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Monitoring sustainable urban development using built-up area indicators: a case study of Stellenbosch, South Africa

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Abstract Rapid urbanisation in many developing countries causes land transformation from agricultural, rural, and natural landscapes into urban areas. Data to monitor this transformation are often out of date, unreliable, not in standard format, cumbersome and expensive to collect or simply unavailable.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 towards sustainable urban development. This paper investigates the use of earth observation (EO) data for supporting sustainable urban development planning. 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, and facilitate evidence-based decision-making and an array of other practical uses.

Keywords Sustainable urban development · Building density · Impervious surfaces · Building height · Earth observation

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, how

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people live in harmony with nature and causing public health problems (Dewan et al. 2012; 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 hyper-changing 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In developing countries, data on the built-up area are often unavailable, inadequate, generalised, un-standardised and out of date and require cumbersome processes to acquire (Santos et al. 2011). For example, the City of Harare, like many cities in developing countries does not have a GIS department, making it impossible to obtain area-wide data on the urban built-up area (The Herald 2012). 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 2010a, b; Wigbells et al. 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 provide 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; Wurm et al. 2009).

Although EO provides timely and relatively cost-effective data, which is a solution to data unavailability in developing countries, 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 et al. 2012; Gomez-Chova et al. 2006; Taubenböck et al. 2012, Ural et al. 2011; Gamba et al. 2011).

Accordingly, this paper develops simple spatial built-up area indicators (building density, building height and impervious surface concentration) of urban sustainability from EO data and investigates the practical implications for urban planning in data scarce rapidly urbanising cities in developing countries.

1.1 Sustainable urban development

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 as defined by the WCED is a noble but fuzzy concept, which is difficult to put into practice for day-to-day decision-making. For simple application in decision-making, sustainable urban development should be defined as an ongoing process as opposed to an end where cities should continuously endeavour to improve the quality of life for an increasing urban population (Pickett et al. 2013). Consequently, sustainable urban areas succeed in building resilient ecological, social and economic processes. Platt (2006) goes on to characterise sustainable cities as those that (1) build and restore ecological services, (2) promote physical and mental health of its inhabitants, (3) enhance efficiency through energy, water, matter and time conservation, (4) facilitate social and environmental equity and (5) maintain a sense of community and place. In other words, sustainable cities reduce negative environmental, social and economic costs of urban development.

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 2010a, b). 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 2010a). This is particularly a big challenge in many cities in the global south and South Africa where policies often mandate municipalities to promote sustainable urban development, yet there is little to suggest that there are measures in place to measure progress towards sustainable urban development (Baud et al. 2010; Musakwa and Van Niekerk 2013). The use of objective indicators developed from geographical information systems (GIS) and EO data is proposed in this study. Such indicators can make it possible for municipalities to ascertain if there is progress towards sustainable urban development (Guindon and Zhang 2006). Assessment of sustainable urban development indicators enables municipalities to create different urban growth scenarios and to support 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.

1.2 Built-up area indicators of sustainable development

Sustainability indicators are pointers towards progress in improving the overall health of a community, neighbourhood, town, city, region or larger area. Sustainable urban development indicators have been widely discussed in the literature (Burton 2002; Hall 2010a). Urban sustainability indicators reflect the general well-being of urban built-up areas and should be integratable, forward-looking (Huang et al. 1998; Maclaren 2004), distributional and subject to feedback loops (Hall 2010a). 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 (de Noronha Vaz et al. 2012). Built-up area parameters that have been shown to specifically affect sustainable urban development are building height (Yabuki et al. 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 et al. 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.

1.2.1 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 (Veneri 2010). In South Africa, 20 or less building units per hectare (bu/ha) are regarded as low density, between 20–50 bu/ha medium density and >50 bu/ha as high density (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). It is widely accepted that there is a positive relationship between medium-to-high densities and the reduction in costs of connecting infrastructure services, travel, travel time and energy (Litman 2010; Victoria Transport Policy Institute 2010). 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 Bertini 2009). These assist in the reduction in 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 improve quality of life (Eid et al. 2008; Frank et al. 2006, 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. However, the acquisition of up-to-date area-wide information on building density is a challenging task (Santos et al. 2011).

