (Taubenböck and Esch 2011).

## 3.4 EO APPLICATIONS IN URBAN PLANNING

A search on Scopus (the largest database of peer-reviewed journal articles) revealed that the number of published items on EO and urban planning increased significantly over the past two decades. Figure 3.1 shows that between 2000 and 2005 this increase amounted to 500%. This is mainly attributable to recent technological advances that have made the high-resolution and very-high-resolution (VHR) imagery needed for urban monitoring (Weng 2012), commercially viable (Liu et al. 2012). This surge in publications also coincided with rapid urbanisation in developing countries (UN-HABITAT 2010) and the emergence of new methodologies and techniques (e.g. GEOBIA) which enable the extraction of better-quality data from VHR satellite imagery (Santos et al. 2011). It is clear that EO has emerged as a cost-effective way for supplying much-needed data for urban monitoring, climate change mitigation and disaster management (Heldens, Taubenböck and Esch 2012).

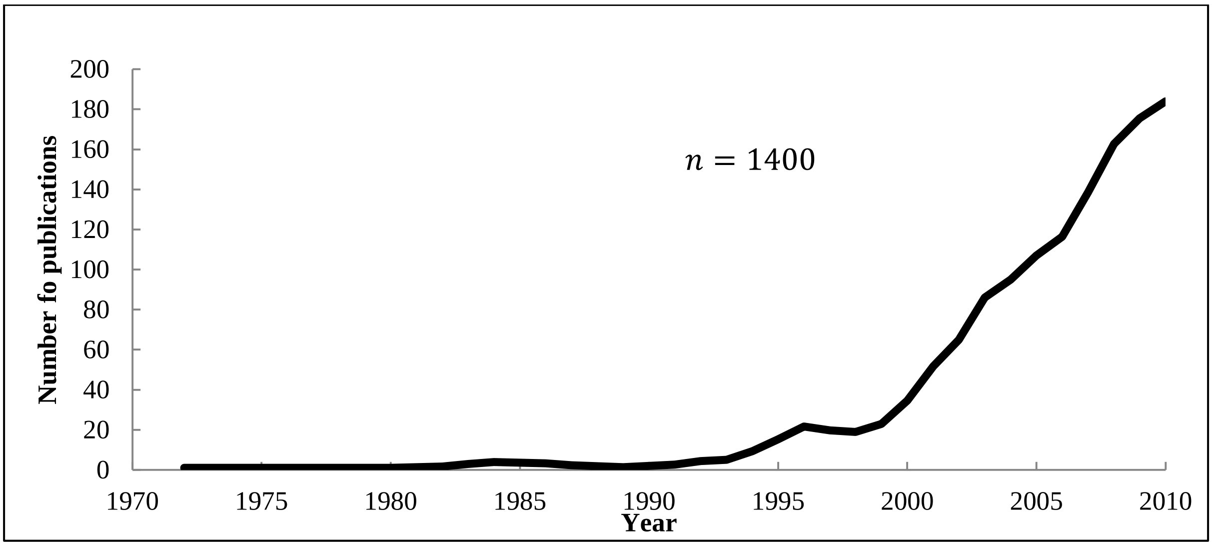



Figure 3.1: Annual publications on ‘earth observation’ or ‘remote sensing’ and ‘urban’ indexed in Scopus from 1972 to 2010. Search conducted on 5 August 2012.

The Scopus search also revealed that the application of EO has been dominated by earth and planetary sciences (25%), engineering (22%) and computer sciences (22%), while limited publications were found within environmental (6%) and social (9%) sciences. Most urban planning applications were in the latter domains. There is a well-documented gap between social science and EO application as a result of the imperfect coupling of EO and social data (Hall 2010). Esch et al. (2010) and Hall (2010) predict that, given the increased availability and quality of data, more use will be made of EO for urban planning in the future. Current applications of EO for urban planning are dominated by Asian (36%), North American (33%) and European (29%) counties with few applications in Africa (2%) where it is probably needed the most given the rapid rates of urbanisation (Figure 3.2).

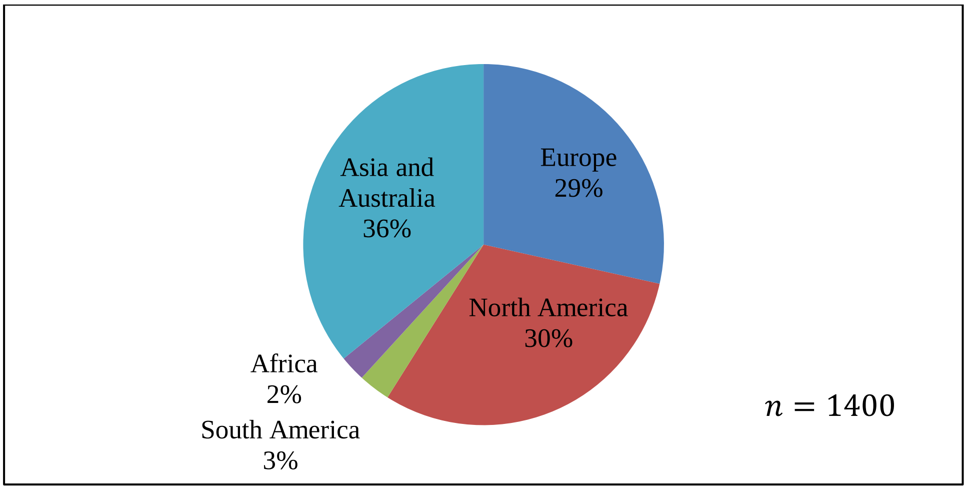



Figure 3.2: Percentage of publications related to earth observation indexed in Scopus from 1972 to 2010 by continent. Search conducted on 5 August 2012.

EO has been used in various aspects of urban monitoring. Examples include measuring physical properties, population, quality-of-life studies, analysis of land use cover change, buildings analysis, transportation studies and monitoring growth and urban sprawl. These applications are examined next.

### 3.4.1 Measurement of physical properties

EO has been applied in monitoring the urban environment by providing scientifically verifiable measurements of physical properties and their changes which are crucial to achieving sustainable urban development (CIESIN 2010). These include air quality (Zhang et al. 2008), vegetation cover studies (Mathieu, Freeman and Aryal 2007) and the impacts of urban structure on microclimate (Christensen 2010). Schwarz (2010) and Keramitsoglou et al. (2011) employed moderate resolution imaging spectroradiometer (MODIS) data to demonstrate the urban heat island effect, whereas Santana (2007) derived leaf water content (LWC) and surface temperature from Landsat data to aid sustainable landscape design. The

Landsat-derived normalised difference vegetation index (NDVI) was used by Weng, Lu and Schubring (2004) to measure vegetation abundance in urban areas. EO data for air-pollution studies is still very coarse (low resolution) and in many cases, it is unsuitable for detailed urban analyses (Nichol et al. 2007).

### 3.4.2 Population and quality of life studies

EO has been shown to be useful in population studies and for estimating population size between censuses (Almedia et al. 2011; Levin and Duke 2012). The latter is particularly helpful in countries with high rates of population growth and urbanisation or where censuses are infrequent (Baud et al., 2010). Such estimates are dependent on conditions such as knowledge of average household size and the availability of high-resolution spatial and multispectral imagery to differentiate informal building structures (Ural, Hussain and Shan 2011). EO is also applicable in quality-of-life studies (Toure et al. 2012). In Athens-Clarke County in Georgia, for example, a high NDVI obtained from Landsat data correlated positively with high income, whereas in Detroit a high NDVI strongly correlated with severe social decay (Lo and Faber 1997). When Toure et al. (2012) compared Kompsat imagery with income data, they found that access to water supply is closely related to income. Remote sensing can thus be used to identify and infer causal relationships which, in turn, aid decisions pertaining to sustainable urban development.

### 3.4.3 Land use and land cover classification

EO data has been extensively used for land use and land cover mapping in urban areas (Wang, Cheng and Chen 2011). Land cover refers to the physical surface of the earth, for example vegetation, soils and anthropogenic features such as buildings (CSIR 2010; Heldens, Esch and Taubenböck 2012). Conversely, land use is the human activity associated with land cover, such as residential or commercial use. Mapping of urban land use requires VHR imagery (Department of Rural Development and Land Reform 2009; Weng 2012). Land uses such as recreation, mixed uses, office space and community facilities are difficult to infer from land cover data and they require image interpretation and field visits to confirm classification efforts (Department of Rural Development and Land Reform 2009; CSIR 2010; Zhang, Zhang and Lin 2012).

Information on land use and land cover is required by planners for site selection, zoning regulation, resource allocation, monitoring the state of the environment and urban growth management (Cowen and Jensen 1998). Land use and land cover maps are important for monitoring sustainability trajectories as land use change and cover transition can be employed as sustainability indicators. For example, satellite images have been used to determine the rate of agricultural conversion in rural areas (Schneider, Friedl and Potere 2010) as well as the transformation of natural environments to urban uses (Yang et al. 2009). It has been demonstrated that high rates of land use and land cover change as a result of urban growth lead to increased motorised transport (Victoria Transport Policy Institute 2010), higher energy consumption (Urban Land Institute 2010), loss of agricultural land (Comber, Brunsdon and Green 2006), loss of biodiversity (Yang et al. 2009), and an increase in water pollution (Zhang, Wu and Shen 2011). These changes pose severe threats to the realisation of urban sustainability and can ultimately contribute to climate change (Renetzeder et al. 2010; Heldens, Esch and Taubenböck 2012).

Impervious surfaces, defined as anthropogenic features that water cannot infiltrate (e.g. rooftops and parking lots), have attracted increasing attention in planning literature (Weng 2012; Zhang, Zhang and Lin 2012). Impervious surfaces are increasingly being recognised as key indicators of land use sustainability (Santos et al. 2011), global environmental change and human-environment interaction (Schneider, Friedl and Potere 2010). Municipal authorities, researchers and non-governmental authorities often map impervious surfaces as a measure of urban sustainability and for assessing flood-risk vulnerability (Nichol et al. 2007; Schwarz, Lautenbach and Seppelt 2011). Various EO methods, including pixel-based (Whiteside, Boggs and Maier 2011), artificial neural networks (Taubenböck and Esch 2011), image fusion (Beger et al. 2011), expert systems (Weng 2012) and object-based classification methods (Doxani, Karantzalos and Strati 2012) have been used to map impervious surfaces from satellite imagery (Heldens, Esch and Taubenböck 2012). Qi et al. employed RADARSAT-2 polarimetric SAR (Synthetic Aperture Radar) data and observed that this data improved the accuracy of land cover and land use classification. These types of data and extraction techniques have opened new possibilities for the use of EO in urban planning.

Although land use and land cover classification have been extensively researched, there is a scarcity of research on deriving measures of land use mix (Song and Knaap 2004; Song and Rodriguez 2005; NEAT GIS Protocols 2010) from land use data. Guindon and Zhang (2005) and Zhang, Guindon and Sun (2010) have identified EO’s key role in urban sustainability studies because it is a vital source of land use data for obtaining measures of land use mix (Frank, Anderson and Schmid, 2004; Frank et al. 2006) which are integral to the monitoring of urban sustainability (Song and Rodriguez 2005; Frank, L. et al. 2010; Frank, L.D. et al. 2010; Urban Land Institute 2010; Victoria Transport Policy Institute 2010).

### 3.4.4 Analysis of urban built-up areas

Because buildings are an integral feature of urban areas, local authorities require area-wide and up-to-date inventories of buildings to monitor urbanisation (Wei, Zhao and Song 2004). EO data is a cost-and time-effective alternative to conventional methods for obtaining buildings data (Taubenböck et al. 2010) and it allows planners to monitor changes in the number (Mudau 2010), size and area (footprint) (Erener 2012), density, layout (Geiss et al. 2011), height (Wurm, Taubenböck and Roth. 2009) and volume (Taubenböck and Esch 2011) of buildings. Despite satellite imagery being valuable in developing a buildings and structures database, none of the existing extraction methods have been effective in all scenarios because there is no uniform approach (Santos et al. 2011). Extraction of buildings is a challenging task, even from VHR satellite imagery. This is due to building obstructions and the heterogeneity of features (Nichol et al. 2007). However, with the availability of LIDAR (light detection and ranging) data (Weng 2012), buildings can be extracted with better accuracy (Taubenböck and Esch 2011). Data fusion of LIDAR data and VHR satellite imagery has yielded better-quality information than using a single data source for urban monitoring. Beger et al. (2011) used LIDAR and orthorectified aerial photographs to automate railroad extraction while Wang, Zen and Lerhbass (2012) employed LIDAR data and aerial images to detect building footprints. Data fusion is indispensable because it is highly unlikely that one EO sensor can provide all the necessary information on urban centres.

### 3.4.5 Transportation studies

Motor vehicles are at the centre of the sustainability debate as they are major contributors to greenhouse gas (GHG) emissions (Urban Land Institute 2010). Studies on vehicle movement include traffic counts, parking availability, road conditions, congestion and road networks which are crucial to providing meaningful information (Cowen and Jensen 1998). EO can provide only limited information since most data on transportation, such as traffic counts, requires a very high temporal resolution (NAS 2003). LIDAR data is a possible solution as it provides information on traffic volumes, motor vehicle classifications and queue sizes (Schwach, Morris and Michalopoulos 2009). EO has been used to derive sustainable transportation indicators such as road network connectivity, transportation sustainability assessment based on Landsat data (Guindon and Zhang 2007) and the impacts of land use patterns on sustainable transportation (Urban Land Institute 2010; Victoria Transport Policy Institute 2010; Litman 2010).

Some studies have concentrated on semi-automated and automated techniques of extracting roads from satellite imagery. Nobrega, Hara and Quintanilha (2008) devised a semi-automated GEOBIA technique to satisfactorily extract road features in informal settlements in Sao Paulo, Brazil. Yuan et al. (2009) used a local excitatory global inhibitory oscillator network (LEGION) to automatically extract road networks from satellite imagery. Although various methods exist for extracting road networks, none are successful in a variety of contexts (Sobrino et al 2012). Multisource data fusion ably improves the classification of roads from satellite imagery (Jin and Davis 2005). Research on automated road extraction is urgently needed to save time spent on digitising roads.

### 3.4.6 Monitoring urban growth and sprawl

Urban sprawl often has adverse environmental and socio-economic effects like consumption of natural ecosystems by urban uses, increases in transport costs, as well as infrastructure costs (Le Néchet 2011). Local authorities find it difficult to monitor rapid urban changes. EO has become a vital source of data on urban growth because of its high temporal resolution. For example, Landsat images were applied in demarcating the urban boundaries of Orlando, Florida (Sims and Mesev 2011), while on a broader scale Schneider, Friedl and Potere (2010) used MODIS data to map the urban extents for 140 cities. Other studies applied high-resolution night-time light satellite imagery (Bruce and Townsend 2010) and the US Defence Meteorological Satellite Program’s operational linescan system (Sutton and Costanza 2002) to delineate urban extents. However, the use of night-time lights was found to overestimate urban areas due to overglow while underestimating such areas when there are power outages, a common occurrence in sub-Saharan Africa (Sutton and Costanza 2002).

Several other indicators addressing various aspects of urban morphology have been derived using EO. These include Shannon’s entropy (Kumar, Garg and Khare 2008), a shape and path index (Esch et al. 2010) and the degree-of-goodness of fit (Bhatta, Saraswati and Bandyopadhyay 2010) which were used to determine the direction, extent, pattern, rate and concentration of urban sprawl. It is clear from the literature (Anselin et al. 2000; Tsai 2005;

Gerundo and Grimaldi 2011; Le Néchet 2011; Anselin 2012) that more spatial metrics and statistics (such as Moran statistics) that capture various aspects and relationships of urban growth are needed for urban planning.

## 3.5 INTEGRATING EO INTO MONITORING URBAN SUSTAINABILITY

EO can supply much-needed data for urban planning, particularly in hyperchanging environments. To advance EO application in urban planning there is a need to move from purely science-driven approaches of extracting data to the provision of practical information for precisely defined urban sustainability applications which entail coordinated user needs for day-to-day decision making (Taubenböck and Esch 2011). Hoalst-Pullen and Patterson (2011) emphasise that there is a disconnection between academic research on EO applications in urban planning and the actual adoption and use of remote sensing technologies as well as data by professional urban planners. Consequently, cities must become laboratories where EO is applied in decision making and where information is shared, published and transferred to expand and improve the body of knowledge and ultimately to promote sound decision making.

Concerning the specific literature on ‘EO and urban sustainability’, a Scopus search returned only five items. A combined search (Scopus and Science Direct) revealed five key authors on the subject. Guindon and Zhang (2005; 2007) applied satellite remote sensing to survey transport-related sustainability indicators. Guindon and Zhang concluded that EO significantly improves sustainability assessments done on census data by providing spatial data on land use and land use mix, urban form as well as a historical perspective on spatial growth. Meanwhile, Esch et al. (2010) demonstrated that the increasing availability of EO data for a wide variety of applications can add value in urban sustainability studies. Similarly, the Moland approach demonstrated the capability of using EO techniques for producing comparable data series which can be used for various planning tasks and environmental impact assessments (Lavalle et al. 1998; 2001).

Only since 2000 has the application of EO to urban sustainability issues gained importance. This coincided with the Johannesburg World Summit on Sustainable Development in 2000 and the improved quality of data obtained from satellite imagery. Evidently, there is need for more research on obtaining urban sustainability indicators from EO and applying this in urban sustainability practice.

A few recent projects have specifically applied EO for monitoring urban sustainability. The German Aerospace Centre (DLR) is experimenting on obtaining urban sustainability indicators from EO data (Esch et al. 2010). DLR has developed concepts, methods and applications to support stakeholders in urban, regional and environmental planning with geoinformation productions derived from satellite remote sensing. For example, DLR has a global urban footprint map derived from radar data and the Urban Atlas in Europe, a large-scale monotemporal geodata set for use as an independent tool to monitor urban changes (Taubenböck and Esch 2011). Similary, the REFINA project in Germany has established the land consumption barometer, a set of sustainability indicators for evaluating sustainable urban development (Esch et al. 2010). The land barometer has a functional role in the identification of construction sites and vacant plots, and as a valuable information source for decision making. NASA is engaged in the 100 Cities Project aimed at producing urban remote sensing data sets for use by planners in making decisions regarding the environment, urbanisation and sustainability (CIESIN 2010; Center for Environmental Science Applications 2012). In developing countries where cities are being planned in hyperchanging environments, there is an even greater need for research on the application of EO in urban planning. The South African National Space Agency (SANSA) (SANSA, 2012), the Cape Urban Observatory (COU) and the Gauteng Region Observatory and UN-HABITAT's Global Urban Observatory Network (GOUNet) projects are examples of EO being used to add value to urban planning (UN-HABITAT 2010). GOUNet and COU aim to promote evidence-based decisions that respond to the increasing challenges faced by and opportunities offered by rapidly urbanising areas.

### 3.6 LIMITATIONS AND OUTLOOK FOR EO IN URBAN PLANNING

The past decade has witnessed significant progress in the application of EO in urban environments (Nichol et al. 2007; Weng 2012). Still, urban remote sensing is riddled with technical and non-technical limitations (Table 3.1). The non-technical limitations are financial constraints (Hoalst-Pullen and Patterson 2011), many inhibiting institutional, political, organisational and human factors, along with licence management issues (NAS 2003). Technical limitations include the spectral (Heiden et al. 2012), geometric (NAS 2003), textural (Klemas 2012) and contextual complexities (Miller and Small 2003) of urban areas which make it difficult to extract features. Weng (2012) points out a need to improve the temporal resolution required for urban mapping.

Table 3.1: Strengths and weaknesses of earth observation in urban planning

| Strengths | Weaknesses |
|---|---|
| Launch of more sensors resulting in increased data availability, a constant stream of data and reduction of costs. Moreover increased public awareness of remotely sensed data from platforms such as Google Earth and Bing Maps has increased use of remotely sensed data in decision making | Limited technological base as well as lack of trained personnel |
| Processing techniques of remotely sensed data and technological advances have vastly improved the geometric and thematic classification of urban areas. This has opened up new possibilities in urban planning applications. | High costs of data especially VHR images |
| Synoptic view and non-obtrusive nature of earth observation (EO) data would be difficult and cumbersome to obtain from other research methods. | A single satellite image or remotely sensed data source does not provide all the information |
| EO techniques allow for normalisation and standardisation of data, which enable comparisons, consistency, and reliability of results. | Licensing issues |
| Normalised and standardised EO indicators also enable transferability of the methodology and development of place-independent (universal) planning support systems or models. | Political, organisational and institutional constraints |
| Simple integration of EO data with a GIS enables interoperability. Moreover, multiple remotely sensed data sources can be fused which produces data rich in quality and information. | Spectral, geometric, textural and contextual complexities make it difficult to extract urban features. |
| EO data and GIS analysis enables spatial, visual, quantitative, and temporal analysis. This enables identification of 'hot spots' and 'cold spots' of critical importance to decision-making. | EO data often requires some ground truthing |
| EO-derived urban planning data can be used for other urban applications such as disaster management and population estimates for informal settlements. | |

Sources: Klosterman (2001); Göcmen and Ventura (2010); Heiden et al. (2012)

Many local governments have cited financial constraints as a hindrance to the adoption of remote sensing technology (Klosterman 2001). This is compounded by institutional, political and organisational factors (Göcmen and Ventura 2010). It has been noted that it often takes time to convince political structures, particularly in local government, to support the use of EO. However, it is hoped that the demonstrated capabilities of EO will reduce political and institutional intransigence. Licensing complicates the use of satellite imagery (NAS 2003) because when government agencies or practitioners purchase satellite imagery it comes with various licensing restrictions which may create confusion. This acts as a deterrent to use the data. The lack of trained personnel also limits the utility of EO (Aneja et al. 2011).

Despite these limitations, the future of urban remote sensing looks promising for a variety of reasons . The advent of LIDAR data, very high spatial resolution sensors (Ni 2011), EO data warehouses (Liu et al. 2012) and spaceborne hyperspectral images (Weng 2012) have extended the frontiers of urban remote sensing. This coincides with the emergence of advanced algorithms such as image fusion (Wang, Zen and Lerhbass 2012) to extract data from satellite imagery thus opening new possibilities for urban remote sensing applications like monitoring urban sustainability (Kumar and Misra 2007; Almedia et al. 2011).

Moreover, with the advent of publicly accessible EO data from Google Earth and Microsoft's Virtual Earth and Streetmaps, EO has become common and socialised thus reducing non-technical barriers to it. Furthermore, advances in technology, greater computational power and the integration of EO with GIS all bode well for expanded application of EO in urban planning (Drummond and French 2008). The launch of more sensors means the relative price of remote sensing data will continue to decline (Liu et al. 2012; Patino and Duque 2012). EO also allows for consistent unobtrusive updating of information (CIESIN 2010) which can be used for a wide variety of applications. Consequently, EO now provides unparalleled continuous, up-to-date, low-cost data collection for large areas of the globe. EO can also benefit from use of other in situ earth observations and other forms of remote sensing.

Other urban sustainability studies have demonstrated that in-situ observations using cellphone signals, streetmaps, crowd sourcing and social media as well as remote sensing using unmanned aerial vehicles (UAVs) or drones provide useful information to augment satellite imagery (Calabrese et al. 2011). Calabrese et al. (2011) have, for example, developed a system for real time monitoring of urban vehicular traffic and pedestrians using cellphone signals. Similarly, Bulatov et al (2011) used UAVs for developing geo-referenced three-dimensional urban terrain models. Data from UAVs and cellphone signals can enhance urban planners' knowledge on urban sustainability when used in conjunction with EO data.

Crowdsourcing, a mechanism for leveraging the collective intelligence of online users towards productive intelligence, has been applied in urban planning (Brabham 2009). For example, Studiolab (2012) developed Mobilecityscapes, a crowd sourcing mobile platform for knowledge on urban sustainability. Mobilecityscapes merges features from process-based urban design, locative media art, and spatial practice theory. It uses global positioning system (GPS) technology as a collaborative, participatory, and creative medium. Similarly, use of cellphone apps technology has increasingly influenced urban planning decisions particularly those relating to urban traffic. Use of cellphone apps facilitate provision of real time traffic information such as accident incidents, vehicle navigation and traffic flow. Google, Samsung, Ericson, and Apple are technology giants who have designed mobile apps that are GPS enabled to capture traffic data, and this has huge potential for use by planners (Tao et al. 2011). Similarly, the emergence of social media which encompass statistical and deliberative technologies including blogs, forums, wikis, open source software, social networking sites, media sharing sites, creative commons licensing, online polls, user-populated maps, and prediction markets (Planning Pool 2012) have an important role in the planning process. Social media enable public sharing and participation which can lead to new ideas on urban sustainability, for example through Facebook or Twitter. Consequently, urban planners have to embrace these new technologies as they have huge potential in facilitating the comprehension of urban changes and complexities.

## 3.7 CONCLUSION AND THE WAY FORWARD

In summary, the applications of EO in urban planning look promising given the availability of powerful techniques such as GEOBIA, data fusion and artificial neural networks  and new technologies such as mobile apps, crowd sourcing, social media and use of UAVs that have created new possibilities for urban applications. However, there is a disconnect between academic research on EO applications in urban planning and the actual adoption and use of remotely sensed technologies as well as data by professional urban planners. Therefore, there should be a shift from science-driven approaches to precisely defined user-orientated applications of EO for monitoring urban sustainability.

Although EO has been applied in various urban sustainability studies, three key issues emerge that require more research. First, despite extensive research on land use and land cover classification there is little research on deriving measures of land use mix, which are essential for monitoring urban sustainability. Second, more research on spatial statistics and metrics which go beyond the urban extent are required to monitor urban sprawl. Third, EO is crucial in updating or developing indicators for built-up areas that can be used to monitor sustainable land use planning and urban growth. It has been demonstrated that EO can play an important role in monitoring human-nature interaction as a result of rapid urbanisation.

## 3.8 REFERENCES

Addink, E.A., Van Coillie, F.M.B., and S.M. De Jong. 2012. " From Pixels to Geographic Objects in Remote Sensing Image Analysis." *International Journal of Applied Earth Observation and Geoinformation* 15:16.

Almedia, C.M., Oliveira, C.G., Rennó, C.D., and Q. Feitosa. 2011. "*Population Estimates in Informal Settlements Using Object-Based Image Analysis and 3D Modelling.*" In Articles, Earthzine Earth Observation, Urban Monitoring, edited by Racette, P.E. [Online]. Retrieved 5 May 2010, Available from: http://www.earthzine.org/themes-page/urban-monitoring/.

Aneja, S., Gross, C.P., Soulos, P.R., and J.B. Yu. 2011. "Geographical Information Systems: Applications and Limitations in Oncology Research." *Oncology* 25:12211225.

Angel, S. 2010. *Making Room for a Planet of Cities*. Boston: Lincoln Institute of Land Policy.

Anselin, L. 2012. "From SpaceStat to CyberGIS: Twenty Years of Spatial Data Analysis Software. " *International Regional Science Review* 35:131157.

Anselin, L., Cohen, J., Cook, D., Gorr, W., and G. Tita. 2000. "Spatial Analysis of Crime." [Online]. Retrieved 5 May 2012, Available from:https://www.ncjrs.gov/criminal_justice2000/vol_4/04e.pdf.

Aubrecht, C., Steinnocher, K., Hollaus, M., and W. Wagner. 2009. "Integrating Earth Observation and GIScience for High Resolution Spatial and Functional Modelling of Urban Land Use." *Computers, Environment and Urban Systems* 33:1525.

Barr, S., and A. Ford. 2010. "Integrating Urban Remote Sensing With GIS". In *Proceedings Comparative Genetics Cities Workshop*, 22 May 2010, 2836. University of California, Berkeley.

Baud, I., Kuffer, M., Pfeffer, K., Sliuzas, R., and S. Karuppannan. 2010. "Understanding Heterogeneity in Metropolitan India: The Added Value of Remote Sensing Data for Analyzing Sub-Standard Residential Areas." *International Journal of Applied Earth Observation and Geoinformation* 12:359374.

Bayhan, D. 2011. "History of Remote Sensing." [Online]. Retrieved 20 May 2012, Available from: web.itu.edu.tr/.../remote_sensing/History_DUYGU_BAYHAN.ppt.

Beger, R., Gedrange, C., Hecht, R., and M. Neubert. 2011. "Data Fusion of Extremely High Resolution Aerial Imagery and Lidar Data for Automated Railroad Centre Line Reconstruction." *Journal of Photogrammetry and Remote Sensing* 66:4051.

Bhatta, B., Saraswati, S., and D. Bandyopadhyay. 2010. "Quantifying the Degree of Freedom, Degree of Sprawl, and Degree -of-Goodness of Urban Growth from Remote Sensing Data." *Applied Geography* 30:96111.

Brabham, B.C. 2009. "Crowdsourcing The Public Participation Process For Planning Projects." *Planning Theory 8*0:248262.

Bruce, A.C., and D.A. Townsend. 2010. "The Use of Night-Time Lights Satellite Imagery as a Measure of Australia's Regional Electricity Consumption and Population Distribution." *International Journal of Remote Sensing* 31:44594480.

Bulatov, D., Solbrig, P., Gross, H., Wernerus. P., Repasi, E., and C. Heipke 2011. "Context-Based Urban Terrain Reconstruction from UAV-Videos For Geoinformation Applications." *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 22: 16

Calabrese F, Colonna, M., Lovisolo, .P, Parata, D., and C. Ratti 2011. "Real-Time Urban Monitoring Using Cell Phones: A Case Study in Rome." *Transactions on Intelligent Transport Systems* 12:145151.

Campbell J.B. 2011. *Introduction to Remote Sensing*. New York: Guilford Press.

Center for Environmental Science Applications. 2012. "100 Cities Project: Urban Systems." [Online]. Retrieved 18 May 2012, Available from:http://cesa.asu.edu/urban-systems/100-cities-project/.

Christensen, P. 2010. "New Opportunities for Urban Remote Sensing." [Online]. Retreived 18 May, 2012 Available from: http://cssa.asu.edu/sites/default/files/Phil%20Christensen%20Remote%20Sensing.pdf.

CIESIN. 2010. "Remote Sensing and the Social Sciences." [Online]. Centre for International Earth Science Network. Retrieved 6 May 2012, Available from: http://sedac.ciesin.columbia.edu/tg/guide_glue.jsp?rd=rs&ds=5

Comber, A., Brunsdon, C. and E. Green. 2006. "Using A GIS-Based Network Analysis to Determine Urban Greenspace Accessibility for Different Ethnic and Religious Groups." *Landscape and Urban Planning* 86:103114.

Cowen, D.J., and J.R. Jensen. 1998. "Extraction and Modelling of Urban Attributes Using Remote Sensing Technology." In *People and Pixels: Linking Remote Sensing and Social Science*, edited by Liverman, D., Moran, E.F., Rindfuss, R.R., and P.C Stern, 164188. Washington DC: National Academy of Sciences.

CSIR. 2010. *Land Cover Field Guide*. Pretoria: Council for Scientific and Industrial Research.

Department of Rural Development and land Reform. 2009. *Development of a Methodology for National Land Use Mapping for Chief Directorate: Geo Spatial Information*. Cape Town: Department of Rural Development and Land Reform.

Doxani, G., Karantzalos, K., and M.T Strati. 2012. "Monitoring Urban Changes Based on Scale-Space Filtering and Object-Oriented Classification." *International Journal of Applied Earth Observation and Geoinformation* 15:3848.

Drummond, W.J., and S.P French. 2008. "The Future of GIS in Planning: Converging Technologies and Diverging Interests." *Journal of the American Planning Association* 74:161174.

Erener, A. 2012. "Classification Method, Spectral Diversity, Band Combination and Accuracy Assessment Evaluation for Urban Feature Detection." *International Journal of Applied and Geoinformation*. Article in press.

Esch, T., Taubenböck, H., Heldens, H., Theil, M., Wrum, M., Geiss. C., and S. Dech, S. 2010. "Urban Remote Sensing-How Can EO Support Sustainable Development of Urban Environments?" In *Proceedings Cities for Everyone. Liveable, Healthy and Prosperous, Real Corp*, 18-20 May, 837847, Vienna.

Frank, L., Kerr, J., Rosenberg, D., and A. King. 2010. "Healthy Aging and Where You Live: Community Design Relationships With Physical Activity and Body Weight in Older Americans." *Journal of Physical Activity and Health* 7:8290.

Frank, L.D., Andersen, M. A., and T.I Schmid. 2004. "Obesity Relationships With Community Design, Physical Activity and Time Spent In Cars." *American Journal of Preventative Medicine* 27:8796.

Frank, L.D., Greenwald, M.J., Winkelman, S., Chapman, J., and S. Kavage. 2010. "Carbonless Footprints: Promoting Health and Climate Stabilization Through Active Transportation." *Preventive Medicine* 50:99105.

Frank, L.D., Sallis, J.F., Conway, T.L., Chapman, J.E., Saelens, B.E., and W. Bachman. 2006. "Many Pathways from Land Use to Health: Associations Between Neighbourhood Walkability and Active Transportation, Body Mass Index, and Air Quality." *Journal of the American Planning Association* 72:7587.

Geiss, C., Taubenböck, H., Wurm, M., Esch, T., Nast, M., Schillings, C., and T. Blaschke. 2011. "Remote Sensing-Based Characterisation of Settlement Structures for Assessing Local Potential of District Heat." *Remote Sensing* 3:14471471.

Gerundo, R., and M. Grimaldi. 2011. "The Measure of Land Consumption Caused by Urban Planning." *Procedia Engineering* 21:11521160.

Göcmen, Z.A., and S.J Ventura. 2010. "Barriers to GIS Use in Planning." *Journal of the American Planning Association* 76:172183.

Guindon, B., and Y. Zhang. 2005. "Using Satellite Remote Sensing to Survey Transport-Related Urban Sustainability: Part 1: Methodologies for Indicator Quantification." *International Journal of Applied Earth Observation* 8:149164.

Guindon, B., and Y. Zhang. 2007. "Using Satellite Remote Sensing to Survey Transport-Related Urban Sustainability: Part II: Results of A Canadian Urban Assessment." *International Journal of Applied Earth Observation* 9:276293.

Hall, O. 2010. "Remote Sensing in Social Science Research." *Open Remote Sensing Journal* 31:1631.

Hay, G. J., and G. Castilla. 2008. "Geographic Object-Based Image Analysis (GEOBIA): A New Name for a New Discipline." In *Lecture Notes in Geoinformation and Cartography*, edited by Blaschke, T. J., Lang, S., and G.J Hay: 7589. Berlin: Springer.

Haulst-Pullen, N., and M. Patterson. 2011. "Applications and Trends of remote Sensing in Proffesional Urban Planning." *Geography Compass* 5:249-269.

Heiden, U., Heldens, W., Roessner, S., Segl, K., Esch, T., and A. Mueller. 2012. "Urban Structure Type Characterization Using Hyperspectral Remote Sensing and Height Information." *Landscape and Urban Planning* 105:361375.

Heldens, W., Esch, T., and H. Taubenböck. 2012. "Climate Change in Cities – Can Remote Sensing Help to Optimise Mitigation Strategies?" In *Proceedings REAL CORP 2012:Re-Mixing the City – Towards Sustainability and Resilience*, 14-16 May, 2028. Schwechat, Austria.

Jin, X., and C.H Davis. 2005. "An Integrated Systems for Automatic Road Mapping From High-Resolution Multi-Spectral Satellite Imagery by Information Fusion." I*nformation Fusion* 6:257273.

Keramitsoglou, I., Kiranoudis, C.T., Ceriola, G., Weng, Q., and U. Rajasekar. 2011. "Identification and Analysis of Urban Surface Temperature Patterns in Greater Athens, Greece, Using MODIS Imagery." *Remote Sensing of Environment* 115:30803090.

Klemas, V. 2012. "Remote Sensing of Algal Blooms: An Overview with Case Studies." *Journal of Coastal Research* 28:3443.

Klosterman, R. E. 2008. "A New Tool for a New Planning: The What if? (Planning Support System)" In *Planning Support Systems for Cities and Regions*, edited by Brail, R.K, 8589. Cambridge, Massachusetts: Lincoln Institute of Land Policy.

Klosterman, R.E. 1995. "The Appropriateness of Geographic Information Systems for Regional Planning in the Developing World." *Computers, Environment and Urban Systems* 19:113.

Klosterman, R.E. 2001. "Urban Planning: Methods and Technologies." In *International Encyclopaedia of the Social and Behavioural Sciences*, edited by Smelser, N.J., and P.B.B. Baltes, 1605516058. Oxford: Pergamon.

Kooistra, L. 2012. "Accessibility of Earth Observation Data." [Online]. Retrieved 10 October 2012, Available from: http://www.geo-informatie.nl/courses/grs20306/course/Schedule/Accessibility-of-EO-data.pdf

Kumar, A.S.K. and T. Misra. 2007. "Sensors Technology for Earth Observation: An ISRO Perspective." [Online]. Retrieved 6 May 2012, Available from: http://www.iafastro.net/iac/archive/browse/IAC-07/B1/3/6904/.

Kumar, M.K., Garg, P.K., and D. Khare. 2008. "Monitoring and Modelling of Urban Sprawl Using Remote Sensing and GIS Techniques." *International Journal of Applied Earth Observation and Geoinformation* 10:2643.

Lavalle, C., Demicheli, L., Turchini, M., Casals-Carrasco, P., and M. Niederhuber. 2001. "Monitoring Megacities: The MURBANDY/MOLAND Approach." *Development in Practice* 11:350357.

Lavalle, C., Ehrlich, D., and A. Annoni. 1998. "Sustainable Urban Development: The MURBANDY Project of the Centre for Earth Observation (CEO)." *Geoscience and Remote Sensing Symposium Proceedings* 5:25712573.

Le Néchet, F. 2011. "Urban Spatial Structure, Daily Mobility and Energy Consumption: A Study of 34 European Cities." *CyberGeo* 2011:132.

Levin, N., and Y. Duke. 2012. "High Spatial Resolution Night-Time Light Images for Demographic and Socio-Economic Studies." *Remote Sensing of Environment* 119:110.

Litman, T. 2010. *Land Use Impacts on Transport: How Land Use Factors Affect Travel Behaviour*. Vancouver: Victoria Transport Policy Institute.

Liu, H., and Q. Weng. 2012. "Enhancing Temporal Resolution of Satellite Imagery for Public Health Studies: A Case Study of West Nile Virus Outbreak in Los Angeles In 2007." *Remote Sensing of Environment* 117: 5771.

Liu, S., Han, C., Wang, S. and Q. Luo. 2012. "Data Warehouse Design for Earth Observation Satellites." *Procedia Engineering* 29:38763882.

Lo, C.P., and B.J Faber. 1997. "Integration of Landsat Thematic Mapper and Census Data for Quality of Life Assessment." *Remote Sensing of the Environment* 60:143157.

Mathieu, R., Freeman, C., and J. Aryal. 2007. "Mapping Private Gardens in Urban Areas Using Object-Oriented Techniques and Very High-Resolution Satellite Imagery." *Landscape and Urban Planning* 81:179192.

Miller, R.B., and C. Small. 2003. "Cities from Space: Potential Applications of Remote Sensing in Urban Environmental Research and Policy." *European Planning Studies* 61:129137.

Mudau, N. 2010. "Spot Building Count Supporting Informed Decisions." *Position IT* 10:51-52.

NAS. 2003. *Using Remote Sensing in State and Local Government: Information for Management and Decision Making.*" Washington DC: National Academy of Sciences.

NEAT GIS Protocols. 2010. *Neighbourhood Environment for Active Transport-Geographic Information Systems Version 5.1.* New York: Design for Health.net, Cornell University.

Ni, L. 2011. "Object and Rule Based Approach for Classification of High Spatial Resolution Data over Urban Areas." *The International Society for Optical Engineering* 8203:82030-82038.

Nichol, J., King, B., Quattrochi, D., Dowman, I., Ehlers, M., and X. Ding. 2007. "EO for Urban Planning and Management: State of the Art and Recommendations for Applications in Urban Planning." *Photogrammetric Engineering and Remote Sensing* 73:973979.

Nobrega, R.A.A., Hara, C.G.O., and J.A. Quintanilha. (2008). "An Object-Based Approach to Detect Road Features for Informal Settlements near Sao Paulo, Brazil." In *Lecture Notes in Geoinformation and Cartography,* edited by Blaschke, T.H., Lang., S and G.J Hay, 589607. Berlin: Springer.

Patino J.E., and J.C. Duque. 2012. "A Review of Regional Science Applications of Satellite Remote Sensing in urban settings." *Computers, Environments and Urban Systems*. *Article* in Press.

Planning Pool, 2012. "Why mix urban planning and Social media. [Online]. Retrieved 10 October 2012, Available from http://planningpool.com/about/mix-urban-planning-social-media/.

Qi, Z., Yeh, A.G., Li, X., and Z. Lin. 2012. " A Novel Algorithm for Land Use and Land Cover Classification Using RADARSAT-2 Polarimetric SAR Data." *Remote Sensing of Environment* 118:2139.

Renetzeder, C., Schindler, S., Prinz, M.A., Mucher, C.A., and T. Wrbka. 2010. "Can We Measure Ecological Sustainability? Landscape Pattern as an Indicator for Naturalness and Land Use Intensity at Regional, National and European Level." *Ecological Indicators* 10:3948.

Repetti, A., Soutter, M., and A. Musy. 2005. "Introducing SMURF: A Software System for Monitoring Urban Functionalities." *Computers, Environment and Urban Systems* 30:687-707.

SANSA. 2012. "South African National Space Agency." [Online]. Retrieved 2 June 2012, Available from: http://www.sansa.org.za/.

Santana, L.M. 2007. "Landsat ETM+ Image Applications to Extract Information for Environmental Planning in a Colombian City." *International Journal of Remote Sensing* 28:42254242.

Santos, T., Freire, S., Tenedório, J.A., Fonseca, A., Afonso, N., Navarro, A., and F. Soares. 2011. "The Geosat Project: Using Remote Sensing to Keep Pace With Urban Dynamics."

In Articles, Earthzine Earth Observation, Urban Monitoring, edited by Racette, P.E. [Online]. Retrieved 5 May 2012, Available from: http://www.earthzine.org/themes-page/urban-monitoring/

Schaepman, M.E. 2007. "Spectrodirectional Remote Sensing: From Pixels to Processes." *International Journal of Applied Earth Observation and Geoinformation* 9:204223.

Schneider, A., Friedl, M.A., and D. Potere. 2010. "Mapping Global Urban Areas Using MODIS 500-M Data: New Methods And Datasets Based On 'Urban Ecoregions." *Remote Sensing of Environment* 114:17331746.

Schwach, J.A., Morris, T and P.G. Michalopoulos .2009. *Rapidly Deployable Low Cost Traffic Data and Video Collection Devices*. University of Minnesota: Center for Transportation Studies.

Schwarz, N. 2010. "Urban Form Revisited-Selecting Indicators for Characterising European Cities." *Landscape and Urban Planning* 96:2947.

Schwarz, N., Lautenbach, S., and R. Seppelt. 2011. "Exploring Indicators for Quantifying Surface Urban Heat Islands of European Cities with MODIS Land Surface Temperatures." *Remote Sensing of Environment* 115:31753186.

Sherbinin, A., Balk, D., Yager, K., Jaiteh, M., Pozzi, F., Giri, F., and A. Wannebo. 2002. "Social Science Applications of Remote Sensing". [Online]. Retrieved 5 May 2012 Available: http://sedac.ciesin.columbia.edu/tg/guide_glue.jsp?rd=rs&ds=1

Sims, S., and V. Mesev.2011. "Measuring Urban Sprawl and Compactness: Case study Orlando, USA". In *Proceedings of the 25th International Cartographic Conference,* 3-8 July, Paris, International Cartographic Association.

Skidmore, A.K., Bijker, W., Schmidt, K., and L. Kumar. 1997. "Use of remote Sensing and GIS for Sustainable Land Management." *ITC Journal* 3:302315.

Sobrino, J.A., Oltra-Carrió, R., Jiménez-Muñoz, J.C., Julien, Y., Sòria, G., Franch, B., and C. Matter. 2012. "Emissivity mapping over urban areas using a classification-based approach: Application to the Dual-use European Security IR Experiment (DESIREX)." *International Journal of Applied Earth Observation and Geoinformation* 18:141147.

Song, Y., and G.J Knaap. 2004. "Measuring Urban Form." *Journal of the American Planning Association* 70:210225.

Song, Y., and D.A Rodriguez. 2005. *The Measurement of the Level of Mixed Land Uses: A Synthetic Approach*. Chapel Hill: Carolina Transportation Program.

Stefanov, W., Netzband, M., and C.L. Redman. editors. 2007. *Applied Remote Sensing for Urban Planning, Governance, and Sustainability*. Berlin: Springer.

Studiolab, 2012. "Mobile Cityscapes: Crowdsourcing Knowledge For A Sustainable City." [Online]. Retrieved 5 May 2012 Available from:

http://community.studiolabproject.eu/group/mobile-cityscapes-crowdsourcing-knowledge-sustainable-city.

Sutton, P.C., and R. Costanza. 2002. "Global Estimates of Market and Non-Market Values Derived from Nighttime Satellite Imagery, Land Cover, and Ecosystem Service Valuation." *Ecological Economics* 41:509527.

Tao, S., Manolopaulos, V., Rodriguez, S., and A Rusu. 2011. "Real-Time Urban Traffic State Estimation with A-GPS Mobile Phones as Probes." *Journal of Transportation Technologies* 2012, 2:2231

Taubenböck, H., and T. Esch, T. 2011. "Remote Sensing-An Effective Data Source for Urban Monitoring." In Articles, Earthzine Earth Observation, Urban Monitoring, edited by Racette, P.E. [Online]. Retrieved 5 May 2010 Available http://www.earthzine.org/themes-page/urban-monitoring/

Taubenböck, H., Esch, T., Wurm, M., Roth, A., and S. Dech. 2010. "Object-Based Feature Extraction Using High Spatial Resolution Satellite Data of Urban Areas." *Journal of Spatial Science* 55:117132.

Toure, N.M., Kane, A., Noel, J.F., Turmine, V., Nedeff, V., and G. Lazar. 2012. "Water–Poverty Relationships in the Coastal Town of Mbour (Senegal): Relevance of GIS for Decision Support." *International Journal of Applied Earth Observation and Geoinformation* 14:3339.

Tsai Yu-Hsin. 2005. "Quantifying Urban Form: Compactness Versus Sprawl." *Urban Studies* 42:141161.

UNEP. 2011. "Making the Economic Case for Greening Cities." United Nations Environmental Program. [Online]. Retrieved 25 May 2012 Available: http://www.unep.org/newscentre/default.aspx?DocumentID=2656&ArticleID=8895

UN-HABITAT. 2010. *State of the World's Cities 2010/2011 Bridging the Urban Divide.* London: EarthScan.

