Geospatial information needs for informal settlement upgrading – A review

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Abstract: Accurate, current and complete information is indispensable for any effective intervention to upgrade a slum or informal settlement. Our involvement in supporting informal settlement upgrades with geospatial information prompted us to investigate what we could learn from literature to improve the collection and representation of geospatial information for such projects. For this paper, we systematically reviewed literature about informal settlement upgrading interventions for which geospatial information was used. We classified the geospatial information into three categories – physical, socio-economic, and boundaries – based on the phenomena they described, and categorized the methods of data acquisition. The results show that most studies collect geospatial information that enumerates and measures empirically observable characteristics (e.g, structures, infrastructure, utility services, mobility network, land description) and characteristics of occupants of informal settlements (e.g., socio-economic status). Fewer studies collected geospatial information about social networks and social ties. Data collection methods ranged from primary sources such as paper-based surveys, handheld/mobile GPS devices, vehicle-mounted cameras, etc., to secondary sources such as spaceborne, airborne and web-based platforms. Few studies made use of unmanned aerial vehicles (UAVs), despite their recent popularity as source of base maps, but we expect this to change in the near future. The results can be used to inform data collection strategies for informal settlement upgrades. Policy makers and other stakeholders involved in informal settlement upgrades can benefit from a single source of knowledge about such information.

Keywords: geospatial information; informal settlement upgrading; data collection; urbanization; systematic review

1. Introduction

As the world becomes increasingly urbanised, the estimated one billion urban dwellers currently living in slums and informal settlements will likely triple by 2050 (UN-Habitat, 2016). In 2020, urban areas constituted 56.2% of the global population and long-term projections suggest that urbanisation will continue to rise to 60.4% by 2030, without yet considering the possible impact of the COVID-19 pandemic (UN-Habitat, 2020a). Between 2018 and 2050, most of the urban expansion (90%) is expected to occur in East Asia, South Asia and Africa (UN-DESA, 2019).

While sustainable urbanisation is associated with a plethora of benefits, ranging from economic and social to environmental benefits (UN-Habitat, 2020a), unplanned rapid urbanisation is associated with the proliferation of deprived areas, such as slums and informal settlements, in most low- and middle-income countries (Jaycox, 1997; Wekesa et al., 2011; UN-Habitat, 2020a). Failure to produce affordable housing and basic services for the poor urban residents on a scale commensurate with the demand, triggers the formation of such deprived areas (Jaycox, 1977; UN-Habitat, 2003; Wekesa et al., 2011; Alemie et al., 2015; UN-Habitat, 2020a). Contributing factors include ill-designed housing policies (Jaycox, 1977; UN-Habitat, 2003; UNECE, 2009; Shabane et al., 2011; Mahabir et al., 2016), poor urban governance (Roy, 2005; Alemie et al., 2015; Mahabir et al., 2016), rural-to-urban migration (Mahabir et al., 2016), and poor information systems (Roy, 2005). Despite progress made in minimizing the proportion of households living in deprived areas from 28% in 2000 to 24% in 2018, the absolute number of dwellers residing in these areas has increased (UN-Habitat, 2016). Today, more than half of the urban dwellers living in deprived areas are concentrated in rapidly urbanizing regions of Asia and Africa (UN-Habitat, 2020a). Without appropriate action, the number of dwellers in deprived areas will continue to increase.

The proliferation of slums and informal settlements is a serious problem, as people living in these neighbourhoods face a wide range of deprivations, which impact their health and well-being, aggravated recently by the COVID-19 pandemic (see Corburn et al., 2020; Evans et al., 2000; Furtado and Renski, 2021; Pereira et al., 2020; Twigg et al., 2017). There are many examples: occupants without secure tenure are susceptible to threat of forced eviction and harassment(van der Molen, 2015); occupants without safe drinking water, adequate sanitation and refuse disposal are vulnerable to diseases (Lilford et al., 2017); poor water quality and inadequate sanitation in slums may result in incidences of diarrhea, especially in children younger than five years (Ezeh et al., 2016); poor quality housing poses physical safety risks or scant protection against climatic elements (UN-Habitat, 2003); physical housing conditions, such as overcrowding and poor ventilation, are major risk factors for infectious and respiratory diseases such as tuberculosis (TB) (Marais et al., 2013; Narsai et al., 2013; Richardson et al., 2014) and COVID-19 (Corburn et al., 2020); insufficient living space in dense informal settlements makes physical distancing and self-quarantine impossible and increases risk of rapid spread of infections (Corburn *et al.*, 2020; Gibson and Rush, 2020; Naidu, 2020).Beyond the individual and household level, there are area-level social, environmental, and ecological risks to health and wellbeing (Thomason et al., 2020). This calls for urgent measures to improve the living conditions in deprived areas.