1.2.2 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. Table 1 outlines the positive and negative impacts of increased building height on urban sustainability.

A building with a single floor is regarded as less sustainable than a building with 2–12 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 Van den Dobbelsteen 2004), increases energy costs, can cause a loss of cultural heritage (Yabuki et al. 2011) and may increase pollution. 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.

1.2.3 Impervious surface area

Impervious surfaces are anthropogenic land cover features that prevent water from infiltrating the soil (Table 2). Such surfaces include roads, driveways, parking lots and rooftops (Weng 2012).

Table 1 Impact of increased building height on urban sustainability

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

Sources: Adapted from Ding (2013) and Yabuki et al. (2011)

Table 2 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[a]	Impervious	Compact soils
Improved grassland	Pervious	Sports fields and recreational fields
Vegetation	Pervious	Vegetation, grass, forest and cultivated land
Water	Pervious	Natural water-bodies

[a] 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

Impervious surfaces are good indicators of sustainable urban development because they affect environmental quality and peoples' quality of life (Aubrecht et al. 2009; Slemp et al. 2012). 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 et al. 2012; Zhang et al. 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.

1.3 Methods

1.3.1 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 (Fig. 1). 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; Stellenbosch University 2010). Moreover, Stellenbosch is a data-scarce city where the administration lacks capacity in advanced GIS analysis and use of EO data which inhibits production of objective urban sustainability reports. Consequently, urban sustainability reports are descriptive reports with little or no spatial analysis.

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

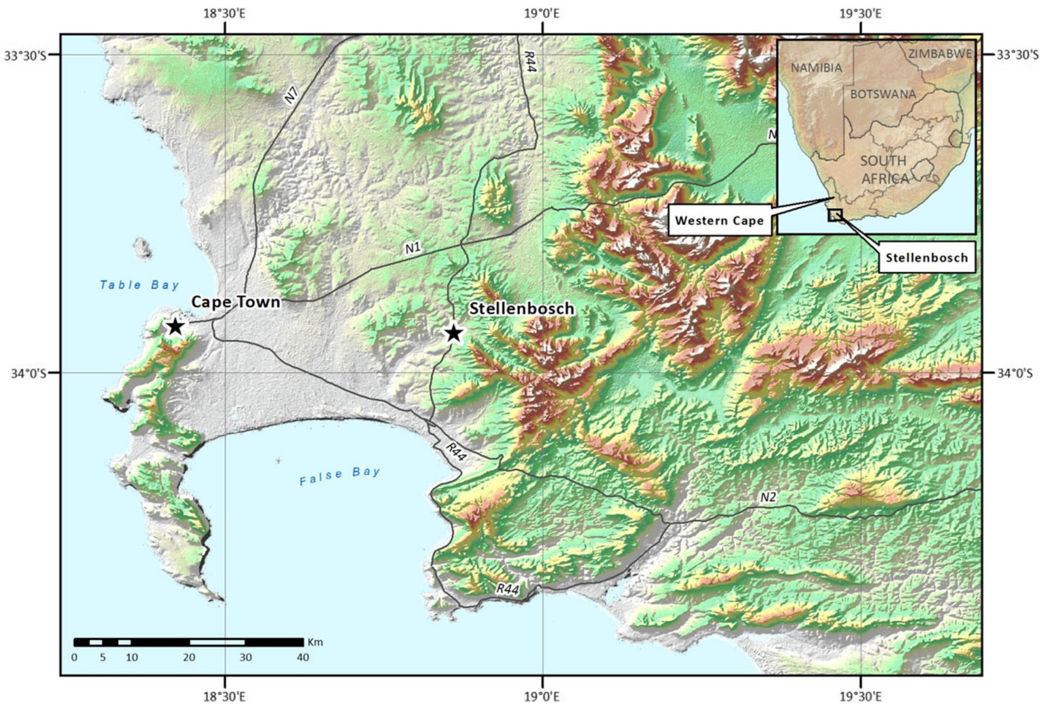

Fig. 1 Location of Stellenbosch within the Western Cape province of South Africa

out field visits. The availability of appropriate reference data to verify the findings was a deciding factor. The period of study is 2000–2010, 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 nonurban purposes (e.g. agriculture).