UN-HABITAT. 2009."Habitat Partner University Network." United Nations Center For Human Settlements. [Online]. Retrieved 30 May 2012 Available: http://www.unhabitat.org/content.asp?typeid=19&catid=570&cid=6002

Ural, S., Hussain, E., and J. Shan. 2011. "Building Population Mapping with Aerial Imagery and GIS Data." *International Journal of Applied Earth Observation and Geoinformation* 13:841852.

Urban Land Institute. 2010. *Land Use and Driving: The Role Compact Development Can Play in Reducing Greenhouse Gas Emissions.* Washington DC: Urban Land Institute.

Victoria Transport Policy Institute. 2010. "Land Use Impacts on Transport: How Land Use Factors Affect Travel Behaviour." [Online]. Retrieved 5 May 2010, Available from: www.vtpi.org/landtravel.pdf

Vintrou, E., Desbrosse, A., Bégué, A., Traoré, S., Baron, C., and D. Lo Seen. 2012, "Crop Area Mapping in West Africa Using Landscape Stratification of MODIS Time Series and Comparison with Existing Global Land Products." *International Journal of Applied Earth Observation and Geoinformation* 14:8393.

Wang, J., Cheng, Q., and J. Chen. 2011. "A GIS and Remote Sensing Based Analysis in Land Use Change Using Asymmetric Relation Analysis Method: A Case Study from the City of Hangzhou, China." *Mathematical Geosciences* 43:435453.

Wang, J., Zen, C., and J. Lerhbass. 2012. "Building Extraction from Lidar and Aerial Images and Its Accuracy Evaluation." *IGARSS 2012*:6467

WECD. 1987. *Our Common Future*. Oxford: World Commission on Environment and Development.

Wei, Y., Zhao, Z., and J. Song. 2004. "Urban Building Extraction from High-Resolution Satellite Panchromatic Image Using Clustering and Edge Detection." *Geoscience and Remote Sensing Symposium* 7:1417.

Weng, Q. 2012. "Remote Sensing of Impervious Surfaces in the Urban Areas: Requirements, Methods, and Trends." *Remote Sensing of Environment* 117:3449.

Weng, Q., Lu, D., and J. Schubring. 2004. "Estimation of Land Surface Temperature–Vegetation Abundance Relationship for Urban Heat Island Studies." *Remote Sensing of Environment* 89:467483.

Whiteside, T.G., Boggs, G.S., and S.W Maier. 2011. "Comparing Object-Based and Pixel-Based Classifications for Mapping Savannas." *International Journal of Applied Earth Observation and Geoinformation* 13:884893.

Wurm, M., Taubenböck, H., and A.D.S Roth. 2009. "Urban Structuring Using Multisensoral Remote Sensing Data by Example of German Cities Cologne and Dresden." *Urban Remote Sensing Joint Event* 2009:19.

Yang, J., Zhao, L., McBride, J., and P. Gong. 2009. "Can You See Green? Assessing the Visibility of Urban Forests in Cities." *Landscape and Urban Planning* 91:97104.

Yuan, J., Wang, D., Wu, B., Yan, L., and L. Rongxing. 2009. "Automated Road Extraction Using LEGION Networks." *International Joint Neural Networks* 2009:188193.

Zhang, X., Wu, Y., and L. Shen. 2011. "An Evaluation Framework for the Sustainability of Urban Land Use: A Study of Capital Cities and Municipalities in China." *Habitat International* 35:141149.

Zhang, C., Luo, L., Xu, W., and V. Ledwith. 2008. "Use of Morans I and GIS to Identify Pollution Hotspots of Pb in Urban Soils of Galway, Ireland." *Science of the Total Environment* 39:212221.

Zhang, H., Zhang, Y., and H. Lin. 2012. "A Comparison Study of Impervious Surfaces Estimation Using Optical and SAR Remote Sensing Images." *International Journal of Applied Earth Observation and Geoinformation* 18:148156.

Zhang, Y., Guindon, D., and K. Sun. 2010. "Concepts and Application of The Canadian Land Use Survey." Canadian Journal of Remote Sensing 33:224235.

# CHAPTER 4: DEVELOPING A FRAMEWORK FOR EVALUATING SUSTAINABLE URBAN LAND USE

Sustainable development and sustainable urban land use planning are impressive concepts, but they are difficult to put into practice for routine decision making. An effective way to operationalise these concepts is to apply sustainable urban land use indicators to assess progress toward urban sustainability. This chapter identifies and describes various indicators of sustainable urban land use and explains how decision consequence analysis (DCA) can be used as a structured and simple tool to develop a framework for evaluating sustainable urban land use with the aid of earth observation (EO) and geographic information systems (GIS). The data collection, preparation and analysis of data within this framework are discussed and an appropriate framework is developed and demonstrated in a case study (Stellenbosch). Lastly, the chapter concludes by providing an outline of the rest of the dissertation.

## 4.1 STUDY AREA AND PERIOD OF ANALYSIS

Stellenbosch, the second oldest town in South Africa, is the study area to which this dissertation pays attention. The town is situated in the Western Cape province of South Africa approximately 55 km east of Cape Town's central business district (Figure 4. 1).

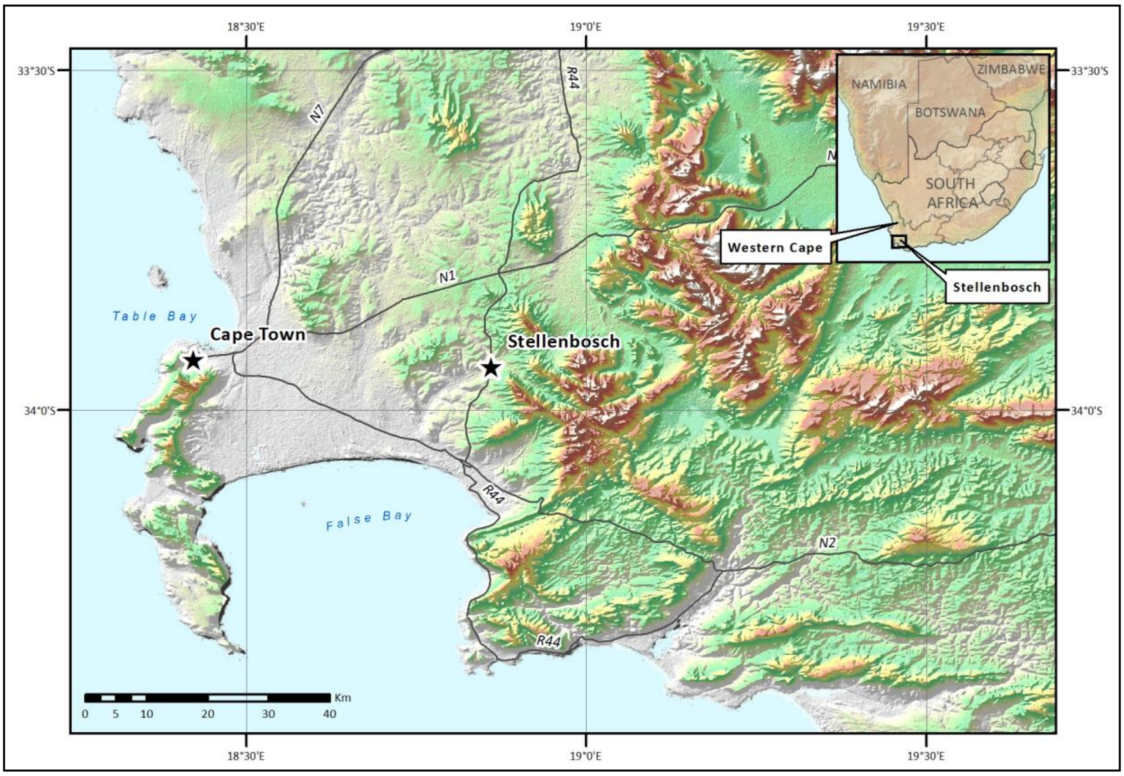



Figure 4.1: Location of Stellenbosch in the South-Western Cape

Stellenbosch is an appropriate case to spotlight because it has grown rapidly during the last two decades which is crucial for showing the impact of land transformation and human-nature interaction on urban sustainability. The town's population increased from 60 000 in 2001 to 90 000 in 2010 at a mean annual growth rate of 8.5% (InterStudy 2009; SA Statistics 2001; Stellenbosch University 2010). The town was shown by Van der Merwe, Ferreira & Zietsman (2005) to have the highest development potential of all 131 non-metropolitan settlements in the Western Cape. Subsequently in 2010, it was rated as one of the six non-metropolitan settlements in the province with the highest development potential (Van Niekerk et al. 2010). Stellenbosch's economy has experienced a transition from servicing its rich agricultural hinterland to a diversified economy based on niche sectors such as tourism, finance, science and technology, the latter two ably supported by Stellenbosch University (Stellenbosch Municipality 2011). Characteristically, Stellenbosch has suburbs of great wealth coexisting with an impoverished township and informal settlements, and poor households. Stellenbosch thus faces the challenges of balancing urban and economic growth against expansion into and consumption of scarce and valuable agricultural land as well as preserving natural and cultural heritage while simultaneously attempting to alleviate abject poverty. Stellenbosch was also selected because it is accessible and convenient for carrying out field visits. The availability of appropriate reference data to verify the findings was an important factor. The period of study is 2000 to 2010, mainly because of data availability.

## 4.2 SELECTING SUSTAINABLE URBAN LAND USE INDICATORS

Sustainability indicators are bellwether tests of sustainability and they reflect characteristics fundamental to the long-term economic, social and environmental health of a community (Maclaren 2004). Sustainability indicators are pointers to progress or lack of progress toward the overall health of a community, neighbourhood, town, city, region or larger area. The indicators must reflect the general state of well-being of urban land use, they should have an integrating function, be forward-looking (Huang, Wong & Chen 1998; Maclaren 2004), distributional and subject to feedback loops (Hall WL 2010). Employing these indicators replaces the ubiquitous advocacy-based qualifications that dominate the sustainability programmes and hinder sound decision making.

The second objective of this study is to identify spatial indicators of sustainable urban land use. Accordingly, the various spatial indicators that were identified in literature are set out in Table 4.1. These indicators have been incorporated in models for monitoring, controlling and benchmarking sustainable land use planning. Monitoring involves continuous auditing of sustainable land use over time, whereas controlling is an evaluation of whether sustainable land use targets are being met (Repetti & Desthieux 2006). Benchmarking uses indicators to identify best practices, which can be replicated universally. An analysis of non-spatial indicators is beyond the scope of this study. However, they can be integrated into an urban sustainability toolbox as developed later in this study.

Table 4.1: Indicators of sustainable urban land use

| Theme | Indicator | Unit of measurement | Sources |
|---|---|---|---|
| **Land use change and land use mix** | Ratio of residential land to non-residential land | Square kilometres ($km^2$) | Song & Knaap (2004); Song & Rodriguez (2005) |
| | Number of key facilities (clinics and banks ) | Number / $km^2$ | Burton (2002) |
| | Number of brownfield development / hectare | Developments/Hectare (ha) | Burton (2002) |
| | Land use count (frequency) | Number | Song & Knaap (2004); Song & Rodriguez (2005) |
| | Land use mix index | 0 to 1 | Song & Knaap (2004); Song & Rodriguez (2005) |
| | Percentage destruction and consumption of protected land; natural habitat, green space and areas of national heritage | ha | Comber, Brunsdon & Green (2008); Wang, Cheng & Chen (2011); Yang et al. (2009) |
| | Dissimilarity index | 0 to 1 | Song & Rodriguez (2005) |
| | Gini coefficient | 0 to 1 | Song & Rodriguez (2005) |
| | Herfindahl-Hirschman index (HHI) | 0 to 10 000 | Song & Rodriguez (2005) |
| | Land use change | ha | Comber, Brunsdon & Green (2008); Hall O (2010); Wang, Cheng & Chen (2011) |
| **Built-up area** | Building density | ha | Angel (2010); Ewing (1997); Urban Land Institute (2010) |
| | Settlement and housing structure | Building type | Canadian Urban Institute (2008); Jabereen (2006); Jones & MacDonald (2004) |
| | Building height | Storeys | Ding (2013); McLennan (2009); Yabuki, Miyashita & Fakuda (2011) |
| | Building volume | Cubic metres | Esch et al. (2010), Geiss et al. (2011) |
| | Impervious surface concentration | Concentration/ha | Nowak & Greenfield (2012); Weng (2012) |
| **Urban sprawl** | Global Moran | -1 to +1 | Anselin (1995, 2003, 2005) |
| | Local Moran (cluster and outlier analysis) | Cluster outlier type | Anselin 1995, 2003, 2005 |
| | Shannon's entropy | 0 to 1 | Baud et al. (2010); Tsai (2005) |
| | Spatial scan statistics | 0 to 1 | Zhang et al. (2008) |
| | Tango index | 0 to 1 | Zhang et al. (2008) |
| | Gini coefficient | 0 to 1 | Tsai (2005) |
| | Urban extent | Shape and growth of urban extent | Ewing (1997); Schwarz (2010); Tsai (2005) |
| **Transportation and circulation** | Mode of transport | Modal split | Frank et al. (2010); Guindon & Zhang (2007); Litman (2010), NEAT GIS Protocols (2010); Victoria Transport Policy Institute (2010) |
| | Population living within 500 m of a metro bus stop | Number of people | |
| | Average length of commuter trips | Minutes | |
| | Average weekday vehicle distance travelled | km | |
| **Air pollution** | Number of days per year on which concentration levels defined by law are exceeded for nitrogen dioxide ($NO_2$), particulate matter and Sulphur dioxide ($SO_2$) (World Health Organization guidelines). | Micrograms per cubic meter (µg/m3) | WHO (2005) |

The listed indicators were gleaned from various literature sources as cited in the table. The indicators were arranged in five broad themes, namely (1) land use change and land use mix, (2) urban sprawl, (3) built-up area, (4) transportation and (5) air pollution. These components are essential for achieving sustainable urban land use as well as for maintaining a good quality of life. It was apparent from the literature review (Chapter 3) that despite an extensive body of literature on land use and land cover classification little work has been reported on deriving substantive measures of land use mix (Neat GIS Protocols 2010; Song & Rodriguez 2005) which are vital in monitoring urban sustainability. The review also established that more research is required on spatial statistics and metrics which go beyond the urban extent in order to monitor urban sprawl (Le Néchet 2011; Tsai 2005). Earth observation (EO) also manifested as being crucial for updating or developing indicators for built-up areas that can be used to monitor sustainable land use planning and urban growth (Sobrino et al. 2012). The following three sub-sections explain the process of selecting appropriate indicators in the first three main themes listed above. These indicators were later used to develop an urban sustainability toolbox.

### 4.2.1 Land use change and land use mix indicators

Of the various indicators relating to land use change and land use mix, land use change (LUC) was identified as a key indicator of urban sustainability as it measures the rate of transformation from agricultural and natural ecosystems into intensive urban uses (Wang, Cheng & Chen 2011). It has been demonstrated that high rates of LUC (often due to urban growth) lead to increased motorised transport (Canadian Urban Institute 2008; Victoria Transport Policy Institute 2010), energy consumption (Urban Land Institute 2010), loss of agricultural land (Comber, Brunsdon & Green 2008), loss of biodiversity (Yang et al. 2009) and greater water pollution (Zhang et al. 2008). These effects pose serious threats to the attainment of urban sustainability and ultimately increase the rate of climate change (Renetzeder et al. 2010). Consequently, it is imperative to obtain information on LUC to understand human—nature interactions in rapidly urbanising countries (Hall O 2010). Consequently, for the purposes of this study it was not necessary to select other indicators such as area of brownfield’s development, percentage destruction of protected land, natural habitat, areas of national heritage and percentage area of green space consumed due to growth (Table 4.1) as these are incorporated in LUC analysis (Wang, Cheng & Chen 2011).

The second key index within the LUC and land use mix theme is the land use mix (LUM) index because it concentrates on a broad type of mixes, such as proximity of residential uses and educational facilities as well as residential to commercial and industrial facilities (Frank et al. 2010). Essentially, the LUM index measures the extent to which land uses are heterogeneously distributed within a neighbourhood (NEAT GIS Protocols 2010). LUM is also easy to communicate because the index ranges from 0 to 1, where 0 indicates land use homogeneity and 1 represents heterogeneity (Song & Rodriguez 2005). The LUM is therefore universally applicable and can be used for comparative studies. Moreover, the LUM index can be calculated at global and town levels and incorporating multiple land uses which demonstrates its versatility. Other land use mix indicators, such as the dissimilarity index and the Gini index, were not applied in this study because the dissimilarity index considers two land uses (residential and non-residential). In addition the Gini and dissimilarity indexes are not good discriminating indicators (NEAT GIS Protocols 2010). For example, it has been shown that two different distributions of land uses can result in the same value (Song & Rodriguez 2005). Similarly, the Herfindahl-Hirschman index (HHI) was not used because it mostly focuses on market concentration. The number of key facilities and ratio of residential and non-residential uses were also not selected for use in this study because the land use mix index gives an indication of the distribution of land uses.

A further reason for selecting the land use mix index is that it reflects social, environmental and economic aspects of urban sustainability (Song & Rodriguez 2005). Recent empirical evidence demonstrates that a high level of land use mix reduces environmental costs because it increases the use of non-motorised transport (NMT), promotes transit use, lowers vehicle miles travelled (VMT), reduces automobile use as well as emissions (Litman 2010) and promotes efficient usage of space and resources (Frank & Engelke 2001). The mixing of land uses reduces social costs by enabling spatial integration as well as community interaction which, in turn, reinforce the idea of pavement cafes (Victoria Transport Policy Institute 2010). A high degree of land use mix has a beneficial economic impact as it increases property values, lowers input costs (Jabereen 2006; Jones & MacDonald 2004), encourages a better employment mix and improves accessibility thereby reducing travelling costs (National Research Council 2009). Calthorpe Associates (2010), Litman (2010), National Research Council (2009), Urban Land Institute (2010) and Victoria Transport Policy Institute (2010) all have commented on the positive relationship between a high degree of land use mix and reductions in VMT, energy consumption and greenhouse gas (GHG) emissions. Land use count (frequency) was chosen as an indicator because it is necessary for calculating the LUM and it is easy to compute from land use data.

### 4.2.2 Urban sprawl indicators

Urban sprawl indicators need to capture the various adverse effects of the different dimensions of urban sprawl, be able to locate urban sprawl hot spots (Sayas 2006), be statistically significant (Tsai 2005) and distinguish between a cluster and an outlier (Zhang & Lin 2006). Several GIS mapping techniques have been used to identify hot spots, but many are not statistically significant, making it impossible to distinguish between clusters and outliers (Zhang et al. 2008). Global Moran I and local Moran *I* were selected because they have been shown to be more effective in detecting urban sprawl hot spots, clusters and outliers (Table 4.1) than indicators like the Tango index and spatial scan statistics which tend to be biased toward positive autocorrelation (Zhang & Lin 2006). Furthermore, global Moran I characterises different aspects of urban sprawl (e.g. density or leapfrogging) so that separate indexes are not required. This also eliminates the need for synchronisation and weighting of different indexes (Tsai 2005). Tsai (2005) demonstrated the convenience of using Moran indexes by providing a summary of quantitative spatial description of urban forms without using maps. This study goes further by mapping spatial distributions of urban sprawl so that urban sprawl hot and cold spots can be identified and visualised. The Moran indexes were selected ahead of indicators such as the Gini coefficient and Shannon’s entropy because there is convincing evidence that the Gini coefficient cannot distinguish between various forms of urban sprawl (Tsai 2005). Shannon’s entropy cannot be applied to data having a density value of zero, a condition which exists, for example with parks (Tsai 2005). Urban extent was selected because it shows the rate of urban growth and it has been widely reported in literature (Anselin 2012, Ewing 1997). Like LUC, urban extent shows the rate of land transformation and human—nature interaction (Gerundo & Grimaldi 2011).

### 4.2.3 Built-up area indicators

Built-up area indicators were selected because urbanisation and urban growth manifest in more buildings and anthropogenic surfaces (UN 2012; UN-HABITAT 2009). These are threats to both natural and rural environments as it raises GHG emissions that cause climate change and elevates air and noise pollution levels that often exceed the agreed human safety limits (Nichol et al. 2007.) Importantly, growth in the size of built-up areas should be monitored to prevent it exceeding certain limits beyond which negative social, economic and environmental impacts are engendered. The built-up area indicators selected for this study are building count and density, building height and impervious surface concentration.

Building density, which refers to the number of building units per unit area (e.g. buildings per hectare) (Angel 2010; Burton 2002) was selected because it is an important measure of urban sustainability as medium-to-high building densities reduce the negative environmental, social and economic costs associated with urbanisation (Ewing 1997; Veneri 2010). In South Africa, 20 or less building units per hectare (bu/ha) is regarded as low density, between 20 and 50bu/ha as medium density and above 50bu/ha as high density (CSIR 2010; Mudau 2010; Western Cape Department of Environmental Affairs and Development Planning, 2009).

Building density was selected because it has wide-ranging environmental, economic and social impacts. Recent studies have shown that although medium-to-high densities increase energy demand, they enable power-energy plants to run efficiently due to constant demand, thereby ensuring good returns on investment (Canadian Urban Institute 2008). Litman (2010) and the Victoria Transport Policy Institute (2010) have commented on the positive relationship between medium-to-high densities and the reduction of connection costs for infrastructure services and reductions of travel costs, travel time and energy costs (Frank et al. 2010; Le Néchet 2011). Similarly, Ewing & Nelson (2008), the Transportation Research Board (2009) and the Urban Land Institute (2010) report that medium-to-high density developments encourage public transit, other modes of transport and reductions in vehicle miles travelled (VMT) (Bigazzi & Burtini 2009). These assist in reducing of GHG emissions, which is an important indicator of sustainable urban development and the mitigation of climate change. Recent empirical evidence indicates that medium-to-high densities encourage more vibrant, diverse, walkable communities, which improve quality of life (Eid et al. 2008; Frank et al. 2010). Last, medium-to-high densities promote the efficient use of space so minimising encroachment into natural ecosystems and agricultural landscapes (Ewing & Nelson 2008; Jabereen 2006; Jones & MacDonald 2004). These effects of building density distinguish it as an indispensable indicator in urban sustainability studies.

Building height, measured in number of floors (storeys), was chosen as an urban sustainability indicator because it influences social, economic and environmental costs (Jones & MacDonald 2004) and is closely related to building density (Jabereen 2006). A building with a single floor is regarded as less sustainable to a building with two to twelve floors because of the inefficient use of space, lower returns on investment, higher infrastructure connection costs and low social vibrancy. However, the benefits of higher buildings diminish as the number of floors exceeds twelve (McLennan 2009). Building height and land use data are used as surrogates for settlement structure and volume because building height is a key determinant of volume.

Impervious surface concentration was selected because it directly measures the rate at which land resources are changing because of growing urban settlements (Esch et al. 2010). Impervious surfaces are anthropogenic land cover features that prevent water from infiltrating the soil. They include roads, driveways, parking lots and rooftops (Weng 2012). Indiscriminate growth of impervious surfaces has adverse consequences such as loss of agricultural land, increase in surface run-off and the burgeoning and severity of the urban heat island (Nowak & Greenfield 2012). The measurement of impervious surfaces is currently receiving unprecedented attention because of its significance to global and local environmental change and human-nature interaction (Weng 2012). It is noteworthy that land use change is closely related to impervious surface concentration because land cover is often determined by human activity (land use) on a particular area.

The three categories of indicators namely land use change and land use mix, urban sprawl and the built-up area are used to develop an urban sustainability toolbox.

## 4.3 DEVELOPING AN URBAN SUSTAINABILITY TOOLBOX

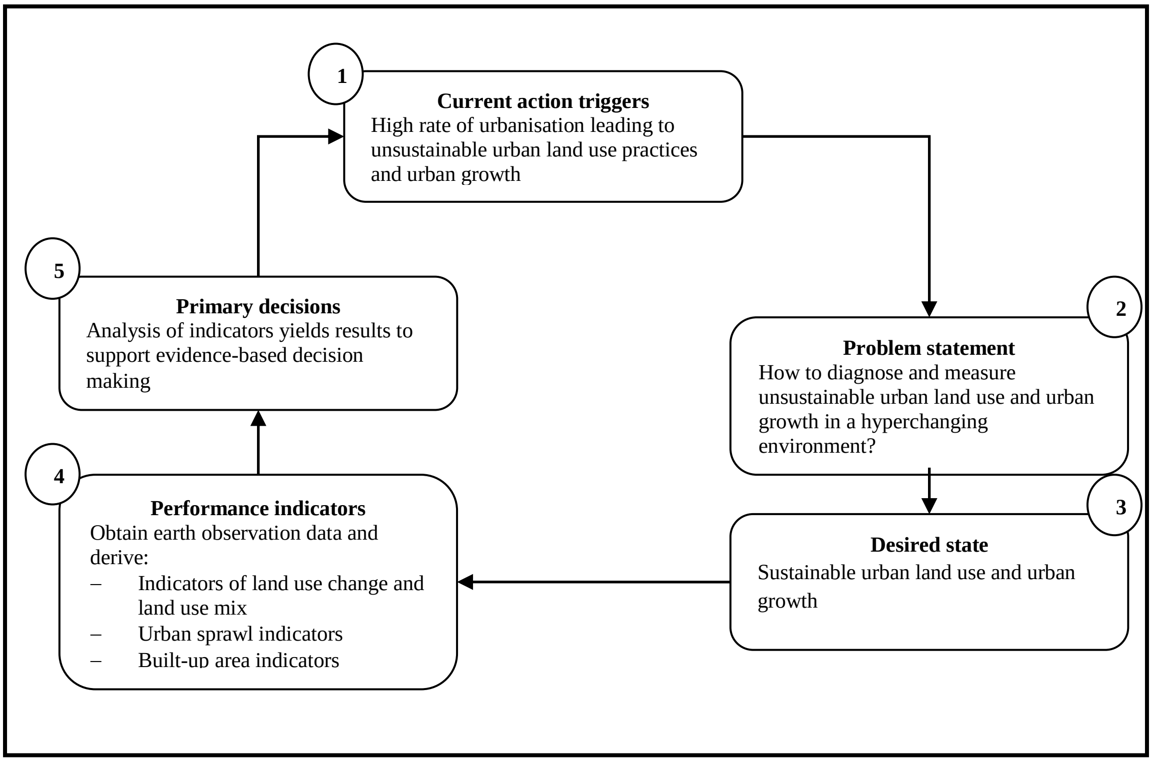
The indicators described in the previous section have mostly been applied as sectoral themes or with a focus on a single theme without considering the urban complex system as a whole (Repetti & Desthieux 2006). This study combines the various themes and develops an urban sustainability toolbox for use by urban planners and policy makers. The urban sustainability toolbox developed in this study comprises various indicators instead of aggregating them into one sustainability index because aggregation does not adequately reflect urban complexity correctly (Winograd & Farrow 2007). The urban sustainability toolbox is limited to a few key indicators because too much information can hamper clear interpretation and hinder the decision-making processes (Nathan & Reddy 2008). The main purpose of the indicators used in the toolbox is to determine the direction in which the urban system is evolving, that is, away from or toward sustainable urban land use.

Indicator selection for the urban sustainability toolbox was inevitably guided by the data availability. For example, travel data, which is crucial for developing transport-related indicators such as modal split, volume of GHG emissions from cars and VMT, was not used in this study because local authorities in developing countries seldom collect this data. However, land use and land use mix, urban sprawl and the structure of the urban built-up area impact on travelling times and transport issues (Ewing 1997; Guindon & Zhang 2005; Urban Land Institute 2010). Therefore, these themes were used as surrogate measures for transport related issues. Data on air pollution is only available for one monitoring station in Stellenbosch, making interpolation to the rest of the town’s neighbourhood impracticable (Stellenbosch Municipality 2011). It is also unlikely that reliable and up-to-date data on air pollution will be available for many towns in developing countries.

The urban sustainability toolbox designed in this work is intended to be an operational tool for determining the status of sustainable land use planning. The toolbox is not static as it can be updated and suited to particular contexts. The devising of the toolbox through the use of decision consequence analysis, the three study themes, namely (1) land use change and land use mix, (2) urban sprawl and (3) the urban built-up area, in conjunction with earth observation data and GIS analysis is discussed in the following sub-sections.

## 4.4 DECISION CONSEQUENCE ANALYSIS

Because sustainable development and sustainable land use planning are difficult to put into practice to support routine decision making, decision consequence analysis (DCA) (Hall WL 2010) is proposed as an appropriate structured model and framework for mapping and evaluating sustainable land use planning. The DCA framework is applicable to qualitative, quantitative and spatial studies as well as various disciplines and settings. DCA also aids the simplification and structuring of complex problems, such as how to plan for sustainable urban land use. DCA is an objective process that replaces the ubiquitous advocacy-based frameworks, which dominate the sustainability debate. Figure 4.2 shows how the DCA framework was implemented in this study.




Source: Adapted from Hall WL (2010)

Figure 4.2: Elements of decision consequence analysis to support sustainable urban land use planning

The basic elements of DCA are current action triggers (high rate of urbanisation leading to unsustainable land use and urban growth) and the desired state (sustainable urban land use and urban growth). To achieve a transition between the two states, acquired EO data on the themes of land use change and land use mix, urban sprawl and built-up area indicators are analysed in a GIS. The results of the analysis are used to determine whether progress has been made in reaching the desired state. The findings are presented quantitatively and spatially. The findings of quantitative analyses show the nature and rate of change of sustainable urban land use and those of the spatial analyses situate the changes in space to facilitate decision making. The following section details the framework used to derive and analyse the sustainable urban land use indicators.

## 4.5 RESEARCH FRAMEWORK AND METHODS

Figure 4.3 shows the research process followed. This framework is an expansion of step 4 in Figure 4.2 as it sets out how the indicators were derived from EO and analysed in a GIS.

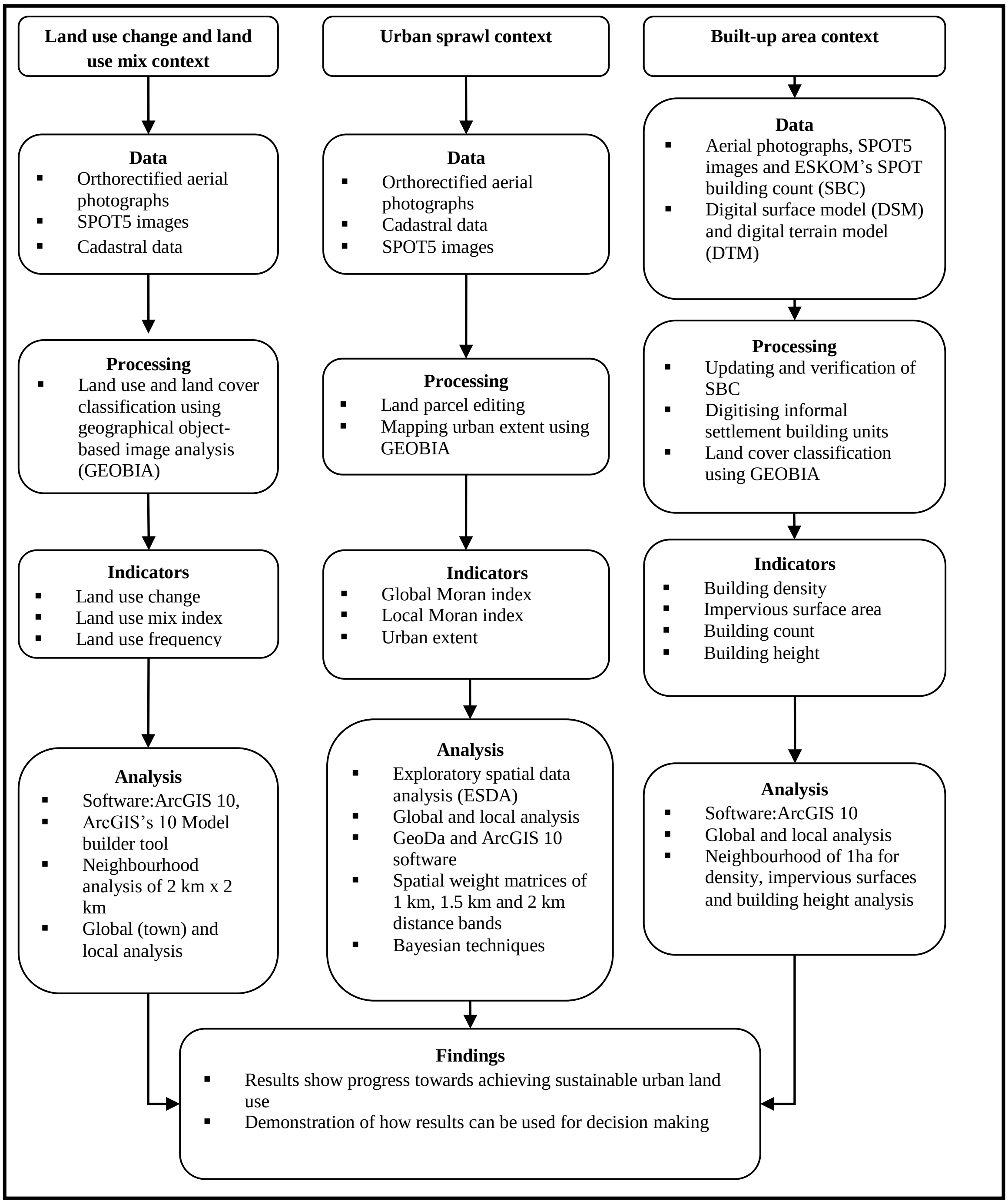



Figure 4.3: Research framework and processes to evaluate the potential of earth observation for supporting sustainable urban land use planning

EO data on the three contexts of sustainable urban land use were obtained and quantitative indicators derived and analysed with GIS software. The analysis is done at global (town) and local (neighbourhood) level. Global analysis shows the overall trajectory of a sustainability indicator in a town while local analysis shows the distribution of an indicator within neighbourhoods. Consequently, the results of the global and local analyses are used to evaluate the efficacy of EO in deriving sustainable urban land use indicators for monitoring and supporting urban planning decisions. Moreover, the results demonstrate the direction in which the urban system is evolving, that is, moving away from or toward sustainable urban land use. This informs decision making about alternatives to improve the status of sustainable urban land use planning. The research framework was also used to develop the urban sustainability toolbox which is presented in Chapter 8. The following five sub-sections discuss the data collection and processing and analysis methods applied to each theme as summarised in Figure 4.3.

### 4.5.1 Collection and preparation of land use change and land mix data

Very-high resolution (0.5 m) orthorectified colour aerial photographs of Stellenbosch were obtained from South Africa's Chief Directorate: National GeoSpatial Information for 2000 and 2010, respectively. Multispectral and panchromatic SPOT5 imagery with resolutions of 10 m and 2.5 m respectively, were acquired for 2010 from the South African National Space Agency (SANSA). Dennis Moss Partnership supplied a land use map of 2000 for verification purposes. The SPOT5 imagery was preprocessed (orthorectified and subjected to atmospheric and radiometric corrections) in PCI Geomatica. The multispectral and panchromatic images were fused using the PANFUSE function. A land cover classification was performed on the fused imagery with a supervised geographical object-based image analysis (GEOBIA) approach and eCognition software. The accuracy of the resulting land cover map for 2010 was assessed during field visits and by comparing the map to the aerial photographs. Land uses[1] were classified per land parcel (cadastral data) in ArcGIS 10 by means of a land use classification scheme adapted from Anderson et al. (1976), CSIR (2010), Department of Rural Development and Land Reform (2009) and NEAT GIS Protocols (2012). Only major land use categories (e.g. commercial, industrial) were classified as suggested by NEAT GIS Protocols (2012). Urban areas were defined as terrains of intensive use where much of the land is covered by building structures. Small areas surrounded by urban areas but having another land use (e.g. agriculture), were classified as urban. The land use classification exercise was complemented by extensive field visits to verify the accuracy of the classification.

[1] Land use is human activity directly related to the land (Anderson et al. 1976) whereas land cover describes the vegetation and artificial constructions covering the land surface. Land use refers to the human use of land, for example residential or commercial purposes, whereas land cover refers to the physical and biological cover types that extend over an area, for example grass or pavement (Hall O 2010).

Due to the unavailability of SPOT5 imagery for 2000 (SPOT5 was launched in 2002), aerial photography was used for producing a comparable (i.e. one with a similar classification scheme) land cover and land use map of 2000. By overlaying the 2010 land cover and land use maps onto the 2000 aerial photographs it was possible to identify significant land cover and land use changes between these dates. The 2000 land cover and land use maps were consequently created by manually editing the 2010 map. The 2000 and 2010 land cover maps were reclassified in ArcGIS 10 to produce impervious surface maps. Validation of the land cover and land use classification was done by creating 50 reference random points for each land cover and land use class using geospatial-modelling environment (GME) software. These were verified by extensive field visits, aerial photographs and Google Earth's Street View tool. The overall accuracy assessment for the land use and land cover classification for Stellenbosch was 86% for 2000 and 88% for 2010.

**4.5.2 Analysis of land use change and land use mix**

The land use maps of 2010 and 2000 were used to calculate land use change (LUC), the global land use mix index (GLUM), the local land use mix index (LLUM) and land use frequency (LUF). According to Song & Rodriguez (2005), discrete mapping makes visual interpretation of the LLUM difficult. Consequently, a continuous surface that employs a circular moving window was used to calculate the LLUM and LUF. The latter two indicators were calculated for neighbourhoods 2 km by 2 km in size. This neighbourhood size was selected as it corresponds to actual land use development patterns and is sufficiently large for use of non-motorised transport and automobile use (Ewing & Cervero 2001). Analysis of land use mix was done in the model builder tool of ArcGIS 10 (Appendix B). Land use changes were determined at global and locals level by overlaying GIS and cross-tabulation operations. A map was created that differentiates between changes from non-urban to urban use (i.e. urban expansion) and all other land use changes.

**4.5.3 Preparation and analysis of urban sprawl data**

To demarcate the built-up urban extent, the land use and land cover map developed for land use and land use mix theme was used to demarcate the urban extent for 2000 and 2010. The urban extent was used for visual interpretation and to separate predominantly urban land uses from agricultural uses and to map new urban developments, which have consumed agricultural land use since 2000. Cadastral data for 2000 and 2010 was obtained from the CGA and used for calculating the Moran indexes (Figure 4.3). The cadastral data was updated and edited through digitising in ArcGIS 10 using VHR (0.5) aerial photography for 2000 and 2010

GeoDa (version 1.0.1) was selected for calculating the global Moran I and local Moran *I* because it provides a wide range of functions (e.g. spatial weights construction, sensitivity analysis and visualisation) and it is relatively easy to use (i.e. no programming is required) (Anselin, Sybari & Kho 2006). GeoDa is also compatible with the popular ESRI ArcGIS software suite (ESRI 2010) which was used for the spatial analyses and mapping. When calculating the indexes, distance band spatial weight matrices (SWMs)[2] of 1 km, 1.5 km and 2 km were created to test the impact of various distance bands on the results. A distance band is a sphere of influence or moving window used to define spatial relationships of the data (ESRI 2010). There is no specific criterion for choosing distance bands, but they should not be longer than half of the study area's length[3] (Zhang et al. 2008). The SWMs were row-standardised to ensure that the results of global Moran I do not fall outside the -1 to 1 range (ESRI 2010). SWMs were created using the weights function (threshold distance) in GeoDa. Polygon centroids and Euclidian distances were used to conceptualise the SWMs. The extent (area) of land parcels and unique polygon IDs were used to calculate the indexes and to create the SWMs (ESRI 2010). Rate smoothing, using the empirical Bayes (EB) function in GeoDa was employed to calculate the indexes so as to prevent potentially biased results (Anselin 2003). In addition, a significance level of <0.05 was set in GeoDa to calculate the indexes.

### 4.5.4 Collection and preparation of built-up area data

A building count data set for 2010 was obtained from Eskom, the South African national electricity provide, who used. SPOT 5 natural colour imagery for creating this data set by manually digitising a point on a building and a polygon demarcating informal settlements (Mudau 2010). The building points were also classified as rural, peri-urban and urban. The Eskom Spot Building Count (Eskom SBC) data set is described as the first truly geographical data set for South Africa, which can be used by various stakeholders to support decisions such as a sample frame for surveys (Mudau 2010). The Eskom SBC was updated in ArcGIS 10 by manually digitising from aerial photography for 2000 and 2010. The Eskom SBC data

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[2] The minimum cut-off distance where each polygon had a neighbour was 1 km and it was determined automatically by invoking the create weights function in GeoDa.

[3] Stellenbosch stretches 9km from north to south and the maximum distance band chosen was 2 km which is within the range of not selecting half the distance of the study area.

set was also edited in ArcGIS 10 using 2000 aerial photography to create a 2000 building data set. Informal structures (shacks) were digitised in the same manner, as such structures were not included in the original Eskom SBC and were considered important for estimating building unit density. VHR (0.5 m) stereo pair aerial photographs of Stellenbosch were also obtained. These photographs were used to create the digital terrain model (DTM) and digital surface model (DSM) used for calculating building height. A DSM with a spatial resolution of two metres was extracted from the stereo aerial photography using PCI Geomatica's Ortho Engine software. Ground-level points, digitised from the aerial photography, were used to interpolate a digital terrain model (DTM) which represents the elevation of the ground surface while a DSM includes the heights of objects on the ground (e.g. buildings and vegetation) (Chen et al. 2012). The DTM was subtracted from the DSM to create a normalised digital surface model (nDSM). The building storey value for each building was extracted in a GIS using the buildings data set. The nDSM was divided by 3.3[4] and rounded to the nearest integer to obtain the number of storeys for each building.

Geospatial modelling environment (GME) software was used to create a random sample of 400 building points, which is a recommended sample size for the total 21 216 buildings to carry out an accuracy assessment. Extensive field visits and the Google Earth's Street View tool were employed to compare nDSM height and actual height. The overall accuracy assessment of the nDSM was 95% for buildings with one storey and 88% for buildings with more than one storey, implying that in most cases the observation of building storeys resembled those on the nDSM.

### 4.5.5 Analysis of built up area

The building count data set was used to calculate building density and count while the land cover classification map developed for the land use change and land use mix was used for the analysis of impervious surfaces. According to Song & Rodriguez (2005), discrete mapping makes visual interpretation difficult. Consequently, a continuous surface that employs a circular moving window was used to calculate building density, impervious surface area concentration and average building height. This enables easy visual interpretation, comparison and consistency in using a single unit of measurement (ha). All the analyses were done in ArcGIS 10. Building density was calculated per hectare because it is the most widely

[4] Three metres is the average building floor height (Stellenbosch Municipality 2010; Wurm et al. 2009).

used measurement according to international standards (Urban Land Institute 2010; Western Cape Department of Environmental Affairs and Development Planning 2009).

## 4.6 SUMMARY AND STRUCTURE OF THE REST OF THE DISSERTATION

This chapter has identified a list of sustainable urban land use indicators. These indicators were divided into three themes that are used to develop a framework for evaluating sustainable urban land use using EO data and GIS analysis in Stellenbosch. The next three chapters explore how these themes were analysed in case studies of Stellenbosch. Each theme is a stand-alone chapter, comprising an article manuscript submitted to a journal for peer review (Table 4.2).

Table 4.2: Structure of the rest of the dissertation

| **Theme** | **Paper** | **Submitted to** |
|---|---|---|
| Land use change and land use mix (Chapter 5) | Implications of land use change for the sustainability of urban areas: a case study of Stellenbosch, South Africa | *Cities Journal* |
| Urban sprawl (Chapter 6) | Monitoring urban sprawl and urban sustainability using the Moran index: A case study of Stellenbosch, South Africa | *International Regional Science Review* |
| Urban built-up area (Chapter 7) | Monitoring urban sustainability using built up area indicators: A case study of Stellenbosch, South Africa | *Habitat International* |

Chapter 8 concludes the study by providing an evaluation and synthesis to the study. The following chapter is an analysis of the implications of land use change for the sustainability in Stellenbosch.

# CHAPTER 5: IMPLICATIONS OF LAND USE CHANGE FOR THE SUSTAINABILITY OF URBAN AREAS: A CASE STUDY OF STELLENBOSCH, SOUTH AFRICA[5]

Musakwa, W and Van Niekerk, A. (2012). Implication of land use change on the sustainability of urban centres: A case study of Stellenbosch, South Africa. *Cities Journal*. Article in Review

**Abstract**
Sustainable development, an objective of urban planning, is difficult to put into practice. Data to monitor sustainable land use management is often lacking, particularly in developing countries. This paper investigates the use of earth observation (EO) data for supporting sustainable land use planning. It proposes the use of decision consequence analysis (DCA) as a simple and structured way to put sustainable development into practice. The study demonstrates how land use change (LUC), the local land use mix (LLUM) index and land use frequency (LUF) can be used as indicators of land use sustainability. The results show that the use of DCA, EO and land use indicators can aid local planning authorities to assess and monitor urban sustainability. Planners can also use the indicators to effect policy change and to support land use decisions.
**Keywords**: Sustainable urban development, decision consequence analysis, indicators, land use mix, land use frequency

## 5.1 INTRODUCTION

Sustainable cities are prominent on the development agendas of many nations, but particularly important in developing countries experiencing alarmingly high rates of urbanisation (UN-HABITAT, 2009; Shen et al., 2010). Rapid urbanisation often leads to land use practices that disregard future generations' needs and inevitably cause problems such as urban sprawl (Breheny and Batey, 1992), collapse of public services (UN-HABITAT, 2002), brownfields (Burton, 2000) and haphazard development (Hicken, 2009). This often leads to sedimentation of watersheds (Farrow and Winograd, 2001), urban pollution (Brandes et al., 2010), overcrowding (WCED, 1987), increase of natural and man-made risks (World Bank, 1994), soil degradation (Sattler et al., 2010) and damage to pristine natural landscapes (Barredo and Demicheli, 2003; UN-HABITAT, 2002).

Many developing cities lack the necessary resources to effectively manage land use (UN-HABITAT, 2009) and, although some governments have tried to balance socio-economic development and environmental concerns, evidence indicates that such attempts have been ineffective (Klosterman, 1995). In addition, many of the institutional structures of local governments are inappropriate for dealing with high rates of urbanisation because they were established during colonial times and consequently designed to deal with predominantly rural and agricultural societies (WCED, 1987). Over the last five decades the focus of developing

[5] Based on: Musakwa W and Van Niekerk A (2012). Implications of land use mix on the sustainability of African urban centres: A case study of Stellenbosch, South Africa. In Proceedings *Real Corp*, Schwechat, Austria, May 14-16, 2012, pp 1237-1244.

nations' urban management policies shifted from centralised to decentralised approaches as governments went through phases of structural adjustments with their main concerns being good governance and privatisation issues (World Bank, 1994; Repetti, Soutter and Musy, 2005). These changes have incapacitated many local planning authorities so that many still follow the master-planning approach which is ineffective in promoting the economic, social and environmental sustainability of urban areas (Barredo and Demicheli, 2003). Also, the availability of spatial information is often poor or non-existent, corruption is widespread, and an inadequate skills base pose formidable hurdles for planning, forecasting, modelling and monitoring land use change (Hicken, 2009). Earth observation data is a proposed solution to availability of spatial information needed for urban planning.