For the past two decades, the need to improve the lives of informal settlements dwellers has been on the agenda of several international initiatives. Examples include the "Cities Without Slums" campaign of 1999 (World Bank/UNCHS, 2000), the Millennium Development Goals (MDGs) (UN, 2000), and now the Sustainable Development Goals (SDGs) (UN, 2015). While the MDGs reported a decline in slum conditions under its target of improving at least 100 million slum dwellers by 2020, in absolute terms, the number of slums has increased (UN-Habitat, 2015; 2016). To continue with progress to date, slum or informal settlement upgrading was incorporated into the SDG 11 goal of "making cities and human settlements inclusive, safe, resilience and sustainable by 2030" (UN, 2015). More specifically, SDG 11.1 aims to achieve "access for all to adequate, safe and affordable housing and basic services and that slums are upgraded" by 2030 (UN, 2015). Informal settlement upgrading is directly linked to several other SDGs: SDG 1 on poverty (indicator 1.4.2 on security of tenure rights to land), SDG 6 on clean water and sanitation, and SDG 3 on health and wellbeing for all ages. The incorporation of informal settlement upgrading into the international development agenda underscores its global importance in building sustainable cities and human settlements.

A slum household is defined as a household lacking one or more of the following: access to an improved drinking water source, access to improved sanitation facilities, sufficient living area, durable housing and security of tenure. Other sources refer to informal settlements as residential areas where 1) inhabitants lack secure tenure of the land or housing units they occupy (ranging from squatting to informal rental housing); 2) housing does not comply with planning and building regulations, and is often located in precarious environments; and 3) the settlements do not have access to city infrastructure and basic services (UN-Habitat, 2016a). In this paper, the terms informal settlement and slum are used to refer to deprived urban areas generally; we do not make a specific distinction between them.

An informal settlement upgrade can be broadly defined as "any sector-based intervention in informal settlements that results in quantifiable improvement in the life of residents", which suggests a variety of possible interventions and approaches to upgrading (Abbott, 2002). The scope of upgrading may range from small-scale projects (e.g., installation of communal water taps or street lighting, and roads) to large-scale provision of legal land tenure, improvements to housing and infrastructure (e.g., piped water and sewer house connections) and services (e.g., social amenities such as schools and health care facilities (Satterthwaite, 2012). Satterwaite (2012) identified two main drivers of upgrading initiatives: upgrading driven by individual investments (e.g., improving dwelling unit) and upgrading driven by neighbourhood investments (e.g., settlement-wide infrastructure such as water pipes and sewer lines, roads and paths, electricity, community centres, health centres). Upgrading outcomes can be measured by three types of indicators, as proposed by Jaitman and Brakarz (2013): individual, housing, and neighbourhood. Individual outcomes include income (e.g., amount, sources), access to labour markets (e.g., number of household members who work), human capital (e.g. access to schools), health (e.g. nutrition, mortality) and wellbeing (e.g. life satisfaction). Housing outcomes comprise indicators about access to the financial system and some related to housing, namely construction of the dwelling (e.g., building material) and its access to infrastructure (e.g. safe water, sanitation facilities, electricity connection), assets (e.g. value of the dwelling), investment (e.g. source of funds for improvement), property rights (e.g. types of land title), location (e.g. exposure to hazards); and household size (e.g. number of members in the households, their ages). Neighbourhood outcomes include indicators measuring the availability of transport, urban infrastructure and services (e.g., health and education, street lighting, roads, community centres), safety, mobility, integration into the formal city and infrastructure deficits.

There is consensus in the literature that upgrading of informal settlements requires consistent, detailed, accurate, and timely geospatial information (Abbott, 2002; Gevaert et al., 2017; Leonita et al., 2018; Mason et al., 1997; Mason, 1998; Pedro and Queiroz, 2019; van der Molen, 2015; Hachmann et al., 2018) to prepare maps of the current state of deprived areas (Paar and Rekittke, 2011; Thomson et al., 2020) and for planning and implementing the upgrades (Mason and Batavia, 1997; Gevaert et al., 2017). Geospatial information provides answers to questions like *who* are the people living in poor conditions and *who* are looking for better accommodation, *where* do they live, and *how* are those areas growing (Hardoy and Satterthwaite, 1986; Pedro and Queiroz, 2019). Maps of geospatial information facilitate communication amongst role players and can empower local authorities and communities involved in upgrading interventions (Abbott, 2003). Furthermore, knowledge based on scientifically collected data mitigates the risk of ineffective policy adoptions that could lead to costly and wasteful expenditure of already constrained government funds and capacity of low-and middle-income countries. Informal settlement upgrades are generally project-based comprising several phases executed over a period of time, each phase requiring a specific type of geospatial information (Sliuzas, 2003). Abbott (2003) argues that large-scale, replicable informal settlement upgrades are only possible with the use of geospatial information technologies. However, silo-based approaches to informal settlement mapping do not provide accurate, current and complete data to support multiple use cases (Mahabir et al., 2016; Thomson et al., 2020). While there is a growing body of scientific peer-reviewed literature offering a wide range of relevant studies on geospatial information which can support informal settlement upgrading, such studies are largely fragmented and focus on a myriad of specific topics, methods and techniques.