1.3.2 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 preprocessed (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, periurban 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).

1.3.3 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 (see Table 2).

1.3.4 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 et al. 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

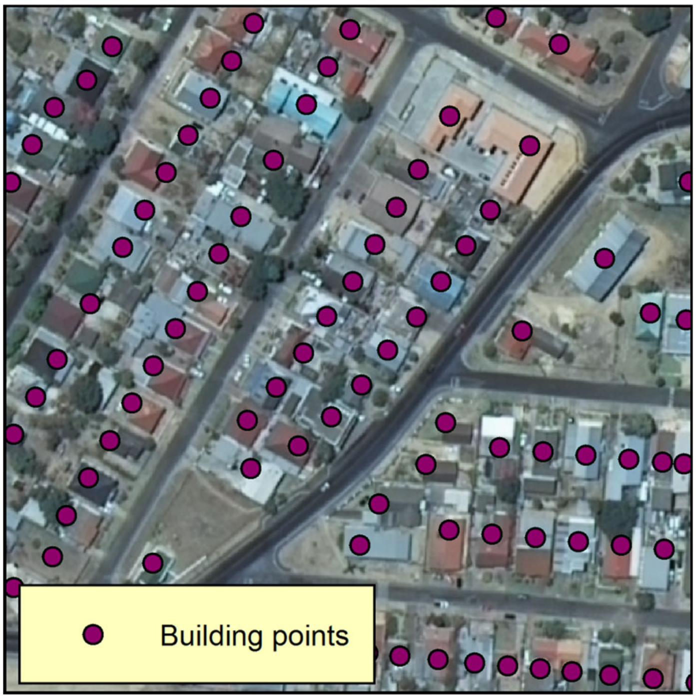

Fig. 2 Sample of the updated building-count data set

buildings in ArcGIS 10 using the 2010 aerial photography (Fig. 2). 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.

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.

1.3.5 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.[1] This workflow is illustrated in Fig. 3. Due to data unavailability and lack of appropriate reference data, the nDSM was only developed for 2010.

[1] Three metres is the average building floor height (Stellenbosch Municipality 2011; Wurm et al. 2009).