Campbell (2011) defines earth observation (EO) as the practice of deriving information about features on the earth's surface using images acquired from an overhead perspective. EO has the capability to provide quick synoptic views of urban areas and is invaluable for collecting information in developing countries where municipal records seldom keep pace with the rate of development (Hall O, 2010; Repetti, Soutter and Musy, 2005). EO can uncover aspects of the built environment often opaque to urban planners and social scientists (Barr and Ford, 2010) and it has been used in sustainability studies as a data source for indicator development (Liu, 2009; National Academy of Sciences, 2003). These indicators include land use and land cover (Barredo and Demicheli, 2003), road network layout (Victoria Transport Policy Institute, 2010) and building density (Angel, 2010). Collecting such data by other means (e.g. field surveys) is difficult, time-consuming and prohibitively expensive in most developing countries (National Academy of Sciences, 1998; Weng, 2012).

Most developing cities and towns pursue sustainable development as their goal, yet little is being done to operationalise the concept. Clearly, new approaches and techniques are needed to support sustainable land use management in rapidly developing cities. This paper aims to demonstrate how maps of land use, derived through EO data and decision consequence analysis (DCA) can be used to develop land use indicators for monitoring sustainable urban land use in towns and cities.

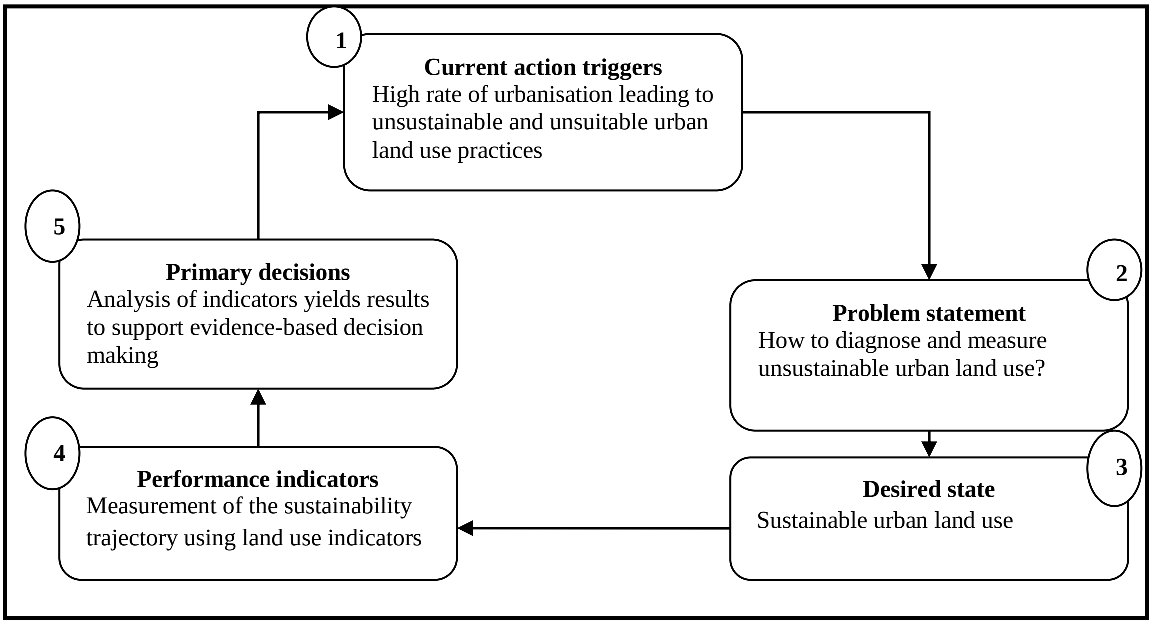
## 5.2 SUSTAINABLE DEVELOPMENT AND LAND USE PLANNING

Sustainable development is a fuzzy concept (Gunder, 2006; Winograd and Farrow, 2007) encapsulated in the seminal definition by the Bruntland Commission as "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987, p. 23). For urban land use to be sustainable it must meet the needs of the current as well as future urban citizens (Seghezzo, 2009; Wolf and Meyer, 2010). Accordingly, city officials must heed the call by today's citizens to alter land use without jeopardising future generations' needs. Sustainable development and urban land use planning are noble concepts (Hall WL, 2010), but the pressing challenge is to put them into practice (Freeman, 2004). Ideally, they should be incorporated into a comprehensive decision framework to guide daily, personal, business or policy decisions (Holden, 2008; Hall WL, 2010; Ness, 2001). However, these grand intentions are difficult to monitor and implement given their complexity, vagueness and, at times, immeasurable tenets (Zhang, Wu and Shen, 2011). Sustainability often remains a condition that can be used and abused by various stakeholders without their clearly defining what sustainability implies in land use planning (Hall WL, 2010). A model of sustainable development is required which accurately captures and allocates costs, such as environmental damage, pollution and land consumption. DCA is a worthwhile option for assisting the simplification of sustainable land use management.

## 5.3 DECISION CONSEQUENCE ANALYSIS

DCA formalises decision making by using decision theory, probability and statistics (Hall WL, 2010). The process breaks down complicated problems, such as sustainable development and land use, into increasingly smaller units until the particular component can be accurately analysed and understood within the context of the overall problem. The basic elements of DCA are an unacceptable current condition and a desired future condition. To achieve a transition between the two conditions it is necessary to understand each condition, to identify possible pathways between the two and a way to measure the progression between them (Figure 5.1).

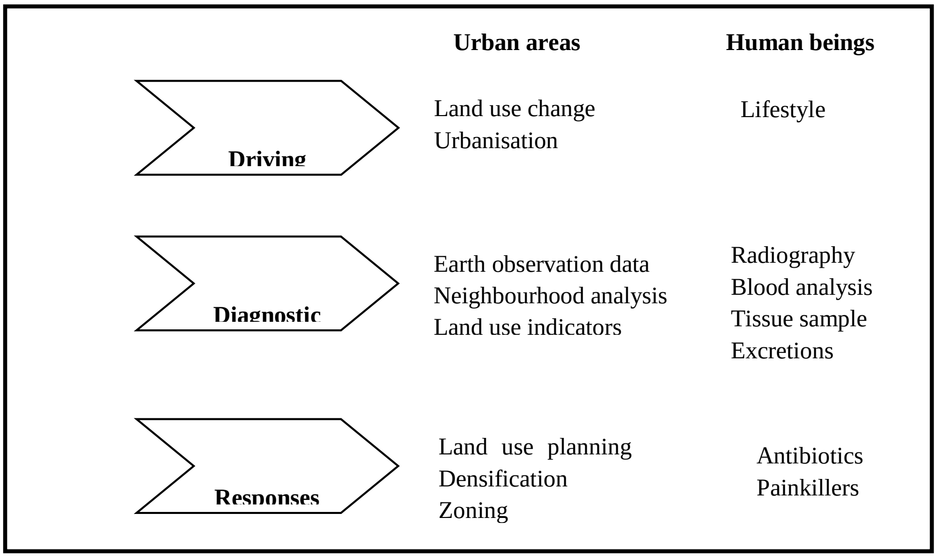
High rates of urbanisation in many developing countries often lead to unsustainable land use practices (Klosterman, 2001). Although much has been done to stifle or even reverse this trend, the main challenge is how progress from the current state (unsustainable land use) to the desired state or objective (sustainable land use practices) can be monitored. The use of objective indicators, developed using geographical information systems (GIS) and EO, is proposed. Such indicators can be used as criteria for creating different land use scenarios and for supporting land use decisions.




Source: Adapted from Hall WL (2010)

Figure 5.1: Elements of decision consequence analysis to assess sustainable urban land use

DCA is a structured and systematic approach to making complex and unstructured decisions concerning sustainable land use. DCA adheres to principles used in medical practice (Farrow and Winograd 2001) and can serve as a robust tool for practical purposes (Figure 5.2).




Source: Adapted from Farrow and Winograd (2001)

Figure 5.2: Diagnostic processes for ailments in human beings and urban areas

Just as the lifestyle of a human being influences his or her health, land use change and high rates of urbanisation in cities and towns affect the sustainability of those urban areas. This condition requires a diagnosis which prompts a response.

## 5.4 EARTH OBSERVATION

EO is a branch of remote sensing concerned with collecting in situ information about the earth's surface through the use of data obtained from airborne and satellite sensors (Liu et al., 2012). The remote sensing process begins with observation of physical objects by sensors to extract useful data and information as images, normally in digital format (Campbell, 2011). Obtaining useful information from these images depends on the spatial, temporal, spectral and radiometric resolution of the sensors. Spatial resolution refers to the smallest feature which can be discerned from an image, while temporal resolution is the frequency at which a sensor collects data or visits the same location. Radiometric differentiation defines the differences in brightness of objects and features, and it also influences image contrast. Spectral resolution refers to a sensor's ability to collect data at specific electromagnetic wavelength ranges. In general, sensors with higher spatial, temporal, radiometric and spectral resolutions provide better-quality information (Weng, 2012).

Satellite images normally undergo pre-processing procedures such as image restoration, image enhancement, image transformation and image classification (Schaepman, 2007). Restoration refers to correction and calibration of the image to fully represent the earth while enhancement involves modification to optimise visual appearance. Classification entails computer-assisted interpretation of images using software such as PCI Geomatica and eCognition. Classification can be categorised as unsupervised or supervised, the latter involving the training of computer software to automatically map land cover classes according to the statistical characterisation of known data (i.e. training sites) (Addink, Van Coillie and De Jong, 2012). Unsupervised classification involves using a clustering algorithm to classify an image into spectral classes which are interpreted and classified by an operator. Image classification has traditionally been carried out on individual pixels (pixel-based approach), but recent advancements in image analysis software have made it possible to carry out object-based classification. This geographic object-based image analysis (GEOBIA) approach (Hay and Castilla, 2008) partitions remotely sensed imagery into meaningful image-objects (groups of contiguous pixels) and assesses their spatial, temporal, spectral and contextual characteristics to generate new geographic information in GIS-ready format (Blaschke, 2010; Qi et al., 2012). GEOBIA is similar to visual interpretation as it uses tone, shape, size, pattern, texture and association in classification exercises. This not only improves the accuracy of classifications (Duro, Franklin and Dubé, 2012), but enables the development of logical rules whereby information such as land cover can be extracted from images with greater cost-efficiency (Ardila et al., 2012). These improvements in EO hold much potential for the development of sustainability indicators.

## 5.5 SUSTAINABILITY INDICATORS

Sustainability indicators are bellwether tests of sustainability and they reflect something basic and fundamental about the long-term economic, social, and environmental health of a community (Maclaren, 2004). Sustainability indicators are pointers toward progress or lack of the overall health of a community, neighbourhood, town, city, region or larger area. They must reflect the general well-being of urban land use, they should have an integrating function, be forward-looking (Huang, Wong and Chen, 1998; Maclaren, 2004), be distributional, and subject to feedback loops (Hall WP, 2010). Examples of such indicators are land use change (Wang, Cheng and Chen 2011), land use mix (Song and Rodriguez, 2005) and land use frequency (Guindon and Zhang, 2005). Employing these indicators replaces the ubiquitous advocacy-based qualifications which dominate the sustainability programmes in Africa and hinder sound decision making.

Land use change (LUC) is an important indicator in urban sustainability as it can be used to measure the rate of transformation of mostly agricultural and natural ecosystems into intensive urban uses (Wang, Cheng and Chen, 2011). It has been demonstrated that high rates of LUC (often due to urban growth) lead to increased motorised transport (Canadian Urban Institute, 2008; Victoria Transport Policy Institute, 2010), energy consumption (Urban Land Institute, 2010), loss of agricultural land (Comber, Brunsdon and Green, 2008), loss of biodiversity (Yang et al., 2009) and greater air pollution (Zhang et al., 2011). These effects pose serious threats to the attainment of urban sustainability and ultimately increase the rate of climate change (Renetzeder et al., 2010). Consequently, it is imperative to obtain information on LUC to understand human-nature interactions in rapidly urbanising countries (Hall O, 2010).

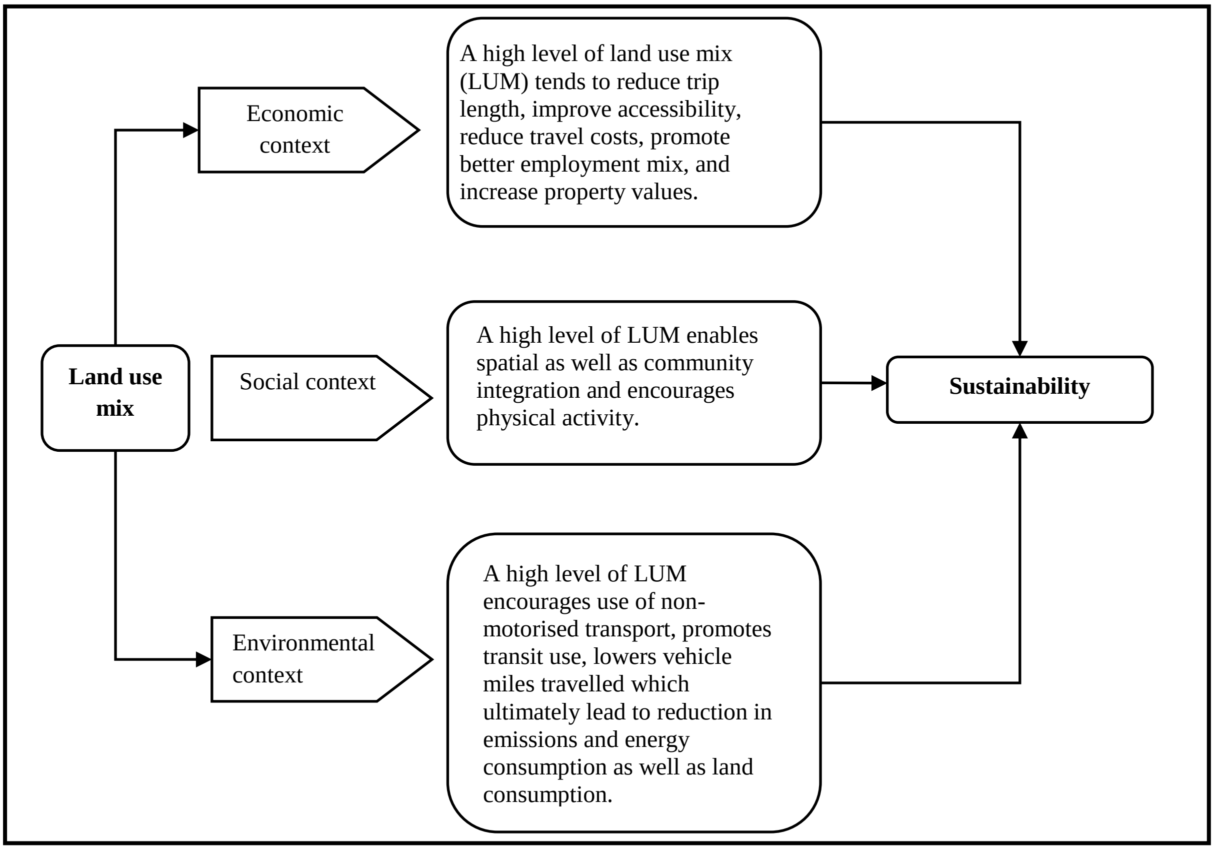
The impact of land use mix (LUM) on urban sustainability has been demonstrated by Song and Rodriguez (2005). The land use mix index measures the degree to which land use activities are separated. Consequently, the LUM affects the way people move between different activities or different destinations such as home to workplace or shops, and home to civic institutions such as places of worship and parks (Litman, 2010; Polzin, 2006). The

LUM index is thus a measure of variation (Song and Knaap, 2004), dispersion or diversity of land uses (NEAT GIS Protocols, 2010). The LUM index is defined as:

$$\text{LUM} = \{-\Sigma[(p_i)(ln\ p_i)]\}\ /\ ln_k \qquad \text{(Equation 5.1)}$$

where $p_i$ is the proportion of each land use class per neighbourhood; $ln$ is the natural logarithm; and $k$ is the number of land use classes per neighbourhood. Essentially, the LUM index measures the extent to which land uses are heterogeneously distributed within a neighbourhood (NEAT GIS Protocols, 2010). The index values range from 0 to 1 where 0 indicates land use homogeneity and 1 represents heterogeneity (Song and Rodriguez, 2005). The LUM index can be calculated globally (GLUM) or locally (LLUM). GLUM is a measure of the overall land use mix of a city or town while LLUM shows distribution of LUM within a city.

LUM affects sustainability through its impact on environmental, social and economic costs (Figure 5.3). It has been demonstrated that mixing of complementary land uses such as residential, retail, offices, commercial, non-obnoxious industrial use and civic uses is beneficial for urban sustainability. For example, recent empirical evidence suggests that a high level of LUM reduces environmental costs because it increases use of non-motorised transport (NMT), promotes transit use, lowers vehicle miles travelled (VMT), reduces automobile use as well as emissions (Litman, 2010) and promotes efficient usage of space and resources (Frank and Engelke, 2001). Mixing residential with civic, commercial, and retail land uses reduces social costs by enabling spatial integration as well as community interaction both of which reinforce the idea of pavement cafes (Victoria Transport Policy Institute, 2010). A high degree of LUM has an economic impact as it increases property values, lowers input costs (Jabereen, 2006; Jones and MacDonald, 2004), encourages a better employment mix and improves accessibility, thereby reducing travelling costs (National Research Council, 2009). Song and Knaap (2004) observed that a mixing of residential and commercial uses generally correlates with high land prices while other studies observed that land prices and the mixing of residential with open spaces are positively related (Song and Rodriguez, 2005). Calthorpe Associates (2010), Litman (2010), National Research Council (2009), Urban Land Institute (2010), and Victoria Transport Policy Institute (2010) have commented on the positive relationship between a high degree of LUM and reductions in VMT, energy consumption and greenhouse gas (GHG) emissions. However, there is disagreement about the level of this impact, the National Research Council (2009) arguing that a high degree of LUM reduces VMT by 25%, whereas others maintain that a high degree of LUM can reduce VMT by more than 50% (Calthorpe Associates, 2010; Ewing and Cervero, 2001; Litman, 2010).




Sources: Adapted from Litman (2010) and Victoria Transport Policy Institute (2010)

Figure 5.3: Impacts of land use mix on urban sustainability

These studies show that changes to planning policy (particularly zoning) encourage mixing of land uses because activities can provide a platform for meeting the social, economic and environmental contexts of sustainable development. It is critical that land use mix be monitored by planners, particularly in cities and towns experiencing rapid growth.

Land use frequency (LUF) refers to the number of land uses found in a neighbourhood or city. It is analogous to having a diversity of land uses such as commercial, residential, education and recreation within a neighbourhood (Song and Rodriguez, 2005). As with the LUM index, LUF is perceived to have social, environmental and economic impacts. A high LUF promotes active communities (Frank, Andersen and Schmid, 2004), interaction (Frank and Engelke, 2001) and transit uses that, in turn, reduce transport costs (Ewing and Nelson, 2008). High LUF leads to lower automobile use (Guindon and Zhang, 2005), low rates of urban expansion and reductions in GHG emissions (Urban Land Institute, 2010). LUC, LUM and LUF can be applied together to determine urban land use sustainability.

## 5.6 METHODS

The study area and period, data collection as well as preparation and data analysis are discussed in the following sub-sections.

### 5.6.1 Study area and period

Stellenbosch, the second oldest town in South Africa, is the study area. The town is situated in the Western Cape province of South Africa approximately 55 km east of Cape Town's central business district (Figure 5. 4).

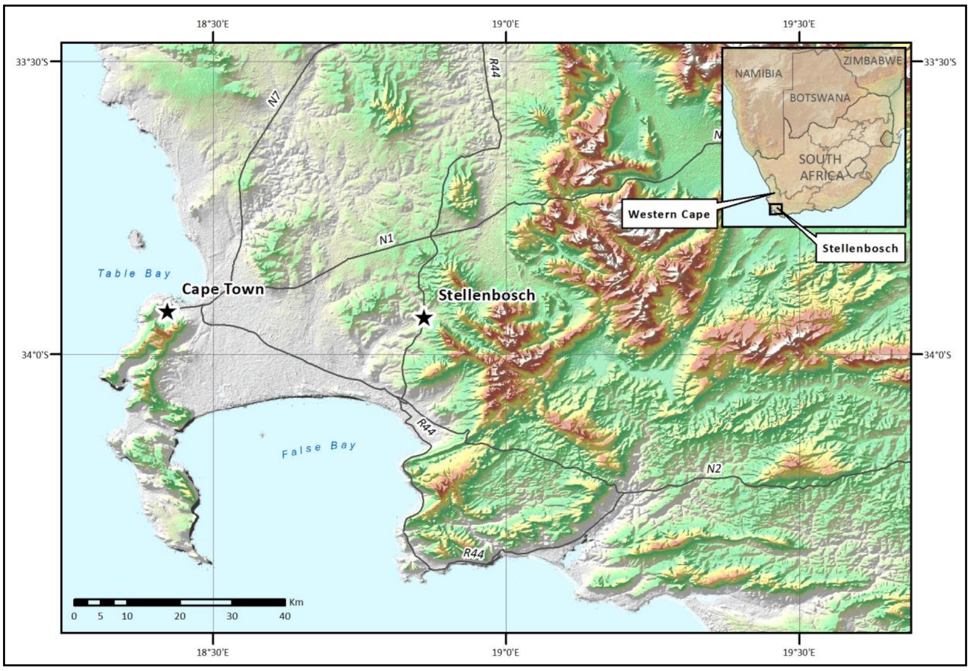



Figure 5.4: Location of Stellenbosch in the South-Western Cape

Stellenbosch is an appropriate study case as it has grown rapidly during the last two decades. Its population increased from 60 000 in 2001 to 90 000 in 2010 at a mean annual growth rate of 8.5% (InterStudy, 2009; SA Statistics, 2001; Stellenbosch University, 2010). The town was earlier shown by Van der Merwe, Ferreira and Zietsman (2005) to have the highest development potential of all 131 non-metropolitan settlements in the Western Cape. In 2010, it was rated as one of the six non-metropolitan settlements in the province with the highest development potential (Van Niekerk et al., 2010).

Stellenbosch's economy has experienced a transition from servicing its rich agricultural hinterland to a diversified economy based on niche sectors such as tourism, finance, science and technology, the latter two ably supported by Stellenbosch University (Stellenbosch Municipality, 2011). Characteristically, Stellenbosch has suburbs of great wealth coexisting with an impoverished township and informal settlements, and poor households. Stellenbosch thus faces the challenges of balancing urban and economic growth against expansion into and consumption of scarce and valuable agricultural land as well as preserving natural and cultural heritage while simultaneously attempting to alleviate abject poverty. Stellenbosch was also selected because it is accessible and convenient for carrying out field visits. The availability of appropriate reference data to verify the findings was also an important factor. The period of study is 2000 to 2010, mainly because of data availability. The study area was demarcated as the 2010 urban built-up extent and consequently includes areas used in 2000 for non-urban purposes (e.g. agriculture).

### 5.6.2 Data collection and land use mapping

Very-high resolution (0.5 m) orthorectified colour aerial photographs of Stellenbosch were obtained from South Africa's Chief Directorate: National GeoSpatial Information for 2000 and 2010, respectively. Multispectral and panchromatic SPOT5 imagery with resolutions of 10 m and 2.5 m respectively, were acquired for 2010 from the South African National Space Agency (SANSA). A land use map of 2000 was supplied by Dennis Moss Partnership for verification purposes. The SPOT5 imagery was pre-processed (orthorectified and subjected to atmospheric and radiometric corrections) in PCI Geomatica. The multispectral and panchromatic images were fused using the PANFUSE function. A land cover classification was performed on the fused imagery with a supervised geographical object-based image analysis (GEOBIA) approach and eCognition software. The accuracy of the resulting land cover map for 2010 was assessed during field visits and by comparing the map to the aerial photographs. The land cover map was visually interpreted along with ancillary data to develop a land use map. Land uses were classified per land parcel in ArcGIS 10 by means of a land use classification scheme (Table 5.1) adapted from Anderson et al. (1976), CSIR (2010), Department of Rural Development and Land Reform (2009) and NEAT GIS

Protocols (2012). Only major land use[6] categories (e.g. commercial, industrial) were classified as suggested by NEAT GIS Protocols (2012).

Table 5.1: Land use classification scheme

| Land use | Density[1] | Spacing and pattern | Height[2] | Common features |
|---|---|---|---|---|
| Cluster housing | Ranges between low, medium and high | Building units at the centre of site or attached to another, while housing units can be similar or varied | Single storey, two storeys to three storeys | Housing units in an enclosed perimeter around a common space such as gardens, play areas, mall and waterbody |
| Residential (single-family dwelling units) | Ranges between low, medium and high | Building units at centre of site, almost similar spacing between units and a discernible road pattern | Single storey, two storeys to three storeys | Gardens, driveways and swimming pools |
| Informal settlements | Very-high density, more than 60 units /ha | Irregular pattern as well as an indiscernible road hierarchy | Not applicable | Variety of substandard building material and lack of basic services and infrastructure |
| Industrial | Ranges between low, medium and high. Light manufacturing normally exhibits medium to high density | Buildings normally elongated and building pattern irregular for heavy industry | Minimum of two storeys for heavy industry, while for light industries height varies | Warehouses, masts, tanks, stockpiles of raw materials and waste, transportation facilities, chimneys, cooling towers, little or no vegetation in vicinity |
| Industrial parks | Building density normally medium (30-50 units/ha) | Building units at centre of site, almost similar spacing between units and a discernible pattern of building units | Varies with establishments | Well-manicured lawns, enclosed or defined perimeter, well-defined access points and discernible road hierarchy |
| Commercial (CBD) | High, more than 50 units /ha | Rectangular grid layout and buildings closely spaced | Average building height of two storeys | Sealed impervious surfaces, building material (concrete asphalt) and parking lots |
| Vertical mix | Depends on location | If in or next to CBD, buildings closely spaced | Average height of two storeys | Mix of uses within one building with uses stacked on top of each other |
| Horizontal mix | Low to high | Varies with location | Varies with location | Land use mix where different uses occur side by side |

Notes¹: Density standards are defined as: fewer than 30 building units per hectare regarded as low density, 30-50 units/ha as medium density and more than 50 units/ha as high density (Urban land Institute, 2010; Western Cape Department of Environmental Affairs and Development Planning, 2009; Urban Land Institute, 2010).

Urban areas are terrains of intensive use where much of the land is covered by building structures. Small areas surrounded by urban areas but having another land use (e.g. agriculture) were classified as urban. The land use classification exercise was complemented by extensive field visits to verify the accuracy of the classification. Land uses such as single-family dwelling units, informal settlements, cluster housing, commercial (CBD), educational and heavy industrial activities required relatively less groundtruthing due to their discernible shape, locational context and height (Table 5.1) which aided their identification on the

[6] Land use is human activity directly related to the land (Anderson et al., 1976) whereas land cover describes the vegetation and artificial constructions covering the land surface. Land use refers to the human use of land, for example residential or commercial purposes, whereas land cover refers to the physical and biological cover types that extend over an area, for example grass or pavement (Hall O, 2010).

remotely sensed imagery. For example, heavy industry was easily identifiable by its elongated buildings, waste-disposal sites and warehouses. Community facilities, such as churches, have discernible features and required little or no groundtruthing. However, mixed uses (vertical and horizontal), recreational areas and government use required extensive groundtruthing.

Due to the unavailability of SPOT5 imagery for 2000 (SPOT5 was launched in 2002), one had to rely on aerial photography to produce a comparable (i.e. one with a similar classification scheme) land cover and land use map of 2000. By comparing the 2010 and 2000 imagery, it was possible in most cases to identify significant changes in land cover and land use. A land use map for 2000 was created by editing the 2010 map. The 2000 land use map developed by Dennis Moss Partnership was used to verify the created 2000 land use map. The overall accuracy assessment for the land use and land cover classification for Stellenbosch was 86% for 2000 and 88% for 2010.

### 5.6.3 Land use change, mix and frequency analyses

The land use maps of 2010 and 2000 were used to calculate LUC, GLUM, LLUM and LUF (Table 5.2). The latter two were calculated for neighbourhoods 2x2 km in size. This neighbourhood size was selected as it corresponds to actual land use development patterns and is sufficiently large for use of non-motorised transport and automobile use (Ewing and Cervero, 2001).

Table 5.2: Indicators of sustainable land use

| Indicator | Unit of measurement | Analysis scale | Significance and thresholds |
|---|---|---|---|
| Land use mix index | 0 to 1 | Neighbourhood | A land use index of 0 denotes low sustainability and 1 highly sustainable. |
| Land use frequency | Frequency | Neighbourhood | A high number of complementary land uses per neighbourhood is desirable for sustainability, unlike low mixing intensity. |
| Land use change | Percentage | City or town | Land use change impacts all the other indicators. A change from natural ecosystems to urban use is generally unsustainable. |

Sources: Adapted from Song and Knaap (2004) and Wang, Cheng and Chen (2011)

According to Song and Rodriguez (2005), the problem with existing land use mix mapping techniques is the discrete nature of the results, which makes visual interpretation difficult. Consequently, a new technique that produces a continuous surface of land use mix was developed in this paper. The technique employs a circular 2x2 km moving window to calculate a land use mix value. Land use changes were determined at town level by GIS overlaying and cross-tabulation operations. A map was created that differentiates between changes from non-urban to urban use (i.e. urban expansion) and all other land use changes. All analyses were automated in the model builder tool of ArcGIS 10.

## 5.7 RESULTS AND DISCUSSION

The following sub sections discuss the impact of the LUC, LUM and LUF on sustainability trajectories in Stellenbosch.

### 5.7.1 Analysis of land use changes

The results of the LUC analysis are shown in Table 5.3. During the ten-year study period the area of land use within the built-up urban extent of Stellenbosch increased from 1471 ha to 1881 ha (28%), representing a mean annual (physical) growth rate of 2.8%. Table 5.4 shows net land use transition from 2000 to 2010 and Figure 5.5 shows the land use maps for the two years.

Table 5.3: Land use change (LUC) in Stellenbosch within the 2010 urban extent

| Land use | Area (ha) 2000 | Area (ha) 2010 | Change (ha) | Percentage change |
|---|---|---|---|---|
| **Agriculture** | 412.1 | 163.1 | -249.0 | -60.4 |
| **Cluster housing** | 13.4 | 75.9 | 62.5 | 467.7 |
| **Commercial** | 34.3 | 43.8 | 9.5 | 27.6 |
| **Community** | 25.8 | 26.4 | 0.6 | 2.4 |
| **Education** | 147.2 | 151.3 | 4.2 | 2.8 |
| **Government** | 82.8 | 67.6 | -15.3 | -18.4 |
| **Industrial** | 92.7 | 100.1 | 7.4 | 8.0 |
| **Informal** | 9.6 | 27.4 | 17.8 | 186.6 |
| **Mixed** | 21.5 | 26.9 | 5.4 | 25.2 |
| **Nature reserve** | 5.6 | 5.6 | 0.0 | 0.0 |
| **Office park** | 56.5 | 66.3 | 9.8 | 17.4 |
| **Open space** | 124.1 | 104.3 | -19.8 | -16.0 |
| **Other**[1] | 34.3 | 68.2 | 33.9 | 98.7 |
| **Recreation** | 192.4 | 312.9 | 120.5 | 62.6 |
| **Residential** | 622.9 | 635.0 | 12.1 | 1.9 |
| **Transportation** | 6.3 | 6.7 | 0.4 | 6.1 |

Note[1]: 'Other' consists of smallholdings and vacant land.

Table 5.4: Net land use transition measured in hectares in Stellenbosch between 2000 and 2010

| **Land use** | **Agriculture** | **Cluster housing** | **Commercial** | **Community** | **Education** | **Government** | **Industrial** | **Informal** | **Mixed** | **Nature reserve** | **Office park** | **Open space** | **Other[1]** | **Recreation** | **Residential** | **Transportation** | **Total change** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Agriculture** | | -61.0 | -7.2 | 0.0 | -0.6 | 15.3 | 0.0 | 0.0 | -1.5 | 0.0 | -6.0 | -15.5 | -46.6 | -113.4 | -12.6 | 0.0 | **-249.0** |
| **Cluster housing** | 61.0 | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.6 | 0.0 | 0.0 | 0.0 | 0.0 | **62.6** |
| **Commercial** | 7.2 | 0.0 | | 0.0 | 0.0 | 0.0 | 0.8 | 0.0 | 0.0 | 0.0 | 0.0 | 1.5 | 0.0 | 0.0 | 0.0 | 0.0 | **9.5** |
| **Community** | 0.0 | 0.0 | 0.0 | | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.6 | 0.0 | 0.0 | 0.0 | 0.0 | **0.6** |
| **Education** | 0.6 | 0.0 | 0.0 | 0.0 | | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 3.1 | 0.5 | 0.0 | 0.0 | 0.0 | **4.2** |
| **Government** | -15.3 | 0.0 | 0.0 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | **-15.3** |
| **Industrial** | 0.0 | 0.0 | -0.8 | 0.0 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.0 | 0.0 | 8.3 | 0.0 | 0.0 | 0.0 | 0.0 | **7.5** |
| **Informal** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.0 | 17.8 | 0.0 | 0.0 | 0.0 | 0.0 | **17.8** |
| **Mixed** | 1.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 3.9 | 0.0 | **5.4** |
| **Nature reserve** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | **0.0** |
| **Office park** | 6.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | | | 3.9 | 0.0 | 0.0 | 0.0 | **9.9** |
| **Open space** | 15.5 | -1.6 | -1.5 | -0.6 | -3.4 | 0.0 | -8.3 | -17.8 | 0.0 | 0.0 | 0.0 | | 8.9 | -7.1 | -3.4 | -0.4 | **-19.7** |
| **Other[1]** | 46.6 | 0.0 | 0.0 | 0.0 | -0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | -3.9 | -8.9 | | 0.0 | 0.0 | 0.0 | **33.3** |
| **Recreation** | 113.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 7.1 | 0.0 | | 0.0 | 0.0 | **120.5** |
| **Residential** | 12.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | -3.9 | 0.0 | 0.0 | 3.4 | 0.0 | 0.0 | | 0.0 | **12.1** |
| **Transportation** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.4 | 0.0 | 0.0 | 0.0 | | **0.4** |

Note[1]: 'Other' consists of smallholdings and vacant land.

During the ten-year period there was a gain of 62.6 ha (468%) in cluster housing, 17.8 ha (187%) in informal housing, 33.3 ha (99%) in smallholdings and vacant land (i.e. other), 5.4 ha (25%) in mixed use, 125 ha (63%) in recreation, 9 ha (28%) in commercial and 9.9 ha (17%) in office park use (Table 5.3). Meanwhile, Table 5.4 shows that Stellenbosch's highly productive agricultural land in 2000 had been significantly transformed to other uses by 2010, particularly recreation (113.4 ha), cluster housing (61 ha), as well as smallholdings and vacant land (i.e. other) (46.6 ha). Likewise, open space was reduced by 19.7 ha (-19%) as a result of a significant transition to informal (17.8 ha), industrial (8.3 ha), recreation (7.1 ha) and residential use (3.4 ha).

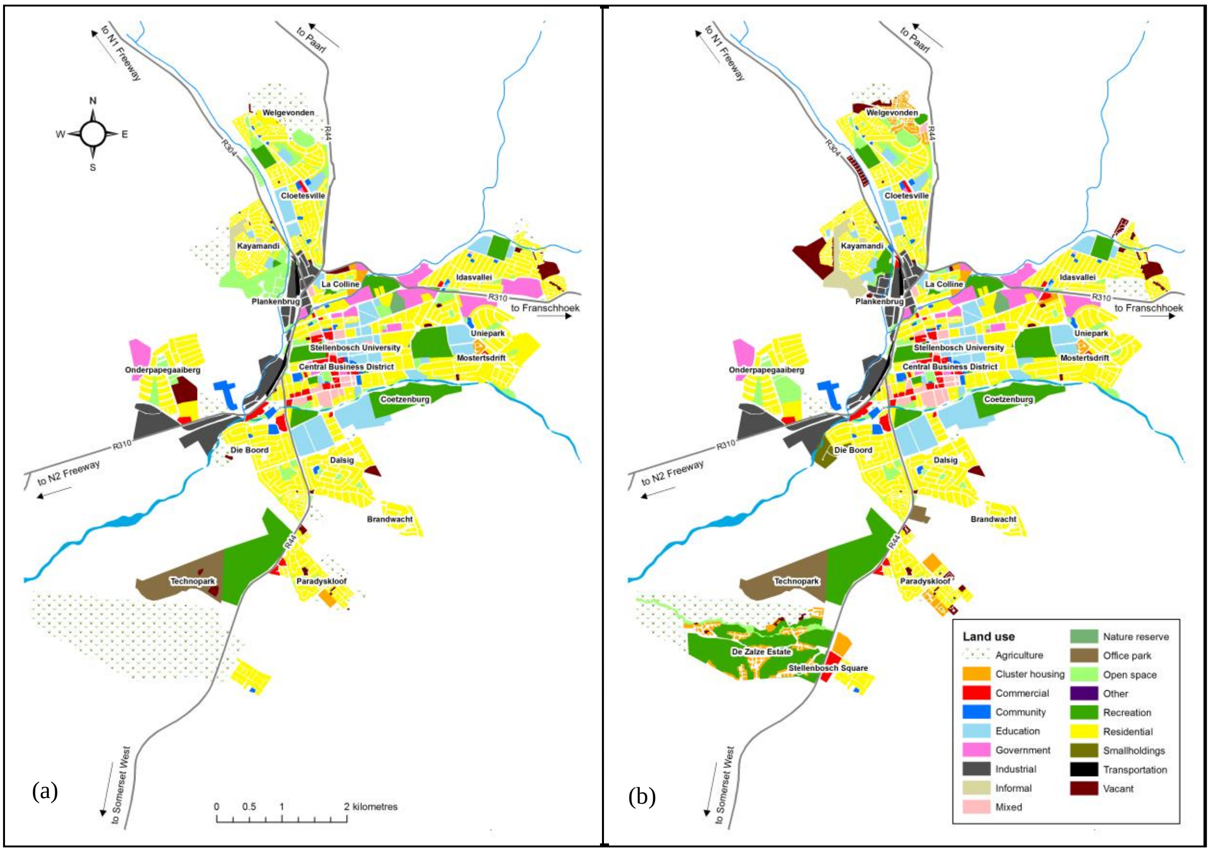



Figure 5.5: Land use in Stellenbosch, (a) 2000 and (b) 2010

Figure 5.6 portrays the land use changes between 2000 and 2010 according to urban and non-urban uses. Urban-to-urban changes are more sustainable than changes from non-urban to urban which imply loss of agricultural land and natural ecosystem services, hence adding adverse socio-economic and environmental costs. The most unsustainable (i.e. non-urban to urban) changes occurred in De Zalze, Kayamandi, Welgevonden, Paradyskloof, Die Boord and northern parts of Idas Vallei. Many of these changes led to loss of agricultural land and ecosystem services. Urban-to-urban land use changes occurred throughout Stellenbosch, the most significant ones in the western parts of Kayamandi. There were no cases of urban uses changing to non-urban uses.

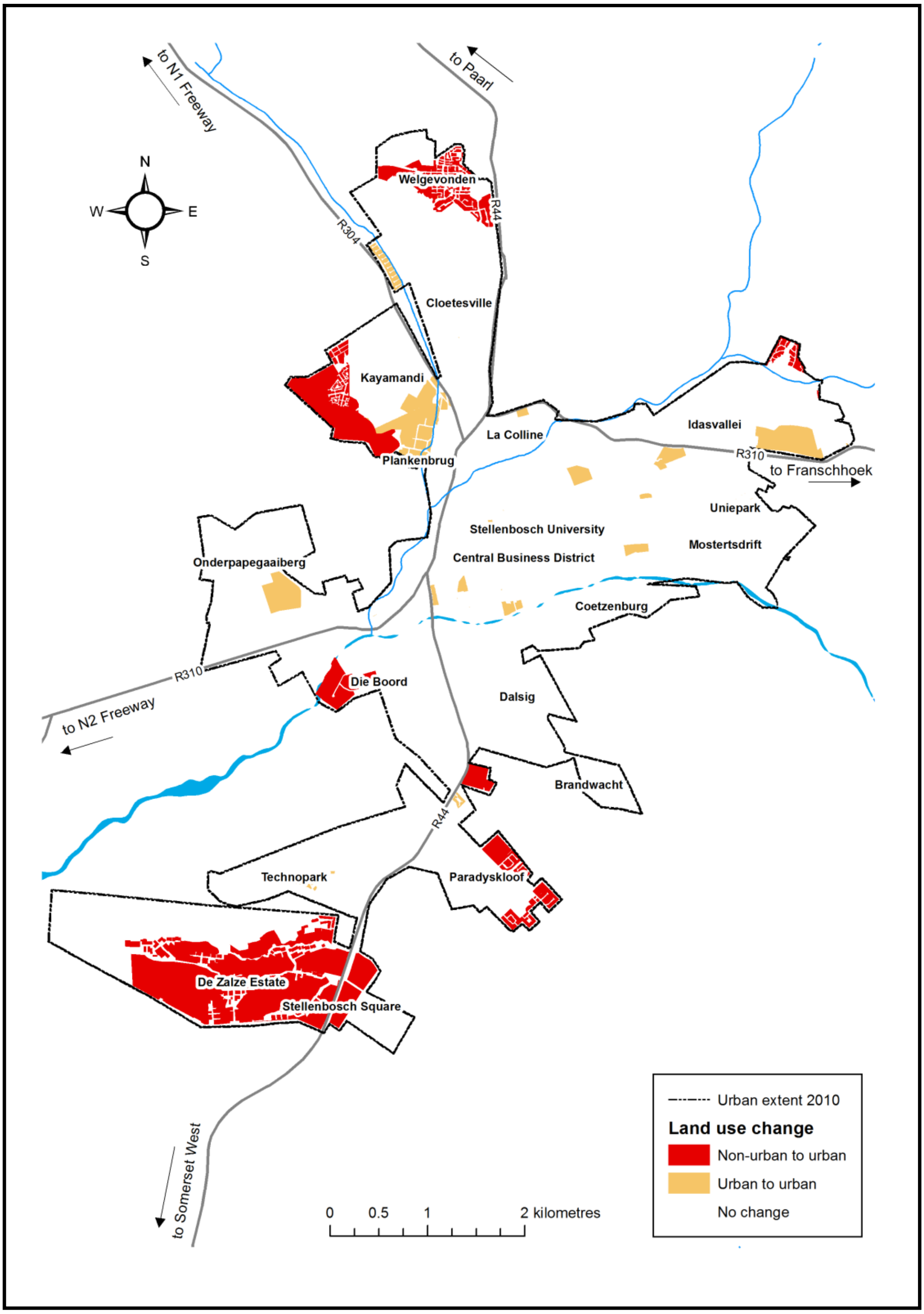



Figure 5.6: Land use change (LUC) in Stellenbosch

Analysis of LUC is an effective way of gauging the sustainability trajectory of Stellenbosch because each change contributes distinctively to sustainable urban development. Losses of agricultural land and open spaces, as well as the significant gains in informal settlements and minimal gain in transportation use do not augur well for sustainable urban development. The reduction in open space and agricultural land has a negative effect on sustainable urban development because these uses act as heat sinks, carbon sequestration spaces (Comber, Brunsdon and Green, 2006), habitat for animals and infiltration sinks. The result of such changes can be higher temperatures, reduction in biodiversity, increased runoff and loss of fertile agricultural land, all of which threaten the achievement of a sustainable urban environment (Yang et al., 2009).

The large increase in informal settlements and marginal increase in transportation in Stellenbosch are a concern. The notable growth in informal settlements indicates poor health of the urban system characterised by substandard shelter, overcrowding, lack of basic infrastructure and services, poverty and inadequate housing delivery (UN-HABITAT, 2002). The small change in land uses associated with transportation (from 6.3 ha in 2000 to 6.7 ha in 2010) also affects sustainable urban development negatively. During the study period, only one new formal transit station (Bergzicht taxi rank) was established despite an 8.3% annual increase in population. No intraurban bus service is available and many local residents must rely on the erratic taxi service for public transport (Stellenbosch Municipality, 2011). This encourages use of private motor vehicles, which has resulted in increased congestion (*Eikestad Nuus*, 2012), as well as more VMT and the emission of GHGs.

By contrast, the significant gains in cluster housing (468%) and mixed use (25%) have a positive effect on sustainability because these uses reduce environmental and economic costs through more efficient use of space (Guindon and Zhang, 2005). Cluster housing, as in Welgevonden Estate and De Zalze Estate, promotes spatial and civic integration, although the latter merit is a debated issue (National Research Council, 2009). Growth in mixed-use areas signals a sustainable urban development path because mixed use encourages interaction, spatial integration of activities (which enables ease of access and greater modal choice) (Urban Land Institute, 2010), use of NMT and a reduction in VMT (which reduces energy consumption and GHG emissions) (Zhang, Wu and Sheng, 2011).

The strong gains in commercial and industrial land (28% and 8% respectively) are indicative of increases in economic and employment opportunities which have positive effects on the socio-economic sustainability of Stellenbosch. The significant increase (17%) in office space between 2000 and 2010 is largely attributable to growth of Technopark, the office and industrial park in south-western Stellenbosch. This has enhanced Stellenbosch's importance as a financial and innovation hub. This increase in office space in Stellenbosch can imply growth of economic opportunities, a better land use mix and more local work-related destinations as opposed to out-of-town destinations, thus reducing VMT and GHGs. Moreover, Technopark is located within a radius of 5 km from most major services (CBD, Stellenbosch Square and Stellenbosch University) and because it is a mixed-use development some trips will be intracomplex further reducing VMT and GHG emissions (Frank and Engelke, 2001). However, Technopark is inaccessible by public transport, which often encourages automobile use as a mode of transport to and from work, thereby increasing VMT and GHGs.

The analysis of LUC has revealed that some transitions in land use (e.g. cluster housing, mixed use, commercial use and industrial) have a positive bearing on the town's sustainability. The sustainability trajectory of office space is indeterminate as it is difficult to gauge the cost and benefits of office use in Stellenbosch. Conversely, the changes in open space, agriculture, informal settlements and transportation presage sustainable urban development. It is noteworthy that most of the growth occurred in the western (Kayamandi), southern (De Zalze Estate and Stellenbosch Square) and northern (Welgevonden Estate) parts of Stellenbosch (Figures 5.5 and 5.6), while the consumption of agricultural land and open space by urban uses, as well as the increases in other uses (i.e. smallholdings and vacant land) clearly indicate urban sprawl. The effects of LUC on sustainability are highlighted in the next section which considers the GLUM and LLUM of Stellenbosch.