Our involvement in supporting informal settlement upgrading projects at the City of Ekurhuleni Metropolitan Municipality in South Africa with geospatial information has prompted us to investigate how the collection and representation of geospatial information for such projects can be improved. We could not find a consolidated review of scientific literature about geospatial information and data collection to support informal settlement upgrading. Therefore, we systematically reviewed peer-reviewed journal articles about informal settlement upgrading interventions for which geospatial information was used. The objective was to understand which type of geospatial information is used in informal settlement upgrades and how it is collected.

The remainder of the paper is structured as follows: section 2 presents the methods used to select relevant articles for the review, how they were analyzed and how the information in them was categorized. Section 3 describes the results of the systematic review, presenting a hierarchical categorisation of data and data collection methods. This is followed by section 4 which discusses the results. Section 5 concludes with a summary of the results and suggestions for further research.

2. Method

2.1 Search for literature, data gathering and quality

A systematic search for literature was undertaken to identify relevant peer-reviewed scientific publications for inclusion in this review, based on four concept groups – settings, intervention, information/data and systems – each described by several keywords. See Table 1.

Table 1. Concept groups and keywords for identifying relevant literature

Concept group	Keywords
Settings	informal settlement, slums, squatter settlements, illegal settlements, unauthorised settlements, shanty town.
Intervention	upgrade, improve, enhance, renew, transform, formalize, regularize.
Information/data	geospatial, geographic, spatial
Systems	geographical information system (GIS), Global Positioning Systems (GPS), remote sensing.

Settings refer to the context within which the study is conducted. To identify literature about informal settlements, several terms that are used interchangeably in the literature were included as keywords: slums, squatter settlements, illegal settlements, unauthorised settlements, shanty town. The intervention concept group relates to the type of intervention represented by the following verbs: upgrade, improve, enhance, renew, transform, formalize, and regularize. The information/data group describes the type of information we are looking for, namely, geospatial, geographic or spatial. The systems concept group covers the three technologies involved in handling geospatial information, commonly referred to as geospatial technologies (Bossler, 2010): the Global Positioning Systems (GPS), remote sensing, and geographic information system (GIS). Even though the review is not focused on the these technologies, we included them because they could assist in identifying literature related to geospatial information.

The search for relevant literature was conducted via Elsevier's Scopus database, which indexes a comprehensive collection of research output in the fields of science, technology, medicine, social science, arts and humanities (https://www.scopus.com). There are other databases, such as ScienceDirect and Web of Science, but Scopus was chosen since it is considered to be the largest abstract and citation database of peer-reviewed literature (journals, books and conference proceedings) with more than 67 million items derived from over 22,500 serial titles, 96, 0000 conferences and 136, 000 books from over 7,500 different publishers globally (Schotten et al., 2017).

An initial search was performed between January 2019 and December 2019, followed by an update between January 2020 and April 2020. A comprehensive search strategy for SCOPUS was developed based on the four concept groups and their keywords. Results were sifted manually for study design (methods) and outcomes (geospatial data or information). Only peer-reviewed journal articles in English were selected for the review. For a small number of articles, access to the full text could not be obtained.

Articles retrieved from these searches were evaluated for relevance through examining their title, abstract and keywords (using the TITLE-ABS-KEY keyword). The assumption was that if there was no relevant information in the title, abstract and keywords, there would also not be anything relevant in the remainder of the paper. Only articles deemed relevant were read in full to further establish whether it was about geospatial information and informal settlement upgrades. One conference paper was excluded from this evaluation process because it was incorrectly indexed as a journal article. Out of 76 articles retrieved, 44 were included in the review based on their relevance. Figure 1 illustrates the distribution of the 44 articles across subject area, with most articles falling under the social sciences (22%), followed by earth and plenary sciences (19%), environmental sciences (12%), medicine (12%) and engineering (11%). References to the 44 articles deemed eligible for full-text review are provided as Annexure A**.**