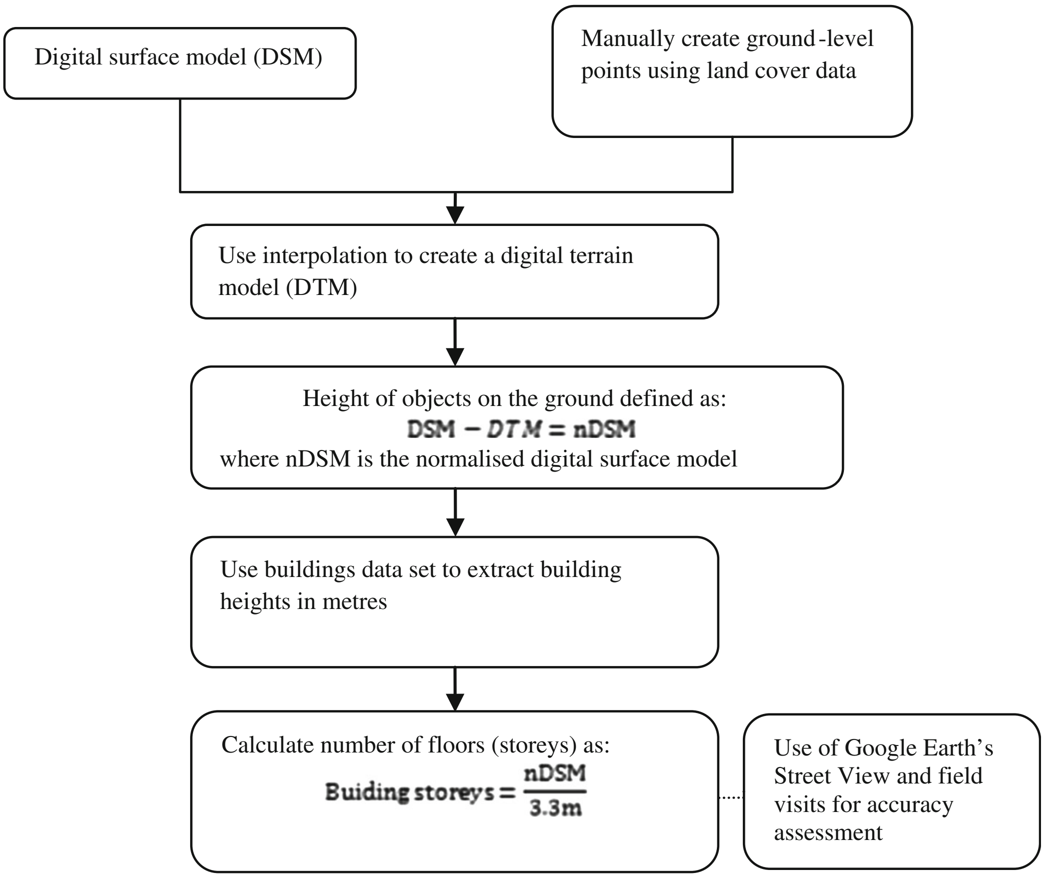

Fig. 3 Workflow to calculate building height (in *storeys*)

Fig. 4 Google's Street View extract showing **a** two storeys, **b** six storeys and **c** field picture of **b**

Geospatial modelling environment software was used to create a random sample of 400 building points, the recommended sample size required of the 21,216 buildings to carry out an accuracy assessment. Extensive field visits and Google Earth's Street View tool were employed to compare nDSM height and actual height (Fig. 4).

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

1.3.6 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. The spatial analyst point density tool was utilised to compute the building density using the following formula [number of building units per unit area (hectare)] on a moving window basis. 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 using the spatial analyst, neighbourhood focal statistics function and map algebra tools, respectively. Impervious surface was computed by scaling the area of impervious surfaces per hectare as a percentage on a moving window basis.

1.4 Results and discussion

1.4.1 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 5 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