### 5.7.2 Land use mix indexes

The GLUM index for Stellenbosch is relatively high at 0.74 and 0.72 in 2000 and 2010 respectively. This suggests relatively high heterogeneity of land use patterns as well as good spatial integration. According to Song and Rodriguez (2005), high GLUM denotes a high level of social integration and is a proxy for the vibrancy of a town's civic life. This does not reflect racial integration as Stellenbosch's land use still reflects the country's history of spatial segregation (Donaldson, Morkel and Paquet 2012; James, 2000; Naudé, 2008; Todes and Watson; 1986). Given that South Africa's post-apartheid spatial policy is geared toward integrated development, the GLUM index is useful for measuring the spatial as well as social integration of the country's towns.

Figure 5.7 shows the distribution of the LLUM index for 2000 and 2010. The areas that had a low (0.4 or less) LLUM in 2000 includes Technopark, Die Boord, Dalsig, Mostertsdrift and Uniepark. This points to a lack of diversity in land use, meaning high social, environmental and economic costs which presage unsustainable urban development. Note that in 2000 the De Zalze and Welgevonden areas were used for agricultural purposes (Figure 5.5). LLUM in this area increased significantly by 2010 with the transition of farmland to a residential golf estate and a residential estate, respectively (Figure 5.5). Thus, the LLUM index is not a good indicator of sustainable urban development in this particular area because it suggests that urban sprawl has a positive effect on sustainable urban development. Welgevonden has a consistent coverage of a high LLUM (>0.6) as opposed to De Zalze with large portions of low LLUM (<0.6). Therefore, Welgevonden is a much more sustainable form of urban growth as opposed to De Zalze because the former encourages social and spatial integration which helps to reduce the negative environmental and economic costs associated with urban development.

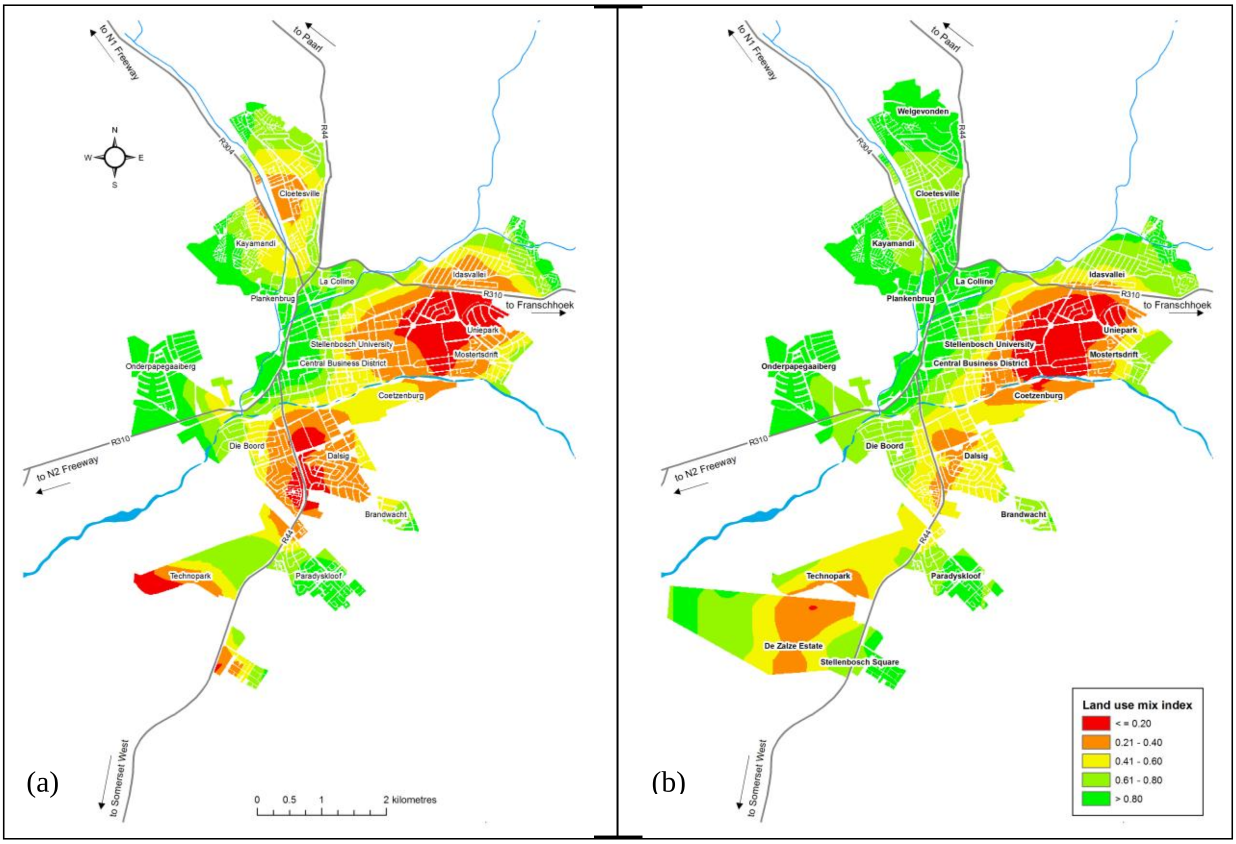



Figure 5.7: Distribution of the local land use mix (LLUM) index in Stellenbosch, (a) 2000 and (b) 2010

The LLUM in the Mostersdrift and Uniepark areas remained low from 2000 to 2010. Interestingly, the area with low LLUM seems to have spread towards Coetzenburg due to changes from residential to mixed use and the locating of the new Stellenbosch Institute of Advanced Study (STIAS) on the University's Mostertsdrift terrain. LLUM increased slightly in Die Boord with a number of office developments there. Areas that had consistently high (>0.6) LLUM for both dates include Kayamandi (western area), Plankenbrug, La Colline and Onderpapegaaiberg, suggesting that the diversity of land uses in these areas has low economic, social and environmental costs.

Kayamandi, a 'township' created for factory workers during apartheid, is relatively sustainable due to a high LLUM (>0.6) (Stellenbosch Municipality, 2011). This is due to the complementary land uses that occur in close proximity and the positive effect that this has on social networks (Frank and Engelke, 2001; Victoria Transport Policy Institute, 2010). For example, Kayamandi is within a 3-km radius of the Plankenbrug industrial area, a major source of employment in the area. It is also relatively close to the CBD, Kayamandi shopping mall and other amenities such as schools and churches. Although some concerns have been raised about Kayamandi's groundwater quality (Stellenbosch Municipality, 2011), some reduction in environmental costs can be inferred from the high level of land use mix usually associated with lower use of automobiles, which reduces GHG emissions. This is in stark contrast to large sections of Uniepark and Mostertsdrift which are highlighted as having a very low LLUM (<0.6). These high-income residential areas have few complementary land uses, which suggests less vibrancy (Frank, Andersen and Schmid, 2004). Consequently, residents are more likely to make extensive use of automobiles to access services, community facilities and employment. Distribution of the LUF used in calculating LUM is discussed next.

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### 5.7.3 Land use frequency

The maps of LUF for Stellenbosch (Figure 5.8) show slight increases between 2000 and 2010, particularly in the central and southern parts of the town. As with LLUM, the increase in LUF in the south can be attributed to the De Zalze Estate and Stellenbosch Square shopping centre developments. The LUF remained relatively constant in the rest of the town over the decade.

Visual comparison of Figures 5.7 and 5.8 provides evidence that LUF does not necessarily correspond to LLUM. For example, neighbourhoods abutting the CBD have a high (>10) LUF, but a low (<0.6) LLUM. This is because LLUM is affected by the proportion of area of land uses in a neighbourhood while LUF denotes number (count) of land uses. A large number of relatively small spatial units with different land uses will consequently produce a high LUF, but may produce a low LLUM if one large spatial unit is present. This makes LUF less reliable than LLUM for capturing diversity, isolation, distribution and clustering of land uses (Song and Rodriguez, 2005).

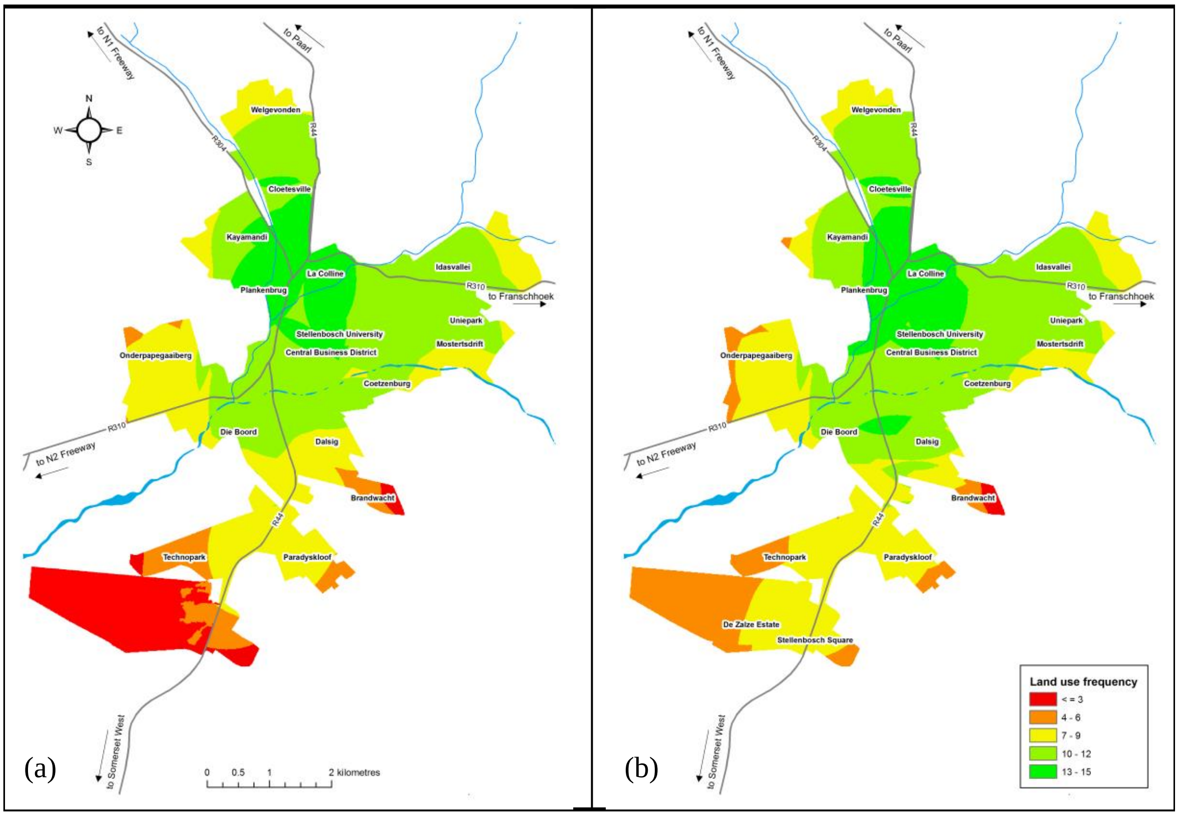


Figure 5.8: Land use frequency (LUF) distribution in Stellenbosch, (a) 2000 and (b) 2010

LLUM is consequently a good indicator of socio-economic costs associated with unsustainable land use. However, LLUM should not be used in isolation as it fails to incorporate urban sprawl, as demonstrated in the Stellenbosch Square (south) and Welgevonden (north) developments (Figure 5.6). Combined analysis of the LUC, LUM and LUF have important practical implications for land use planning.

## 5.8 PRACTICAL IMPLICATIONS AND CONCLUSION

Land use maps derived from EO data can be used to calculate GLUM, LLUM and LUF. These indicators can help local planning authorities to make better decisions regarding land use. The land use change analysis revealed that the informal settlements (in western Kayamandi) have grown significantly. Such developments are often associated with poor service delivery and living conditions and should be curtailed if Stellenbosch is to progress towards sustainable urban development. Moreover, the indicators suggested that cluster housing coupled with mixed-use developments are relatively sustainable, particularly in Welgevonden and Stellenbosch Square. The indicators can also be used as a basis to guide decisions on infill development to promote a better land use mix. For example, Mostertsdrift, with a low LLUM (<0.6), can be targeted for infill development with complementary land uses such as residential, with offices, hi-tech industrial and commercial uses. This approach is in line with Stellenbosch Municipality's infill policy (Stellenbosch Municipality, 2010).

This study introduced a new method for mapping LLUM and LUF as continuous surfaces. The maps were much easier to interpret than the traditional discrete outputs of such indexes. The study demonstrated that the observation of subtle changes in LLUM and LUF over time can assist in the identification of potential problem areas. Indicators such as LLUM and LUF can also help planners to produce sustainability reports that are less subjective and descriptive and they may serve as mechanisms to monitor interventions. The indexes are normalised, making them transferable to other areas and may even be used for comparing areas with one another. More research is needed to determine how these indexes can be used in combination with other sustainability indicators (e.g. Moran indexes, building density, height and impervious surfaces) to improve decision making. These indicators are required to confirm the environmental costs of unsustainable land use planning. The advent of very-high-resolution EO data such as GeoEye, WorldView-2 and Quickbird, as well as the continuous improvement of GIS analysis tools, will promote better monitoring of sustainable urban planning in developing countries.

## 5.9 REFERENCES

Addink, E A, Van Coillie, F M B and De Jong, S M (2012) Introduction to the GEOBIA: From pixels to geographic objects in remote sensing image analysis. *International Journal of Applied Earth Observation and Geoinformation* 15, 1-6.

Ardila, J P, Bijker, W, Tolpekin, V A and Stein, A (2012) Context-sensitive extraction of tree crown objects in urban areas using VHR satellite images. *International Journal of Applied Earth Observation and Geoinformation* 15, 57-69.

Anderson, J R, Hardy, E E, Roach, J T and Witmer, R E (1976) *A land use and land cover classification for use with remote sensor data*, United States Government Printing Office, Washington D.C.

Angel, S (2010) *Making room for a planet of cities*, Lincoln Institute of Land Policy, Massachusetts.

Barr, S and Ford, A (2010) Integrating urban remote sensing with GIS. In *Comparative Genetics Cities Workshop, 22 May 2010.* University of California, Berkeley, pp. 28-36.

Barredo, J I and Demicheli, L (2003) Urban sustainability in developing countries' megacities: Modelling and predicting future urban growth in Lagos. *Cities* 20 (5), 297-310.

Blaschke, T (2010) Object based image analysis for remote sensing. *ISPRS Journal of Photogrammetry and Remote Sensing* 65, 2-16.

Brandes, U, MacCleery, R, Peterson, J and Johnston, M (2010) *Land use and driving: The role compact development can play in reducing greenhouse gas emissions*, Urban Land Institute, Washington DC.

Breheny, P and Batey P W J (Eds) (1992) *Sustainable development and urban form* (2nd ed), Pion Limited, London.

Burton, E (2000) Measuring urban compactness in UK towns and cities. *Environmental Planning B: Planning and Design* 29, 219-250.

Calthorpe Associates (2010) *The role of land use in reducing VMT and GHG emissions: A critique of TRB special report 298*, Calthorpe Associates, Berkeley.

Campbell J B (2011) *Introduction to remote sensing* (5th ed.), Guilford Press, New York.

Canadian Urban Institute (2008) *Energy mapping study*, Canadian Urban Institute, Toronto.

Comber, A, Brunsdon, C and Green, E (2008) Using a GIS-based network analysis to determine urban green space accessibility for different ethnic and religious groups. *Landscape and Urban Planning* 86, 103-114.

CSIR (2010) *Land cover field guide*, Council for Scientific and Industrial Research, Pretoria.

Department of Rural Development and land Reform (2009) *Development of a methodology for national land use mapping for Chief Directorate: Geo Spatial Information*, Department of Rural Development and Land Reform, Cape Town.

Donaldson, R, Morkel, J and Paquet, T (2012) Urban spaces: The quartering of Stellenbosch's urban space. In M. Swilling, & B. Sebitosi (Eds.), *Sustainable Stellenbosch 2030,* SunMedia, Stellenbosch, pp. 11-18 .

Duro, D C, Franklin, S E and Dubé, M G (2012) A comparison of pixel-based and object-based image analysis with selected machine learning algorithms for the classification of agricultural landscapes using SPOT-5 HRG imagery. *Remote Sensing of Environment* 118, 259-272

*EikestadNuus* (2012) Bus service welcomed, 3 May 2012, pp 3.

Esch, T, Taubenböck, H, Heldens, W, Theil, M, Wrum, M, Geiss, C and Dech, S (2010) Urban remote sensing-how can earth observation support sustainable development of urban environments? In Proceedings *Cities for everyone. liveable, healthy, prosperous.* Real Corp, Vienna, pp 837-847.

Ewing, R and Cervero R *(*2001) *Travel and the Built Environment: A Synthesis*, Transportation Research Board, Washington DC

Ewing, R and Nelson, A (2008) *CO2 reductions attributable to smart growth in California,* National Center for Smart Growth Research and Education, University of Maryland, College Park.

Farrow, A and Winograd, W M (2001) Landuse modelling at the regional scale: An input into rural sustainability indicators in Central America. *Agriculture, Ecosystems and Environment* 85, 249-269.

Frank, L and Engelke, P (2001) The built environment and human activity patterns: Exploring the impacts of urban form on human health. *Journal of Planning Literature* 16, 202-218.

Frank, L D, Andersen, M A and Schmid, T I (2004) Obesity relationships with community design, physical activity and time spent in cars. *American Journal of Preventative Medicine* 27, 87-96.

Freeman, C (2004) Sustainable development from rhetoric to practice? A New Zealand perspective. *International Planning Studies* 9, 307-326.

Guindon, B and Zhang, Y (2005) Using satellite remote sensing to survey transport-related urban sustainability: Part 1: Methodologies for indicator quantification. *International Journal of Applied Earth Observation* 8, 149-164.

Gunder, M (2006) Sustainability: Planning savings grace or road to perdition. *Journal of Planning Education and Research* 20, 208-221.

Hall, O (2010) Remote sensing in social science research. *Open Remote Sensing Journal* 3, 1-16.

Hall, W L (2010) Decision consequence analysis: A paradigm for decision making. In Brown, K and Hall W l (Eds), *Sustainable land development and restoration: Decision consequence analysis.* Elsevier, Amsterdam, pp. 75-85.

Hay, G J and Castilla, G (2008) Geographic object-based image analysis (GEOBIA): A new name for a new discipline. In Blaschke, T J, Lang, S and Hay, G J (Eds.), *Lecture notes in geoinformation and cartography*. Springer, Berlin, pp. 75-89

Hicken, E (2009). The application of GIS at a local governmental level as a facilitation tool for sustainable development in rural Africa, Master's Thesis. Kingston University, London.

Holden, M (2008) The tough minded and the tender minded: A pragmatic turn for sustainable development planning and policy. *Planning Theory and Practice* 9, 475-496.

Huang, A, Wong, J and Chen, T C (1998) A framework of indicator system for measuring Taipei's urban sustainability. *Landscape and Urban Planning* 42, 15-27.

InterStudy (2009) *Stellenbosch University*. Retrieved 11/11, 2011, from http://www.interstudy.org/u/23-stellenbosch-university

Jabereen, R Y (2006) Sustainable urban forms: their typologies, models and concepts. *Journal of Planning Education and Research* 26, 38-52.

James, W J (2000) South Africa: Urban transformation. *Cities*, 17(3), 167-183.

Jones, C and MacDonald, C (2004) *Sustainable urban form and real estate markets*, Herriot -Watt University, Edinburg.

Klosterman, R E (1995) The appropriateness of geographic information systems for regional planning in the developing world. *Computers, Environment and Urban Systems* 19, 1-13.

Klosterman R E (2001) Urban planning: Methods and technologies. In Smelser, N J and Baltes, P B (Eds), *International encyclopaedia of the social and behavioural sciences*. Pergamon, Oxford, pp. 16055-16058.

Litman, T (2010) *Land use impacts on transport: How land use factors affect travel behaviour*, Victoria Transport Policy Institute, Vancouver.

Liu, Y (2009) *Modelling urban development with geographical information systems and cellular automata*, CRC Press, Boca Raton.

Maclaren, V W (2004) Urban sustainability reporting. In Wheeler, S M and Beatley, T (Eds), *The sustainable urban development reader.* Routledge, New York, pp. 2003-2010.

Musakwa, W and Van Niekerk, A (2012). Implications of land use mix on the sustainability of African urban centres: A case study of Stellenbosch, South Africa. *In Proceedings Real Corp, Schwechat, Austria, May 14-16, 2012*, pp 1237-1244

National Academy of Sciences (1998) *People and Pixels: Linking remote sensing and social science,* National Academy of Sciences, Washington DC.

National Academy of Sciences (2003) *Using remote sensing in state and local government: Information for management and decision making*, National Academy of Sciences, Washington DC.

National Research Council (2009) *Driving and the built environment: The effects of compact development on motorised travel, energy use and CO2 emissions,* National Academy of Sciences, Washington DC.

Naudé, W (2008) Is there a spatial mismatch in South Africa's metropolitan labour market? *Cities* 25 (5), 268-276.

NEAT GIS Protocols (2012) *Neighbourhood environment for active transport-geographic information systems version 5.2,* Design for health.net, Cornell University, New York.

NEAT GIS Protocols (2010) *Neighbourhood environment for active transport-geographic information systems version 5.1,* Design for health.net, Cornell University, New York.

Ness, P (2001) Urban planning and sustainable development. *European Planning Studies* 9, 503-525.

Nijkamp, P, Lasschuit, P and Soetmaan, F (1992) Sustainable development in a regional system. In Breheny, P and Batey, P W J (Eds), *Sustainable development and urban form*. Pion, London, pp. 39-66.

Polzin, S E (2006) The *case for moderate growth in vehicle miles of travel: A critical juncture in U.S. travel behaviour trends*, US Department of Transportation, Washington DC.

Qi, Z, Yeh, A G, Li, X and Lin, Z (2012) A novel algorithm for land use and land cover classification using RADARSAT-2 polarimetric SAR data. *Remote Sensing of Environment* 118, 21-39.

Renetzeder, C, Schindler, S, Prinz M A, Mucher, C A and Wrbka, T (2010). Can we measure ecological sustainability? Landscape pattern as an indicator for naturalness and land use intensity at regional, national and European level. *Ecological Indicators* 10, 39-48.

Repetti, A, Soutter, M and Musy, A (2005) Introducing SMURF: A software system for monitoring urban functionalities. *Computers, Environment and Urban Systems* 30, 687-707.

SA Statistics (2001) *Census 2001*. Retrieved 12/02, 2011, from http://www.statssa.gov.za/census01/html/WCPrimary.pdf

Sattler, C, Nagel, U J, Werner, A and Zander, P (2010) Integrated assessment of agricultural production practices to enhance sustainable development in agricultural landscapes. *Ecological Indicators* 10, 49-61.

Schaepman, M E (2007) Spectrodirectional remote sensing: From pixels to processes. *International Journal of Applied Earth Observation and Geoinformation* 9 (2), 204-223.

Schneider, A, Friedl, M A and Potere, D (2010) Mapping global urban areas using MODIS 500-m data: New methods and datasets based on 'urban ecoregions'. *Remote Sensing of Environment* 114 (8), 1733-1746.

Seghezzo, L (2009) The five dimensions of sustainability. *Environmental Politics* 18 (4), 539-556.

Shen, Y, Ochoa, J J, Shah, M N and Zhang, X L (2010) The application of urban sustainability indicators: a comparison between various practices. *Habitat International* 35, 17-29.

Song, Y and Knaap, G J (2004) Measuring urban form. *Journal of the American Planning Association* 70, 210-225.

Song, Y and Rodriguez, D A (2005) *The measurement of the level of mixed land uses: A synthetic approach*, Carolina Transportation Program, Chapel Hill.

Stellenbosch Municipality (2011) *Stellenbosch municipality integrated development plan*, Stellenbosch Municipality, Stellenbosch.

Stellenbosch University (2010) *Fast fact statistics 2010*, Stellenbosch University, Stellenbosch.

Todes, A and Watson, V (1986) Local government reform, urban crisis and development in South Africa. *Geoforum* 17 (2), 251-266.

UN-HABITAT (2009) *Habitat partner university network.* Retrieved 07/07, 2010, from http://www.unhabitat.org/content.asp?typeid=19&catid=570&cid=6002

UN-HABITAT (2002) *Sustainable urbanisation: Achieving Agenda 21*, UN-HABITAT, Nairobi.

United Nations Environmental Program (2011) *Making the economic case for greening cities*. Retrieved 12/11, 2011, from http://www.unep.org/newscentre/default.aspx?DocumentID=2656&ArticleID=8895

Urban Land Institute (2010) *Land use and driving: The role compact development can play in reducing greenhouse gas emissions*, Urban Land Institute, Washington DC.

Van der Merwe I J, Ferreira, S L A and Zietsman, H L (2005) Growth Potential of towns in the Western Cape, Centre for Geographical Analysis, Stellenbosch University, Stellenbosch.

Van Niekerk, A, Donaldson, R, Du Plessis, D and Spocter, M (2010) *A revision of the 2004 growth potential of towns in the Western Cape study: Discussion document*. Stellenbosch University, Stellenbosch.

Victoria Transport Policy Institute (2010) *Land use impacts on transport: How land use factors affect travel behaviour.* Retrieved 08/09, 2011, from www.vtpi.org/landtravel.pdf

Wang, J, Cheng, Q and Chen, J (2011) A GIS and remote sensing based analysis in land use change using asymmetric relation analysis method: A case study from the city of Hangzhou, China. *Mathematical Geosciences* 43, 435-453.

Weng, Q (2012) Remote sensing of impervious surfaces in the urban areas: Requirements, methods, and trends. *Remote Sensing of Environment* 117, 34-49.

Western Cape Department of Environmental Affairs and Development Planning (2009) *Western Cape provincial spatial development framework.* Retrieved 04/16, 2010, from http://www.capegateway.gov.za/other/2009/9/settlement_restructuring_explanatory_manual_mar_09_final.pdf .

Winograd, M and Farrow, A (2007) Sustainable development indicators for decision making: Concepts, definition and use. Retrieved 10/10, 2010, from http://www.eolss.net/ebooks/Sample%20Chapters/C13/E1-46B-02.pdf .

Wolf, T and Meyer, B C (2010) Suburban scenario development based on multiple landscape assessments. *Ecological Indicators* 10, 74-86.

World Bank (1994) *Making development sustainable,* World Bank, Washington DC.

WCED (1987) *Our common future,* World Commission on Environment and Development, Oxford.

Yang, J, Zhao, L, McBride, J and Gong, P (2009) Can you see green? Assessing the visibility of urban forests in cities. *Landscape and Urban Planning* 91 (2), 97-104.

Zhang, X, Wu, Y and Shen, L (2011) An evaluation framework for the sustainability of urban land use: A study of capital cities and municipalities in China. *Habitat International* 35, 141-149.

# CHAPTER 6: MONITORING URBAN SPRAWL AND SUSTAINABLE URBAN DEVELOPMENT USING THE MORAN INDEX: A CASE STUDY OF STELLENBOSCH, SOUTH AFRICA

Musakwa, W and Van Niekerk, A. (2013). Monitoring urban sprawl and sustainable urban development using the Moran index: a case study of Stellenbosch, South Africa**.** *International Journal of Applied Geospatial Research.* Accepted for publication**.**

**Abstract**

The management of urban sprawl is fundamental to achieving sustainable urban development. Monitoring urban sprawl is, however, challenging. This study proposes the use of two spatial statistics, namely global Moran and local Moran to indentify statistically significant urban sprawl hot and cold spots. The findings reveal that the Moran indexes are sensitive to the distance band spatial weight matrices employed and that multiple bands should be used for these indexes. It is demonstrated how the indexes can be used in combination with various visualisation methods to support planning decisions.

**Keywords**: urban sprawl, global Moran I, local Moran *I,* distance band, spatial cluster and outlier, sustainable urban development

## 6.1 INTRODUCTION

Urban sprawl is a fundamental theme in the sustainability debate (Zhao et al., 2011) and the literature often equates sprawl with unsustainability (Le Néchet, 2011). What is unsustainable about urban sprawl is its wasteful forms so that future generations can be deprived as a result of dwindling resources used to make way for urban expansion (Gerundo & Grimaldi, 2011). If urban growth is to continue it should be sustainable rather than wasteful (Ewing, 1997; Veneri, 2010). Planners have accordingly adopted the use of geographic information systems (GIS) and earth observation (EO) data to identify wasteful forms of urban sprawl commonly referred to as hot spots (Levine, 1996; Liu, Dong & Chi, 2010). Most GIS packages are able to do this by providing summary statistics such as means, sums and medians. However, such statistics cannot easily be transferred to different locations making it difficult to compare various urban centres. Moreover, visual representations of such results are also known to be misinterpreted (Zhang et al., 2008). What is required are new software and exploratory data analysis techniques that focus on the spatial aspects of the data such as dispersion, concentration and spatial autocorrelation which can be used to capture the impacts of urban sprawl on urban sustainability (Le Néchet, 2011). This provides a scientific basis for improved sustainable land use planning. Similar analyses have been successfully carried out for pollution (Zhang et al., 2008), conflict (Anselin, 1995), disease (Ruiz et al, 2004; Zhang & Lin, 2006) and crime management (Anselin et al., 2000; Lin & Brown, 2006).

Concerning urban sprawl, a search on Science Direct, Scopus and Web of Science databases[7] indicates that Tsai (2005) was the first to apply the global Moran index (Moran I) to distinguish urban sprawl from compactness. Similar studies citing Tsai (2005) ensued, such as Gerundo & Grimaldi (2011), Le Néchet (2011), Sim & Mesev (2011), Zhao et al. (2011) which employed global Moran index (Moran I) and other metrics to distinguish between urban sprawl and compactness in European, American and Asian cities. Moran I has attracted interest from researchers and planners because it is apparently more robust than other metrics (Bhatta, Saraswati & Bandyopadhyay, 2010). No studies exist that have applied the global Moran and local Moran indexes with cluster and outlier analysis to cadastral data to determine sprawl hot spots and cold spots. This study investigates the use of these indexes with GIS software and cadastral data to identify urban sprawl hot spots. Moreover, the impact of various simulations (weights) of the indexes is explored and the practical implementation of this process in policy change and decision making toward sustainable urban development is investigated.

## 6.2 URBAN SPRAWL

The debate on measuring and monitoring urban sprawl continues unabated (Bhatta, Saraswati & Bandyopadhyay, 2010). However, there is consensus that urban sprawl is primarily characterised by three attributes, namely leapfrog and scattered development, commercial strip development and large expanses of low-density or single-use development (Frenkel & Ashkenazi, 2008; Sayas, 2006; Sims & Mesev, 2011; Tsai, 2005). Leapfrog development, strip and low-density development do not necessarily equate to unsustainable urban development. Consequently, it is a matter of degree and the impact of the development that make various types of urban sprawl unsustainable (Ewing, 1997; Vaz et al., 2012). For example, a housing development may leapfrog a rock outcrop and have a mix of uses which support non-motorised transport (NMT), promote accessibility, reduce vehicle miles travelled (VMT), and encourage social interaction. Such developments are unlikely to be unsustainable forms of urban sprawl (Le Néchet, 2011). It is the quantifiable and related impacts that that constitute urban sprawl (Ewing, 1997).

The literature identifies poor accessibility as one of the most important indicators of urban sprawl (Cervero, 2002; Irwin & Bockstael, 2007). Accessibility implies that urban

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[7] Search done on 02 April 2012. The search was on 'Moran index' filtered to 'urban sprawl'.

development patterns are spatial and that accessibility can be quantified by indicators such as VMT (Le Néchet, 2011). Other urban sprawl indicators include lack of functional open space, visual aesthetics, spatial geometry and densities (Hayek et al., 2011; Schwarz, 2010).

Poor accessibility impacts household travel patterns. Recent studies demonstrate that average trip length and travel time which impact greenhouse gas (GHG) emissions increase with the poor accessibility associated with urban sprawl (Urban Land Institute, 2010). For example, in some low-density single-use developments everything is far apart as a consequence of the separation of land uses, leading to increased trip lengths (Irwin & Bockstael, 2007). Gore (1993) argues that a gallon of gasoline can be used just driving to get a gallon of milk.

An important urban development problem related to accessibility is lack of functional open space. It is difficult to preserve large open spaces in low-density developments where the emphasis is on subdividing every piece of land, leaving little space for community use or the creation of elite social enclaves (Ewing, 1997; Frank & Engelke, 2001). Furthermore, lack of functional open space normally entails deprived visual aesthetic stimulation, reduced biodiversity support and ineffective flood control (Giarrusso, 2003). Residential areas in many cities in developing countries are located far from areas of economic opportunity, and they have little or no functional open spaces and basic services: the result of pre-independence urban planning policies (Western Cape Department of Environmental Affairs and Development Planning, (WCDEADP 2009). Convalescing such types of planning will perhaps lead to better accessibility and ultimately gains in urban sustainability.

Another indicator of urban sprawl is spatial geometry which determines the configuration and composition of the urban landscape (Frenkel & Ashkenazi, 2008). Urban sprawl’s geometric configuration is usually irregular, scattered or fragmented (Sims & Mesev, 2011), whereas composition refers to homogenous land use and segregation of land uses. Measures to classify geometry and composition include leapfrog measures and the land use mix index.

Besides spatial geometry, densities are probably the most common and widely studied measures of urban sprawl (Huang, Lu & Sellers, 2007). Density is the ratio between the quantity of an urban activity, for example buildings or population, and the area within which the activity takes place (Angel, 2010; Burton, 2002). In South Africa, very low building densities of less than 30 buildings per hectare signify a sprawling pattern (WCDEADP, 2009). Although the above indicators do denote urban sprawl, they have to be quantified and measured or scaled to determine the impact of urban sprawl on sustainable urban development. Various studies have been undertaken to determine how these indicators impact urban sustainability (Burton, 2002; Urban Land Institute, 2010).

### 6.2.1 Urban sprawl and sustainable urban development

Urban sprawl is inevitable, especially given the high rate of urbanisation in many developing countries, and it is not necessarily a detrimental phenomenon. It is the inefficient forms and adverse costs of urban sprawl, namely environmental and socio-economic costs, which are deemed unsustainable (Hall, 2010). Environmental costs include increases in VMT, loss of natural resources, increases in energy consumption and air pollution. Socio-economic costs include increases in infrastructure and public services costs, decay in city centres and psychic and social costs which are deemed unsustainable (Ewing, 1997).

Concerning the adverse environmental effects of urban sprawl, recent studies have demonstrated the link between VMT and accessibility. Evidence suggests that households in most accessible locations spend 40 minutes less per day travelling than households in the least accessible locations (Victoria Transport Policy Institute, 2010). This results in cost savings as well as lower GHG emissions. Furthermore a study of 34 European cities found that an increase in density implies that trips get shorter while the share of transit and other modes of transport increases (Le Néchet, 2011). Equally important is the impact of urban sprawl on energy consumption because sprawl affects travel patterns and energy consumption in buildings (Canadian Urban Institute, 2008). Findings point out that as people and buildings continue to be spread across urban space, as measured by average distance between two individuals, energy efficiency is reduced (Newman & Kenworthy, 1999). Le Néchet (2011) has concluded that per capita fuel consumption for motor vehicles is much lower in compact cities than in low-density sprawling cities, even though fuel efficiency is less (Bigazzi & Burtini, 2009; Zhao, Lu & de Roo, 2011).

There is consensus that vehicle emissions increase with VMT and decrease with average operating speed (Bigazzi & Burtini, 2009). These findings confirm that compact development is more sustainable than urban sprawl given the latter’s effect on increasing GHGs which contribute to global warming. Recent studies in Canada report that despite compact and dense developments having a high energy demand[8] compared to low-density areas, they allow energy power plants to run at maximum efficiency and they also ensure better return on investment (Canadian Urban Institute, 2008). Notable findings emerged after the USA reduced its GHG emissions by decreasing the carbon content of fuels and through investments that assisted in reducing energy intensity. These include new compact developments and innovative changes to urban planning guidelines (Transportation Research Board, 2009; Urban Land Institute, 2010). The argument that compact development, in contrast to urban sprawl, reduces harmful environmental costs has gained momentum owing to the increased supply of good-quality data and processing tools. There is agreement that compact development, compared to indiscriminate urban sprawl, is the planning practice that best respects people and the environment (Mubareka et al., 2011; Schwarz, 2010). This view challenges Gordon & Richardson's (1997) contention that urban growth in any form, including low-density and scattered single-use developments is not much different from the supposed sustainability benefits of compact developments.

As for infrastructure and service costs, per capita infrastructure costs tend to fall as densities increase but tend to rise in sprawling low-density areas (Glaeser & Kahn, 2004; Song & Zenou, 2006). At very-high densities these economies of scale diminish so that specific thresholds have to be met, for example limiting densities to 60 buildings per hectare (Urban Land Institute, 2010). Ewing (1997) found that leapfrog developments that bypass suitable land for residential developments raise costs considerably. Other costs which can be incurred include travel and defraying costs to taxpayers. In addition, dense developments provide a steady revenue source that covers costs of energy infrastructure and amortises infrastructure costs (Zhao, 2010, 2011).

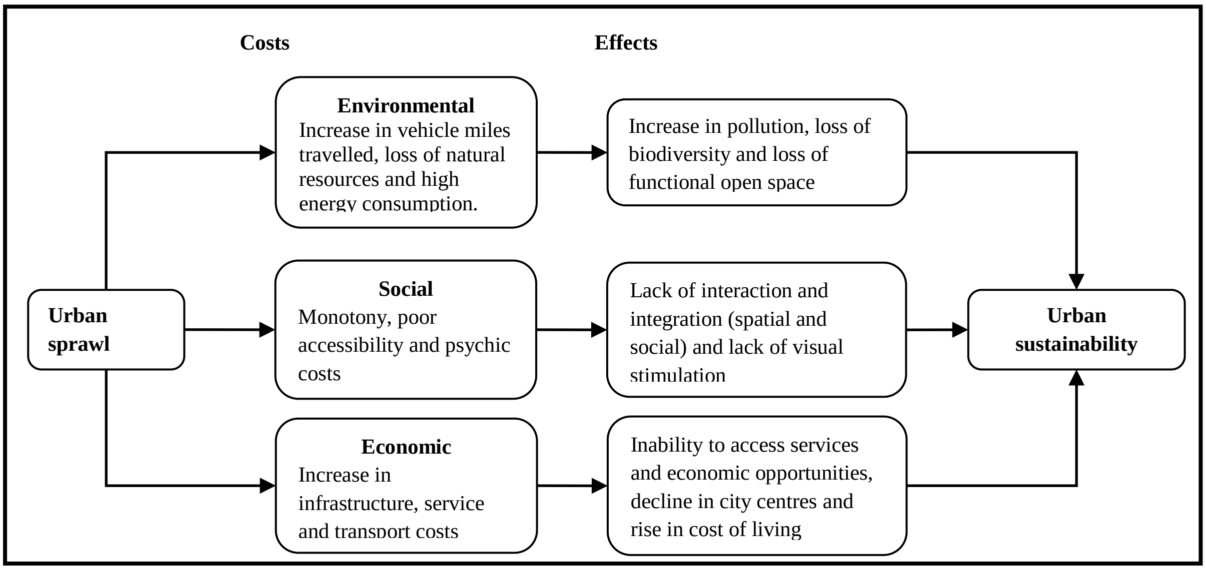
Urban sprawl not only raises infrastructure costs but also escalates the psychic and social costs (Vaz et al., 2012; Wu, 2006). These costs are difficult to measure as they relate to deprivation of access and environmental delight. Deprivation of access is about lack of access to facilities, services and employment for those without cars (Ewing and Cervero, 2001; Stone, 2008). This severely affects the young, the old and the poor. In contrast, environmental deprivation is the absence of elements that provide activity and stimulation

[8] Energy demand or consumption is measured in gigajoules/hectare (GJ/ha). A high GJ/ha (greater than 3000) is associated with dense development while a low GJ/ha (lower than 300) is associated with low-density developments.

(Brown et al., 2009). Studies indicate that urban sprawl's uniformity deprives residents of interaction compared to compact developments that allow social vibrancy (Eid et al, 2008). This is a characteristic of cities in developing countries such as South Africa (Poulsen, 2010).

Urban sprawl also induces loss of natural resources (Angel, 2010). If urban expansion results in rapid losses of flora and fauna, farmland, protected areas and areas of national heritage, they ought to be curtailed as they lead to an impoverishment of resources for future use (Vaz et al., 2012). To minimise loss of resources, planning regulations should be enforced along with raising the awareness of the need for the conservation of natural resources.

Finally, urban sprawl can lead to the decline of city centres as new developments favour out-of-town locations (Glaeser & Kahn, 2004; Song & Zenou, 2006). For example, developments north of Durban's Central Business District (CBD), South Africa, have attracted far more development than central Durban has (EThekwini Municipality, 2007). Similarly, in Harare, Zimbabwe, there has been a flight of capital from the CBD to the north-eastern part of the city, leaving the CBD to invasion by informal businesses (Muronda, 2008). Such developments can lead to inner-city decline as jobs become located farther away and, moreover, they discourage social and spatial mixing because they promote the creation of social enclaves. In summary, urban sprawl impacts on urban sustainability through its wasteful forms, which have unfavourable effects for contemporary and future generations (Figure 6.1).




Sources: Adapted from Ewing (1997), Urban Land Institute (2010)

Figure 6.1: Urban sprawl and its impacts

Measuring and monitoring the environmental and the socio-economic costs of urban sprawl is challenging. The advent of EO and GIS tools has provided a range of techniques that could potentially be used for this purpose (Frenkel & Ashkenazi, 2008; Schwarz, 2010). However, most of these techniques capture the negative effects of sprawl visually, but remain uninformative regarding the statistical significance of what they visualise (Zhang & Lin, 2006; Zhang et al., 2008). Moreover, urban planners, particularly in sub-Saharan Africa, have a long history of using exploratory data analysis which ignores the spatial aspects of data despite urban planning and urban sprawl being essentially spatial processes (Mabogunje, 1990; Sayas, 2006). The field of exploratory spatial data analysis (ESDA) which takes into account spatial aspects of data, may offer a solution. Anselin (2012) defines ESDA as a "collection of techniques to describe and visualise spatial distributions, identify atypical locations or outliers, discover patterns of spatial heterogeneity" (p. 137). Urban planners have adopted ESDA and GIS to derive statistics which rigorously quantify spatial relationships (spatial distribution and spatial autocorrelation[9]) so that conclusions can be drawn to facilitate decision making (Anselin & Getis, 1992). These statistics can be used as indicators of urban sprawl.

## 6.3 INDICATORS OF URBAN SPRAWL

Urban sprawl indicators should be able to capture the various adverse effects of the different dimensions of urban sprawl. Urban sprawl indicators should be able to locate urban sprawl hot spots (Sayas, 2006), be statistically significant (Tsai, 2005) and distinguish between a cluster and an outlier (Zhang & Lin, 2006). Several GIS mapping techniques have been used to identify hot spots, but many are not statistically significant (Zhang et al., 2008). The global Moran I and local Moran *I* indexes have been shown to be more effective in detecting urban sprawl hot spots, clusters and outliers (Table 6.1) than other indicators such as the Tango index and spatial scan statistics which tend to have a bias toward positive autocorrelation (Zhang & Lin, 2006). Furthermore, global Moran I characterises different aspects of urban sprawl (e.g. density or leapfrogging), which means that separate indexes are not required. This also eliminates the need for synchronisation and weighting of different indexes (Tsai, 2005).

[9] Spatial autocorrelation refers to dependency among observations. Positive spatial autocorrelation means similar observations in space are located next to each other. Conversely, negative spatial autocorrelation implies dissimilar values among neighbours in space (Anselin, 1995).

Table 6.1: Selected indicators of urban sprawl

| Indicator | Unit of measurement | Analysis scale | Significance and thresholds |
|---|---|---|---|
| Global Moran I | -1 to 1 | Global | A value close to 1 denotes compactness, which is highly sustainable, a value close to 0 indicates random scattering, while -1 denotes a dispersed pattern, which is highly unsustainable. |
| Local Moran *I* | A positive value denotes spatial clustering and a negative value indicates presence of outliers. | Neighbourhood | HH and HL denote hot spots, which are relatively unsustainable, whereas LL and LH denote cold spots that are relatively sustainable. |
| Spatial cluster and outlier identification | High-high (HH), low-low (LL), low-high (LH) and high-low (HL). HH and LL are spatial clusters while LH and HL are outliers. | | |

Sources: Adapted from Anselin (1995) and Anselin et al. (2000)

### 6.3.1 Global Moran I

The global Moran I dates from 1948 as a measure of spatial autocorrelation which quantifies the spatial association between the same variable in neighbouring locations (Moran, 1948). Positive spatial autocorrelation arises when neighbouring areas have similar variable values, while negative spatial autocorrelation occurs when the values of neighbouring areas vary considerably (Anselin, 1995). Global Moran I is expressed as:

$$\mathrm{I} = n\frac{n}{S_o}\frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{i,j}\, z_i\, z_j}{\sum_{i=1}^{n} z_i^2} \qquad \text{(Equation 6.1)}$$

where $z_i$ is the deviation of an attribute for feature *i* from its mean; $w_{i,j}$ is the spatial weight between feature *i* and *j*; *n* is the total number of features; and $S_o$ is the aggregate of the weights[10] (ESRI, 2010). Moran I ranges from -1 to 1 with 1 indicating strong positive spatial autocorrelation (i.e. clustering of similar values), 0 indicates random spatial ordering and -1 indicates strong negative spatial autocorrelation (i.e. a checkerboard pattern) (Moran, 1948). Concerning urban sprawl, global Moran I can be used to determine the level of compactness or density of land parcels in an urban area by taking into account a feature's location and its value (area) in an urban area. It evaluates whether land parcels are clustered, dispersed or randomly scattered (Tsai, 2005). A high positive value indicates close clustering of sub-areas

[10] The weights can be in row-standardised form for ease of interpretation and the sets can be set to equal weights.

or land parcels, a value of zero indicates random scattering (Tsai, 2005), while -1 represents scattered, dispersed or checkerboard patterns of development of land parcels. A positive value denotes sustainability, whereas a negative value denotes unsustainability due to its associated high environmental and social-economic costs (Figure 6.2).

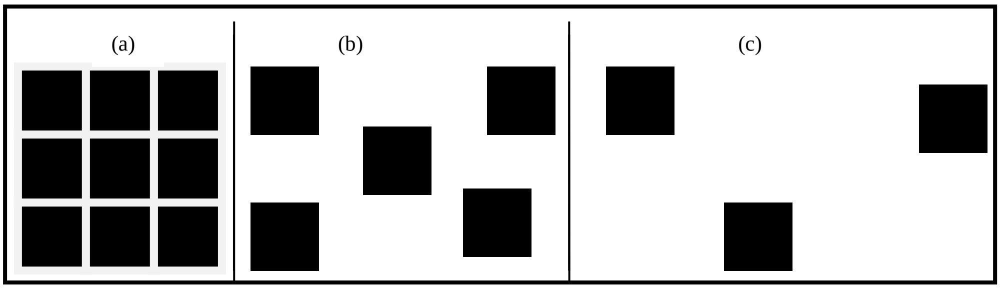



Figure 6.2: Illustration showing (a) clustered development (Moran I close to 1); (b) random scattering (Moran I close to 0); and (c) dispersed development (Moran I close to -1)

When interpreting results of global Moran I, it must be noted that it is an inferential statistic and has to be interpreted within the context of its null hypothesis (Anselin, 2003; ESRI, 2010). The null hypothesis states that the spatial processes promoting the observed pattern of values are random[11].