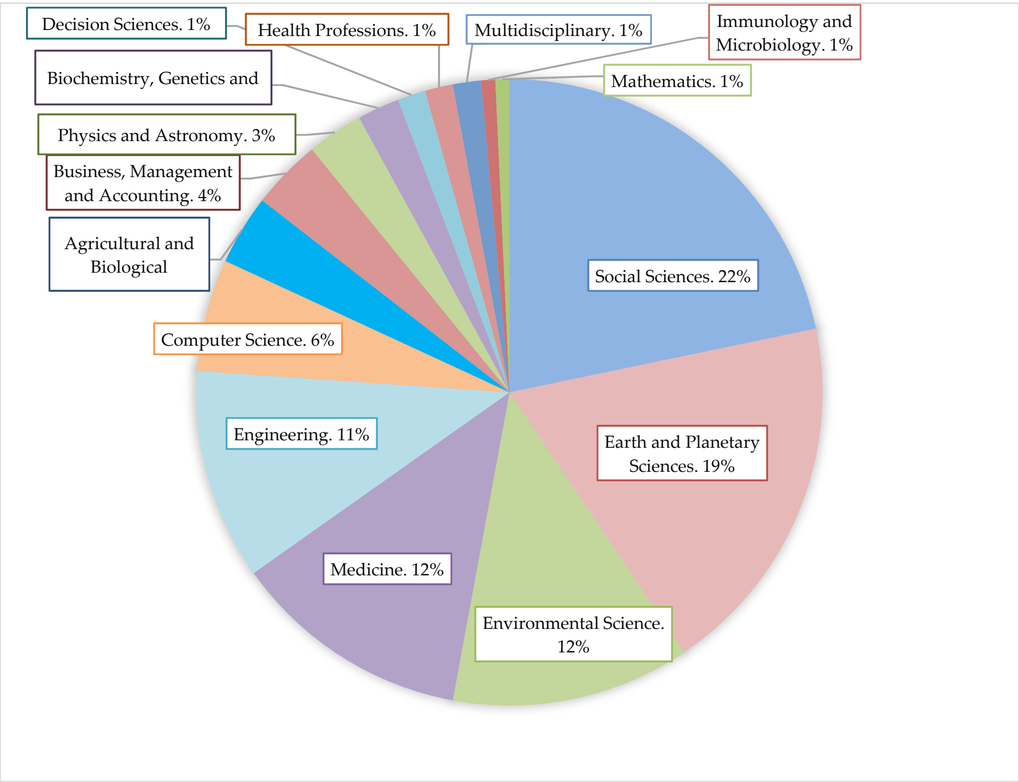

Figure 1. Distribution of the 44 reviewed articles by subject area

A limitation of our search strategy is that among the plethora of terms for informal settlements, not all could be considered as keywords. For example, local terms used in different geographical locations, often in languages other than English, were not included. Furthermore, a variety of terms are used for upgrading interventions. Common English synonymous verbs, such as improve, upgrade, renew, enhance, etc., were used in our search but they might not have identified all relevant literature. Using Scopus as the only source may be considered as a limitation, but the database is regarded to be one of the largest bibliometric databases (Schotten et al., 2017) and therefore sufficiently comprehensive for a review of scientific literature. However, the TITLE-ABS-KEY keyword in Scopus has some unexpected side effects that reduced the articles included in our review: searching with the TITLE, ABS and KEY keywords individually returns a different set of articles than a search with the TITLE-ABS-KEY keyword. To address this limitation, in the discussion we included some of the more recent articles retrieved with individual searches with the TITLE, ABS and KEY keywords.

2.2 Analysis of articles and categorization of the results

Each of the 44 articles were read in full, taking notes of geospatial information used and how it was collected. A myriad of different kinds of geospatial data and data collection methods emerged. We organized them into categories for easier presentation of the results.

Based on the phenomena described by the geospatial information, we identified three categories of geospatial data, namely physical phenomena, socio-economic phenomena and boundaries, each further divided into subcategories with examples from the reviewed literature. This hierarchical classification of different kinds of geospatial data used in informal settlement upgrading is graphically presented as 'trees' in the results section (3.1).

Based on how the data was collected, we identified two categories, namely, primary data collection (collected in the field) and secondary data sources (derived from other sources), also further divided into subcategories with examples from the reviewed literature. The resulting classification trees are represented graphically in the results section (3.2).

In both cases, we distinguished between geospatial (location on or near the earth surface) and non-spatial (attributes that can be linked to a location) data and colour coded them in the graphical presentations: orange for geospatial and green for non-spatial. An example of geospatial data is the building footprint of a dwelling (polygon), while the data value for the number of households living in the dwelling is an attribute that can be linked to the geospatial data (building footprint).

3. Results

3.1. Data

Three categories of data were identified in the studies: data about physical phenomena, about socio-economic phenomena and boundary data (demarcated areas). Each of the categories was further subdivided, as described in this section.