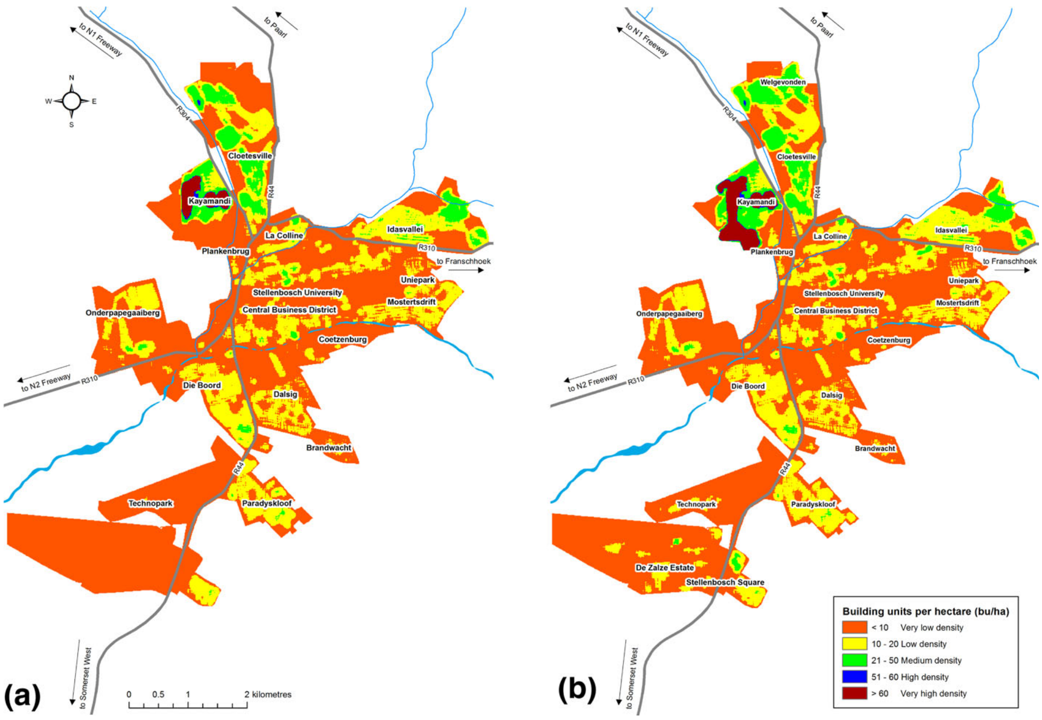

Fig. 5 Building density in Stellenbosch; **a** 2000 and **b** 2010

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).

Much of Stellenbosch, including Technopark, Brandwacht, sections of the CBD, Die Boord, Uniepark, Stellenbosch University and Onderpapegaaiberg, has low densities (<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 is likely to discourage social and spatial integration (Donaldson et al. 2012; Todes and Watson 1986; Williams 2000). Given South Africa's history of spatial segregation and its postapartheid spatial policy geared towards integrated development, building density is useful for assessing progress towards 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, especially in South Africa and other developing countries.

Figure 6 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.

Welgevonden is characterised by medium densities (21–50 bu/ha) and De Zalze by low densities (10 bu/ha) (Fig. 5). 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 towards sustainable urban development. Stellenbosch municipality has a densification policy in place (Stellenbosch Municipality 2011). Increased densities recorded because 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 10-year study period, increased from 1,022 to 3,645 U (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 (>60 bu/ha) 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 hill slopes 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