### 6.3.2 Local Moran *I*

Unlike global Moran I which evaluates the overall level of spatial autocorrelation in an urban area and assumes homogeneity, local Moran *I* is a local indicator of spatial autocorrelation (LISA) and shows the level of spatial autocorrelation at various individual locations within an urban area (Anselin, 1995). Local Moran *I* is therefore a decomposition of global Moran I. Conversely, global Moran I is a summation of individual cross-products of local Moran *I* (Anselin, 1995; 2003; Anselin et al., 2000). Local Moran *I* is expressed as:

$$I_{i} = z_i \sum_j w_{ij} \quad z_{ji} \qquad \text{(Equation 6.2)}$$

where observations $z_i$ and $z_j$ are deviations from the mean and the summation over $j$ only includes neighbouring values where j ≠ i are included (Anselin, 1995). The weight $w_{ij}$ can be determined using a distance band and is normally in row-standardised form (Anselin, 2003). Unlike global Moran I, local Moran *I* does not range between -1 and +1. However, a positive value still implies positive spatial autocorrelation (clusters) and a negative value indicates negative spatial autocorrelation (outliers) (Zhang et al., 2008). The distribution of

[11] If the p-value is greater than 0.05 the result is not statistically significant and the null hypothesis cannot be rejected (i.e. the observed spatial pattern is due to chance).

these clusters and outliers can be shown in a Moran scatter plot, which has four quadrants (Figure 6.3).

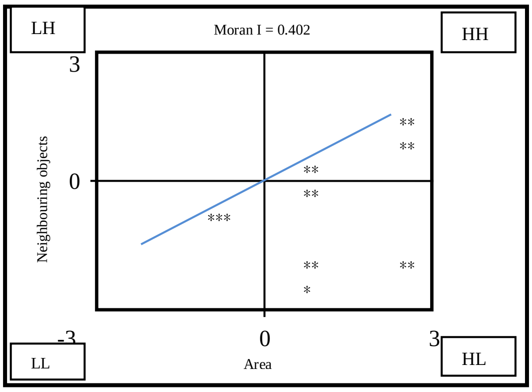
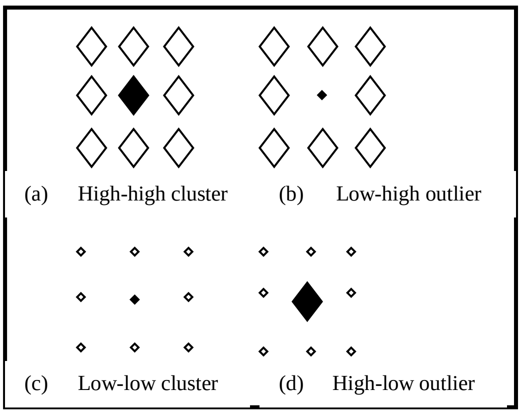



Figure 6.3: Example of a Moran scatter plot

The x-axis of the scatter plot represents the standardised values (area) of the geographical object (cadastral unit) and the y-axis measures the mean standardised values of neighbouring objects. The upper-right quadrant of the scatter plot contains the cases where the geographical objects and their neighbours have high values (i.e. relatively large extents). These so-called high-high (HH) situations are associated with clusters. The lower-left quadrant shows cases where the geographical objects and their neighbours are relatively small (i.e. a low-low or LL situation) which also signifies clustering. The lower-right quadrant contains the high-low (HL) cases while low-high (LH) cases are shown in the upper-left quadrant (Anselin, 1995; 2003; 2005). The latter two quadrants (LH and HL) represent outliers. HH cases are referred to as grouped hot spots and LL cases as grouped cold spots (Figure 6.4), whereas HL and LH are referred to as individual hot spots and cold spots, respectively (Anselin, 2005).




Source: Adapted from Zhang et al. (2008)

Figure 6.4: Relationships between locations and neighbourhoods, where (a) and (c) represent spatial clusters; (b) and (d) spatial outliers; (a) and (d) hot spots; and (b) and (c) cold spots.

The HH, HL, LH and LL cases can be mapped to better understand the spatial distribution of hot and cold spots and to see where clustering occurs. When applied to land parcel (cadastral) data, this type of visualisation helps in the identification of areas with a concentration of large land parcels (hot spots) and areas with a large concentration of small land parcels (cold spots). Areas classified as HH are characterised as having sprawling low-density land parcels (Table 6.2) that are located close together (spatial clustering), while a HL classification is indicative of low-density land parcels close to high-density[12] developments (spatial outliers). In contrast, high-to-medium density land parcels close to each other occur in areas classified as LL, while high-to-medium density land parcels close to low-density land parcels are classified as LH (Figure 6.4).

Table 6.2: Typology of land parcel sizes

| Land parcel | Size | Characteristics |
|---|---|---|
| Low density | Large land parcels of approximately 75 m x 365 m | One house or building per plot, with private front and back garden |
| Medium density | Narrow land parcels with a frontage of 10 m to 15 m. The length varies. | Can be single storey, double storey, detached or semi-detached. |
| High density | Narrow land parcels with small street frontage of 5 m to 7 m | Predominantly single-storey row houses; may also be apartments |

Source: Adapted from Western Cape Department of Environmental Affairs and Development Planning (2009)

Analogous to global Moran I, local Moran *I* and cluster and outlier identification are inferential and have to be interpreted using the null hypothesis which states that the observed spatial pattern is random (Anselin et al., 2000; Anselin, Sybari & Kho, 2006).

This paper explores the use of global Moran I and local Moran *I* to describe the relationships between the size and location of land parcels as key identifiers of urban sprawl hot spots and cold spots in Stellenbosch, South Africa.

## 6.4 METHODS

The study area and period, data collection as well as preparation and analysis are discussed in the following sub-sections.

[12] Land parcels larger than 800 $m^2$ are generally regarded as low density, 400-800 $m^2$ as medium density and less than 400 $m^2$ as high density.

### 6.4.1 Study area

Stellenbosch, a university town in the Western Cape province of South Africa, is located approximately 55 km east of Cape Town’s CBD (Figure 6.5). The N1 and N2 freeways link Stellenbosch and Cape Town via R44. The town is located between latitude -33.9333° (33°55’59.88”) South and longitude 18.8500° (18°51’) East.

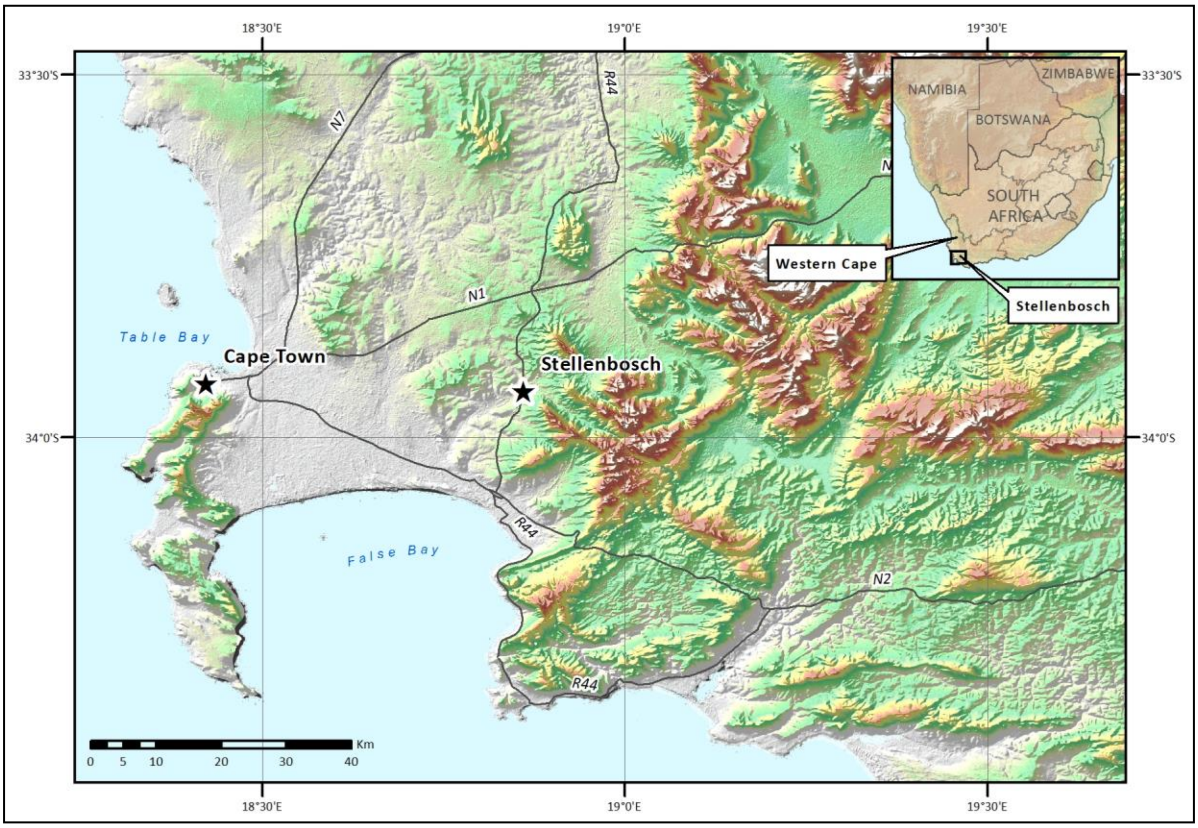



Figure 6.5: Location of Stellenbosch within the South-Western Cape

Stellenbosch is an appropriate study area as it has developed rapidly over the last two decades. Its population increased from 60 000 in 2001 to 90 000 in 2010 at a mean annual growth rate of 8.5% (InterStudy, 2009; SA Statistics, 2001; Stellenbosch University, 2010). The town is well known for the world-class Stellenbosch University which forms a distinct part of the urban fabric and contributes to the town’s cultural heritage. The economy has also witnessed a transition from servicing a rich agricultural hinterland to a diversified economy based on niche sectors such as tourism, finance, science and technology, the latter two ably supported by the university (Stellenbosch Municipality, 2011). This diversity of economic activities is largely why Stellenbosch was rated as one of the six non-metropolitan settlements in the Western Cape with a very high development potential (Van Niekerk et al., 2010). Stellenbosch thus faces the daunting challenge of balancing urban and economic growth with expansion into and consumption of valuable agricultural land, and the preservation of its natural and cultural heritage. Identifying sprawl patterns in Stellenbosch can help planners to mitigate the negative impacts of urban sprawl.

### 6.4.2 Data collection, preparation and analysis

Very-high resolution (0.5 m) orthorectified colour aerial photographs of Stellenbosch were obtained from the Chief Directorate: National GeoSpatial Information for 2000 and 2010. Multispectral (10 m) and panchromatic (2.5 m) SPOT5 imagery were acquired from the South African National Space Agency (SANSA). The SPOT imagery was pre-processed (orthorectified and subjected to atmospheric and radiometric corrections) in PCI Geomatica. To demarcate the built-up urban extent, a land cover classification was performed on the processed SPOT imagery using supervised geographical object-based image analysis (GEOBIA) in eCognition software. The urban extent was used for visual interpretation to separate predominantly urban land uses from agricultural uses and to map new urban developments which have consumed agricultural land use since 2000. Cadastral data for 2000 and 2010 was obtained from the Centre for Geographical Analysis (CGA).

GeoDa (version 1.0.1) was selected for calculating global Moran I and local Moran *I* because it provides a wide range of functions (e.g. spatial weights construction, sensitivity analysis and visualisation) and it is relatively easy to use (i.e. no programming is required) (Anselin, Sybari & Kho, 2006). GeoDa is also compatible with the popular ESRI ArcGIS software suite (ESRI Inc, 2010) which was used for the spatial analyses and mapping. When calculating the indexes, distance band spatial weight matrices (SWMs) of 1 km[13], 1.5 km and 2 km were created to test the impact of various distance bands on the results. Distance band refers to sphere of influence or moving window used to define spatial relationships of the data (ESRI Inc, 2010). There is no specific criterion for choosing distance bands, but they should not be longer than half of the study area's length[14] (Zhang et al., 2008). The SWMs were row-standardised to ensure that results of global Moran I do not fall outside the -1 to 1 range (ESRI Inc 2010). SWMs were created using the weights function (threshold distance) in GeoDa. Polygon centroids and Euclidian distances were used to conceptualise the SWMs.

[13] The minimum cut-off distance where each polygon had a neighbour was 1 km and it was determined automatically by invoking the create weights function in GeoDa.
[14] Stellenbosch stretches 9 km from north to south and the maximum distance band chosen was 2 km which is within the range of not exceeding half the distance of the study area.

The extent (area) of land parcels and unique polygon IDs were used to calculate the indexes and to create the SWMs (ESRI Inc, 2010). Rate smoothing, using the empirical Bayes (EB) function in GeoDa was employed to calculate the indexes so as to prevent potentially biased results (Anselin, 2003). In addition, a significance level of < 0.05 was set in GeoDa to calculate the indexes.

Execution of local Moran *I* analyses (at all distance bands) in GeoDa created new attribute fields (local Moran *I*, p value, as well as cluster and outlier type (COT)). Local Moran *I* and COT with a p value of > 0.05 was regarded as statistically insignificant. COT was mapped and visually displayed in ArcGIS 10 to show the spatial distribution of the hot and cold spots of urban sprawl. Cross-tabulation techniques in ArcGIS were used to show the percentage change in the distribution of the urban sprawl hot and cold spots. To test the sensitivity of global Moran I to leapfrogging, the index was recalculated after the removal of such areas.

## 6.5 RESULTS AND DISCUSSION

The following sub sections discuss application of the global Moran, local Moran and the sensitivity of the Moran indexes in monitoring urban sprawl in Stellenbosch.

### 6.5.1 Global Moran I analysis

Table 6.3 summarises the global spatial autocorrelation of Stellenbosch cadastral units at all distance bands.

Table 6.3: Change in global Moran I from 2000 to 2010

| Distance band (kilometres) | Moran I 2000 | Moran I 2010 | Moran I 2010 (excluding leapfrogged areas) |
|---|---|---|---|
| 1 | 0.008 | 0.002 | 0.010 |
| 1.5 | 0.005 | 0.002 | 0.007 |
| 2 | 0.001 | 0.001 | 0.006 |

Over the ten-year period there was minimal change, the global Moran I values of close to 0 indicating a pattern of random scattering. Tsai (2005) and Le Néchet (2011) observed that a global Moran I value of close to 0 represents a discontinuous or less compact pattern of urban development which tends to increase the environmental, social and environmental costs that presage unsustainable development (Tsai, 2005). The almost cross-shaped or wing-shaped nature of the urban extent of Stellenbosch (see Figure 6.6) contributes to this pattern and makes the provision of transit services difficult. It also reduces connectivity between sub-areas (Glaeser & Kahn, 2004; Song & Zenou, 2006).

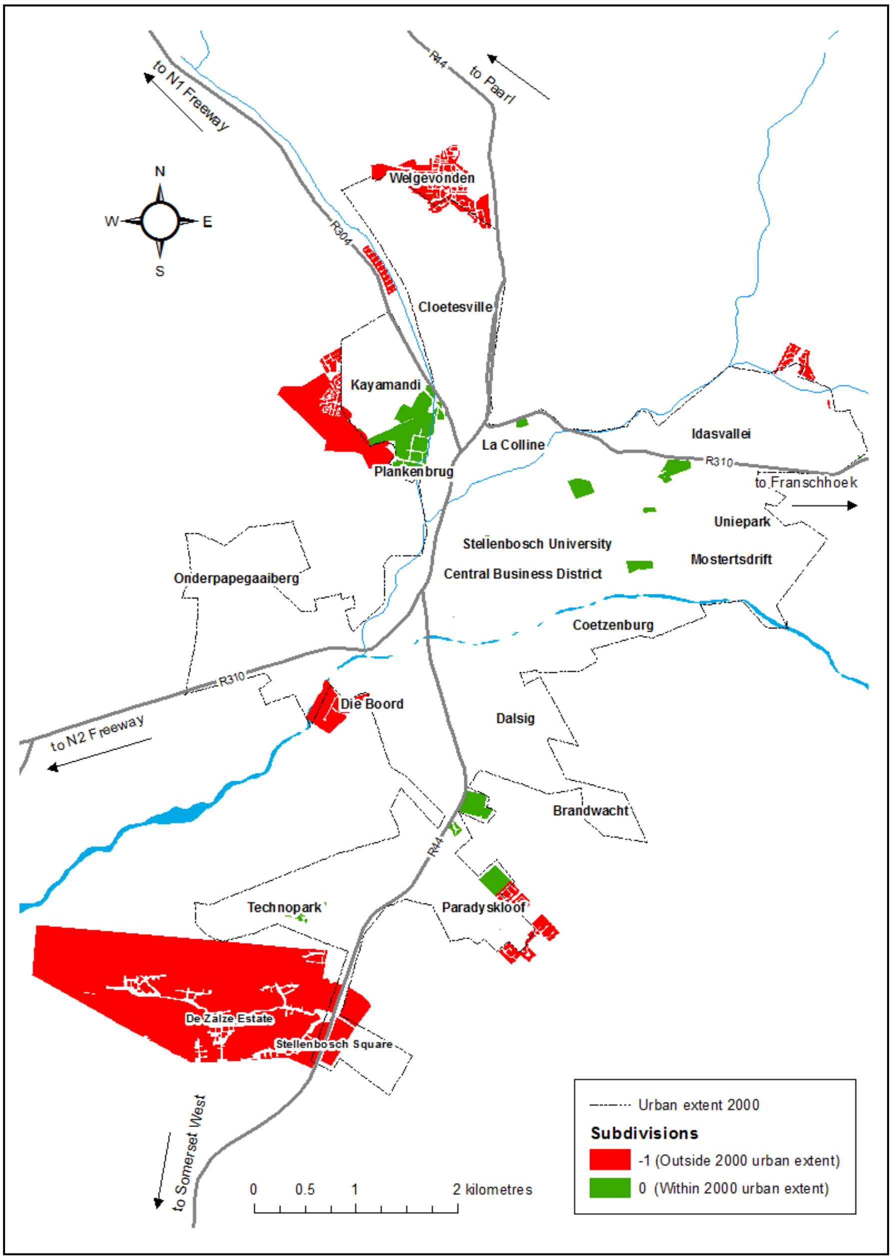



Figure 6.6: Distribution of new subdivisions in Stellenbosch

Sprawling leapfrog developments near De Zalze, Paradyskloof and Stellenbosch Square (see Figure 6.7d) reinforce the discontinuous nature of Stellenbosch. Interestingly, when these leapfrog areas are eliminated from the analysis for 2010, the global Moran I values increase slightly by 0.006 which shows that the global Moran I is sensitive to such developments. The ability of the index to respond to minor differences in urban structure demonstrates that it is an effective and practical tool for urban sprawl monitoring at town or city levels (Tsai, 2005). However, because it is an overall estimate, it does not show the spatial distribution of sprawl within the town, a feature which is of practical importance to decision makers.

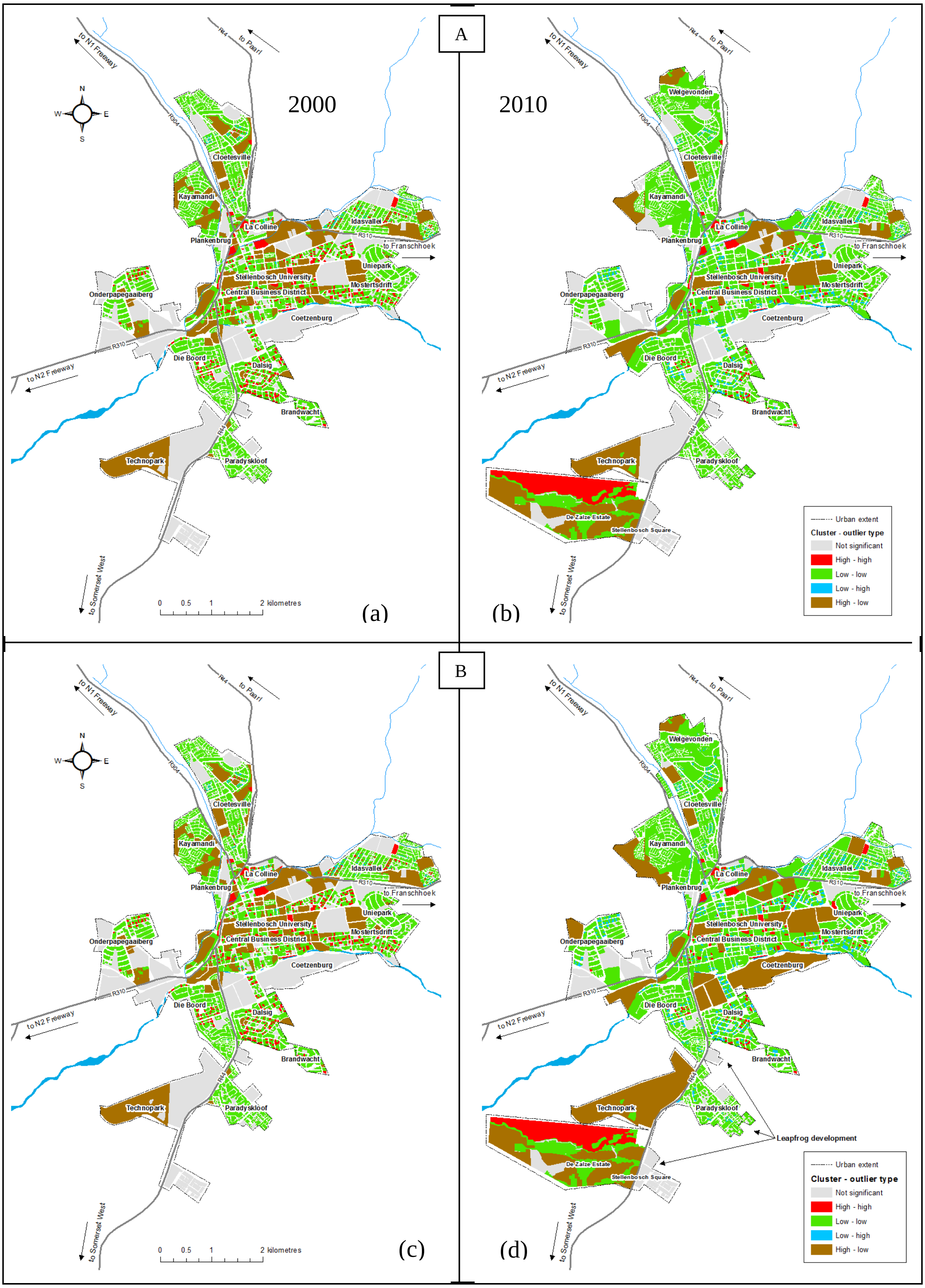



Figure 6.7: Hot and cold spot distribution in Stellenbosch using distance bands of 1 km (A), 1.5 km (B) for 2000 (a) and (c) and 2010 (b) and (d).

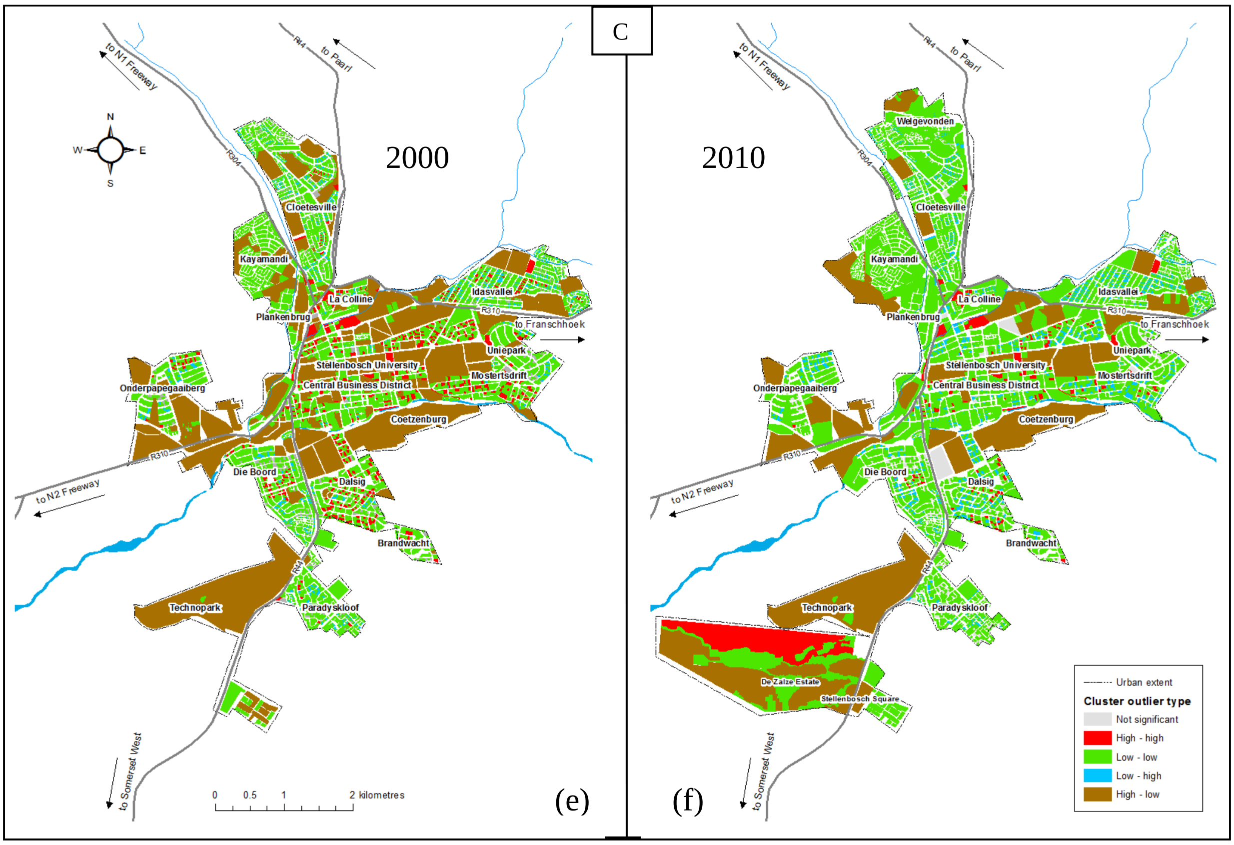



Figure 6.7 (*continued*): Hot and cold spot distribution in Stellenbosch using a distance band of 2 km (C), (e) 2000 and (f) 2010.

### 6.5.2 Local Moran *I* analysis

Table 6.4 gives the overall areas of the hot and cold spots expressed as percentages. Between 2000 and 2010, there was an overall increase in the cold spots and a decrease in the hot spots for all distance bands (except when using a 1.5km distance band), likely due to new developments and cadastral subdivisions (Figure 6.6).

Table 6.4: Percentage hot and cold spots for 2000 and 2010 calculated using three distance bands (1, 1.5, and 2 km)

| | 1 km | | | 1.5 km | | | 2 km | | |
|---|---|---|---|---|---|---|---|---|---|
| | Area and change (%) | | | Area and change (%) | | | Area and change (%) | | |
| | 2000 | 2010 | Change | 2000 | 2010 | Change | 2000 | 2010 | Change |
| **Hot spots** | 30.83 | 26.45 | -4.38 | 30.84 | 37.72 | 6.88 | 58.19 | 41.24 | -16.95 |
| **Cold spots** | 36.12 | 48.77 | 12.65 | 36.13 | 52.23 | 16.10 | 39.90 | 56.43 | 16.52 |
| **Not significant** | 33.04 | 24.78 | -8.27 | 33.03 | 10.05 | -22.98 | 1.91 | 2.34 | 0.43 |

The spatial distribution of hot and cold spots within Stellenbosch is shown in Figure 6.7, while Table 6.5 differentiates the share of hot and cold spots occurring inside and outside the 2000 urban edge. When a 1-km distance band is used, some 52% of the developments outside the 2000 urban extent can be considered wasteful forms of urban sprawl (HH and HL COT). Only 32% of this area was classified as having LL and LH COT which indicate efficient utilisation of space. The proportions remain similar when 1.5-km and 2-km distance bands are used.

Table 6.5: Percentage hot and cold spots within and outside the 2000 urban extent calculated using three distance bands (1, 1.5, and 2 km)

| | **1 km** | | **1.5 km** | | **2 km** | |
|---|---|---|---|---|---|---|
| | **Percentage of area** | | **Percentage of area** | | **Percentage of area** | |
| | **Outside 2000 urban extent** | **Within 2000 urban extent** | **Outside 2000 urban extent** | **Within 2000 urban extent** | **Outside 2000 urban extent** | **Within 2000 urban extent** |
| **Hot spots** | 52.25 | 12.01 | 52.25 | 12.01 | 63.46 | 12.01 |
| **Cold spots** | 31.59 | 61.05 | 32.47 | 62.99 | 35.70 | 87.76 |
| **Not significant** | 16.16 | 26.94 | 15.29 | 25.00 | 0.84 | 0.23 |

It is clear from these results that some developments are unsustainable. For example, the new De Zalze housing estate presages unsustainable urban development as its extent is covered by a majority (57%) of hot spots (HH and HL COT) and only 23% cold spots (LL and LH COT) using a 2-km distance band (Figure 6.7f). In contrast, using the same distance band, Welgevonden Estate consists of a majority (92%) cold spots (LL and LH COT), mainly due to its overall compactness. Decision makers should promote urban growth like that of Welgevonden as it ensures more efficient use of space. Cluster outlier analysis seems to be a very useful measure for distinguishing between sustainable and unsustainable urban sprawl. It is recommended that the local Moran *I* be used in combination with global Moran I because it enables visualization of the COT distribution of the urban sprawl hot and cold spots.

Table 6.6 shows the changes in clusters and outliers between 2000 and 2010. A negative change in HH clusters was recorded from 2000 and 2010 for all distance bands, while a positive change was observed for LL clusters. This result is attributed to land parcel intensification as supported by the large proportion (61% to 88% depending on the distance band) of new subdivisions within the 2000 urban extent of Stellenbosch classified as cold spots (Table 6.5).

Table 6.6: Changes in clusters and outliers from 2000 to 2010 calculated using three distance bands (1, 1.5, and 2 km)

| | 1 km | | | 1.5 km | | | 2 km | | |
|---|---|---|---|---|---|---|---|---|---|
| | Area and change (%) | | | Area and change (%) | | | Area and change (%) | | |
| | 2000 | 2010 | Change | 2000 | 2010 | Change | 2000 | 2010 | Change |
| High-high | 6.33 | 6.17 | -0.16 | 6.34 | 6.25 | -0.09 | 7.43 | 6.30 | -1.14 |
| Low-low | 35.68 | 46.75 | 11.07 | 35.69 | 49.00 | 13.32 | 37.59 | 52.21 | 14.63 |
| Low-high | 0.45 | 2.02 | 1.58 | 0.45 | 3.23 | 2.78 | 2.31 | 4.21 | 1.90 |
| High-low | 24.50 | 20.28 | -4.22 | 24.50 | 31.46 | 6.97 | 50.76 | 34.94 | -15.81 |
| Not significant | 33.04 | 24.78 | -8.27 | 33.03 | 10.05 | -22.98 | 1.91 | 2.34 | 0.43 |

Figure 6.7 shows that significant changes from LH to LL occurred in central Stellenbosch, mainly because of new cold spot (high-density) developments in Plankenbrug, Paradyskloof, Cloetesville, and Welgevonden – all within a 6-km radius from Stellenbosch CBD. It is clear that the change in clusters and outliers is strongly influenced by the proximity of neighbours to each other. If neighbours are close to one another, the change is likely to be higher compared to when they are farther apart. This seems to indicate that Stellenbosch is experiencing an increase in sustainable developments. Parcel intensification is known to have a positive effect on sustainable urban development. This alters and reshuffles the overall cluster and outlier distribution in Stellenbosch. For example, Figure 6.7 shows that at all distance bands there is a significant change in central Stellenbosch from LH to LL as a consequence of land parcel intensification.

### 6.5.3 Effects of weight matrices

It is evident from Figure 6.7 and Table 6.4 that increasing the distance bands[15] from 1 km, 1.5 km to 2 km reduces the number of insignificant land parcels (p value above 0.05) from 33% to 2% in 2000 and 24% to 2% in 2010. Percentages are similar for 1 km and 1.5 km distance bands, while a 2-km distance band produced significantly different values. This seems to indicate that there is no optimal distance band. Therefore, multiple distance bands should be employed so that the general patterns that emerge should facilitate decision making.

[15] Distance bands determined in GeoDa where the minimum cut-off distance where every land parcel had a neighbour was 1 km.

Figure 6.7c (2-km distance band) appears to produce the most meaningful results as the number of insignificant land parcels is minimal (2%). However, a high level of significance does not necessarily mean that the result is more valuable. It simply indicates that the number of parcels within the distance band was large enough to produce a statistically significant result. This increase in significance is achieved at a cost of detail, as a larger distance band produces more generalised results. There are, however, patterns that emerge at all distance bands. For instance, there are more cold spots for new subdivisions within the 2000 urban extent than outside. Conversely, there are more hot spots for new subdivisions outside the 2000 urban extent. This indicates wasteful forms of urban sprawl which should be reduced if sustainable urban development is to be achieved. Even with increasing distance bands the CBD is abutted in 2000 by individual LH cold spots and HL hot spots which had diminished in intensity by 2010. Similarly, De Zalze, Technopark and western Kayamandi are identified as hot spots.

## 6.6 PRACTICAL IMPLICATIONS AND CONCLUSION

This research found that the global and local Moran indexes are useful tools for monitoring the sustainability of towns and cities. As Venable (2012) insists, “you cannot manage what you do not know or measure” (p. 1). Accordingly, this study demonstrates that by using global Moran I the overall level of urban sprawl in a town can be determined. At all distance bands, the global Moran I value for Stellenbosch is close to 0 which signals a discontinuous and less compact pattern of development. However, using global Moran I alone is not very useful for identifying problematic areas within a town or city and should be complemented by a local Moran *I* analysis which enables spatial visualisation of the urban sprawl hot and cold spots. Local Moran *I*, specifically spatial visualisation of COT, assists planning authorities and decision makers to identify the location of sprawl hot spots so as to develop mitigatory measures, attain local targets, learn from best practices, model future scenarios and effect policy changes.

In the attainment of local targets and the development of mitigatory measures, cluster and outlier analyses can be used to direct densification and infill strategies, particularly in areas with large proportions of HH land parcels. Such a densification approach is in line with Stellenbosch Municipality’s infill policy (Stellenbosch Municipality, 2010). However, the use of land parcels alone is insufficient as the density of development on each parcel is not taken into account (e.g. a parcel may be vacant). Other data, such as building footprints and heights, is required for more accurate densification analyses. There are also other land use considerations, such as heritage sites or open spaces, which should be taken into account when interpreting the Moran indexes. But generally, cluster and outlier analysis is very useful and can be employed to promote settlement restructuring that encourages a mixture of land parcel sizes. This promotes sustainability as it encourages both social and physical integration which ensures that complementary uses are located in close proximity. Mixing sizes of land parcels allows for a mix of income groups, thus preventing enclave formation within urban areas. For example, the De Zalze Estate and Technopark are dominated by an HL outlier type (Figure 6.7) and may require a rebalancing of land parcel sizes. It was found that most of the urban development outside the 2000 urban extent was classified as being sprawl hot spots and can consequently be considered wasteful. The only exception is Welgevonden which can be regarded as a best-practice model for sustainable urban growth because it consists of 92% cold spots.

This study also demonstrated that using global Moran I and local Moran *I* captures the various dimensions of urban sprawl, namely spatial geometry, low-density development and leapfrogging developments that make urban sprawl unsustainable due to the associated costs and wasteful forms. The findings show that removing leapfrogging developments from the analysis results in a positive change in global Moran I. Similarly, because of the cross-shaped geometry of Stellenbosch's urban extent, global Moran I values at all distance bands are close to 0. Moreover, the significant changes in the Stellenbosch CBD were attributed to property subdivisions. The research also showed that the use of different distance bands had an effect on the results. Consequently, simulations at different distance bands are vital if local authorities wish to identify problematic areas.

The global Moran I and local Moran *I* can be applied in urban centres of any size to plan for sustainable urban growth and to make efficient use of space. It is recommended that various visualisation methods be used to better understand the distribution of hot spots and cold spots. More research is, however, needed to test the sensitivity of the Moran indexes in different contexts (e.g. metropolitan areas) and to find a surrogate for cadastral data in areas for which such data is unavailable. The use of very-high resolution EO data and remote sensing techniques should be investigated for the improved monitoring and managing of urban sustainability, particularly in developing countries where suitable spatial data is often unavailable.

## 6.7 REFERENCES

Angel, S. (2010). *Making room for a planet of cities*. Cambridge: Lincoln Institute of Land Policy.

Anselin, L. (1995). Local indicators of spatial association. *Geographical Analysis, 27*, 93-115.

Anselin, L., & Getis, A. (1992). Spatial statistical analysis and geographic information systems. *The Annals of Regional Science*, 26, 19-33.

Anselin, L., Cohen, J., Cook, D., Gorr, W. & Tita, G. (2000). *Spatial analysis of crime.* Retrieved January 6, 2012, from https://www.ncjrs.gov/criminal_justice2000/vol_4/04e.pdf

Anselin, L. (2003). *GeoDa 0.9 users guide*. Phoenix: Spatial Analysis Laboratory.

Anselin, L. (2005). *Exploring spatial data with GeoDa™: A workbook*. Phoenix: Spatial Analysis Laboratory.

Anselin, L., Sybari, I., & Kho, Y. (2006). GeoDa: An introduction to spatial data analysis. *Geographical Analysis*, 38, 5-22.

Anselin, L. (2012). From SpaceStat to CyberGIS: Twenty years of spatial data analysis software. *International Regional Science Review*, 35, 131-157.

Bhatta, B., Saraswati, S., & Bandyopadhyay, D. (2010). Quantifying the degree of freedom, degree of sprawl, and degree-of-goodness of urban growth from remote sensing data. *Applied Geography*, *30*, 96-111.

Bigazzi, Y. A., & Bertini, R. L. (2009). Adding green performance metrics to a transportation data archive. Paper presented at 88th Annual Meeting of the Transportation Research Board January, Washington DC.

Brown, B. B., Yamada, I., Smith, K. R., Zick, C. D., Kowaleski-Jones, L., & Fan, J. X. (2009). Mixed land use and walkability: Variations in land use measures and relationships with BMI, overweight, and obesity. *Health and Place*, *15*(4), 1130-1141.

Burton, E. (2002). Measuring urban compactness in UK towns and cities. *Environment and Planning B: Planning and Design*, *29*, 219-250.

Canadian Urban Institute. (2008). *Energy mapping study*. Toronto: Canadian Urban Institute.

Cervero, R. (2002). Built environments and mode choice: Toward a normative framework. *Transportation Research Part D*, *74*(4), 265-285.

Eid, J., Overman, H. G., Puga, D., & Turner, M. A. (2008). Fat city: Questioning the relationship between urban sprawl and obesity. *Journal of Urban Economics*, *63*(2), 385-404.

ESRI 2010 (Environmental Systems Research Institute). *Spatial autocorrelation.* Retrieved January 6, 2012, from http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?TopicName=Spatial_Autocorrelation_%28Morans_I%29_%28Spatial_Statistics%29

Ethekwini Municipality. (2007). *Ethekwini municipal report.* Durban*:* Ethekwini Municipality.

Ewing, R. (1997). Is Los Angeles style sprawl desirable? *Journal of American Planning Association, 63*(1), 107-127.

Ewing, R., & Cervero, R. (2001). Travel and the built environment: A synthesis. Washington DC: Transportation Research Board.

Frank, L., & Engelke, P. (2001). The built environment and human activity patterns: Exploring the impacts of urban form on human health. *Journal of Planning Literature, 16* (2), 202-218.

Frenkel, A., & Ashkenazi, M. (2008). Measuring urban sprawl: How can we deal with it? *Environment and Planning B: Planning and Design, 35*, 56-79.

GeoDa Centre. (2012). *Feedback from GeoDa users.* Retrieved May 10, 2012, from https://geodacenter.asu.edu/software/products

Gerundo, R., & Grimaldi, M. (2011). The measure of land consumption caused by urban planning. *International Conference on Green Buildings and Sustainable Cities, GBSC 2011,* Bologna.

Giarrusso, T. (2003). *Combating urban sprawl.* Atlanta: Environmental Systems Research Institute.

Glaeser, E. L., & Kahn, M. E. (2004). Sprawl and urban growth. In *Handbook of regional and urban economics* (pp. 2481-2527). Amsterdam: Elsevier.

Gordon, P., & Richardson, H. W. (1997). Are compact cities a desirable planning goal? *Journal of American Planning Association*, *63*(1), 65-105.

Gore, A. (1993). *Earth in the balance: Ecology and the human spirit*. New York: Penguin.

Haase, D., & Nuissl, H. (2010). The urban-to-rural gradient of land use change and impervious cover: A long-term trajectory for the city of Leipzig. *Journal of Land use Science, 5* (2), 123-141.

Hall, W. P. (2010). Decision consequence analysis: A paradigm for decision making. In *Sustainable land development and restoration: Decision consequence analysis* (pp. 75-85). Amsterdam: Elesevier.

Hayek, U. W., Jaeger, J. A. G., Schwick, C., Jarne, A., & Schuler, M. (2011). Measuring and assessing urban sprawl: What are the remaining options for future settlement development in Switzerland for 2030? *Applied Spatial Analysis and Policy*, *4*(4), 249-279.

Huang, J., Lu, X. X., & Sellers, J. M. (2007). A global comparative analysis of urban form: Applying spatial metrics and remote sensing. *Landscape and Urban Planning, 82*(4), 184-197.

InterStudy. (2009). *Stellenbosch university*. Retrieved November 11, 2011 from http://www.interstudy.org/u/23-stellenbosch-university

Irwin, E. G., & Bockstael, N. E. (2007). The evolution of urban sprawl: Evidence of spatial heterogeneity and increasing land fragmentation. *Proceedings of the National Academy of Science United States of America, 105* (52), 20673-20677.

Le Néchet, F. (2011). Urban spatial structure, daily mobility and energy consumption: A study of 34 European cities. *European Journal of Geography*. Retrieved February 4, 2012 from http:cybergeo.revues.org/24966

Levine, P. (1996). Spatial statistics and GIS: Software tools to quantify spatial patterns. *Journal of the American Planning Association*, *62* (3), 381-391.

Lin, S., & Brown, D. E. (2006). An outlier-based data association method for linking criminal incidents. *Decision Support Systems, 41*(3), 604-615.

Liu, L., Dong, X., & Chi, S. (2010). Quantitative delimitation of metropolitan areas based on a synthetic method: Case study in the Lanzhou metropolitan area. *Journal of Urban Planning and Development*, *136* (4), 357-364.

Mabogunje, A. L. (1990). Urban planning and the post-colonial state in Africa: A research overview. *African Studies Review*, *33*(2), 121-203.

Moran, P. A. P. (1948). Interpretation of statistical maps: Series B (methodological). *Journal of the Royal Statistical Society*, *10*(2), 243-251.

Mubareka, S., Koomen, E., Estreguil, C., & Lavalle, C. (2011). Development of a composite index of urban compactness for land use modelling applications. *Landscape and Urban Planning*, *103*(3-4), 303-317.

Muronda, T. (2008). Evolution of Harare as Zimbabwe's capital city and a major central place in southern Africa in the context of by Byland's model of settlement evolution. *Journal of Geography and Regional Planning, 1*(2), 34-40.

Newman, P., & Kenworthy, J. (1999). *Sustainability and cities*. New York: Island Press.

Poulsen, L. (2010). A room in the city: Strategies for accessing affordable accommodation. *Urban Forum, 21*, 21-36.

Ruiz, M. O., Tedesco, C., McTighe, T. J., Austin, C., & Kitron, U. (2004). Environmental and social determinants of human risk during a west Nile virus outbreak in the greater Chicago area, 2002. *International Journal of Health Geography, 3,* 8-26.

Sayas, J. P. (2006). Urban sprawl in the peri urban coastal zones of Athens. *The Greek Review of Social Research, 121*, 71-124.

SA Statistics. (2001). *Census 2001.* Retrieved February 2, 2011, from http://www.statssa.gov.za/census01/html/WCPrimary.pdf

Schwarz, N. (2010). Urban form revisited—Selecting indicators for characterising European cities. *Landscape and Urban Planning, 96*(1), 29-47.

Sims, S., & Mesev, V. (2011). Measuring urban sprawl and compactness: Case study Orlando, USA. *Proceedings of the 25th International Cartographic Conference*, Paris.

Song, Y., & Zenou, Y. (2006). Property tax and urban sprawl: Theory and implications for US cities. *Journal of Urban Economics, 60*(3), 519-534.

Stellenbosch Municipality. (2011). *Stellenbosch municipality integrated development plan.* Stellenbosch: Stellenbosch Municipality.

Stellenbosch University. (2010). *Fast fact statistics 2010.* Stellenbosch: Stellenbosch University.

Stone Jr., B. (2008). Urban sprawl and air quality in large US cities. *Journal of Environmental Management, 86*(4), 688-698.

Transportation Research Board. (2009). *Driving and the built environment the effects of compact development on motorized travel, energy use, and CO2 emissions.* (No. 298). Washington D.C: National Research Council.

Tsai Yu-Hsin. (2005). Quantifying urban form: Compactness versus sprawl. *Urban Studies, 42* (1), 141-161.

Urban Land Institute. (2010). *Land use and driving: The role compact development can play in reducing greenhouse gas emissions*. Washington DC: Urban Land Institute.

Van Niekerk, A., Donaldson, R., Du Plessis, D., & Spocter, M. (2010). *A revision of the 2004 growth potential of towns in the Western Cape study discussion document*. Stellenbosch: Stellenbosch University

Vaz, E., Cabral, P., Caetano, M., Nijkamp, P., & Painho, M. (2012). Urban heritage endangerment at the interface of future cities and past heritage: A spatial vulnerability assessment. *Habitat International, 36*(2), 287-294.

Venable, G. (2012). *You cannot manage what you do not measure*. Retrieved May 5, 2012, from http://www.ipeweek13.org/media/docs/2012_IntrotoManagementRelease.pdf

Veneri, P. (2010). Urban polycentricity and the costs of commuting: Evidence from Italian metropolitan areas. *Growth and Change, 41* (3), 403-429.