3.1.1. Physical phenomena

Data describing physical phenomena was subdivided into three sub-categories (see Figure 2): structures, such as shacks or houses; infrastructure, e.g., for services, utilities or mobility; and land descriptions, e.g. its use and cover or landmarks. Physical phenomena are represented as points, lines, polygons or 3D shapes with associated descriptive information. Most data in this category include the shape of the physical phenomenon that they represent (i.e., 'geospatial' in Figure 2), but there are also examples of attribute information linked to a point location representing the phenomenon ('Attribute linked to geospatial' in Figure 2). For example, buildings are represented as points (Sur et al.2006; Kakembo and van Niekerk, 2014; Mokoena and Musakwa 2018) polygons (Mason et al. 1997; Sliuzas, 2003; Wayumba et al. 2015; Rautenbach et al. 2015; Kuffer et al.2018) or 3D shapes (Rautenbach et al., 2015).

The attributes for structures describe, amongst others, the use, height, and estimate of the roof or floor area. For shacks, houses or dwelling structures, descriptive information is included, such as the type of dwelling (e.g., formal, informal or backyard shack), construction materials, and number of rooms. Several researchers captured photographs of structures (e.g., Barry et al., 2010; Wayumba et al., 2015; Mokoena and Musakwa, 2018).

Infrastructure information includes location information about services (e.g., water collection points, healthcare facilities) or utilities (e.g., powerlines) and mobility networks (e.g. footpaths, roads and railway tracks). There was also non-spatial (descriptive) information to describe energy infrastructure development trends and stormwater drainage.

Land description data describes how land is used, such as residential, commercial, open space, or waste dumping sites; what covers the land, e.g., built-up (or not), water or vegetation; and landmarks (or points of interests) such as schools and churches.