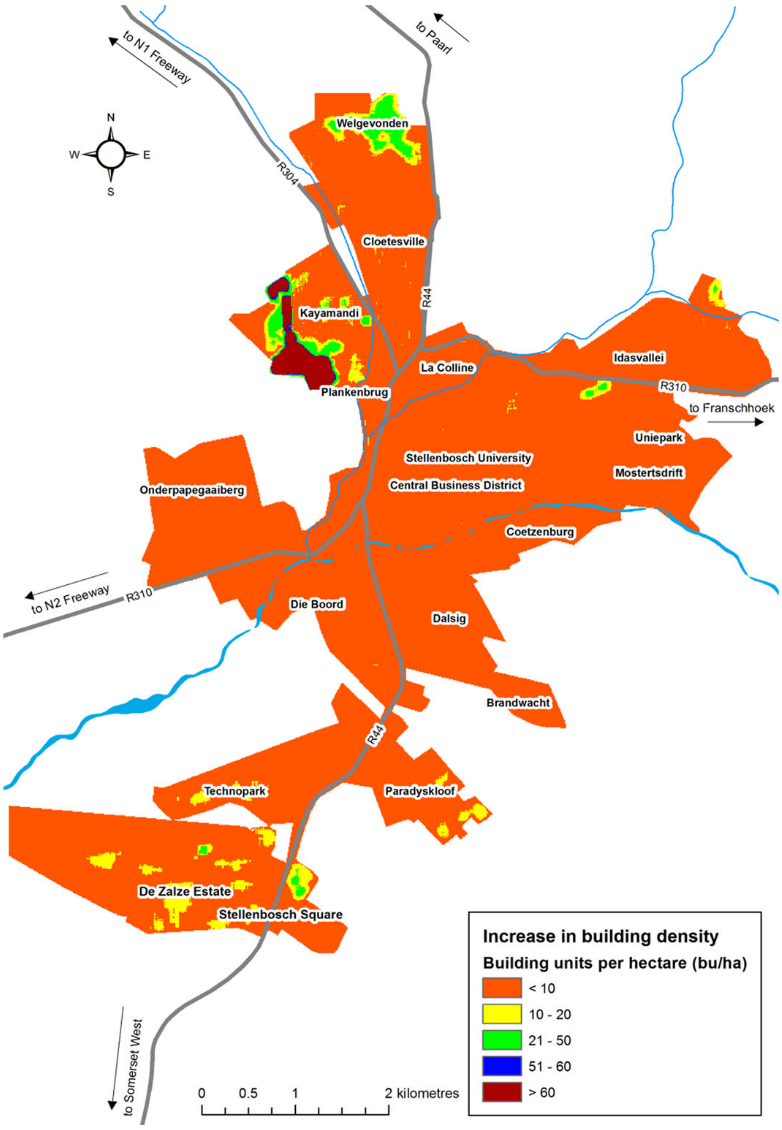

Fig. 6 Increase in building density in Stellenbosch between 2000 and 2010

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 towards unsustainable urban development. When densities exceed certain thresholds (>60 bu/ha) the prospects for sustainable urban development begin to diminish (Jabereen 2006). This also highlights the limits and challenges of achieving urban sustainability. Continued growth of informal settlements is a strong indicator of unsustainable urban development (UN 2008). Similarly, 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; McLennan 2009). However, density alone is not sufficient because footprint and height are not depicted to

Table 3 Building-floor (storeys) distribution in the 2010 urban extent of Stellenbosch

Floors	Count[a]	Percentage
1	11,498	80.8
2	2,123	14.9
3	408	2.9
4	155	1.1
5	35	0.3
6	12	0.1
7	2	0.0
Total	14,233	100

[a] The building count excludes informal settlements

fully characterise the sustainability of the urban built-up area (Jabereen 2006; Jones and MacDonald 2004).

1.4.2 Analysis of building height

Table 3 and Fig. 7 show the frequency and spatial distributions of building heights in Stellenbosch, respectively. The majority (81 %) of the buildings in Stellenbosch are single-storey structures.

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.

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 densification. They are all within the five-storey[2] 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 Figs. 7 and 5 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 et al. 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.

1.4.3 Analysis of impervious surface area

Table 4 and Fig. 8 show that over the decadal study period, there was an increase in impervious surface area from 777 to 925 ha at a mean annual growth rate of 2 %. This

[2] Up to three additional storeys can be added given permission by the municipality's planning department (Stellenbosch Municipality 2011).