Victoria transport Policy Institute. (2010). *Land use impacts on transport: How land use factors affect travel behaviour*. Retrieved September 9, 2011, from www.vtpi.org/landtravel.pdf

Western Cape Department of Environmental Affairs and Development Planning. (2009). *Western Cape provincial spatial development framework.* Retrieved May 16, 2010, from http://www.capegateway.gov.za/other/2009/9/settlement_restructuring_explanatory_manual_mar_09_final.pdf

Wu, J. (2006). Environmental amenities, urban sprawl, and community characteristics. *Journal of Environmental Economics and Management, 52*(2), 527-547.

Zhang, T., & Lin, G. (2006). A supplemental indicator of high-value or low-value spatial clustering. *Geographical Analysis, 38*(2), 209-225.

Zhang, C., Luo, L., Xu, W., & Ledwith, V. (2008). Use of local Morans I and GIS to identify pollution hotspots of Pb in urban soils of Galway, Ireland. *Science of the Total Environment, 398,* 212-221.

Zhao, P. (2010). Sustainable urban expansion and transportation in a growing megacity: Consequences of urban sprawl for mobility on the urban fringe of Beijing. *Habitat International, 34*(2), 236-243.

Zhao, J., Song, Y., Shi, L., & Tang, L. (2011). Study on the compactness assessment model of urban spatial form. *Shengtai Xuebao/ Acta Ecologica Sinica, 31* (21), 6338-6343.

Zhao, P. (2011). Managing urban growth in transforming china: Evidence from Beijing. *Land use Policy, 28* (1), 96-109.

Zhao, P., Lu, B., & de Roo, G. (2011). The impact of urban growth on commuting patterns in a restructuring city: Evidence from Beijing. *Papers in Regional Science, 90* (4), 735-754.

Zhang, T., & Lin, G. (2006). A supplemental indicator of high-value or low-value spatial clustering. *Geographical Analysis, 38*(2), 209-225.

# CHAPTER 7: MONITORING SUSTAINABLE URBAN DEVELOPMENT USING BUILT-UP AREA INDICATORS: A CASE STUDY OF STELLENBOSCH, SOUTH AFRICA

Musakwa, W and Van Niekerk, A. (2012). Monitoring sustainable urban development using built-up area indicators: A case study of Stellenbosch, South Africa. *Habitat International*. Article under Review.

## Abstract

Rapid urbanisation in many developing countries causes land transformation from agricultural, rural, and natural landscapes into urban areas. Data to monitor this transformation is often out of date, unreliable, not in standard format, cumbersome and expensive to collect or simply unavailable. This inhibits local authorities and other stakeholders' capacity to monitor and leverage resources toward sustainable urban development. This paper investigates the use of earth observation (EO) data for supporting sustainable urban development planning. It proposes the use of decision consequence analysis (DCA) as a simple and structured way to put sustainable urban development into practice. The study demonstrates that EO adds value to sustainable urban development by providing area-wide and up-to-date thematic and geometric characterisation of the urban built-up area, which would be difficult to obtain from other data sources. This helps local planning authorities to monitor urban growth and sustainability, facilitate evidence-based decision making and an array of other practical uses.

**Keywords**: Sustainable urban development, building density, impervious surfaces, building height, earth observation

## 7.1 INTRODUCTION

The urban landscape is constantly experiencing spatial and temporal changes, particularly in developing countries experiencing high rates of urbanisation (Taubenböck and Esch, 2011; Taubenböck et al., 2011). This change affects the way cities are managed and how people live in harmony with nature (UNEP, 2011). Over the next 30 years people will continue to be absorbed into urban areas that will continue to grow both horizontally and vertically (UN-HABITAT, 2009). Pressure will mount on urban managers to gather data and information to effectively monitor and manage these changes in cities. Without this information, it will be difficult to achieve sustainable urban development.

The hyperchanging urban environment necessitates periodic collection of spatial data and information needed for urban planning (Taubenböck et al., 2010). In developing countries, data on the built-up area is often unavailable, inadequate, generalised, unstandardised, out of date and requires cumbersome processes to acquire (Santos et al., 2011). For example, the City of Harare does not have a GIS department, making it impossible to obtain area-wide data on the urban built-up area (Machakaire, 2012, pers com). Unlike the natural sciences where data and information are compiled and shared on a regular basis, information regarding cities in developing countries is often not compiled and shared, thus hindering decision making and our understanding of urban metamorphosis (Hall O, 2010; Wigbells, Faith and Sabathier, 2008). Accordingly, researchers in the new discipline of sustainability science are required to compile, compare and publish information on urban experiments in an attempt to facilitate better urban management (Clark, 2007). Earth observation's (EO) synoptic view is likely a solution to providing critical up-to-date and area-wide data on the built-up area in the rapidly changing cities of developing countries (Baud et al., 2010; Klosterman, 1995; Wrum et al., 2009). The aim of this paper is to investigate how to derive urban sustainability indicators (building density, building height and impervious surface concentration) from EO data. The practical implications for urban planning when using these indicators are also discussed.

The structure of the built-up area of a city is a result of socio-economic, environmental and political forces operating in the urban landscape (Wurm et al., 2009). These forces affect urban features such as building height (storeys), density of buildings (Erener 2012; Geiss et al., 2011), and the concentration of impervious surfaces (Lu and Weng, 2006). The ability to acquire information about these characteristics is often a function of the spatial, spectral and temporal resolution of the EO sensor and classification techniques used to extract the features from satellite imagery (Barnsley and Barr, 2000; Camps-Valls et al., 2012). Spatial resolution refers to the smallest possible feature detectable from an image or that a ground feature can be distinguished as a separate entity in an image (Jensen, 2005).

Table 7.1 shows that there has been a shift from sensors with low spatial resolution (80 m for Landsat-1) to very-high resolution (VHR) sensors (0.5 m for WorldView-2 and GeoEye-1) which promote the extraction of urban thematic features (land use and land cover), structural features (buildings and roads) and metric information (area, height and volume) in greater detail (Taubenböck et al., 2010; Taubenböck et al., 2011). Similarly, spectral capacities have improved from a limited four bands (Landsat-4) to multispectral (ASTER with 14 bands and MODIS with 36 bands) and hyperspectral (EO-1 with 224 bands) dimensions which enable the classification of a wide variety of urban surface materials (Satellite Imaging Corporation, 2012; Sobrino et al., 2012a). Temporal resolution is the time a sensor takes to revisit a previous location (Campbell, 2011). Table 7.1 shows how the temporal resolution of satellite sensors has improved from 18 to 2 days since 1972. However, improved spatial and spectral resolutions introduce difficulties such as shadows which obscure urban features and high intraspectral variation which reduces image classification accuracy (Esch et al., 2010).

Table 7.1: Selected earth observation sensors and specifications

| Sensor | Launch year | Spatial resolution (metres) | Spectral bands (number) | Temporal resolution (days) |
|---|---|---|---|---|
| Landsat-1 | 1972 | 80 | 4 | 18 |
| Landsat-4 | 1982 | 30 | 4 | 18 |
| SPOT2 | 1990 | 20 | 4 | 26 |
| Landsat-7 | 1999 | 30 | 7 | 16 |
| MODIS | 1999 | 250 | 36 | 2 |
| ASTER | 1999 | 15 | 14 | 16 |
| Ikonos | 1999 | 1 | 4 | 3 |
| EO-1 | 2001 | 30 | 224 | 16 |
| Quickbird | 2001 | 0.6 | 4 | 3 |
| SPOT 5 | 2002 | 10 | 3 | 3 |
| WorldView-2 | 2007 | 0.5 | 1 | 3 |
| GeoEye-1 | 2008 | 0.5 | 3 | 3 |

Source: Adapted from Satellite Imaging Corporation (2012)

Classification methods to extract information from VHR satellite imagery have evolved from pixel-based to object-based classification techniques (Nichol et al., 2007). Pixel-based classification involves allocating individual pixels to urban land cover on the basis of spectral features (Lu and Weng, 2006). However, the presence of mixed pixels results in spectral confusion that reduces the usability of the derived urban land cover data, particularly for impervious surfaces (Weng, 2012). The object-based approach (Hay and Castilla, 2008) partitions remotely sensed imagery into meaningful image-objects (groups of contiguous pixels) which promote the production of more accurate land cover data (Doxani, Karantzalos and Strati, 2012).

Emerging techniques for the classification and extraction of urban features include attribute analysis (Gamba et al., 2011; Ural, Hussein and Shan, 2011), artificial neural networks (Taubenböck et al., 2011 Taubenböck et al., 2012) and expert systems (Sobrino et al., 2012b). Data and image fusion (Qi et al., 2012) and contextual classification (Luo and Mountrakis, 2010) have also been employed in urban contexts. These have markedly improved the quality of the data obtained by reducing the negative effects associated with shadows and high intraspectral variations.

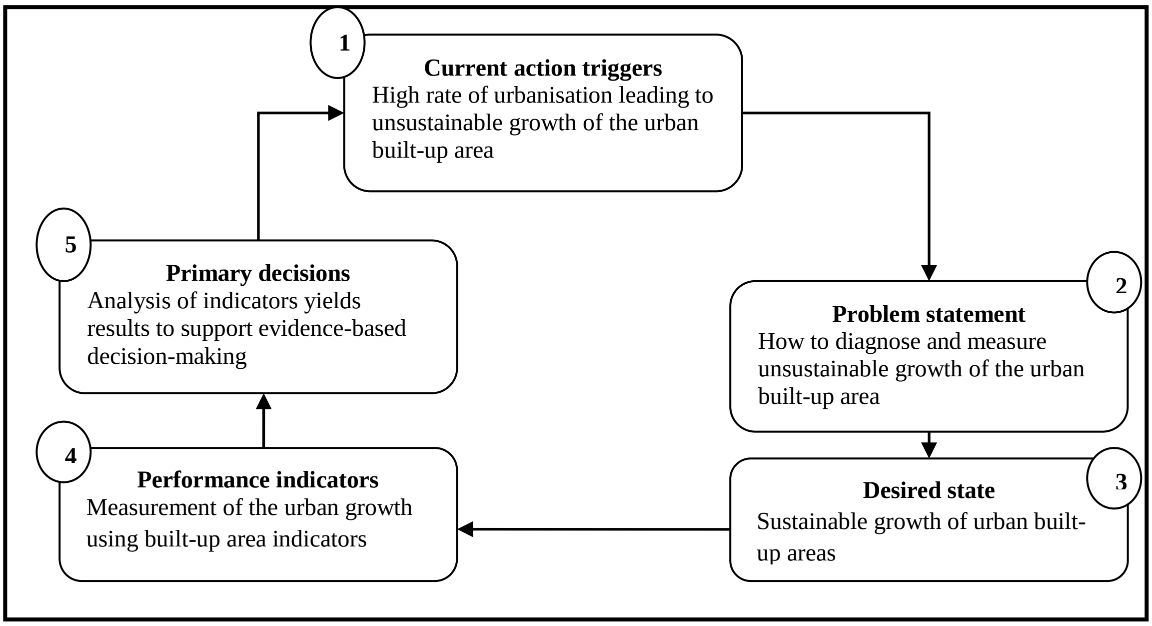
Although EO provides timely and relatively cost-effective data it does not automatically equate to useful information for urban planning. Therefore, EO data should be transformed into useful, structured, organised and summarised information to improve urban planners’ knowledge of complex urban landscapes and ultimately support decisions regarding sustainable urban development (Doxani, Karantzalos and Strati, 2012; Gomez-Chova et al., 2005; Taubenböck et al., 2012, Ural, Hussein and Shan, 2011; Gamba et al., 2011).

A number of studies exist on the use of EO data for supporting decisions regarding sustainable urban development. For instance, the Urban Atlas project in Europe provides harmonised land use and land cover data from satellite imagery for European cities with over 100 000 inhabitants. The Urban Atlas is a neutral and independent tool for monitoring the effects of urban structural changes resulting from land use and land cover change (Taubenböck and Esch, 2011). However, its major drawbacks are that the atlas data set is monotemporal and only covers European cities. Similarly, the Reduction of Land Consumption and for Sustainable Land Management (REFINA) project evaluates sustainable urban development in Germany using indicators derived from remotely sensed data (REFINA, 2012). Germany's urban planners use the REFINA tool to estimate the need for construction sites, to identify vacant land and as a source of information for planning decisions. However, the REFINA project is limited to land use and specific sites. The Centre for International Earth Science Information Network (CIESIN, 2009), the National Aeronautics and Space Administration (NASA, 2009), the German Aerospace Centre (Esch et al., 2010) and the Canada Centre for Remote Sensing are all involved identifying new urban remote sensing applications for sustainable urban development. This paper takes a different tack by seeking to develop indicators of built-up area urban sustainability from remotely sensed data and to investigate the practical implications for urban planning in rapidly urbanising cities in developing countries. Decision consequence analysis (DCA) is applied to assess sustainability of the urban built-up area.

## 7.2 SUSTAINABLE URBAN DEVELOPMENT AND DECISION CONSEQUENCE ANALYSIS

Sustainable development is defined by the WCED (1987) as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987, p. 23). Sustainable development is a noble but fuzzy concept which is difficult to put into practice for day-to-day decision making. Therefore, sustainable urban development should be able "to create and maintain dynamic feedback loops for decisions that accurately measure, allocate, and internalize costs in a manner that allows humans and nature to exist in productive harmony, while providing, within the unavoidable constraints of human nature, for the social, psychological, economic, and physical well-being of present and future generations" (Hall WL, 2010, p. 41).

DCA formalises decision-making by using decision theory, probability and statistics (Hall WL, 2010). It breaks down complicated problems, such as sustainable urban development, into increasingly smaller units until the particular component can be accurately analysed and understood within the context of the overall problem. DCA offers an alternative to the WCED narrative because it provides a structural model fundamental to decision making. The basic elements of DCA are an unacceptable current condition and a desired future condition. To achieve a transition between the two conditions it is necessary to understand each condition, to identify possible pathways between the two and a way to measure the progression between them (Figure 7.1).




Source: Adapted from Hall WL (2010)

Figure 7.1: Elements of decision consequence analysis

Unmonitored growth of the urban built-up area in many developing countries as a result of urbanisation often leads to negative socio-economic and environmental effects (Hall WL, 2001). Although much has been done to stifle or even reverse this trend, the main challenge is how to monitor progress from the current state (continuous growth of the built-up area) to the desired state or objective (sustainable urban growth) (Angel, 2010; Hall WL, 2010). The use of objective indicators developed from geographical information systems (GIS) and EO data is proposed in this study. Such indicators are usable as criteria for creating different urban growth scenarios and for supporting urban development decisions. For example, applying the indicators to decide whether to promote the containment paradigm based on intensification within the urban extent or to resort to the making room paradigm (Angel, 2010). The latter paradigm follows the notion that urban managers should prepare for sustainable urban growth and expanding cities based on realistic projections of urban land needs, selective protection of open space and generous metropolitan limits. These projections can only be made after analysis of built-up area indicators of sustainable urban development.

## 7.3 BUILT-UP AREA INDICATORS OF SUSTAINABLE DEVELOPMENT

Sustainability indicators are pointers toward progress in improving the overall health of a community, neighbourhood, town, city, region or larger area. Urban sustainability indicators reflect the general well-being of urban built-up areas and should be integratable, forward-looking (Huang, Wong and Chen, 1998; Maclaren, 2004), distributional and subject to feedback loops (Hall WL, 2010). Such indicators, particularly those relating to the built-up area of a settlement, are vital in the sustainability debate as they denote consequences of urbanisation and human–nature interaction (Vaz et al., 2012). Built-up area parameters that have been shown to specifically impact sustainable urban development are building height (McLennan, 2009; Yabuki, Miyashita and Fashida, 2011; Ding 2013), building density (Angel, 2010) and proportion of impervious surfaces (Nowak and Greenfield 2012; Weng, 2012). Built-up area indicators are also useful in deriving information such as population estimates (Almedia et al., 2011; Ural, Hussain and Shan 2011; Toure et al. 2012), particularly in the informal settlements commonly occurring in developing countries (Baud et al., 2010). Building density, height and impervious surface concentration are discussed next as indicators of sustainable urban development.

### 7.3.1 Building density

Building density refers to the number of building units per unit area (e.g. buildings per hectare) (Angel, 2010; Burton, 2002). It is an important measure of urban sustainability as medium-to-high building densities reduce the adverse environmental, social and economic costs of urbanisation (Ewing, 1997, Veneri, 2010). In South Africa, 20 or less building units per hectare (bu/ha) is regarded as low density, between 20 to 50 bu/ha medium density and greater than 50 bu/ha as high density (CSIR, 2010a; Mudau, 2010, Western Cape Department of Environmental Affairs and Development Planning, 2009).

Recent studies have demonstrated that although medium-to-high densities increase energy demand, they enable power-energy plants to run efficiently due to constant demand, thereby ensuring good returns on investment (Canadian Urban Institute, 2008). The Victoria Transport Policy Institute (2010) and Litman (2010) have commented on the positive relationship between medium-to-high densities and the reduction of costs of connecting infrastructure services, travel, travel time and energy (Frank et al., 2010; Le Néchet, 2012). Similarly, the Transportation Research Board (2009), Ewing and Nelson (2008), and the Urban Land Institute (2010) have reported that medium-to-high density developments encourage the use of public transit and other modes of transport, and they reduce vehicle miles travelled (VMT) (Bigazzi and Burtini, 2009). These assist in the reduction of greenhouse gas (GHG) emissions, an important indicator of sustainable urban development, and the mitigation of climate change. Recent empirical evidence indicates that, medium-to-high densities encourage more vibrant, diverse and walkable communities which all contribute to improved quality of life (Eid et al, 2008; Frank et al., 2006; Frank et al., 2010; Kligerman et al., 2007). Medium-to-high densities also promote efficient use of space, so minimising urban encroachment into natural ecosystems and agricultural landscapes (Jabereen, 2006; Jones and MacDonald, 2004; Ewing and Nelson, 2008).

These studies substantiate the standpoint that changes to urban planning policy regarding densification can provide a platform for meeting the social, economic and environmental conditions for sustainable urban development. It is noteworthy that when densities shift from high to very-high the returns on sustainable urban development efforts can diminish (Jabereen, 2006; Jones and MacDonald, 2004). For example, in some cases very-high densities (above 60 bu/ha) can be associated with congestion, pollution and high land prices in the most accessible locations leading, in turn to increased service costs (Ewing, 1997). However, the acquisition of up-to-date area-wide information on building density is a challenging task (Santos et al., 2011).

### 7.3.2 Building height

Building height, normally measured in number of floors (storeys), influences social, economic and environmental costs (Jones and MacDonald, 2004) and it is closely related to building density (Jabereen, 2006). Table 7.2 outlines the positive and negative impacts of increased building height on urban sustainability.

Table 7.2: Impact of increased building height on urban sustainability

| **Positive** | **Negative** |
|---|---|
| *Social* | *Social* |
| – Social interaction and vibrancy<br>– Encourages and promotes efficient public transit systems | – Decline in cultural heritage |
| *Environmental* | *Environmental* |
| – Efficient use of space<br>– Increases potential for local heating and cooling systems<br>– Increase in energy efficiency<br>– Encourages other modes of transport such as walking | – May result in congestion which reduces fuel efficiency<br>– Urban heat island development which increases need for air conditioning<br>– Concentration of high-rise buildings reduces potential for natural lighting and ventilation thereby increasing energy costs |
| *Economic* | *Economic* |
| – Reduction of automobile trips and trip costs<br>– Amortisation of infrastructure costs of water, sewerage and electricity<br>– Greater returns to investment | – Need for lifts which may increase energy consumption. |

Sources: Adapted from Ding (2013); Hui (2001) and Yabuki, Miyashita and Fashida (2011).

A building with a single floor is regarded as less sustainable than a building with two to 12 floors because of the inefficient use of space, lower returns on investment, higher infrastructure-connection costs and low social vibrancy. However, the benefits of taller buildings diminish when the number of floors exceeds 12 (McLennan, 2009). A concentration of high-rise buildings promotes the urban heat island (UHI) effect (De Wilde and Dobbelsteen, 2004), increases energy costs, can cause a loss of cultural heritage (Yabuki, Miyashita and Fashida, 2011) and may increase pollution (Hui, 2001). Planning policy, particularly zoning, should consequently provide sensible height restrictions as well as urban designs which do not encourage continuous impervious surfaces to reduce the UHI effect.

### 7.3.3 Impervious surface area

Impervious surfaces are anthropogenic land cover features that prevent water from infiltrating the soil (see Table 7.3). Such surfaces include roads, driveways, parking lots and rooftops (Weng, 2012). Impervious surfaces are good indicators of sustainable urban development because they affect environmental quality and also peoples' quality of life (Lu and Weng, 2006). Nowak and Greenfield (2012) have demonstrated how an increase in impervious surface area reduces the aesthetic appeal and environmental quality of urban areas. Increases in impervious surface area are also environmentally detrimental because they increase intensity of run-off, decrease groundwater replenishment and promote higher flood frequencies (Aubrecht et al., 2009). Growth in impervious surfaces also increases the transportation of pollutants that impact negatively on riparian users and aquatic life (Slemp et al., 2012). It has been observed that increases in impervious surface area increase urban ambient temperatures, the UHI effect and this impacts negatively on efforts to combat climate change (Heldens, Taubenböck and Esch, 2012; Zhang, Zhang and Lin, 2012). Clearly, urban planners must plan urban development that minimises the negative impacts of increases in impervious surface areas. Impervious surfaces should preferably be interspersed with open spaces, gardens, and green areas, which do not result in very-low building densities. Green spaces have been shown to reverse the negative environmental impacts of impervious surfaces (Haase and Nuissl, 2010; Mathieu, Freeman and Aryal, 2007), reduce the UHI effect and act as carbon sequestration spaces (Strohbach, Arnold and Haase, 2012). How impervious surface area, building density and height are applied in Stellenbosch is tackled in the following sections.

## 7.4 METHODS

The study area and period, data collection as well as preparation and data analysis of the built-up area indicators are discussed in the following sub-sections.

### 7.4.1 Study area and period

Stellenbosch, the second oldest town in South Africa, is the study area. Stellenbosch is situated in the Western Cape province of South Africa approximately 55 km east of Cape Town's CBD (Figure 7.2). Stellenbosch is an appropriate case to study as it has grown rapidly during last two decades. Its population increased from 60 000 in 2001 to 90 000 in 2010 at a mean annual growth rate of 8.5% (InterStudy, 2009; SA Statistics, 2001; Stellenbosch University, 2010).

Stellenbosch's economic potential is mainly based on agriculture, heritage and tourism. These rely heavily on the quality of the natural environment with regarding water supply, soil suitability and visual attractiveness (Stellenbosch Municipality, 2011). Consequently, Stellenbosch faces the challenges of balancing urban and economic growth against expansion into and consumption of scarce and valuable agricultural land as well as preserving natural and cultural heritage. Stellenbosch is accessible and convenient for carrying out field visits. The availability of appropriate reference data to verify the findings was a deciding factor. The period of study is 2000 to 2010, mainly because of data availability.

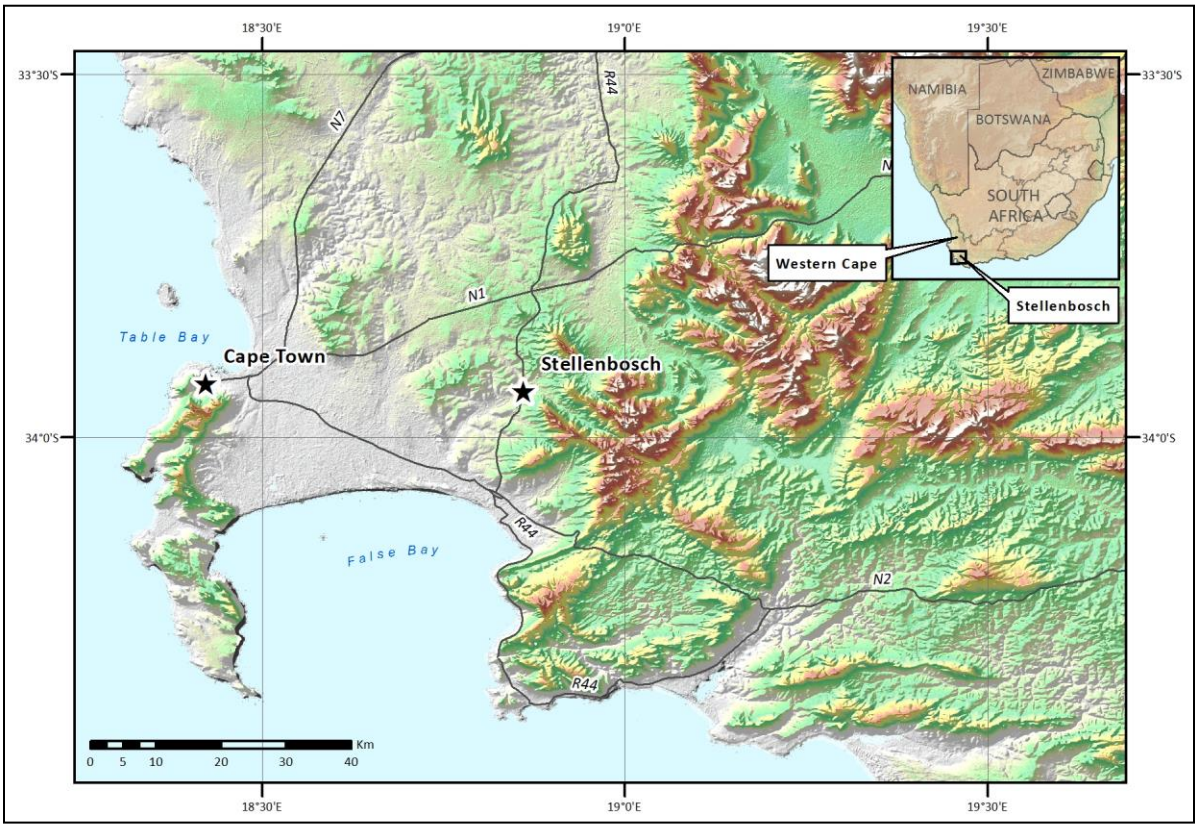



Figure 7.2: Location of Stellenbosch within the Western Cape province of South Africa

The study area was demarcated as the 2010 urban built-up extent and consequently includes areas used in 2000 for non-urban purposes (e.g. agriculture).

### 7.4.2 Data collection and preparation

Very-high resolution (0.5 m) orthorectified colour aerial photographs of Stellenbosch were obtained from South Africa’s Chief Directorate: National GeoSpatial Information for 2000 and 2010, respectively. Multispectral (10 m) and panchromatic (2.5 m) SPOT5 images were acquired for 2010 from the South African National Space Agency (SANSA). The SPOT5 imagery was pre-processed (orthorectified and subjected to atmospheric and radiometric corrections) in PCI Geomatica. The multispectral and panchromatic images were fused using the PANSHARP function in PCI Geomatica.

A building-count data set for 2010 was obtained from Eskom, the South African national electricity provider. SPOT5 natural-colour imagery was used for creating this data set by manually digitising a building point on a building and a polygon in the case of informal settlements. The building points were also classified as rural, peri-urban and urban. The Eskom Spot Building Count (Eskom SBC) data set is claimed to be the first truly geographical data set for South Africa with vast potential for use by various stakeholders to support decisions and tasks such as providing a sample frame for surveys (Mudau, 2010).

### 7.4.3 Impervious surfaces

A land cover classification was performed on the fused SPOT5 imagery with a supervised geographical object-based image analysis (GEOBIA) approach in eCognition software. Validation of the land cover classification was done by creating 50 random reference points for each land cover class using geospatial modelling environment (GME) software. Verification was done by extensive field visits, analysis of aerial photographs and with Google Earth's Street View tool. The overall accuracy of the land cover classification was 86% for 2000 and 88% for 2010. Due to the unavailability of SPOT5 imagery for 2000 (SPOT5 was launched in 2002), aerial photography was used for producing a comparable (i.e. one with a similar classification scheme) land cover map of 2000. By overlaying the 2010 land cover map on the 2000 aerial photographs the significant land cover changes between the two dates were identified. The 2000 land cover map was subsequently created by manually editing the 2010 map. The 2000 and 2010 land cover maps were reclassified in ArcGIS 10 to produce maps of impervious surfaces using the classification given in Table 7.3.

Table 7.3: Classification of impervious surfaces

| **Original land cover classes** | **Reclassification (Impervious or pervious surfaces)** | **Characteristics** |
|---|---|---|
| Built-up | Impervious | Buildings, rooftops, tarred roads, pavements, driveways, parking lots, storm water drains, swimming pools and sidewalks |
| Bare soil[1] | Impervious | Compact soils |
| Improved grassland | Pervious | Sports fields and recreational fields |
| Vegetation | Pervious | Vegetation, grass, forest and cultivated land |
| Water | Pervious | Natural water-bodies |

Note[1]: Compact bare soil where water cannot infiltrate is classified as impervious. However, bare soil such as golf bunkers where water can infiltrate is classified as pervious.

### 7.4.4 Buildings

Buildings can be mapped as polygons (i.e. footprints) or points (i.e. centroids) depending on the scale of mapping (Mudau 2010; Santos et al. 2011). Manual digitising of building footprints from remotely sensed imagery is a laborious and costly process so that automated methods have been suggested to do the task (Almedia et al., 2011; Ural, Hussain and Shan 2011), but these require data sets, for example, light detection and ranging (LIDAR) and VHR multispectral imagery, that are not yet widely available. Building centroids, digitised from remotely sensed imagery remain the most cost-effective way to map buildings over large areas. In this study, the Eskom SBC data set of 2010 was edited by digitising missing buildings in ArcGIS 10 using the 2010 aerial photography (Figure 7.3). The buildings were missing due to the lower-resolution (2.5 m) SPOT5 imagery used to develop the original Eskom SBC. The higher resolution (0.5 m) of the aerial photographs made it possible to identify additional buildings.

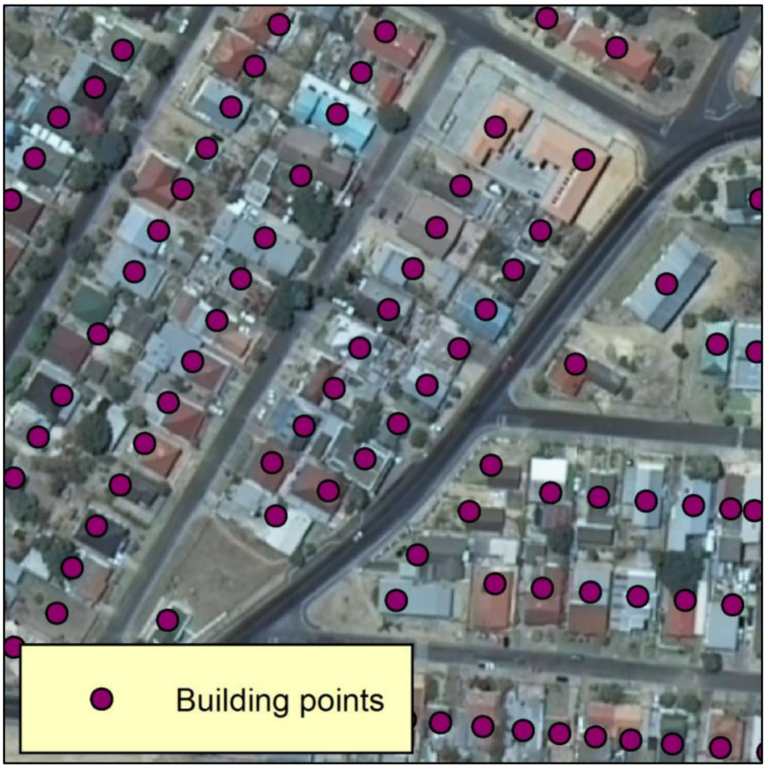



Figure 7.3: Sample of the updated building count data set

The Eskom SBC data set was edited in ArcGIS 10 using 2000 aerial photography to create a 2000 building data set. Informal structures (shacks) were digitised in the same way because they were not included in the original Eskom SBC and they are important for estimating building-unit density.

### 7.4.5 Building height

A digital surface model (DSM) with a spatial resolution of two metres was extracted from stereo aerial photography using PCI Geomatica's Ortho Engine software. Ground-level points, digitised from the aerial photography, were used to interpolate a digital terrain model (DTM). A DTM represents the elevation of the ground surface while a DSM includes the height of objects on the ground (e.g. buildings and vegetation) (Chen et al., 2012). The DTM was subtracted from the DSM to create a normalised digital surface model (nDSM). The storey value for each building was extracted in a GIS using the buildings data set. The nDSM was divided by 3.3 and rounded to the nearest integer to obtain the number of storeys for each building[16]. This workflow is illustrated in Figure 7.4. Due to data unavailability and lack of appropriate reference data, the nDSM was only developed for 2010.

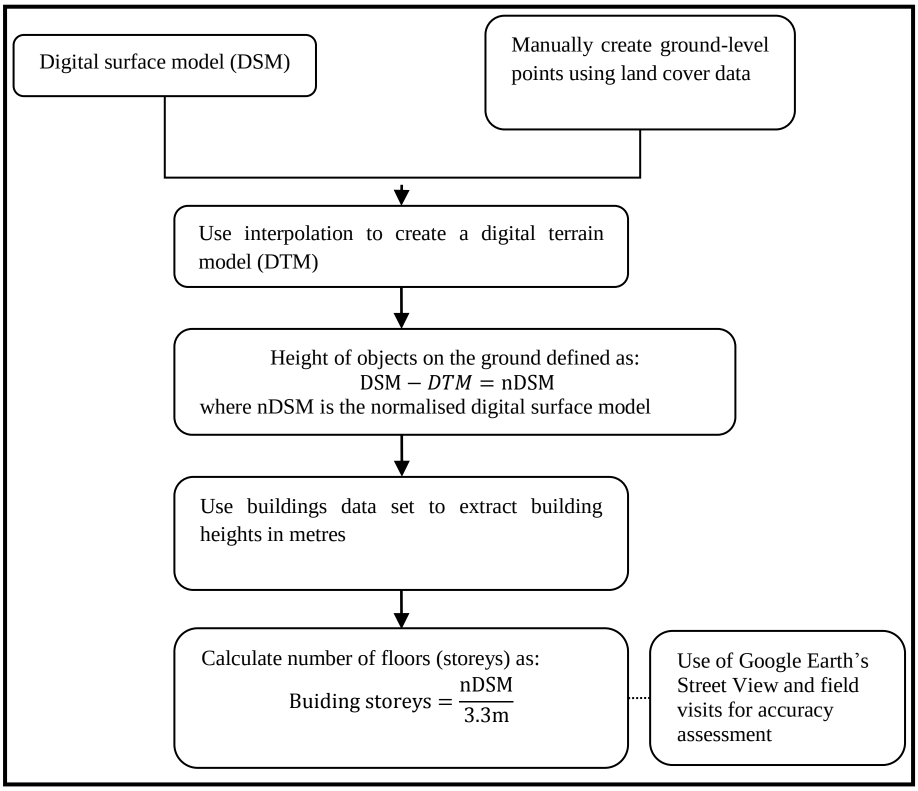



Figure 7.4: Workflow to calculate building height (in storeys)

Geospatial modelling environment (GME) software was used to create a random sample of 400 building points, the recommended sample size required of the 21 216 buildings to carry

[16] Three metres is the average building floor height (Stellenbosch Municipality, 2010; Wurm et al., 2009)

out an accuracy assessment. Extensive field visits and Google Earth's Street View tool were employed to compare nDSM height and actual height (Figure 7.5).


Figure 7.5: Google's Street View extract showing (a) two storeys, (b) 6 storeys and (c) field picture of (b)

The overall accuracy assessment of the nDSM was 95% for buildings with one storey and 88% for buildings with more than one storey, implying that in most cases the observation of building storeys resembled those on the nDSM

### 7.4.6 Analysis

According to Song and Rodriguez (2005), discrete mapping makes visual interpretation difficult. Consequently, a continuous surface that employs a circular hectare-moving window was used to calculate building density, concentration of impervious surface area and average building height. This promotes easy visual interpretation, comparison and consistency with a single unit of measurement (ha). All the analyses were done in ArcGIS 10. Building density was calculated per hectare because it is the most widely used measurement according to international standards (Urban Land Institute, 2010; Western Cape Department of Environmental Affairs and Development Planning, 2009). Concentration of impervious surface area concentration and building height (storeys) were also calculated per hectare by using the spatial analyst, neighbourhood focal statistics function.

## 7.5 RESULTS AND DISCUSSION

The following sub sections discuss findings of the application of building density, height and impervious surface concentration in Stellenbosch.

### 7.5.1 Density analysis

During the decadal study period, the building count in Stellenbosch grew by 6201 from 15 015 to 21 216, an annual growth rate of 4%. Forty per cent of this growth occurred in informal settlements, particularly in rapidly growing Kayamandi. Figure 7.6 shows building densities in Stellenbosch for 2000 and 2010. Cloetesville, Idasvallei, and Kayamandi have middle-to-high building densities denoting sustainable urban development due to efficient use of space, amortisation of infrastructure costs and perceived social integration. These medium-to-high densities also suggest potential for the provision of cost-effective public transit systems (Frank et al., 2006).

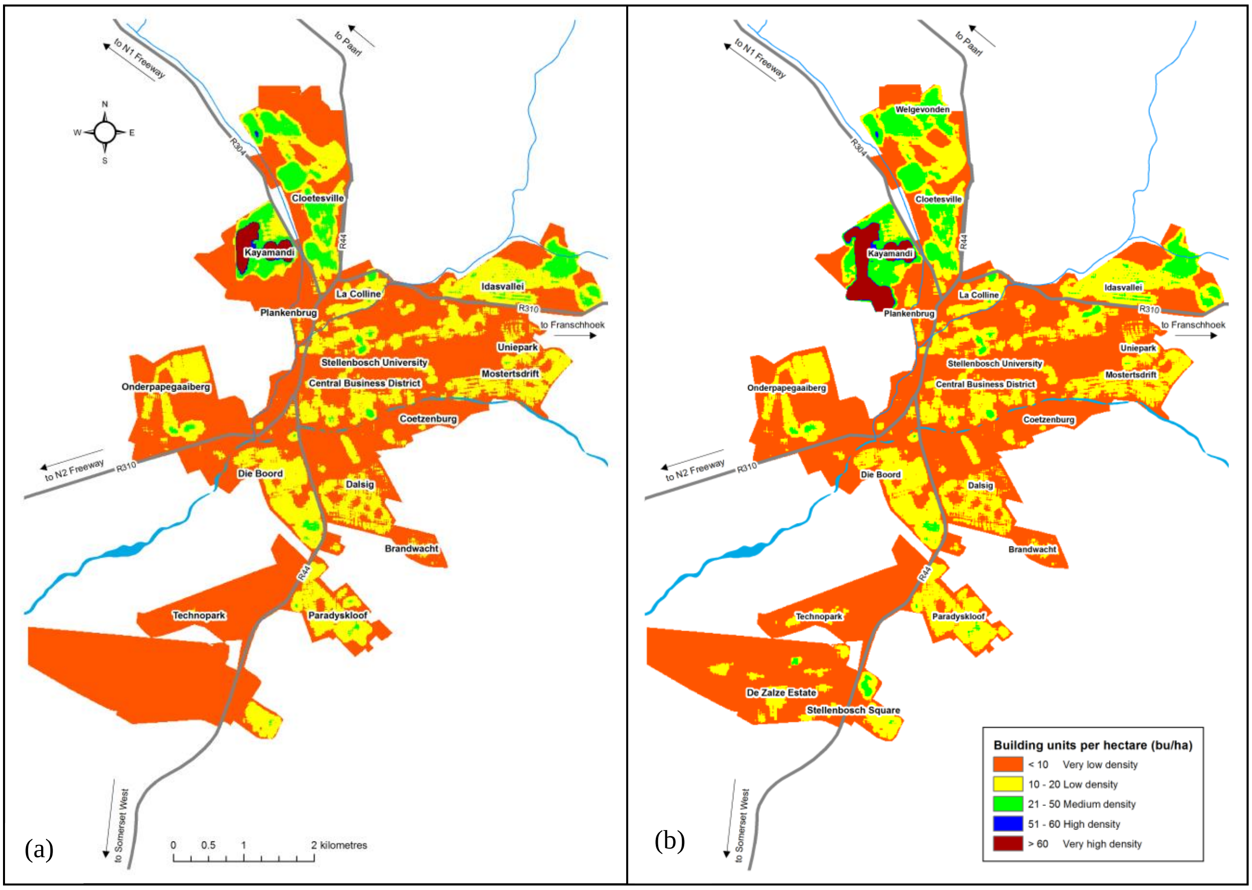



Figure 7.6: Building density in Stellenbosch; (a) 2000 and (b) 2010

Much of Stellenbosch, including Technopark, Brandwacht, sections of the CBD, Die Boord, Uniepark, Stellenbosch University and Onderpapegaaiberg, has low densities (less than 20 bu/ha). This signifies unsustainable urban development due to wastage of space, high infrastructure costs and perceived low social vibrancy. According to this criterion, Stellenbosch is not meeting its sustainable urban development targets as stipulated by the Western Cape Provincial Department. The low densities in Stellenbosch also signify high potential for densification. The low building densities in most parts of Stellenbosch are likely to discourage social and spatial integration (Donaldson, Morkel and Paquet 2012; James, 2000; Todes and Watson; 1986). Given South Africa's history of spatial segregation and its post-apartheid spatial policy geared toward integrated development, building density is useful for assessing progress toward spatial as well as social integration. Low building density in

Stellenbosch is also likely to encourage dependence on motor vehicles which will contribute to increased GHG emissions (Transportation Research Board, 2009). More studies are required to quantify the causal relationship between building density and travel behaviour (Cao and Fan, 2012) especially in South Africa and other developing countries.

Figure 7.7 shows that there was minimal change (<10 bu/ha) in building density throughout Stellenbosch between 2000 and 2010. Significant changes that did occur were in Welgevonden and De Zalze Estate as these areas were used for agriculture in 2000.

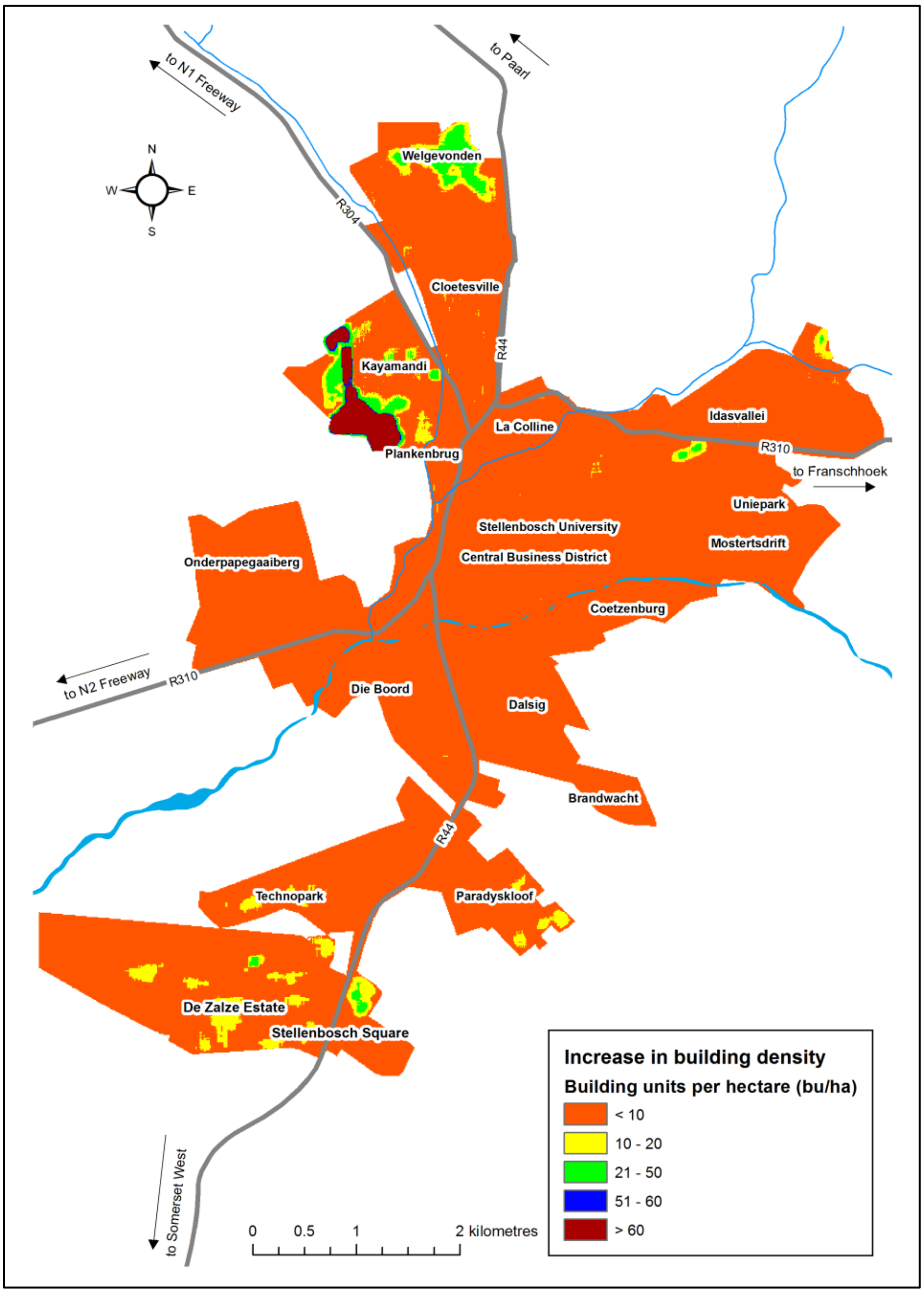



Figure 7.7: Increase in building density in Stellenbosch between 2000 and 2010

Welgevonden is characterised by medium densities (21 to 50 bu/ha) and De Zalze by low densities (10 bu/ha) (Figure 7.6). It is advisable to encourage and plan for medium-density developments such as Welgevonden on the urban periphery to achieve sustainable urban growth because medium densities promote efficient use of space, thereby reducing the consumption of pristine agricultural and natural ecosystems. Significant density changes also occurred in Kayamandi, Plankenbrug, Paradyskloof, Idasvallei, Uniepark, Stellenbosch Square and Technopark where they indicate densification that denotes a trajectory toward sustainable urban development. Stellenbosch municipality has a densification policy in place (Stellenbosch Municipality, 2010). Increased densities recorded as a result of growth in Plankenbrug industrial area and Technopark are indicative of increases in economic and employment opportunities which have positive effects on the socio-economic sustainability of Stellenbosch.

Kayamandi experienced the greatest change (>60 bu/ha) in density owing to the proliferation of informal structures during the ten-year study period, increased from 1022 to 3645 units (256%). Although densities increased in Kayamandi, the returns for urban sustainability diminished as a result of the negative costs associated with informal settlements (Baud et al., 2010). Growth of the informal settlements puts pressure on the socio-economic, physical and environmental carrying capacities of Stellenbosch. The very high densities, coupled with haphazard development patterns make it difficult to provide essential services (water, electricity and sewerage) necessary for creating liveable environments. Growth in the number of informal structures also symbolises inadequate housing delivery, insecure tenure, inadequate land use planning, poverty and rural-to-urban migration that all portend unsustainable urban development (UN-HABITAT, 2009). Some informal building units are located on hillslopes exposed to flooding and landslides during rainy seasons. Many of the informal structures were damaged by flooding in 2012, the unstable terrain and very-high densities (>60 bu/ha) being cited as causes (*Cape Argus*, 2012). Continued growth of informal settlements should be curtailed if Stellenbosch is to meet its sustainable urban development targets, particularly the millennium development goal 7 which seeks to reduce the number of people living in informal settlements by 2020 (UN, 2008).