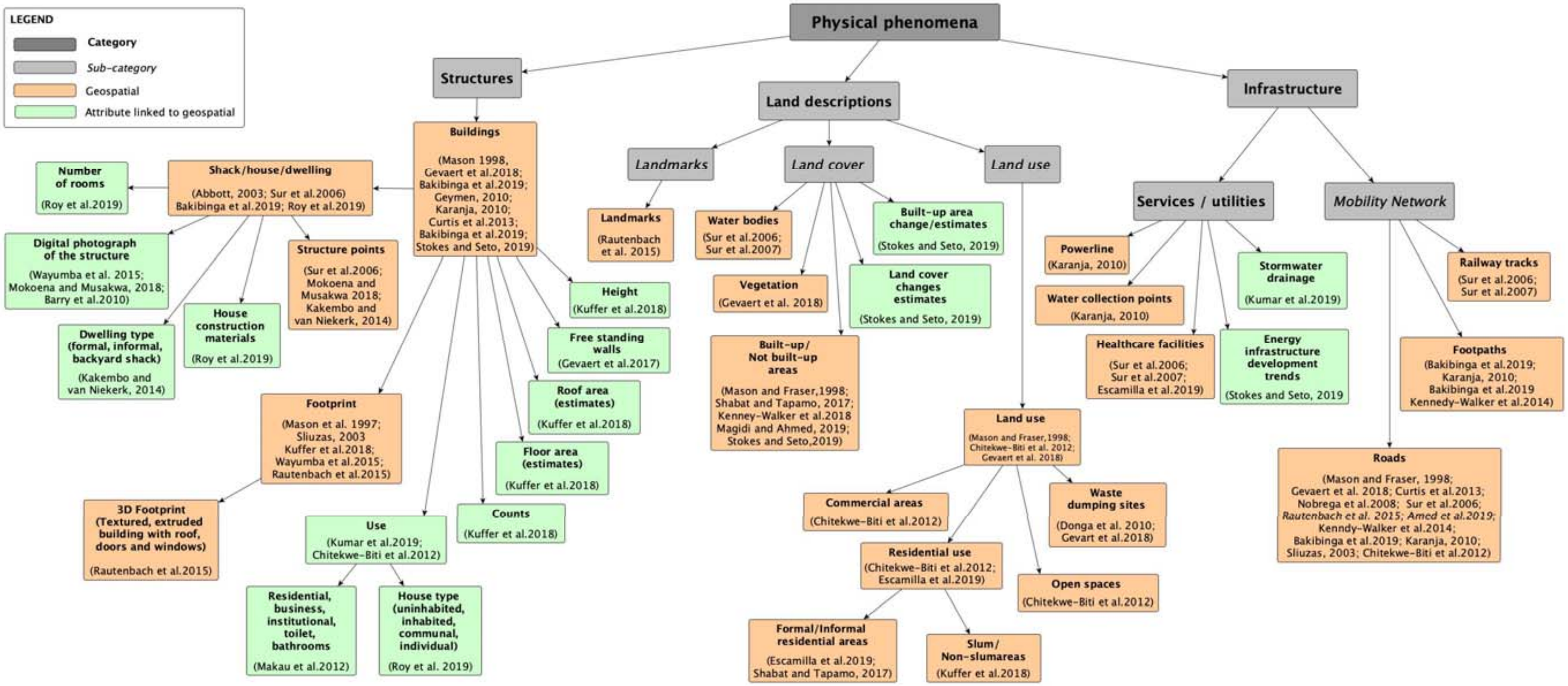

Figure 2. Categories of data representing physical phenomena

3.1.2. Socio-economic phenomena

This category deals with information describing the people living in informal settlements, such as their demographics (e.g., age, gender, disability) or socio-economic status based on education, employment or income. This data was subdivided into data that is aggregated for an area or community and data that describes either a household or an individual household member, as illustrated in Figure 3. All this data was collected as attribute information that can be linked to a location.

Data was aggregated to an area, such as the ward boundary, or it provided aggregated information about a community. Examples of data aggregated to an area include Baud et al. (2008, 2009) who aggregated income, education and employment status of households to ward level using census-type socio-economic survey data, while Chitekwe-Biti et al. (2012) counted the number of households per ward. Livengood and Kunte (2012) counted the number of households in a community and Baud et al. (2008, 2009) record the percentage of households with little space and without electricity, both examples of data aggregated at community level.

For households the number of occupants of a dwelling, access to services or infrastructure, such as water, sanitation, housing and health-care facilities, was collected, as well as access to other resources, e.g., land, assets or income. Examples include land information, such as land use, land type, plot sizes (Karanja, 2010); information about tenure status of households such as structure-owner, structure-tenant of land owner (Barry et al., 2010; Karanja, 2010; Chitekwe-Biti et al., 2012) and information about the perceptions of occupiers about their rights, interests and obligations (Barry et al., 2010) was also collected.

Information relating to individual household members included personal details, such as names, national card identity number, and a photo of the household head or structure owners (e.g., Wayumba et al., 2015; Mokoena and Musakwa, 2018). Demographic attributes include age, gender, disability, race, religion, relationship to head of household and marital status; socio-economic descriptors include education or literacy level, income and employment status. The full categorization of information collected about individual household members, together with references for examples, is provided in Figure 4.