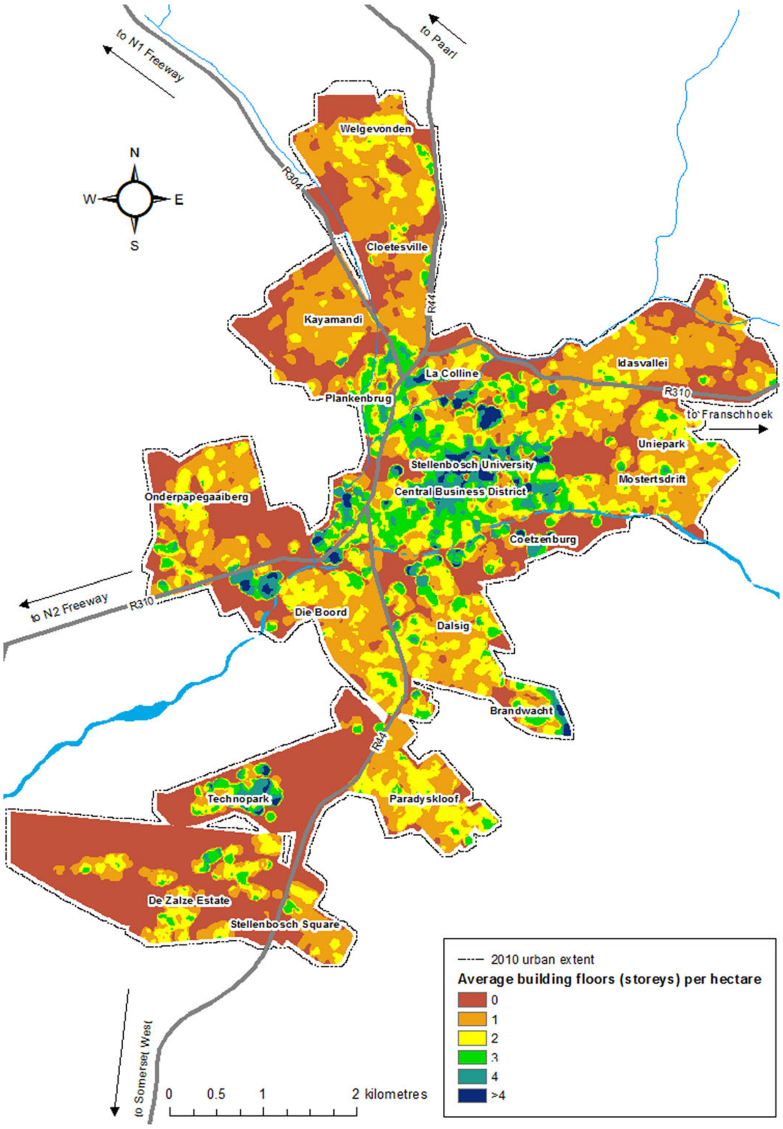

Fig. 7 Spatial distribution of building floor (*storeys*) Stellenbosch, 2010

Table 4 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	2,475.0	2,475.0	0	10.3

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 et al. 2012) as well as surface water run-off.

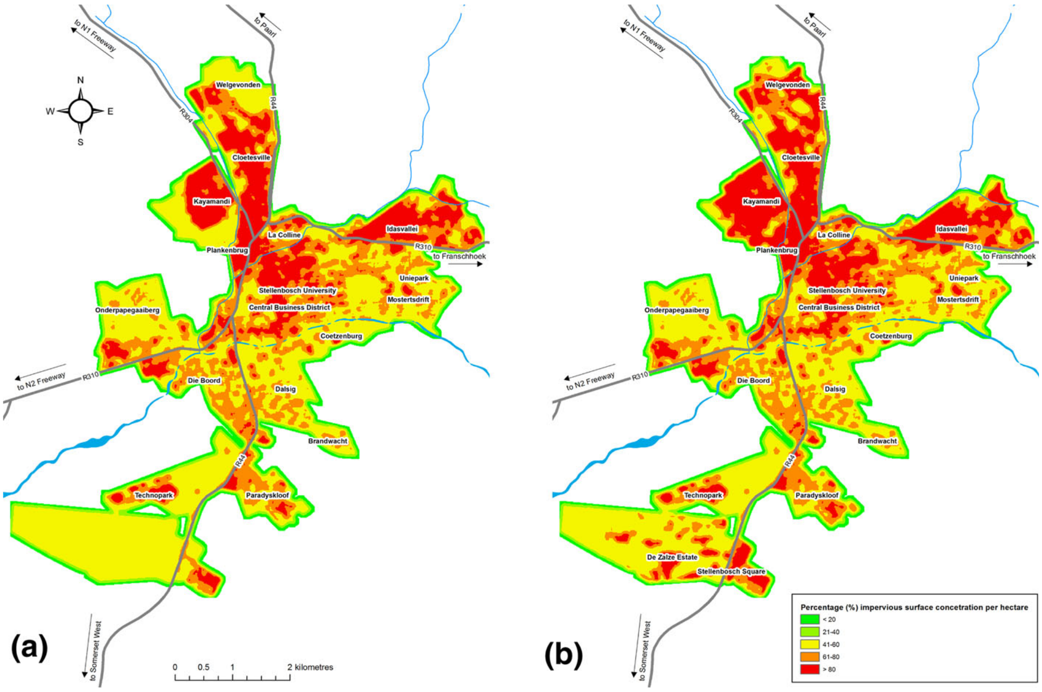

Fig. 8 Distribution of impervious surface area in Stellenbosch; **a** 2000 and **b** 2010

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 et al. 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 9 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 because of urban sprawl and urbanisation. Some minor changes in the town are indicative of densification and compaction that point to sustainable urban development.