The medium densities of Welgevonden, Idasvallei and Cloetesville indicate sustainable urban development while Kayamandi’s very-high densities point toward unsustainable urban development. When densities exceed certain thresholds (>60 bu/ha) the prospects for sustainable urban development begin to diminish (Ewing, 1997; Jabereen, 2006). Continued growth of informal settlements is a strong indicator of unsustainable urban development (UN, 2008). Because most (71%) of Stellenbosch consists of low-density areas, sustainable urban development targets are not being met. The study confirms the literature's contentions that building density has environmental, social and economic costs that make it a core and optimal indicator of sustainable urban development (Burton, 2002; MacLennan, 2009). However, density alone is not sufficient because footprint and height are not depicted to fully characterise the sustainability of the urban built-up area (Jabereen, 2006; Jones and MacDonald, 2004).

### 7.5.2 Analysis of building height

Table 7.4 and Figure 7.8 show the frequency and spatial distributions of building heights in Stellenbosch, respectively. The majority (81%) of the buildings in Stellenbosch are single-storey structures.

Table 7.4: Building-floor (storeys) distribution in the 2010 urban extent of Stellenbosch

| Floors | Count[1] | Percentage |
|---|---|---|
| 1 | 11498 | 80.8 |
| 2 | 2123 | 14.9 |
| 3 | 408 | 2.9 |
| 4 | 155 | 1.1 |
| 5 | 35 | 0.3 |
| 6 | 12 | 0.1 |
| 7 | 2 | 0.0 |
| **Total** | **14233** | **100** |

Note[1]: The building count excludes informal settlements.

Multi-storey buildings are mostly located in the CBD, on the campus of Stellenbosch University, La Colline, Welgevonden, Technopark, Paradyskloof and Plankenbrug areas. Multi-storey buildings tell of urban sustainability due to efficient use of space, promotion of mixed uses and social vibrancy, particularly in the CBD (McLennan, 2009). The high proportion of single-storey buildings suggests that there is much potential for vertical urban growth in Stellenbosch.

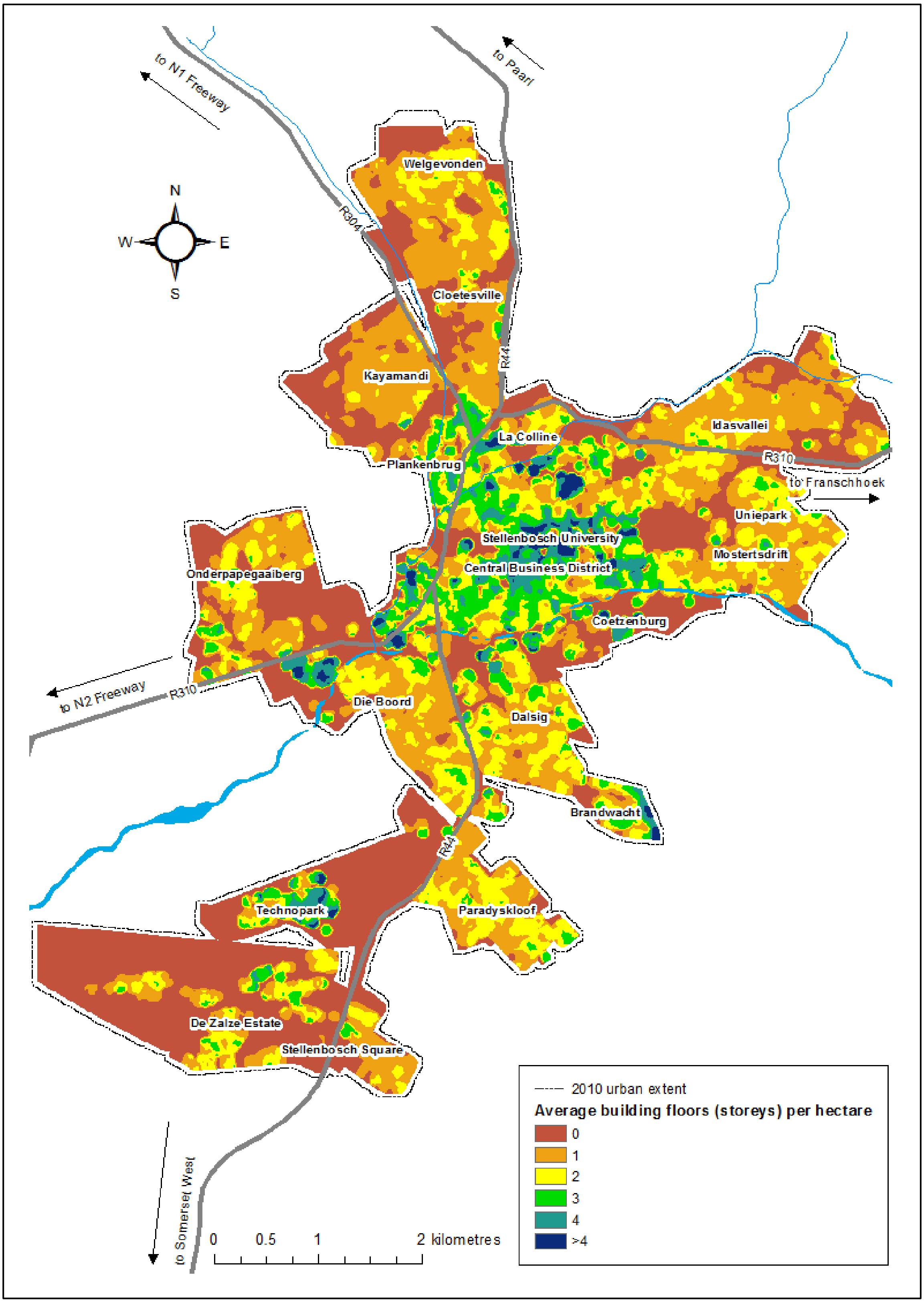



Figure 7.8: Spatial distribution of building floor (storeys) Stellenbosch, 2010

Field visits and use of Google Earth's Street View confirmed that a significant portion of new developments (since 2010) and redevelopments in the CBD, La Colline and Stellenbosch

University campus are multi-storey buildings which represent intensification. They are all within the five storey[17] height restriction of Stellenbosch (Stellenbosch Municipality, 2011). This height restriction inadvertently ensures that declining returns on sustainable urban development do not occur due to a concentration of high-rise buildings (Stellenbosch Municipality, 2011). Moreover, the restrictions aim to maintain the building heritage of Stellenbosch which is a major tourist attraction.

Comparison of Figures 7.8 and 7.6b shows that high building density and building height patterns relate to each other. Welgevonden's medium density coupled with an average building height of two floors attest to high sustainability characterised by efficient use of space and social vibrancy (Yabuki, Miyashita and Fashida, 2011). The CBD, Paradyskloof, Technopark and Brandwacht also have averages of two floors but low densities make them less sustainable than Welgevonden, which is a case of best practice. Building height and densities also influence concentration of impervious surfaces.

### 7.5.3 Analysis of impervious surface area

Table 7.5 and Figure 7.9 show that over the decadal study period there was an increase in impervious surface area from 777 ha to 925 ha at a mean annual growth rate of 2%. This growth is attributed to the spatial expansion of urban areas into agricultural and natural areas, a clear manifestation of unsustainable land transformation. This land transformation will most likely cause increases in surface temperatures (UHI effect) (Strohbach, Arnold and Haase, 2012) as well as surface water run-off.

Table 7.5: Change in impervious surface area in the 2010 urban extent of Stellenbosch since 2000

| Type | Area (ha) 2000 | Area (ha) 2010 | Change (ha) | Percentage change |
|---|---|---|---|---|
| Impervious | 777.6 | 925.2 | 147.6 | 19.0 |
| Pervious | 1697.5 | 1549.9 | -147.6 | -8.7 |
| **Total** | 2475.0 | 2475.0 | 0 | 10.3 |

[17] Up to three aadditional storeys can be added given permission by the municipality's planning department (Stellenbosch Municipality, 2010).

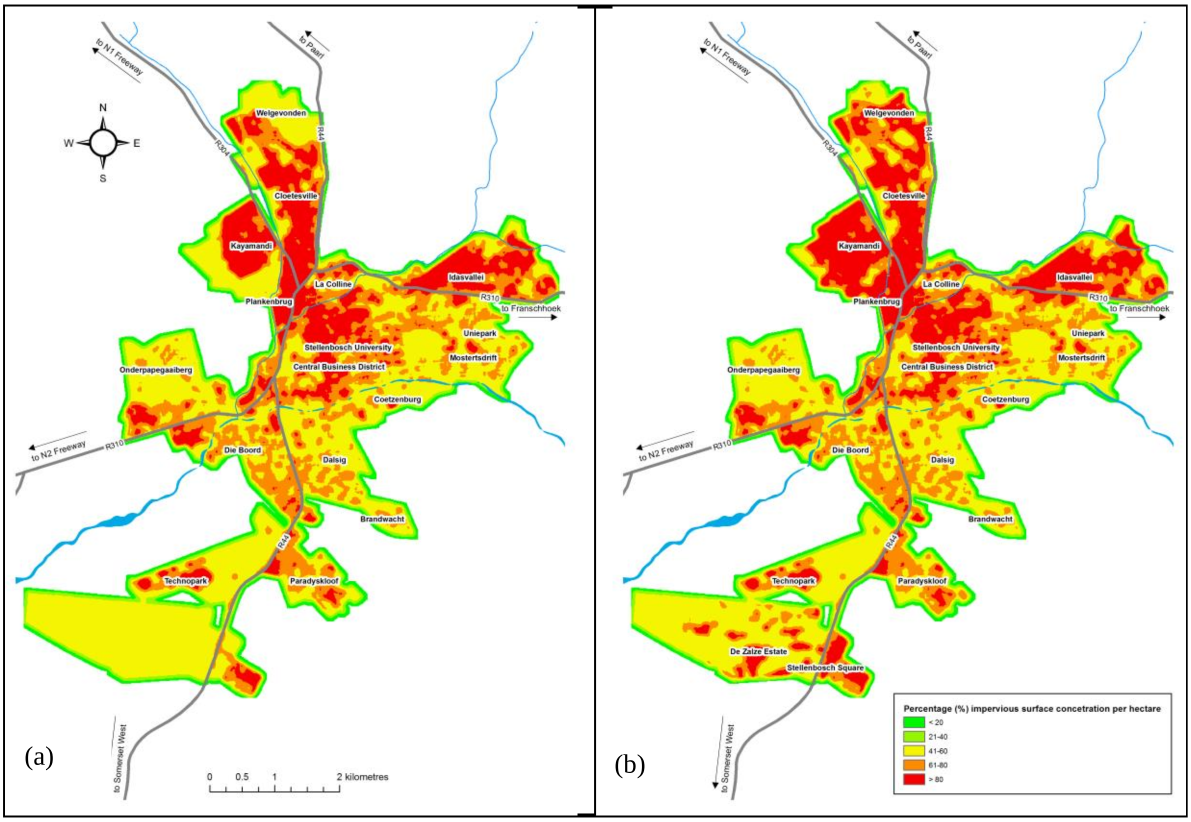



Figure 7.9: Distribution of impervious surface area in Stellenbosch; (a) 2000 and (b) 2010

Areas with low concentrations of impervious surfaces (60% or less per hectare) on both dates are Die Boord, Dalsig, Mostertsdrift, Coetzenburg, Brandwacht, Uniepark and Onderpapegaaiberg. These areas are characterised by open spaces and private gardens which tend to reverse the adverse environmental impacts such as UHI associated with urbanisation (Mathieu, Freeman and Aryal, 2007). However, this is accompanied by low building density that implies low social vibrancy and inefficient utilisation of space, both pointing to an unsustainable trajectory. These conflicting findings emphasise the need to apply various indicators of urban sustainability rather than adopting a narrow definition of sustainability. Areas with high concentrations of impervious surfaces (above 60% per hectare) include the eastern parts of Kayamandi, the CBD, Stellenbosch University campus, Plankenbrug and Idasvallei, which most likely increases the UHI effect and surface water run-off. Figure 7.10 shows the increase in percentage of impervious surface area per hectare between 2000 and 2010 in Stellenbosch. De Zalze Estate, Stellenbosch Square, Paradyskloof, Kayamandi and Welgevonden exhibit significant increases. Most of this change is attributable to the growth in urban footprint as a result of urban sprawl and urbanisation. Some minor changes in the town are indicative of densification and compaction that point to sustainable urban development.

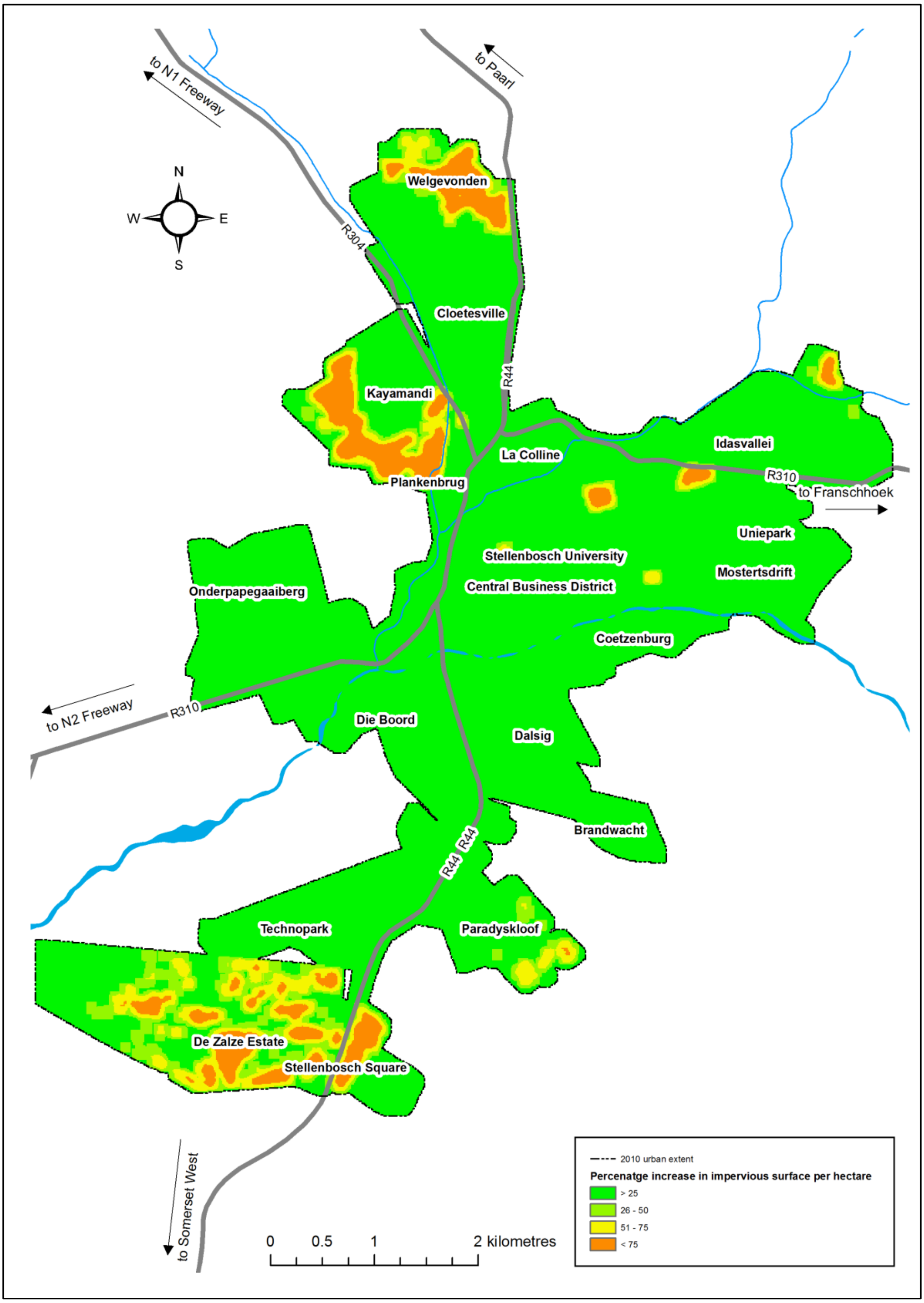



Figure 7.10: Increase in impervious surface concentrations in Stellenbosch between 2000 and 2010

Large sections of Kayamandi have medium-to-very-high building densities (>60 bu/ha) and a very high concentration of impervious surfaces (80%/ha). Eighty per cent of the houses in

Kayamandi are shacks. This combination of factors has led to declining water quality of the Plankenbrug River which flows past Kayamandi. Paulse, Jackson and Khan (2005) have documented a rise in E.coli counts in the river downstream. The river is polluted because of inadequate sanitation facilities (bucket system) in some parts of Kayamandi and an over extended sewerage system. The population and spatial growth of informal settlements in Stellenbosch should be urgently curtailed and sanitation systems improved if the town is to achieve goal 7D (improve life of slum dwellers by 2020) of the millennium development goals (UN 2008). The very-high densities and concentrations of impervious surfaces in Kayamandi deprive residents of access to nature and open space (Nowak and Greenfield, 2012; Slemp et al., 2012). In contrast, De Zalze Estate has a low building density (<20 bu/ha) with 560 building units on 300 ha of land (De Zalze Winelands Golf Estate, 2012), that is, 1 bu/ha on a matrix of gardens, public open space and golf course fairways (41-60% impervious surface per hectare) which is inefficient usage of space on the urban periphery (Stellenbosch Municipality, 2010). From the onset the municipality opposed the development of this area (approved only after appeal at provincial level) because it does not help achieve the targets of increasing densities to 40 bu/ha and housing provision for the poor (Stellenbosch Municipality, 2010). Kayamandi and De Zalze are two extreme cases of unsustainable urban development. The middle ground needs to be occupied to achieve sustainable urban development.

## 7.6 PRACTICAL IMPLICATIONS AND CONCLUSIONS

The findings demonstrate that EO adds value to monitoring sustainable urban development by providing area-wide and up-to-date thematic (impervious surfaces) and geometric (building count, density and building height) characterisation of urban built-up areas. Visual and quantitative distributions that show relationships between various urban sustainability indicators is possible. This information would  be difficult to collect from other sources, such as poring over municipal records if at all available. Remotely sensed data also help to reveal problem areas that require urgent attention and best practices that can be replicated. For example, the analysis of building count, building density and impervious surface revealed that informal settlements require urgent attention if Stellenbosch is to achieve its desired sustainable urban development goals. Consequently, the use of an array of indicators obtained from remotely sensed data is recommended for obtaining a holistic picture of the sustainability trajectory. Building height, building density and impervious surface concentration derived from EO data are applicable to telecommunications planning (Ding, 2013), planning for local heating systems (Geiss et al., 2010), population estimates in informal settlements (Baud et al., 2010) and disaster risk management (Almedia et al., 2011; Ding, 2013). Clearly, it is cost-effective and beneficial to extract information from EO data for a variety of practical uses.

The method for deriving building height and building density was applied to very-high-resolution (0.5 m) aerial photography which is similar to GeoEye and WorldView-2 satellite imagery. The procedures can be applied to high-resolution satellite imagery making replication in other urban centres feasible. Because the exercise used different sources of EO data for various purposes, one cannot be optimistic that one EO sensor will provide all the data needed for monitoring urban sustainability. Fortunately, the data and image fusion techniques needed to do this are available and they are expected to be progressively applied for enhanced monitoring of urban sustainability (Qi et al., 2012).

The DCA framework and the indicators of sustainable urban development derived from EO data equip local authorities to make evidence-based decisions rather than relying on advocacy based planning or compact development as the only options. For example, further compact development in Kayamandi is unfeasible so that space has to be found elsewhere to channel growth away from Kayamandi. Similarly, urban planners can use the density maps to identify areas for densification and infill development. Suburbs such as Uniepark and Brandwacht apparently have potential for densification which is in line with Stellenbosch municipality's infill policy (Stellenbosch Municipality, 2010). The findings confirm that building density is a core and optimal indicator so that it is recommended to be an indispensable indicator for sustainable urban development studies. Similarly, information about impervious surfaces is all important as an indicator of land transformation, urban growth, and climate change.

EO is undoubtedly an invaluable tool for providing area-wide up-to-date data on the built-up area of rapidly urbanising cities in developing countries. This facilitates evidence-based decision-making where local authorities are able to choose between compact development and the making room paradigm of sustainable urban development depending on the context. EO data on the built-up area revealed that sustainable urban development is an optimising procedure. The advent of very-high-resolution EO data from GeoEye, WorldView-2 and Quickbird, as well as the continuous improvement of image classification techniques, will promote better monitoring of sustainable urban planning in developing countries.

## 7.7 REFERENCES

Almedia, C. M., Oliveira, C. G., Rennó, C. D., & Feitosa, Q. (2011). Population estimates in informal settlements using object-based image analysis and 3D modelling [Online].Earthzine. Available from: http://www.earthzine.org/2011/08/16/population-estimates-in-informal-settlements-using-object-based-image-analysis-and-3d-modeling/ [Accessed on 20 July 2012].

Anderson, J. R., Hardy, E. E., Roach, J. T., & Witmer, R. E. (1976). *A land use and land cover classification for use with remote sensor data*. Washington DC: United States Government Printing Office.

Angel, S. (2010). *Making room for a planet of cities*. Cambridge, Massachusetts: Lincoln Institute of Land Policy.

Aubrecht, C., Steinnocher, K., Hollaus, M., &Wagner, W. (2009). Integrating earth observation and GIScience for high resolution spatial and functional modeling of urban land use. *Computers, Environment and Urban Systems*, 33(1), 15-25.

Barnsley, M. J., & Barr, S. L. (2000). Monitoring urban land use by earth observation. *Surveys in Geophysics*, 21(2-3), 269-289.

Baud, I., Kuffer, M., Pfeffer, K., Sliuzas, R., & Karuppannan, S. (2010). Understanding heterogeneity in metropolitan India: The added value of remote sensing data for analyzing sub-standard residential areas. *International Journal of Applied Earth Observation and Geoinformation*, 12(5), 359-374.

Bigazzi, Y. A., & Burtini, R. L. (2009) Adding green performance metrics to a transportation data archive. *Transportation Report Record*, 2021, 30-40.

Burton, E. (2002). Measuring urban compactness in UK towns and cities. *Environmental Planning B:Planning and Design*, 29, 219-50.

Campbell J. B. (2011). *Introduction to remote sensing*. New York: Guilford Press.

Camps-Valls, G., Tuia, D., Gómez-Chova, L., Jiménez, S., & Malo, J. (2012). Remote sensing image processing. *Synthesis Lectures on Image, Video, and Multimedia Processing*, 12,194-210.

Canadian Urban Institute. (2008). *Energy mapping study*. Toronto: Canadian Urban Institute.

Cao, X & Fan, Y. (2012). Exploring the influences of density on travel behaviour using propensity score matching. *Environmental and Planning B: Planning and Design*, 39, 459-470.

*Cape Argus*. (2012). 42 left in the cold. 7 May 2012, p5.

Chen, L., Zhao, S., Han, W., & Li, Y. (2012). Building detection in an urban area using lidar data and QuickBird imagery. *International Journal of Remote Sensing*, 33(16), 5135-5148.

CIESIN. (2009). Remote sensing and the social sciences [Online]. Palisades New York: Center for International Earth Science Network. Available from:http://sedac.ciesin.columbia.edu/tg/guide_glue.jsp?rd=rs&ds=5. [Accessed 2 December 2011].

Clark, C. (2007). Sustainability Science: A room of its own [Online]. Washington DC: National Academy of Science. Available from: http://www.pnas.org/site/misc/sustainability.shtml.[ Accessed 5 June 2010].

CSIR. (2010a). *Science Scope*. Council for Scientific and Industrial Research: Pretoria: CSIR.

CSIR. (2010b). *Land cover field guide.* Pretoria: Council for Scientific and Industrial Research.

De Wilde, S., & Van den Dobbelsteen, A. (2004). Space use optimisation and sustainability—environmental comparison of international cases. *Journal of Environmental Management*, *73*(2), 91-101.

De Zalze Winelands Golf Estate. (2012). De Zalze Winelands golf estate [Online]. Available from: http://www.blueberry.co.za/dezalze.co.za/index.php [Accessed 29 August 2012].

Department of Rural Development and Land Reform. (2009). *Development of a methodology for national land use mapping for Chief Directorate: Geo Spatial Information.* Cape Town*:* Department of Rural Development and Land Reform.

Ding, C. (2013). Building height restrictions, land development and economic costs. *Land use Policy*, 30(1), 485-495.

Donaldson, R., Morkel, J., & Paquet, T. (2012). Urban spaces: The quartering of Stellenbosch’s urban space. In M. Swilling, & B. Sebitosi (Eds.), *Sustainable Stellenbosch 2030*, 11-18. Stellenbosch: Sun Media.

Doxani, G., Karantzalos, K., & Strati, M. T. (2012). Monitoring urban changes based on scale-space filtering and object-oriented classification. *International Journal of Applied Earth Observation and Geoinformation*, 15, 38-48.

Eid, J., Overman, H. G., Puga, D., &Turner, M. A. (2008). Fat city: Questioning the relationship between urban sprawl and obesity. *Journal of Urban Economics*, 63(2), 385-404.

Erener, A. (2012). Classification method, spectral diversity, band combination and accuracy assessment evaluation for urban feature detection. *International Journal of Applied Earth Observation and Geoinformation*, Article in Press:http://dx.doi.org/10.1016/j.jag.2011.12.008, Esch, T., Taubenböck, H., Heldens, W., Theil, M., Wrum, M., Geiss, C., & Dech, S. (2010). Urban remote sensing-how can earth observation support sustianble development of urban environments? Cities for everyone. In Proceedings *Cities for everyone. liveable, healthy, prosperous* 18-20 May, Vienna: Real Corp.

Ewing, R. (1997). Is Los Angeles style sprawl desirable? *Journal of American Planning Ascociation,* 63(1), 107-27.

Ewing, R., & Nelson, A. (2008). *CO2 reductions attributable to smart growth in California*. University of Maryland: National Center for Smart Growth Research and Education.

Frank, L. D, Sallis JF, Conway TL, Chapman JE, Saelens BE, Bachman W. (2006). Many pathways from land use to health: Associations between neighborhood walkability and active transportation, body mass index, and air quality. *Journal of the American Planning Associatio,*72(1), 75-87.

Frank, L. D., Greenwald, M. J., Winkelman, S., Chapman, J., & Kavage, S. (2010). Carbonless footprints: Promoting health and climate stabilization through active transportation. *Preventative Medicine*, 50, 99-105.

Gamba, P., Du, P., Juergens, C., & Maktav, D. (2011). Foreword to the special issue on human settlements: A global remote sensing challenge. *Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 4(1), 5-7.

Geiss, C., Taubenböck, H., Wurm, M., Esch, T., Nast, M., Schillings, C., & Blaschke, T. (2011). Remote sesning-based charactrisation of settelemnt structures for assesing local potential of district heat. *Remote Sensing,* 3, 1447-1471.

Gomez-Chova, L., Fernández-Prieto, D., Calpe, J., Soria, E., Vila, J., & Camps-Valls, G. (2006). Urban monitoring using multi-temporal SAR and multi-spectral data. *Pattern Recognition Letters,* 27(4), 234-243.

Haase, D., & Nuissl, H. (2010). The urban-to-rural gradient of land use change and impervious cover: A long-term trajectory for the city of Leipzig. *Journal of Land use Science*, 5(2), 123-141.

Hall, O. (2010). Remote sensing in social science research. *Open Remote Sensing Journal*, 3, 1-16.

Hall, W. L. (2010). Decision consequence analysis: A paradigm for decison making. In Brown, K., & Hall, W. L. eds. *Sustainable land development and restoration: Decision consequence analysis*, 75-85. Amsterdam: Elsevier..

Hay, G. J., & Castilla, G. (2008). Geographic object-based image analysis (GEOBIA): A new name for a new discipline. In Blaschke, T. J., Lang, S., & Hay, G. J. eds. *Lecture notes in geoinformation and cartography*. Berlin: Springer.

Heldens, W., Taubenböck, H., & Esch, T. (2012). Climate change in cities – can remote sensing help to optimise mitigation strategies? In Proceedings Real Corp 2012: Re-Mixing the city – towards sustainability and resilience? May 14-16, 2012, edited by Schrenk, M. Poppvoch, V. V., & Zeile, P. Schwechat: Austria.

Huang, A., Wong, J., & Chen, T. C. (1998). A framework of indicator system for measring taipe's urban sustainability. *Landscape and Urban Planning*, 42, 15-27.

Hui, S. C. M. (2001). Low energy buildings desing in high density urban cities. *Renewable Energy*, 24, 627-640.

InterStudy. (2009). Stellenbosch University [Online]. Available from:http://www.interstudy.org/u/23-stellenbosch-university [Accessed 11 November 2011]

Jabereen, R. Y. (2006). Sustianble urban forms; their typologies, models and concepts. *Journal of Planning Education and Research*, 26, 38-52.

James W. J. (2000). South Africa: Urban transformation. *Cities,* 17(3), 167-183.

Jensen, J. R. (2005). *Introductory digital image processing: A remote sensing perspective*. Upper Saddle River, New Jersey: Prentice Hall.

Jones, C., & MacDonald, C. (2004). Sustainable urban form and real estate markets [Online]. Coventry: CityForm Network. Available from: http://www.cityform.org/uk/pdfs/Pubs_JonesMacDonald04.pdf [Accessed 26 November 2011]

Kligerman, M., Sallis, J. F., Ryan, S., Frank, L. D., & Nader, P. R. (2007). Association of neighbourhood design and recreation environment variables with physical activity and body mass index in adolescents. *American Journal of Health Promotion*, 21(4), 274-277.

Klosterman, R. E. (1995). The appropriteness of geographic information systems for regional planning in the developing world. *Computers, Environment and Urban Systems*, 19(1), 1-13.

Le Ne'chet, F. (2012). Urban spatial structure, daily mobility and energy consumption: A study of 34 European cities [Online]. *European Journal of Geography*. Available from: http:cybergeo.revues.org/24966 [Accessed 11 November 2011].

Litman, T. (2010). *Land use impacts on transport: How land use factors affect travel behaviour*. Vancouver: Victoria Transport Policy Institute.

Lu, D., & Weng, Q. (2006). Use of impervious surface in urban land-use classification. *Remote Sensing of Environment*, 102, 146-160.

Luo, L., & Mountrakis, G. (2010). Integrating intermediate inputs from partially classified images within a hybrid classification framework: An impervious surface estimation example. *Remote Sensing of Environment,*114(6), 1220-9.

Machakaire, D. (2012). Director, MacDough Planning Consultants. Harare. Email on 20 June about geographic information systems in Harare Municipality.

Maclaren, V. W. (2004). Urban sustainability reporting. In Wheeler, S. M., & Beatly, T. eds. *The sustainable urban development reader,* pp 203-210. New York: Routledge.

Mathieu, R., Freeman, C., & Aryal, J. (2007). Mapping private gardens in urban areas using object-oriented techniques and very high-resolution satellite imagery. *Landscape Urban Planning*, 81(3), 179-92.

McLennan, J. F. (2009). *Density and sustainability-A radical perspective*. Casacadia: Trimtab.

Mudau, N. (2010). Spot building count supporting informed decisions. *Position IT,* 10, 51-52.

NASA. (2009). Urban and land use applications: From Los Angeles to Paris [Online]. Washington DC: National Aeronautics and Space Administration: Available from: http://rst.gsfc.nasa.gov/Sect4/Sect4_1.html. [Accessed 2 December 2011].

Nichol, J., King, B., Quattrochi, D., Dowman, I., Ehlers, M., & Ding, X. (2007). Earth observation for urban planning and management: State of the art and recommendations for application of earth observation in urban planning. *Photogrammetry Engineering and Remote Sensing*, 73(9), 973-979.

Nowak, D. J. & Greenfield E. J. (2012). Tree and impervious cover in the United States. *Landscape Urban Planning*, 107(1), 21-30.

Paulse, A.N., Jackson, V.A., & Khan, W. (2012). Comparison of microbial contamination at various sites along the Plankenbrug- and Diep Rivers, Western Cape, South Africa. *Water SA*, 35, 469-478.

Qi, Z., Yeh, A. G., Li, X., & Lin, Z. (2012). A novel algorithm for land use and land cover classification using RADARSAT-2 polarimetric SAR data. *Remote Sensing for Environment*, 18, 21-39.

REFINA. (2012). Actors [Online]. Reduction of Land Consumption and for Sustainable Land Management. Available from: http://www.refina-info.de/en/akteure/index.phtml.[Accessed 2 September 2012.]

SA Statistics. (2001). Census 2001 [Online]. Pretoria: SA Statistics. Available from: http://www.statssa.gov.za/census01/html/WCPrimary.pdf. [Accessed 2 December 2011]

Santos, T., Freire, S., Tenedório, J. A, Fonseca, A., Afonso, N., Navarro, A., & Soares, F. (2011). The GeoSat project: Using remote sensing to keep pace with urban dynamics [Online]. Earthzine. Available from: http://www.earthzine.org/2011/11/09/the-geosat-project-using-remote-sensing-to-keep-pace-with-urban-dynamics/. [Accessed 25 November 2011].

Satellite Imaging Corporation. (2012). Satellite sensors [Online]. Magnolia, Texas: Satellite Imaging Corporation. Available from: http://www.satimagingcorp.com/satellite-sensors/ [Accessed 20 July 2012].

Slemp, C., Davenport, M. A., Seekamp, E., Brehm, J. M, Schoonover, J. E., & Williard. K. W. J. (2012). Growing too fast: local stakeholders speak out about growth and its consequences for community well-being in the urban–rural interface. *Landscape Urban Planning*, 106(2), 139-148.

Sobrino, J. A., Oltra-Carrió, R., Jiménez-Muñoz, J. C., Julien, Y., Sòria, G., Franch, B., & Mattar, C. (2012a). Emissivity mapping over urban areas using a classification-based approach: Application to the dual-use european security IR experiment (DESIREX). *International Journal of Applied Earth Observation and Geoinformation*, 18,141-147.

Sobrino, J. A., Oltra-Carrió, R., Sòria, G., Bianchi, R., & Paganini, M. (2012b). Impact of spatial resolution and satellite overpass time on evaluation of the surface urban heat island effects. *Remote Sensing of the Environment*, 117, 50-56.

Song, Y., & Rodriguez, D. A. (2005). *The measurement of the level of mixed land uses: A synthetic approach*. Chapel Hill: Carolina Transportation Program.

Stellenbosch Municipality. (2011). *Stellenbosch municipality integrated development plan.* Stellenbosch: Stellenbosch Municipality.

Stellenbosch University. (2010). *Fast fact statistics 2010*. Stellenbosch: Stellenbosch University.

Strohbach, M. W., Arnold, E., & Haase, D. (2012). The carbon footprint of urban green space—A life cycle approach. *Landscape Urban Planning*, 104(2), 220-239.

Taubenböck, H., & Esch, T. (2011). Remote sensing-an effective data source for urban monitoring [Online]. Earthzine. Available from: http://www.earthzine.org/2011/07/20/remote-sensing-%E2%80%93-an-effective-data-source-for-urban-monitoring/ [Accessed 20 January 2012].

Taubenböck, H., Esch, T., Felbier, A., Wiesner, M., Roth, A., & Dech, S. (2012). Monitoring urbanization in mega cities from space. *Remote Sensing of Environment*, 117, 162-76.

Taubenböck, H., Esch, T., Wurm, A., Roth, A., & Dech., S. (2010). Object-based feature extraction using high spatial resolution satellite data of urban ares. *Journal of Spatial Science*, 55(1), 117-32.

Taubenböck, H., Roth, A., Esch, T., Felbier, A., Müller, A., & Dech, S. (2011) The vision of mapping the global urban footprint using the TerraSAR-X and TanDEM-X mission. In Rumour. M. eds. *Urban and Regional Data Management*, 243-251. London: Taylor Francis.

Todes, A., & Watson, V. (1986). Local government reform, urban crisis and development in South Africa. *Geoforum*, 17(2), 251-266.

Toure, N. M., Kane, A., Noel, J. F., Turmine, V., Nedeff, V., & Lazar, G. (2012). Water–poverty relationships in the coastal town of Mbour (Senegal): Relevance of GIS for decision support. *International Journal of Applied Earth Observation and Geoinformation*, 14(1), 33-9.

Transportation Research Board. (2009). *Driving and the built environment the effects of compact development on motorized travel, energy use, and CO2 emissions*. Washington DC: National Research Council.

UN. (2008). Millennium development goals indicators [Online]. United Nations: Available from: http://mdgs.un.org/unsd/mdg/Host.aspx?Content=indicators/officiallist.htm [Accessed on 12 November 2011].

UNEP. (2011). Making the Economic Case for Greening Cities [Online]. Nairobi: United Nations Environmental Program: Available from: http://www.unep.org/newscentre/default.aspx?DocumentID=2656&ArticleID=8895 [Accessed on 12 November 2011].

UNHABITAT. (2009). Habitat Partner University Network [Online]. Nairobi: United Nations Center for Human Settlements. Available from: http://www.unhabitat.org/content.asp?typeid=19&catid=570&cid=6002. [Accessed 7 July 2010].

Ural, S., Hussain, E., & Shan, J. (2011). Building population mapping with aerial imagery and GIS data. *International Journal of Applied Earth Observation and Geoinformation*, 13(6), 841-852.

Urban Land Institute. (2010). *Land use and driving: The role compact development can play in reducing greenhouse gas emissions*. Washington DC: Urban Land Institute.

Vaz, E., Cabral, P., Caetano, M., Nijkamp, P., & Painho, M. (2012). Urban heritage endangerment at the interface of future cities and past heritage: A spatial vulnerability assessment. *Habitat International*, 36(2), 287-94.

Veneri, P. (2010). Urban polycentricity and the costs of commuting: Evidence from italian metropolitan areas. *Growth and Change*, 41(3), 403-429.

Victoria Transport Policy Institute. (2010). *Land use impacts on Transport: How Land use Factors Affect Travel Behaviour*. Vancouver: Victoria Transport Policy Institute.

WCED. (1987). *Our common future*. Oxford: World Commission on Environment and Development.

Weng, Q. (2012). Remote sensing of impervious surfaces in the urban areas: Requirements, methods, and trends. *Remote Sensing of Environment*, 117, 34-49.

Western Cape Department of Environmental Affairs and Development Planning. (2009). *Western Cape Provincial Spatial Development Framework*. Cape Town: Department of Environmental Affairs and Development Planning.

Wigbells, L., Faith, G. R., & Sabathier, V. (2008). *Earth observations and global change: Why? Where we are? What next?* Washington DC: Center for Strategic and International Studies.

Wurm, M., Taubenbock, H., Roth, A., & Dech, S. (2009). Urban structuring using multisensoral remote sensing data by example of German cities, Cologne and Dresden. *Urban Remote Sensing Joint Event, 2009*, 1-8.

Yabuki, N., Miyashita, K., & Fukuda, T. (2011). An invisible height evaluation system for building height regulation to preserve good landscapes using augmented reality. *Automation in Construction*, 20(3), 228-235.

Zhang, H., Zhang, Y., & Lin, H. (2012). A comparison study of impervious surfaces estimation using optical and SAR remote sensing images. *International Journal of Applied Earth Observation and Geoinformation*, 18, 148-156.

# CHAPTER 8: EVALUATION AND CONCLUSION

The aim of the research was to evaluate the potential of earth observation (EO) for monitoring and modelling sustainable land use in urban centres. The unavailability, unreliability, outdatedness and unstandardised nature of urban land use planning data in developing countries was the motivation for the investigation. Many local authorities are inadequately equipped to plan for sustainable development in hyperchanging environments. Because sustainable land use, like sustainable development, are elusive concepts to put into practice in routine decision-making, an emerging structured framework, decision consequence analysis (DCA) was proposed to aid decision making for sustainable urban land use planning. DCA breaks complex problems, such as sustainable urban development, into increasingly smaller units until the particular component can be accurately analysed and understood within the context of the overall problem. Therefore, sustainable urban land use was divided into three themes, namely land use change and land use mix, urban sprawl and the urban built-up area. These three components relate to the first research question; what data is needed to support sustainable land use planning? The following section summarises how the three components relate to each other. The rest of the chapter documents the urban sustainability toolbox, lists the contributions the study makes to knowledge, singles out some limitations of the study, makes suggestions for future research and draws overall conclusions.

## 8.1 SUMMARY

A review of literature on the application of EO in urban planning revealed that there are few substantive studies on the measurement of land use mix and that spatial statistics that go beyond the urban extent are needed to monitor urban sprawl. The review also pointed to the potential of EO as a source of built-up area data which can be used in urban planning. Consequently, EO and geographic information system (GIS) data were collected for Stellenbosch and used to derive sustainable urban land use indicators for land use change and land use mix, urban sprawl and built-up areas.

The study demonstrated that EO data facilitates contemporary area-wide synoptic land use classification needed in land use change (LUC) analysis. LUC is an effective way of gauging the sustainability trajectory of urban centres because each land use change contributes distinctively to sustainable urban development. Urban-to-urban changes are more sustainable than non-urban to urban changes that result in the loss of agricultural land and natural ecosystems, hence leading to adverse socio-economic and environmental costs. Because LUC alone is a necessary but inadequate measure of land use sustainability, land use mix indexes were employed to obtain a broader picture of how spatial relationships of land use (diversity) strongly affect the sustainability trajectory.

Land use change maps derived from EO data were used to calculate the global land use mix (GLUM) index, local land use mix (LLUM) index and land use frequency (LUF) for Stellenbosch. The LLUM and LUF were mapped as continuous surfaces, as opposed to discrete maps, for ease of interpretation and visualisation. GLUM and LLUM are important measures of diversity and vibrancy as well as spatial and social integration. These are crucial properties given the history of spatial and social segregation in South Africa as well as in many other developing countries. The GLUM and LLUM indexes are vital in gauging the socio-economic sustainability of current planning practices. The LLUM index and LUF can help planners to produce sustainability reports that are less subjective and descriptive, and they can also serve as mechanisms to monitor interventions. While LLUM is a good indicator of spatial and social diversity, it does not indicate with certainty where urban sprawl is occurring. To counter this weakness, the Moran indexes were derived from cadastral data to determine urban sprawl hot and cold spots.

The study demonstrated that the Moran I and local Moran *I* facilitate the capturing of three dimensions of urban sprawl, namely spatial geometry, low density developments and strip developments. It was found that the global Moran I is particularly sensitive to leapfrogging developments. Similarly, because of the cross-shaped geometry of Stellenbosch's urban extent, Moran I values at all distance bands are close to zero, which indicates a discontinuous and relatively unsustainable pattern of urban development. But Moran I alone is not sufficient for identifying problem areas within urban centres. It was shown that it should be complemented by local Moran *I* analyses which enable spatial visualisation of the urban sprawl hot and cold spots. The spatial visualisation of the cluster outlier type (COT) is valuable to decision makers because it facilitates the identification of best practices and problem areas. COT can be used to effect policy changes, devise mitigatory strategies and model future scenarios. For optimal decision-making it is recommended that various simulations (distance bands) and visualisation methods be used to enhance understanding of the distribution of hot and cold spots. However, the Moran indexes only make use of land parcel data and do not take into account the built-up area. To remedy this data on built-up areas were obtained using EO, and sustainability indicators were derived to attain a comprehensive picture of urban sustainability in Stellenbosch.

Analyses of the built-up area indicators revealed that EO adds value to sustainable urban development by providing area-wide and current thematic (impervious surfaces) and geometric (building count, density and building height) characterisations of the urban environments. This provides visual and quantitative distributions that show relationships between urban sustainability indicators. It would be a prohibitively expensive and cumbersome task to collect such data from sources such as municipal records (e.g. building plans). Analysis of the built-up area indicators also revealed that sustainable urban development is an optimising procedure and that ‘a middle ground’ has to be maintained to achieve sustainable urban development. Building density was identified as a core indicator because it represents wide-ranging environmental, social and economic costs associated with sustainable land use. Similarly, changes in impervious surfaces are key indicators of land transformation and growth of urban footprints. The quantification and visual display of built-up area indicators enable local authorities to perform evidence-based decision making while affording local authorities room to choose an appropriate and objective sustainable urban development paradigm suitable for a particular situation, as opposed to adopting compact-city development as the only solution. The derivation of built-up area indicators from EO data was shown to be cost-effective and useful in other urban applications such as building count, population and disaster risk management.

## 8.2 SYNTHESIS: URBAN SUSTAINABILITY TOOLBOX

The combination of the three components of sustainable urban land use facilitated the spatial, quantitative and temporal analysis of sustainable urban land use in Stellenbosch. In combination, these indicators constitute a functional toolbox (Table 8.1) to aid urban planners and other professionals working in built environments in making key decisions about urban sustainability and other planning issues.

Table 8.1: Urban sustainability toolbox

| Component | Indicator | Impact on urban sustainability | Urban planning decisions which the indicators can inform | Ideal data sets |
|---|---|---|---|---|
| **Land use change and land use mix** | Land use change (LUC) | Environmental | – Promote efficient use of space by managing change from non-urban to urban uses, that is reduce land transformation and growth of the urban footprint.<br>– Facilitate development of spatial development frameworks, zoning and local plans. | – Land use data<br>– Cadastral data |
| | Global land use mix (GLUM) index<br>Local land use mix (LLUM) index<br>Land use frequency (LUF) | Socio-economic | – Promotion of mixed-use cities<br>– Planning for spatial and social integration as well as urban designs that promote the pavement-cafe idea (social vibrancy).<br>– Planning for safe and healthy communities<br>– Improved access to socio-economic opportunities | |
| **Urban sprawl** | Global Moran index (Moran I)<br>Local Moran index (Moran *I*)s | Environmental and socio-economic | – Identification of urban sprawl hot and cold spots<br>– Land parcel intensification, subdivision and consolidation as well as densification strategies<br>– Promotion of social and spatial interaction through planning of different land parcel sizes.<br>– Efficient use of space to facilitate development of compact cities or the alternative making room paradigm.<br>– Planning for public transport<br>– Planning for new developments that amortise infrastructure costs. | – Land cover<br>– Cadastral data |
| | Urban extent | Environmental | – Demarcation of urban edge and planning for future growth<br>– Rate of land transformation, i.e. non-urban to urban uses | |
| **Built-up area** | Building count and density | Environmental and socio-economic | – Densification and intensification strategies<br>– Service provision, i.e. amortisation of infrastructure costs<br>– Provision of public transport, circulation, accessibility, and parking<br>– Other urban planning issues such as flood risk management, informal settlement upgrading, population estimates and disaster management<br>– Encouraging social and spatial integration | – Land cover data |
| | Impervious surface concentration | Environmental | – Minimising negative land transformation and indiscriminate growth of the urban footprint<br>– Planning for a healthy mix of built-up areas and open spaces to allow cities to breathe (green infrastructure).<br>– Managing the urban microclimate through landscaping techniques which are important tools in mitigating climate change. | – Land cover data |
| | Building height | Cross-cutting | – Conserving the cultural heritage<br>– Managing the urban microclimate<br>– Promoting efficient utilisation of space, intensification and amortisation of service costs | – Digital elevation model<br>– Digital terrain model<br>– Digital surface model |

### 8.2.1 Toolbox overview

The toolbox summarised in Table 8.1 can be considered a synthesis of this study as it encapsulates all the various aspects of urban sustainability discussed in this dissertation. For the exploration of the socio-economic impacts relating to social and spatial integration, health and safety, the GLUM and LLUM indexes and LUF can be used. Similarly, land use change, impervious surface concentration and the urban extent highlights environmental impacts and are useful for determining the rate of land transformation, human-nature interaction and growth of the urban footprint. LUC informs decisions pertaining to the preparation of local and zoning plans and spatial development frameworks (SDFs). SDFs and local plans illustrate projected land patterns and developments. Impervious surface concentration is a vital indicator in the preparation of sustainable urban designs and plans, which allow cities to ‘breathe’ while creating urban microclimates which conserve energy and are comfortable for citizens. The urban extent is important for demarcating sustainable urban growth boundaries as well as a guide for future developments within a defined precinct.