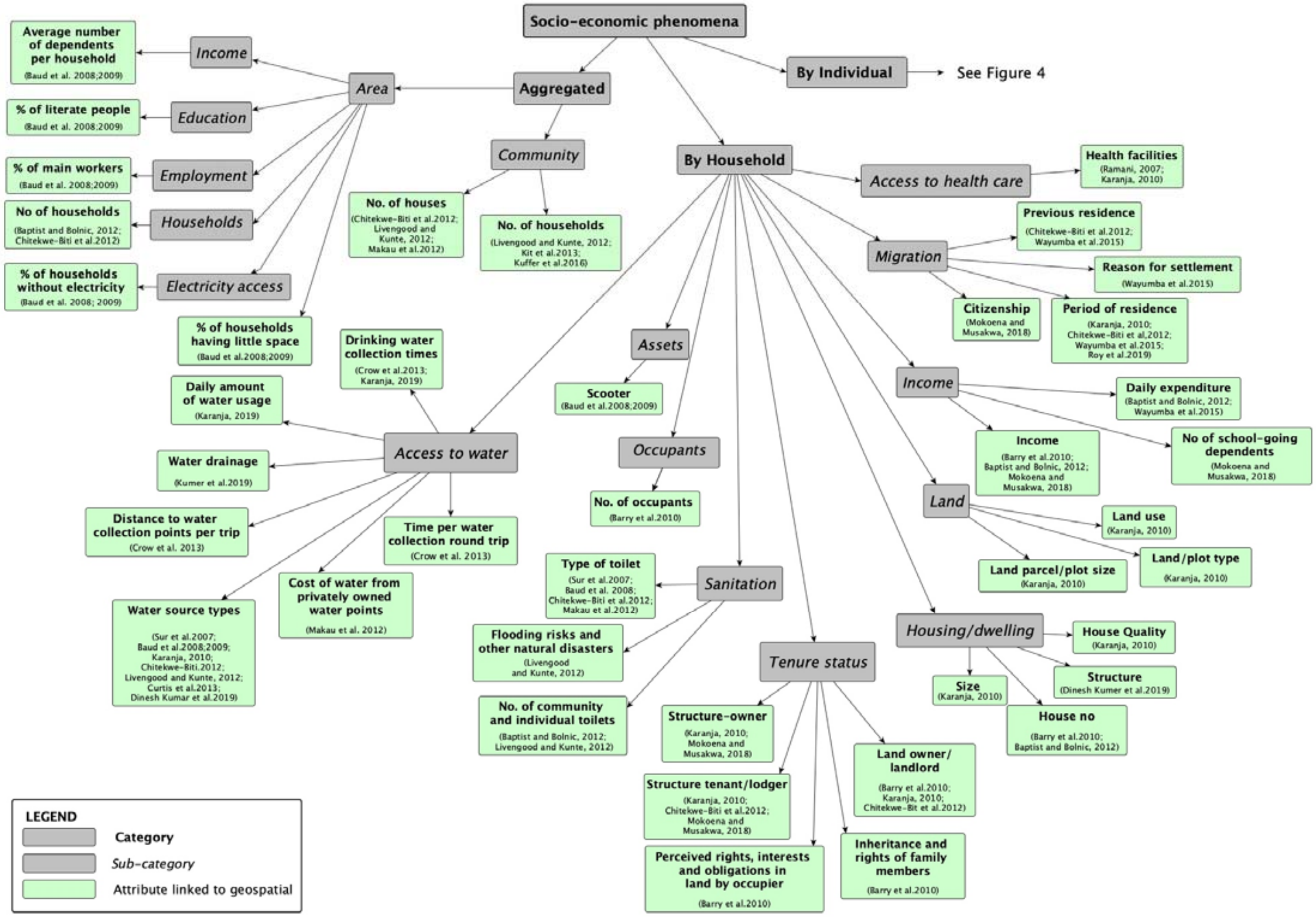

Figure 3. Categories of data representing socio-economic phenomena – Aggregated and By Household