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 public health problems (Dewan et al. 2012) such as the declining water quality of the Plankenbrug River that flows past Kayamandi. Paulse et al. (2012) 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 overextended sewerage system. The population and spatial growth of informal settlements in Stellenbosch should be urgently

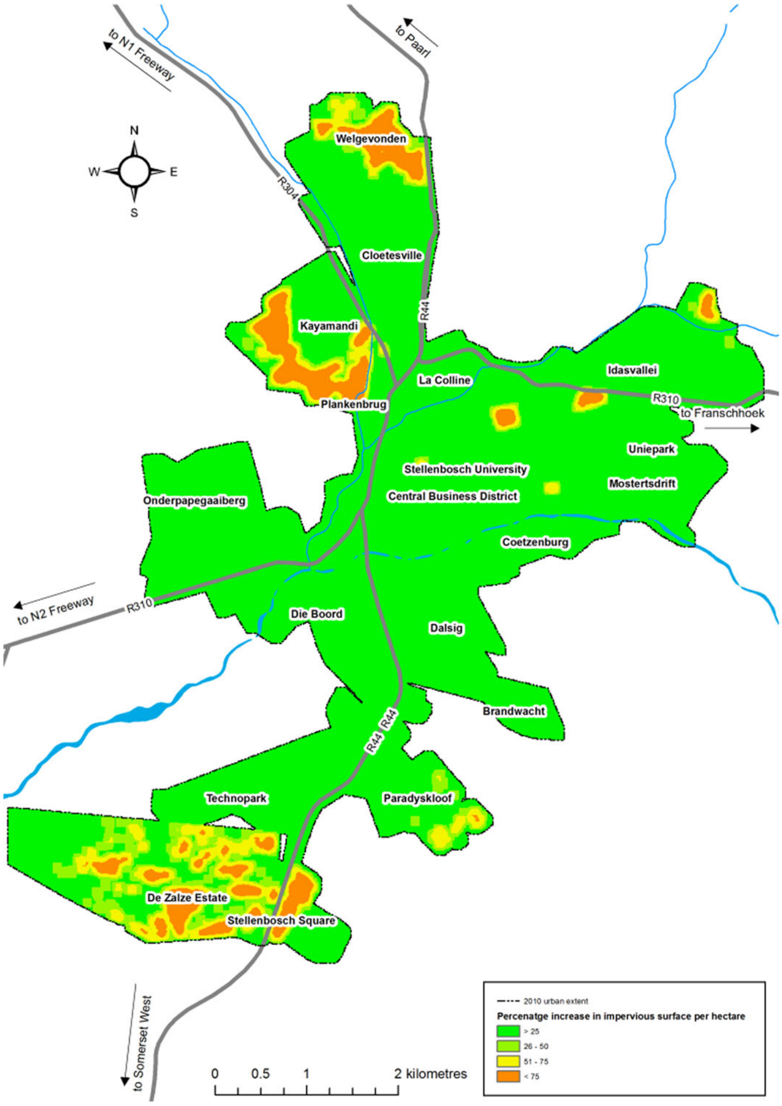

Fig. 9 Increase in impervious surface concentrations in Stellenbosch between 2000 and 2010

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. A middle ground needs to be occupied to achieve sustainable urban development. This middle ground and balance is particularly difficult to attain in data-scarce cities making it challenging to implement land use planning and management decisions to achieve urban sustainability.

1.5 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 simple urban sustainability indicators are possible. This information would otherwise be difficult to collect from other sources, such as poring over municipal records if at all available. Moreover, analysis of simple spatial indicators of sustainable urban development derived from EO data equips local authorities to make evidence-based decisions rather than relying on advocacy-based planning or compact development as the only options. As a result, local authorities are able to choose between compact development and the making room paradigm of sustainable urban development depending on the context. Consequently, 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.

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, 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).

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. 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.

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