The global Moran and local Moran indexes, building density and count as well as building height constituents of the toolbox are cross-cutting (socio-economic and environmental) indicators of urban sustainability. Building density, count and height as well as the Moran indexes are convenient for formulating densification and intensification strategies, promoting efficient use of space, and the amortisation of infrastructure and service costs. The Moran indexes, building densities and building count are useful for determining the feasibility and capacity of public transport systems and parking facilities and for conducting accessibility studies in urban areas. These indicators also facilitate decision making about practical approaches to urban sustainability, that is, selecting between compact-city development or the making room paradigm, depending on the circumstance. Building height is also essential in the conservation of the cultural heritage.

The toolbox can also guide the approval of new urban developments. For example, Stellenbosch is experiencing growth in the number of gated communities marketed as being ‘green’ or ‘sustainable’. The toolbox can test whether these proposed developments are sustainable by applying various indicators to their proposed layouts and the results used for approval of plans or for making suggestions on how property developers can improve their designs and layouts. For instance, the layout of the proposed De Zalze 2 development (see Figure 7.9) next to the existing De Zalze security estate (Stellenbosch Municipality 2010) can be analysed by using the built-up area indicators to test whether the design envisages medium-to-high densities which will enable sustainable urban development targets to be met. Moran analyses can be done on the De Zalze 2 proposal to test if it encourages efficient use. LUC will determine whether the new development will cause indiscriminate transformation of land to urban uses while the LLUM index can be used as a measure of social and spatial integration. Such analyses will help local authorities to approve new developments that are more sustainable.

The urban sustainability toolbox provides the means to monitor sustainable urban land use planning. The toolbox can be applied annually to produce objective sustainability reports and to answer the why, when and what if questions integral to land use decision making. Such reports provide an overview of sustainability status and enables decision makers to identify specific problem areas. In Stellenbosch, the study revealed that Welgevonden has medium-to-high densities, an average building height of two storeys, a low-low cluster outlier type, and a high (0.8) LLUM index. Such developments should be encouraged at the urban edge because they significantly reduce the environmental, social and economic costs of urban development.

An important feature of the toolbox is that it uses EO data and GIS analysis which enable the visual, graphical and spatial representation of urban sustainability making the information produced more comprehensible and usable for decision making. Unlike tables, which show rate of change, maps show where the change is occurring and this assists decision makers to prepare strategic actions and to target specific areas. For example, the maps in this dissertation revealed that the De Zalze-Stellenbosch Square neighbourhood is a problem area, which calls for measures to be designed and implemented to encourage sustainable land use practices. The interoperability of EO data with a variety of GIS systems (ArcGIS and GeoDa) is also demonstrated by the toolbox. The indicators in the toolbox can also be incorporated into a SDSS for scenario building.

### 8.2.2 Data requirements

The urban sustainability toolbox requires certain data sets. For land use change and the land use mix analyses, land use and cadastral data is needed. Google Earths' Street View, available for major cities and towns in Africa and other developing countries, can help in the classification of vertical and horizontal land use mix. Three-dimensional city models and digital surface models, where available, are also invaluable for identifying mixed land uses and other land use classes such as commercial and industrial.

The calculation of Moran indexes requires cadastral data which is available for most developing countries. Scanned layout plans or designs projected for use in GIS software such as ArcGIS can be used for calculating the Moran indexes because they contain land parcel data. The global Moran I requires urban extent data, which can be derived from land cover maps.

The analysis of building density and count also requires land cover data. Three-dimensional building models derived from light detection and ranging (LIDAR) data can be used to demarcate settlement structure as well as building density and count. Land cover data is also necessary for calculating impervious surface concentration. Improved land cover classification of urban surface material calls for hyperspectral satellite imagery because it can better distinguish urban surface materials (Nichol et al. 2007; Weng 2012). Building height calculations require a digital terrain model (DTM) and a digital surface model (DSM) derived from VHR stereo-pair imagery or LIDAR. DSMs are also useful in land use classification and for demarcating the urban extent.

Urban planning has traditionally used VHR 0.5 m aerial photographs for mundane tasks such as property identification. The availability of VHR 0.5 m spatial resolution satellite imagery holds great potential for assisting urban planning because it has the required finer spatial resolution to discriminate urban features and a high temporal resolution to detect changes at high frequency. Consequently, it is possible to produce up-to-date data sets of land use and land cover, which is crucial for understanding human-nature interactions.

The urban sustainability toolbox is flexible and can be modified by adding indicators or by choosing specific indicators depending on the issue in question. For transport issues, for instance, the requisite travel-related data can be added. The toolbox is also not confined to urban sustainability studies as it can be applied for population estimates, disaster management and telecommunications planning. This flexibility and applicability ensures cost-effectiveness and data sharing, which can lead to better urban planning decisions.

## 8.3 RESEARCH OBJECTIVES REVISITED

The aim of this research was to evaluate the potential of EO to model and monitor sustainable urban land use particularly in developing countries where data is often unavailable, unstandardised, unreliable and outdated.

The first objective (see Section 1.4) was to review the literature on the application of EO in urban planning. This was covered by Chapter 3. Chapter 2 discussed the origins of sustainable development and indicator frameworks used to simplify sustainable development for day-to-day decision making. The indicator frameworks were used as a guide for the second objective of compiling a set of sustainable urban land use indicators from the literature as presented in Chapter 4. The indicators cover three key themes namely land use change and land use mix, urban sprawl and the urban built-up area (Objective 2). The literature review presented in Chapter 2 also spotlighted the difficulty of implementing the concept of urban sustainability into day-to-day decision making. Consequently, DCA, a list of sustainable urban land use indicators, EO data and GIS analysis were used to develop a framework for evaluating EO's potential for supporting sustainable urban land use planning (Objective 3). The framework was applied to Stellenbosch for each of the three key indicator themes (Chapters 5, 6 and 7) and the progress made towards urban sustainability was determined (Objective 4). An assessment of this progress demonstrated how EO data, DCA, sustainable land use indicators, and GIS analysis could facilitate decision making on urban sustainability (Objective 5). The framework was also used to develop a holistic, systematic, flexible, universal urban sustainability toolbox for monitoring and facilitating decisions regarding sustainable urban land use planning (Chapter 8). The toolbox was implemented to critically evaluate the impact of urban sustainability indicators on environmental and socio-economic sustainability (Objective 6). Chapter 8 addresses the final objective of evaluating the potential of EO to monitor and model urban land use sustainability. The evaluation revealed that EO has significant potential for monitoring urban sustainability and that EO-derived products will most likely become important tools in urban planning.

## 8.4 RESEARCH VALUE AND CONTRIBUTION

The study's contribution to existing knowledge about sustainable urban land use is twofold. First, a series of indicators for the three components, namely land use change and land use mix, urban sprawl and built-up area of sustainable urban development were derived using EO data and GIS. Analysis of these components gives local authorities a holistic, systematic and objective view of the trajectory of sustainable urban land use development. The developed toolbox empowers role-players to make evidence-based decisions as opposed to incremental planning, subjective decisions and advocacy planning or merely accepting compact development as the only sustainable urban development paradigm. Analyses of sustainability indicators derived from EO data allow local authorities to choose between ‘the making room paradigm’ and the ‘compact development paradigm’ depending on the situation.

Second, the study extended existing methods for monitoring urban sustainability. To the author’s knowledge the way in which the Moran indexes were applied in this study to determine and visualise urban sprawl hot and cold spots is novel. The study extends Tsai (2005) and Le Néchet’s (2011) research in which the Moran Index was used to measure urban sprawl. According to Song and Rodriguez (2005), the challenge with existing land use mix mapping techniques is the discrete nature of the results, which makes visual interpretation difficult. A new technique that produces a continuous surface of land use mix was developed in this study. This technique was implemented as a Python script (Appendix B) which can be applied in other urban centres to calculate LUM and LUF. The continuous surface approach was also applied to the built up area indicators of sustainable development because it promotes easy visual interpretation and comparison which is vital in facilitating decision making. The dissertation also extends the pioneering work of Hall WL (2010) who coined DCA, a framework for improving the quality of decision results. Accordingly, DCA was used to develop a research framework and processes to evaluate the potential of earth observation for supporting sustainable urban land use planning.

The urban sustainability indicators that were derived from EO data in this research are normalised and presented in standard format. This implies that the methods demonstrated in this study are universally applicable and can be used for rapid comparative studies of urban centres and development of place-independent models. Such methods facilitate learning from best practices, knowledge sharing (particularly in developing countries), identification of problem areas, modelling of future scenarios, and the effecting of policy changes. The use of EO data and GIS analysis is a resolution to the issues of unavailability, out-datedness and unreliable forms of data experienced in most developing countries undergoing rapid urbanisation which makes it difficult to monitor and plan for sustainable urban development. Ultimately, the use of EO data helps in bridging the gap in the efficacy of urban monitoring and data availability that exists between developed and developing countries.

## 8.5 LIMITATIONS

Paradoxically a weakness of the study is the reliance on remotely sensed data (satellite imagery and aerial photographs). The presence of errors in EO-derived data sets (e.g. land use, land cover, building height) is acknowledged and should always be taken into consideration when the indexes are used in decision making. Fortunately, the relatively high accuracies achieved in this study (>75%) attest that EO is a reliable source of spatial data. A further limitation of the study and EO in general is the difficulty of determining mixed land use using remotely sensed imagery. This is a major constraint for automating land use mapping using remotely sensed imagery, as field surveys are in most cases necessary for producing accurate land use maps of urban centres. New sources of data, such as Google Earth's Street View product, holds much potential for reducing expensive and time-consuming field surveys for determining vertical and horizontal mixed land use. This data is, however, not yet available for all urban areas.

Stellenbosch was used as a case study to evaluate the potential of EO for supporting sustainable urban land use planning. The situation in Stellenbosch may in some cases not be representative of other urban settlements in developing countries. Although Stellenbosch provided a suitable platform for developing the toolbox, more research is needed to test it in other regions.

Another limitation of this research is that VHR satellite imagery (e.g. GeoEye-1 and WorldVeiw-2) was not employed in deriving the sustainability indicators. Instead, 0.5 m aerial colour photography and 2.5m SPOT5 images were used, mainly due to data availability. It is likely that VHR satellite imagery will provide even better discrimination of urban land covers because its spatial resolution is higher than SPOT5 imagery and its spectral resolution is higher than the colour aerial photography that was used in this research.

The use of cadastral data in calculating the various indices employed in this research can also be regarded as a potential limitation of the study because it may not be available in all urban centres. This type of information is difficult to extract from remotely sensed data, particularly in urban areas. Air pollution data is important in monitoring urban sustainability (NASA 2009; Nichol et al. 2007), but was not used as it was not available at a suitable resolution. Hopefully new initiatives such as the scheduled launch of a space borne sensor for monitoring air pollution in 2017 (Geoinformatics International 2012) will address the lack of such data. Travel-related data is also critical for urban land use planning but was not available for the study area at an intra-urban scale. The lack of travel-related data is a general problem in developing countries (Hicken 2009). Cellphones equipped with global navigation satellite systems (GNSS) and volunteered geographical information (VGI) may provide a solution to monitoring movement of people in urban centres, but this kind of data was not explored in this research.

Census data, another important data source for urban planning, was not used in this study, mainly because the aim of the study was to develop methods that can be applied in countries where such data is not available. It has, however, been shown that EO can be employed to monitor population dynamics (Almedia et al. 2011; Ural, Hussain & Shan 2011). This avenue of research was considered to be outside of the scope of this study.

## 8.6 RECOMMENDATIONS AND SUGGESTIONS FOR FUTURE RESEARCH

The literature review revealed that there are few substantive studies dedicated to the measurement of land use mix despite the growing interest in promoting mixed-use urban areas. Accordingly, it is advisable that the GLUM and LLUM indexes be applied in developing-country situations to gain a better understanding of land use mixing. The influence of land use mixing on the natural environment needs to be explored further. Similarly, studies are needed in which multicriteria decision analyses are employed to measure the sustainable trajectory of vertical and horizontal land use change. Research on the automation of land use classification (vertical and horizontal land uses) is also needed to improve understanding of land use mixing in urban environments and to expedite decision-making processes. Concerning urban sprawl, more research is needed to test the sensitivity of the Moran indexes in different contexts (e.g. metropolitan areas) and to find a surrogate for cadastral data in areas for which such data is not available. LIDAR data or VHR stereo satellite imagery is urgently needed in developing countries to derive indicators of built-up area sustainability (building height, volume, area, height and density). More research is required on obtaining urban sustainability indicators through data and image fusion as this has the potential to make significant advances in urban sustainability monitoring. A shift is needed from purely science-driven applications of EO to finding innovative practical ways to use EO in day-to-day decisions to create sustainable cities of the future.

The urban sustainability indicators identified in this dissertation can be used to design an interactive planning support system (PSS). Such a system should incorporate data analysis and display modules to enable and encourage scenario building.

Other urban sustainability studies have demonstrated that in-situ observations using cellphone signals, Google Earth, Streetmap, crowd-sourcing, mobile apps, social media as well as remote sensing using unmanned aerial vehicles (UAVs) provide useful information such as travel data to augment satellite imagery. More research is needed on the use of these technologies for urban planning.

## 8.7 CONCLUDING REMARKS

The genesis of the research was to assess the extent to which EO is able to support sustainable urban land use planning in a hyperchanging environment. Local authorities often rely on various formats of data, some of which are inadequate, unreliable and outdated. This inevitably makes the monitoring of sustainable land use planning and urban growth unworkable, hindering local authorities capacity to leverage resources towards sustainable development. EO data is becoming readily available and it will most likely play a major role in supporting urban planning in developing countries. The advent of VHR EO data such as GeoEye-1 and WorldView-2, in conjunction with the continuous improvement in image classification techniques and the increasing public awareness of EO through platforms such as Google Earth and Bing Maps will promote the increased use of EO and efficient monitoring of sustainable urban planning in developing countries. Moreover, the use of emerging technologies such as cellphones equipped with GNSS, crowd-sourcing, mobile apps, social media and UAVs will likely improve access to data needed for planning sustainable cities of tomorrow.

**REFERENCES**


Addink EA, Van Coillie, FMB & De Jong, SM 2012. From pixels to geographic objects in remote sensing image analysis. *International Journal of Applied Earth Observation and Geoinformation* 15: 1-6.

Adriaanse A 1993. *Environmental policy performance indicators*. The Hague: Ministry of Housing.

Almedia CM, Oliveira CG, Rennó CD & Feitosa Q 2011. Population estimates in informal settlements using object-based image analysis and 3D modelling [Online]. Available from: http://www.earthzine.org/themes-page/urban-monitoring/. [Accessed 10 July 2012].

Anderson JR, Hardy EE, Roach JT & Witmer RE 1976. *A land use and land cover classification for use with remote sensor data*. Washington DC*:* United States Government Printing Office.

Aneja S, Gross CP, Soulos PR & Yu JB 2011. Geographical information systems: applications and limitations in oncology research. *Oncology* 25: 1221-1225.

Angel S 2010. *Making room for a planet of cities*. Cambridge: Lincoln Institute of Land Policy.

Anselin L 1995. Local indicators of spatial association. *Geographical Analysis* 27: 93-115.

Anselin L 2003. *GeoDa 0.9 users guide*. Phoenix: Spatial Analysis Laboratory.

Anselin L 2005. *Exploring spatial data with GeoDa™: A workbook*. Phoenix: Spatial Analysis Laboratory.

Anselin L 2012. From spacestat to cybergis: Twenty years of spatial data analysis software. *International Regional Science Review* 35: 131-157.

Anselin L, Sybari I & Kho Y 2006. GeoDa: An introduction to spatial data analysis. *Geographical Analysis* 38: 5-22.

Ascough JC, Rector HD, Hoag DL, McMaster SG, Vandenberg BC, Shaffer MJ, Weltz MA & Ahjua LR 2002. Multicriteria spatial decision support systems: Overview, applications, and future research directions [Online]. Available from: http://www.iemss.org/iemss2002/proceedings/pdf/volume%20tre/290_ascough%202.pdf [Accessed 5 May 2010].

Barredo JI & Demicheli L 2003. Urban sustainability in developing countries' megacities: Modelling and predicting future urban growth in Lagos. *Cities* 20: 297-310.

Bartik TJ & Bingham RD 1997. Can economic development programs be evaluated? [Online]. Available from: http://research.upjohn.org/up_workingpapers/29/ [Accessed 20 September 2012].

Baud I, Kuffer M, Pfeffer K, Sliuzas R, & Karuppannan S 2010. Understanding heterogeneity in metropolitan India: The added value of remote sensing data for analyzing sub-standard residential areas. *International Journal of Applied Earth Observation and Geoinformation* 12, 5: 359-374.

Becker B 1997. *Sustainability assessment: A review of values, concepts and methodological approaches*. Washington DC: Consultative Group on International Agricultural Research.

Bhatta B, Saraswati S & Bandyopadhyay D 2010. Quantifying the degree of freedom, degree of sprawl, and degree -of-goodness of urban growth from remote sensing data. *Applied Geography* 30: 96-111.

Bigazzi YA & Burtini RL 2009. Adding green performance metrics to a transportation data archive. *Transportation Report Record* 2021: 30-40.

Bossel H 1999. *Indicators of sustainable development: Theory, method and application*. Winnipeg: Balaton Group.

Breheny P & Batey PWJ (eds) 1992. *Sustainable development and urban form.* 2nd edn. London: Pion Limited.

Brömmelstroet MT 2012. Transparency, flexibility, simplicity: From buzzwords to strategies for real PSS improvement. *Computers, Environment and Urban Systems* 36: 96-104.

Burton E 2002. Measuring urban compactness in UK towns and cities. *Environmental Planning B: Planning and Design* 29: 219-250.

Calthorpe Associates 2010. *The role of land use in reducing VMT and GHG emissions: A critique of TRB special report 298.* Berkeley: Calthorpe Associates.

Canadian Urban Institute 2008. *Energy mapping study*. Toronto: Canadian Urban Institute.

Chen L, Zhao S, Han W & Li Y 2012. Building detection in an urban area using lidar data and QuickBird imagery. *International Journal of Remote Sensing* 33: 5135-5148.

CIESIN (Centre for International Earth Science Information Network) 2009. Remote sensing and the social sciences [Online]. Available from: http://sedac.ciesin.columbia.edu/tg/guide_glue.jsp?rd=rs&ds=5 [Accessed 5 August 2010].

Clark WC. 2007. Sustainability science: A room of its own [Online]. Available from: http://www.pnas.org/site/misc/sustainability.shtml [Accessed 3 June 2010].

Clark WC & Dickson NM 2003. Sustainability science: The emerging research program [Online]. Available from: http://www.pnas.org/content/100/14/8059.full.pdf+html [Accessed 2 June 2010].

Comber A, Brunsdon C & Green E 2008. Using a GIS-based network analysis to determine urban green space accessibility for different ethnic and religious groups. *Landscape and Urban Planning* 86: 103-114.

Cornforth IS 1999. Selecting indicators for assessing sustainable land management. *Environmental Management* 56: 173-179.

Cowen DJ & Jensen JR 1998. Extraction and modelling of urban attributes using remote sensing technology. In Liverman D, Moran EF, Rindfuss RR & Stern PC (eds.) *People and pixels: Linking remote sensing and social science*, 164-188. Washington DC: National Academy of Sciences.

CSIR 2010. *Land cover field guide.* Pretoria: Council for Scientific and Industrial Research.

Department of Rural Development and Land Reform 2009. *Development of a methodology for national land use mapping for Chief Directorate: Geo Spatial Information.* Cape Town: Department of Rural Development and Land Reform.

De Roo G 2003. *Environmental planning in the Netherlands: Too good to be true.* Hampshire: Ashgate.

De Wit P & Verheye W 1997. Land use, land cover and soil sciences [Online]. Available from: http://www.eolss.net/ebooks/Sample%20Chapters/C19/E1-05-03-01.pdf [Accessed 26 October 2010].

Dewan AM & Yamaguchi Y 2009. Land use and land cover change in Greater Dhaka, Bangladesh: Using remote sensing to promote sustainable urbanisation. *Applied Geography* 29: 390-401.

Ding C 2013. Building height restrictions, land development and economic costs. *Land Use Policy* 30: 485-495 Article in Press.

Dumanski J 1997. Criteria and indicators for land quality and sustainable land management. *Instrumental Transcommunication Journal* 3, 4: 216-222.

Dur F, Yigitcanlar T & Bunker JM 2009. A decision support system for sustainable urban development: The integrated land use and transportation indexing model. *In Proceedings of the second infrastructure theme postgraduate conference 2009 - Rethinking sustainable development: planning, infrastructure engineering, design and managing urban infrastructure, held 26 March 2009*, Brisbane: Queensland University of Technology.

Eid J, Overman HG, Puga D &Turner M A 2008. Fat city: Questioning the relationship between urban sprawl and obesity. *Journal of Urban Economics* 63: 385-404.

Erener A (2012). Classification method, spectral diversity, band combination and accuracy assessment evaluation for urban feature detection. *International Journal of Applied Earth Observation and Geoinformation.* Article in press [Online]. Available from: http://dx.doi.org/10.1016/j.jag.2011.12.008. [Accessed 26 October 2012].

Esch T, Taubenböck H, Heldens H, Theil M, Wrum M, Geiss C & Dech S 2010. Urban remote sensing-how can earth observation support sustainable development of urban environments? *Proceedings cities for everyone, liveable, healthy and prosperous, held18-20 May 2010*, Vienna: Real Corp.

ESRI Inc (Environmental Systems Research Institute) 2010. Spatial autocorrelation[Online]. Available from: http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?TopicName=Spatial_Autocorrelation_%28Morans_I%29_%28Spatial_Statistics%29 [Accessed 26 July 2012].

Ewing R 1997. Is Los Angeles style sprawl desirable? *Journal of American Planning Association* 63: 107-127.

Ewing R & Cervero R 2001. *Travel and the built environment: A synthesis*. Washington DC: Transportation Research Board.

Ewing R & Nelson A 2008. *CO2 reductions attributable to smart growth in California*. Maryland: National Center for Smart Growth Research and Education.

FAO (Food and Agriculture Organization) 1976. *A framework for land evaluation*. FAO Soils Bulletin 32. Rome: FAO.

FAO 1993. *Guidelines for land use planning*. FAO Development Series 1. Rome: FAO.

FAO 1995. *Planning for sustainable use of land resources. Towards a new approach*. FAO Land and Water Bulletin 2. Rome: FAO.

FAO 1999. *The future of our land: Facing the challenge. Guidelines for integrated planning for sustainable management of land resources.* Rome: FAO

Farrow A & Winograd M 2001. Land use modelling at the regional scale: An input into rural sustainability indicators in Central America. *Agriculture, Ecosystems and Environment* 85: 249-269.

Feng Y & Liu Y 2012. An optimised cellular automata model based on adaptive genetic algorithm for urban growth simulation. In Shi W, Yeh A & Leung YC (eds) A*dvances in spatial data handling and gis*, 27-38. New York: Springer.

Forster B 1983. Some urban measurements from landsat data. *Photogrammetric Engineering and Remote Sensing* 14: 1693-1707.

Frank L & Engelke P 2001. The built environment and human activity patterns: Exploring the impacts of urban form on human health. *Journal of Planning Literature* 16: 202-218.

Frank LD, Greenwald MJ, Winkelman S, Chapman J & Kavage S 2010. Carbonless footprints: Promoting health and climate stabilization through active transportation. *Preventative Medicine* 50: 99-105.

Freeman C 2004. Sustainable development from rhetoric to practice? A New Zealand perspective. *International Planning Studies* 9: 307-326.

Gatrell JD & Jensen RR 2008. Socio-spatial applications of remote sensing in urban environments. *Geography Compass* 2: 728-743.

Geoinformatics International 2012. Space borne instrument to track air pollution [Online]. Available from: http://www.giminternational.com/news/mapping/earth_observation/id7081-spacebased_instrument_to_track_air_pollution.html [Accessed 30 November 2012].

Geiss C, Taubenböck H, Wurm M, Esch T, Nast M, Schillings C & Blaschke T 2011. Remote sensing-based characterisation of settlement structures for assessing local potential of district heat. *Remote Sensing* 3: 1447-1471.

Gerundo R & Grimaldi M 2011. The measure of land consumption caused by urban planning. *Procedia Engineering* 21:1152-1160.

Göcmen ZA & Ventura SJ 2010. Barriers to GIS use in planning. *Journal of the American Planning Association* 76: 172-183.

Guindon B & Zhang Y 2005. Using satellite remote sensing to survey transport-related urban sustainability: Part 1: Methodologies for indicator quantification. I*nternational Journal of Applied Earth Observation* 8: 149-164.

Guindon B & Zhang Y 2007. Using satellite remote sensing to survey transport-related urban sustainability: Part II: Methodologies for indicator quantification. *International Journal of Applied Earth Observation* 9: 149-164

Gunder M 2006. Sustainability: Planning saving's grace or road to perdition. *Journal of Planning Education and Research* 20: 208-221.

Haberl H & Schandl H 1998. Indicators of sustainable land use-concept for analysis of society nature interrelations and implications for sustainable development. *In Proceedings of the Congress of The European regional science association, Europe quo vadis?-regional questions at the turn of the century held 28 August -1 September 1998,* Vienna, Austria: European Regional Science Association.

Hall O 2010. Remote sensing in social science research. *Open Remote Sensing Journal* 3: 1-16.

Hall P 2004. Walking the talk. *Town and Country Planning* 30: 54-59.

Hall WL 2010. Decision consequence analysis: A paradigm for decision-making. In Brown K & Hall WL (eds) *Sustainable land development and restoration: Decision consequence analysis*, 75-85. Amsterdam: Elsevier.

Halla R, Kennedy CA & Adams BJ 2005. Developing sustainability criteria for urban infrastructure systems. *Canadian Journal of Civil Engineering* 32: 72-89.

Hay GJ & Castilla G 2008. Geographic object-based image analysis (GEOBIA): A new name for a new discipline. In Blaschke TJ, Lang S & Hay GJ (eds.) *Lecture notes in geoinformation and cartography*, 75-89. Berlin: Springer.

Heilmann M & Tillman S 2010. Greenhouse gas assessment at Barksdale air force basea case study. In Brown K & Hall WL (eds) *Sustainable land development and restoration: Decision consequence analysis*, 383-395. Amsterdam: Elsevier.

Hicken E 2009. The application of GIS at a local governmental level as a facilitation tool for sustainable development in rural Africa. Master's thesis. London: Kingston University, Department of Geography.

Huang A, Wong J & Chen TC 1998. A framework for an indicator system for measuring Taipei's urban sustainability. *Landscape and Urban Planning* 42: 15-27.

InterStudy 2009. Stellenbosch University [Online]. Available from: http://www.interstudy.org/u/23-stellenbosch-university [Accessed 11 July 2011].

IUCN 2002. Resource kit for sustainability assessment[Online]. Available from: http://cmsdata.iucn.org/downloads/resource_kit_c_eng.pdf [Accessed 5 July 2010].

Jabereen RY 2006. Sustainable urban forms: Their typologies, models and concepts. *Journal of Planning Education and Research* 26: 38-52.

Jacques PJ, Dunlap RE & Freeman M 2008. The organization of denial: Conservative think tanks and environmental scepticism. *Environmental Politics* 17: 345-389.

Jensen JR & Cowen DC 1999. Remote sensing of urban/suburban infrastructure and socioeconomic attributes. *Photogrammetric Engineering and Remote Sensing* 65: 611-622.

Jin X & Davis CH 2005. An integrated systems for automatic road mapping from high-resolution multi-spectral satellite imagery by information fusion. *Information Fusion* 6: 257-273.

Jones C & MacDonald C 2004. *Sustainable urban form and real estate markets*. Edinburg: HerriotWatt University.

Jozsa A & Brown D 2005. *Neighbourhood sustainability indicators.* Luxembourg: European Communities.

Keenan PB 2006. Spatial decision support systems: A coming of age. *Control and Cybernetics* 35: 9-37.

Keita LK & Zhang L 2010. Analysis of land use change in Siby, Mali, 1986-1999: A remote sensing approach. *Research Journal of Applied Sciences* 5: 32-39.

Klosterman RE 1995. The appropriateness of geographic information systems for regional planning in the developing world. *Computers, Environment and Urban Systems* 19: 1-13.

Klosterman RE 2001. The What If? planning support system. In Brail K & Klosterman RE (eds) *Planning support systems*, 101-112. Redlands: ESRI Press.

Klosterman RE 2008. A new tool for a new planning: The what if? planning support system. In Brail RK (ed) Planning *support systems for cities and regions*, 85-100. Cambridge: Lincoln Institute of Land Policy.

Lai L & Cheng W 2010. Urban heat island and air pollution: An emerging role for hospital respiratory admissions in an urban area. *Journal of Environmental Heath* 72, 6: 32-35.

Le Néchet F 2011. Urban spatial structure, daily mobility and energy consumption: A study of 34 European cities. *CyberGeo* 2011: 1-32.

Li X & Yeh AG 2002. Urban simulation using principle component analysis and cellular automata for land use planning. *Photogrammetric Engineering and Remote Sensing* 60: 341-351.

Litman T 2010. *Land use impacts on transport: How land use factors affect travel behaviour*. Vancouver: Victoria Transport Policy Institute.

Liu H & Weng Q 2012. Enhancing temporal resolution of satellite imagery for public health studies: A case study of West Nile virus outbreak in Los Angeles in 2007. *Remote Sensing of Environment* 117: 57-71.

Liu Y 2009. *Modelling urban development with geographical information systems and cellular automata.* Boca Raton: CRC Press.

Lo CP & Faber BJ 1997. Integration of landsat thematic mapper and census data for quality of life assessment. *Remote Sensing of the Environment* 60: 143-157.

Ludin AMN & Yakup A 2006. Scenario based spatial modelling for land use planning and evaluation. *In Proceedings of the conference: map Malaysia; geospatial information and the knowledge economy held 3-5 May 2006.* Selangor, Malaysia. Palace of Golden Horses.

Maclaren VW 2004. Urban sustainability reporting. In Wheeler SM & Beatley T (eds), *The sustainable urban development reader*, 2003-2010. New York: Routledge.

Malczewski J 1999. *GIS and multicriteria decision analysis.* Toronto: John Wiley and Sons.

Malczewski J 2006. GIS based multicriteria decision analysis: A survey of literature. *International Journal of Geographical Information Science* 20: 703-726.

Mannis A. 2002. Indicators of sustainable development [Online]. Available from: http://www.ess.co.at/GAIA/Reports/indics.html [Accessed 30 March 2010].

McLennan JF 2009. *Density and sustainability-A radical perspective*. Casacadia: Trimtab.

Meadows DH, Meadows DL, Randers J & Behrens WW 1972. *The limits to growth*. New York: New American Library.

Miller RB & Small C 2003. Cities from space: Potential applications of remote sensing in urban environmental research and policy. *Environmental Science and Policy* 6: 129-137

Moldan B & Billharz S (eds) 1997. *Sustainability indicators: Report of the project on Indicators sustainable development.* Sussex: John Wiley & Son.

Moore T 2008. Planning support systems: What are practicing planners looking for? In Brail RK (ed) *Planning support systems for cities and regions*, 231-256. Cambridge: Lincoln Institute of Land Policy.

Mudau N 2010. Spot building count supporting informed decisions. *Position IT* 10: 51-52.

NEAT GIS Protocols 2010. *Neighbourhood environment for active transport-geographic information systems version 5.1.* New York: Design for health.net, Cornell University.

NEAT GIS Protocols 2012. *Neighbourhood environment for active transport-geographic information systems version 5.2.* New York: Design for health.net, Cornell University.

NASA (National Aeronautics and Space Administration) 2009. Urban and land use applications: From Los Angeles to Paris [Online]. Available from: http://rst.gsfc.nasa.gov/Sect4/Sect4_1.html [Accessed 6 August 2010].

Nathan HSK & Reddy BS 2008. *A conceptual framework for development of sustainable development indicators.* Mumbai: Indira Ghandi Institute of Development Research.

National Research Council 2009. *Driving and the built environment: The effects of compact development on motorised travel, energy use and carbon dioxide emissions*. Washington DC: National Academy of Sciences.

Ness P 2001. Urban planning and sustainable development. *European Planning Studies* 9: 503-524.

Nichol J, King B, Quattrochi D, Dowman I, Ehlers M & Ding X 2007. Earth observation for urban planning and management: State of the art and recommendations for application of earth observation in urban planning. *Photogrammetric Engineering and Remote Sensing* 73: 973-979.

Nijkamp P, Lasschuit P & Soetmaan F 1992. Sustainable development in a regional system. In Breheny P & Batey PWJ (eds) *Sustainable development and urban form*, 39-66. London: Pion.

Nowak DJ & Greenfield EJ 2012. Tree and impervious cover in the United States. *Landscape Urban Planning* 107: 21-30.

Opschoor H & Reijnders L 1991. Towards sustainable development indicators. In Kuik O & Verbruggen H (eds) *In search of indicators for sustainable development* ,7-21. Dordrecht: Kluwer Academic.

Patino JE & Duque JC 2012. A review of regional science applications of satellite remote sensing in urban settings. *Computers, Environments and Urban Systems.* Article in press [Online]. Available from: http://dx.doi.org/10.1016/j.compenvurbsys.2012.06.003 [Accessed 26 October 2012].

Pinter L, Hardi P & Bartelmus P 2005. *Indicators of sustainable development: Proposals of a way forward*. New York: United Nations Division of Sustainable Development.

Poch M, Comas J, Roda IR, Sànchez-Marrè M & Cortés U 2004. Designing and building real environmental decision support systems. *Environmental Modelling and Software* 19: 857-873.

Pozzi F & Small C 2002. Vegetation and population density in urban and suburban areas in the USA. *In Proceedings of the Third International Symposyium on Remote Sensing of Urban Areas held 11-13 June 2002*. Istanbul, Turkey.

Prescott-Allen R 1999. Barometer of sustainability [Online]. Available from: http://www2.iucn.org/description [Accessed 5 October 2010].

Rees WR 1992. Ecological footprints and appropriated carrying capacity: What urban economics leaves out. *Environment and Urbanization* 4: 121-130.

Renetzeder C, Schindler S, Prinz MA, Mucher CA & Wrbka T 2010. Can we measure ecological sustainability? Landscape pattern as an indicator for naturalness and land use intensity at regional, national and European level. *Ecological Indicators* 10: 39-48.

Repetti A & Desthieux G 2006. A relational indicatorset model for urban land use planning and management: Methodological approach and application in two case studies. *Landscape and Urban Planning* 77: 196-215

Repetti A, Soutter M & Musy A 2005. Introducing SMURF: A software system for monitoring urban functionalities. *Computers, Environment and Urban Systems* 30: 687-707.

Rossi D & Friedman RE 1990. The emerging third wave: New economic development strategies. *Entrepreneurial Economic Review* 90: 3-10.

SA Statistics 2001. Census 2001 [Online]. Available from: http://www.statssa.gov.za/census01/html/WCPrimary.pdf [Accessed 15 August 2010].

Sachs W 2002. The Jo'burg memo: Fairness in a fragile world: Memorandum for the world summit on sustainable development. Paper for the Henrich Boll Foundation. Berlin.

Sattler C, Nagel UJ, Werner A & Zander P 2010. Integrated assessment of agricultural production practices to enhance sustainable development in agricultural landscapes. *Ecological Indicators* 10: 49-61.

Sayas JP 2006. Urban sprawl in the peri-urban coastal zones of Athens. *The Greek Review of Social Research* 121:71-124.

Schetke S, Haase D & Kotter T 2010. Towards sustainable urban land use: A methodological design for implementing socio- ecological targets into the strategic planning of cities in Germany. *In Proceedings of the Facing the Challenges Congress* held 11-16 April 2010, Sydney, Australia.

Schwarz N 2010. Urban form revisited selecting indicators for characterising European cities. *Landscape and Urban Planning* 96: 29-47.

Sherbinin A, Balk D, Yager K, Jaiteh M, Pozzi F, Giri C & Wannebo A 2002, Social science applications of remote sensing [Online]. Available from: http://sedac.ciesin.columbia.edu/tg/guide_glue.jsp?rd=rs&ds=1 [Accessed 6 August 2010].

Skidmore AK, Bijker W, Schmidt K & Kumar L 1997. Use of remote sensing and GIS for sustainable land management. *Instrumental Transcommunication Journal* 3: 302-315.

Sobrino JA, Oltra-Carrió R, Jiménez-Muñoz JC, Julien Y, Sòria G, Franch B & Mattar C 2012. Emissivity mapping over urban areas using a classification-based approach: Application to the dual-use European security IR experiment (DESIREX). *International Journal of Applied Earth Observation and Geoinformation* 18: 141-147.

Song Y & Knaap GJ 2004. Measuring urban form. *Journal of the American Planning Association* 70: 210-225.

Song Y & Rodriguez DA 2005. *The measurement of the level of mixed land uses: A synthetic approach*. Chapel Hill: Carolina Transportation Program.

Spiekermann K & Wegener M 2003. Modelling urban sustainability. *International Journal of Urban Sciences* 7: 47-64.

Stefanov WL, Ramsey M & Christensen P 2001. Monitoring urban land cover change: An expert system approach to land cover classification of semi-arid urban centers. *Remote Sensing of the Environment* 77: 173-183.

Stellenbosch Municipality 2011. *Stellenbosch municipality integrated development plan*. Stellenbosch: Stellenbosch Municipality.

Stellenbosch University 2010. *Fast fact statistics 2010*. Stellenbosch: Stellenbosch University.

Sustainable Seattle 1998. Indicators of a sustainable community [Online]. Available from: *http://sustainableseattle.org/Programs/RegionalIndicators/1998IndicatorsRpt.pdf*. [Accessed 25 May 2010].

Sustainable Seattle 2010. Responsible land use [Online]. Available from: http://www.b-sustainable.org/built-environment/responsible-land-use [Accessed 25 May 2010].

Sutton P & Costanza R 2002. Global estimates of market and non-market values derived from nighttime satellite imagery, land cover, and ecosystem service valuation. *Ecological Economics* 41:509-527.

Taubenböck H & Esch T 2011. Remote sensingan effective data source for urban monitoring [Online]. Earthzine. Available from: http://www.earthzine.org/2011/07/20/remote-sensing-%E2%80%93-an-effective-data-source-for-urban-monitoring/ [Accessed 20 January 2012].

Taubenböck H, Esch T, Wurm M, Roth A & Dech S 2010. Object-based feature extraction using high spatial resolution satellite data of urban areas. *Journal of Spatial Science* 55: 117-132.

Timmermans H 2008. Disseminating spatial decision support systems in urban planning. In Brail RK (ed). *Planning support systems for cities and regions*, 31-44. Cambridge: Lincoln Institute of land Policy.

Toure NM, Kane A, Noel JF, Turmine V, Nedeff V & Lazar G 2012. Water–poverty relationships in the coastal town of Mbour (Senegal): Relevance of GIS for decision support. *International Journal of Applied Earth Observation and Geoinformation* 14: 33-39.

Transportation Research Board 2009. *Driving and the built environment the effects of compact development on motorized travel, energy use, and CO2 emissions*. Washington DC: National Research Council.

Tsai Y 2005. Quantifying urban form: Compactness versus sprawl. *Urban Studies* 42: 141-161.

UN (United Nations) 2000. United Nations documentation research guide: The environment [Online]. Available from: http://www.un.org/Depts/dhl/resguide/specenv.htm [Accessed 12 September 2012].

UN (United Nations) 2012. About the Rio+20 conference [Online]. Available from: http://www.uncsd2012.org/about.html [Accessed 8 September 2012].

UNDP (United Nations Development Programme ) 2010. *Human development report 2010: The real wealth of nations: Pathways to development*. New York: UNDP.

UNDP (United Nations Development Programme ) 2011. *Human development report 2011: Sustainability and equity: A better future for all*. New York: UNDP

UN-HABITAT (United Nations Human Settlements Programme) 2011. *State of the worlds cities report: Bridging the urban divide*. London: EarthScan.

UN-HABITAT (United Nations Human Settlements Program) 2009. Habitat partner university network [Online]. Available from: http://www.unhabitat.org/content.asp?typeid=19&catid=570&cid=6002 [Accessed 7 July 2010].

Ural S, Hussain E & Shan J 2011. Building population mapping with aerial imagery and GIS data. *International Journal of Applied Earth Observation and Geoinformation* 13: 841-852.

Urban Land Institute 2010. *Land use and driving: The role compact development can play in reducing greenhouse gas emissions*. Washington DC: Urban Land Institute.

Van der Merwe IJ, Ferreira SLA & Zietsman HL 2005. *Growth potential of towns in the Western Cape*. Stellenbosch: Centre for Geographical Analysis, Stellenbosch University.

Van Niekerk A, Donaldson R, Du Plessis D & Spocter M 2010. A revision of the 2004 growth potential of towns in the Western Cape study: Discussion document. Stellenbosch: Stellenbosch University.

Veneri P 2010. Urban polycentricity and the costs of commuting: Evidence from Italian metropolitan areas. Growth and Change 41: 403-429.

Victoria Transport Policy Institute 2010. Land use impacts on transport: How land use factors affect travel behaviour [Online]. Available from:www.vtpi.org/landtravel.pdf [Accessed 10 July 2011].

Vintrou E, Desbrosse A, Bégué A, Traoré S, Baron C & Lo Seen LD 2012. Crop area mapping in West Africa using landscape stratification of MODIS time series and comparison with existing global land products. *International Journal of Applied Earth Observation and Geoinformation* 14: 83-93.

Volk M, Lautenbach S, Van Delden H, Newham LTH & Seppelt R 2010. How can we make progress with decision support systems in landscape and river basin management? Lessons learned from a comparative analysis of four different decision support systems. *Environmental Management* 46: 834-849.

Wackernagel M & Rees W 1996. *Our ecological footprints.* Grabiola: Philadelphia New Society.

Wang J, Cheng Q & Chen J 2011. A GIS and remote sensing based analysis in land use change using asymmetric relation analysis method: A case study from the city of Hangzhou, China. *Mathematical Geosciences* 43: 435-453.

WCED (World Commission on Environment and Development) 1987. *Our common future.* Oxford: Oxford University Press.

Weng Q 2012. Remote sensing of impervious surfaces in the urban areas: Requirements, methods, and trends. *Remote Sensing of Environment* 117: 34-49.

Western Cape Department of Environmental Affairs and Development Planning 2009. *Western Cape provincial spatial development framework*. Cape Town: Department of Environmental Affairs and Development Planning.

Wheeler SM 2000. Planning for metropolitan sustainability. *Journal of Planning Education and Research* 20: 133-145.

WHO (World Health Organization) 2005. *WHO air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulphur oxide*. Geneva: WHO.

Wigbells L, Faith GR & Sabathier V 2008. *Earth observations and global change: Why? Where we are? What next?* Washington DC: Center for Strategic and International Studies.

Wiggering H, Dalchow C, Glemnitz M, Helming K, Muller K, Schultz A, Stachow U & Zander P 2006. Indicators for multifunctional land use-linking socio-economic requirements with landscape potentials. *Ecological Indicators* 6: 238-249.

Winograd M & Farrow A 2007. Sustainable development indicators for decision making: Concepts, methods, definition and use [Online]. Available from: http://www.eolss.net/ebooks/Sample%20Chapters/C13/E1-46B-02.pdf. [Accessed 4 October 2012].

Winograd M 1995. *Environmental indicators for Latin America and the Caribbean: Towards land use sustainability*. Washington DC: World Resources Institute.

Wolf T &Meyer BC 2010. Suburban scenario development based on multiple landscape assessments. *Ecological Indicators* 10: 74-86.

World Bank 1994. *Making development sustainable*. Washington DC: World Bank.

World Bank 2008. *Using training to build capacity for development: An evaluation of the World Bank's project-based and WBI training*. Washington DC: World Bank.

Wurm M, Taubenböck H, Roth A & Dech S 2009. Urban structuring using multisensoral remote sensing data by example of German cities, Cologne and Dresden. *Urban Remote Sensing Joint Event* 2009: 1-8.

Yabuki N, Miyashita K & Fukuda T 2011. An invisible height evaluation system for building height regulation to preserve good landscapes using augmented reality. *Automation in Construction* 20: 228-235.

Yang J, Zhao L, McBride J & Gong P 2009. Can you see green? Assessing the visibility of urban forests in cities. *Landscape and Urban Planning* 91: 97-104.

Yuan F 2008. Land cover change and environmental impact analysis in the Greater Mankato area of Minnesota using remote sensing and GIS modelling. *International Journal of Remote Sensing* 29: 1169-1184.

Yuan J, Wang D, Wu B, Yan L & Rongxing L 2009. Automated road extraction using LEGION networks. *International Joint Neural Networks* 2009: 188-193.

Zhang B 2003. Application of remote sensing technology to population estimation. *Chinese Geographical Science* 13: 267-271

Zhang C, Luo L, Xu W & Ledwith V 2008. Use of local Morans *I* and GIS to identify pollution hotspots of Pb in urban soils of Galway, Ireland. *Science of the Total Environment* 398: 212-221.

Zhang T & Lin G 2006. A supplemental indicator of high-value or low-value spatial clustering. *Geographical Analysis* 38: 209-225.

# APPENDICES

# APPENDIX A

CD containing data for evaluation the potential of earth observation for supporting sustainable urban land use planning

# APPENDIX B

CD containing script for calculating the land use mix index and land use frequency using the model builder tool in ArcGIS