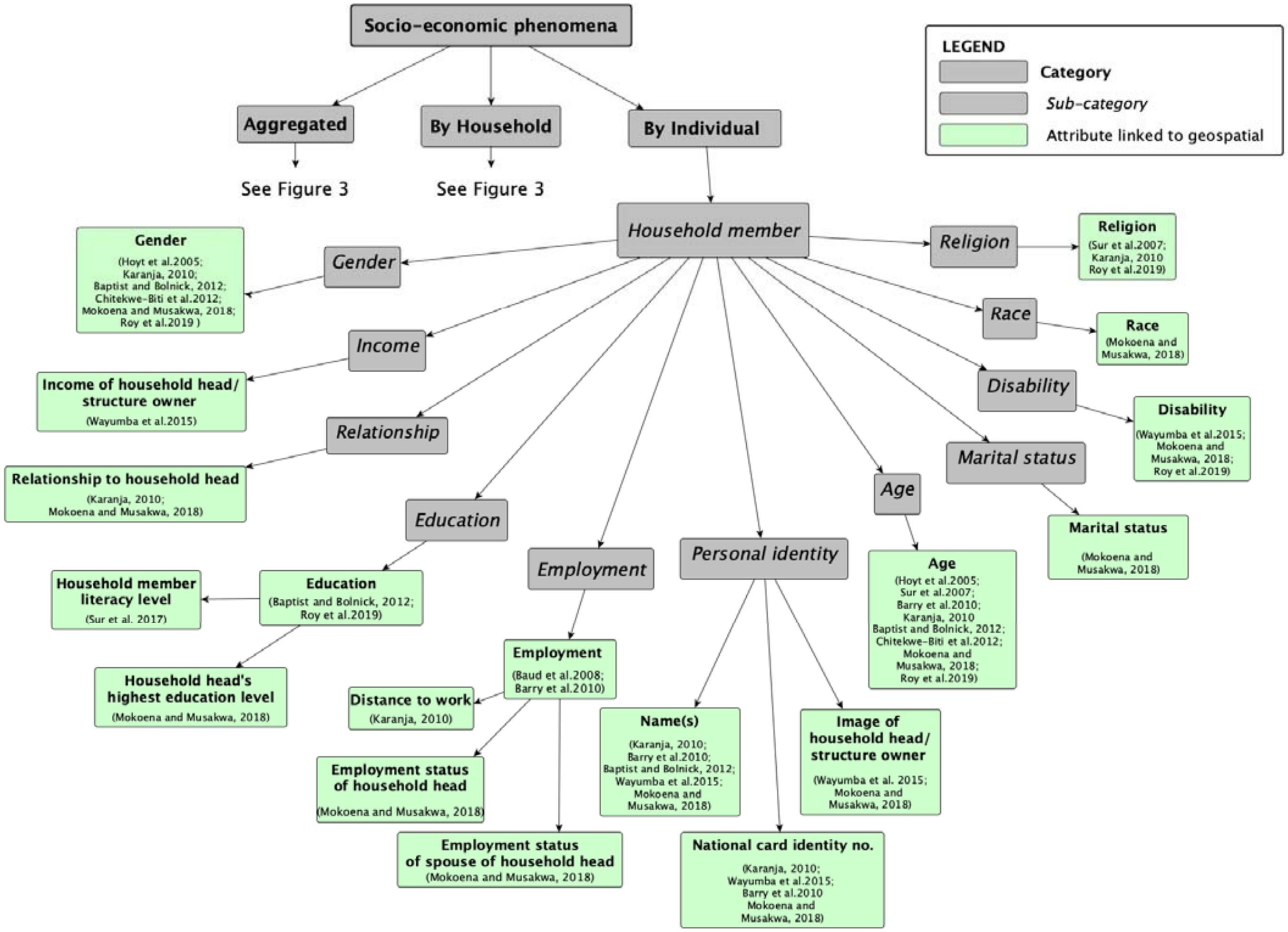

Figure 4. Categories of data representing socio-economic phenomena – By Individual

3.1.3. Boundaries (demarcated areas)

The third category comprises data that represents boundaries, as illustrated in Figure 5. All the data in this category was geo spatial (e.g., shapefiles). There are two subcategories: boundaries of areas demarcated for the purpose of the study, e.g., community-generated settlement layout plans or boundaries of parcels or plots describing the as-is situation; and boundaries representing legally demarcated areas, such as regulated settlement layout plans and parcel boundaries from a cadastre.

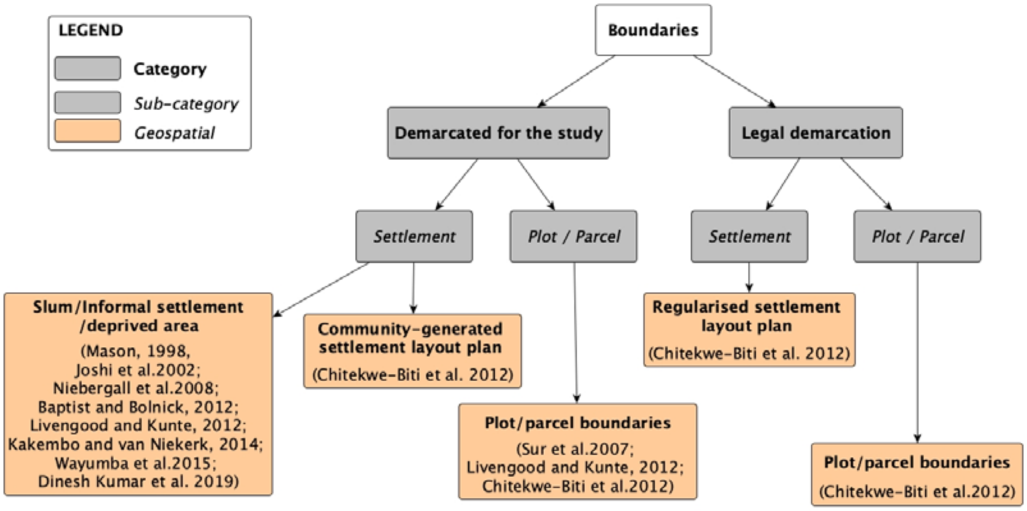

Figure 5. Categories of boundary data

3.2. Data collection

Data collection is categorized into primary data collection and secondary data sources. For the former, data is collected in the field using paper, handheld devices, or vehicle-mounted devices. For the latter, general-purpose data or data collected for other purposes are used.

3.2.1. Primary data collection

As illustrated in Figure 6, the primary data collection methods are divided into three sub-categories: handheld/mobile devices, vehicle-mounted devices, unmanned aerial vehicles (UAVs) and paper-based techniques. In the first case, data is collected with handheld or mobile devices, such as GPS receivers, tablets (with GPS capabilities), cameras, surveying instruments and personal digital assistants (PDAs). Examples of information captured in this way include location-based information about houses or households (Barry et al., 2010; Kakembo and van Niekerk, 2014a)and distances between households and water sources (Crow et al., 2013) captured with GPS devices; elevation levels with line level surveying devices to determine areas that could be flooded (Sliuzas, 2003); photos of people being enumerated (Wayumba et al., 2015; Karanja, 2010; Mokoena and Musakwa, 2018;) and even video clips of community members describing their perceived rights, interests and obligations related to the land they occupy (Barry et al., 2010). There was one example of a vehicle-mounted device used to collect street and building information (including standing water) (Curtis et al., 2013).Data collected with UAVs was used to update base maps or collect images and point clouds for further processing. Paper-based techniques included printed questionnaires, annotations on hardcopy

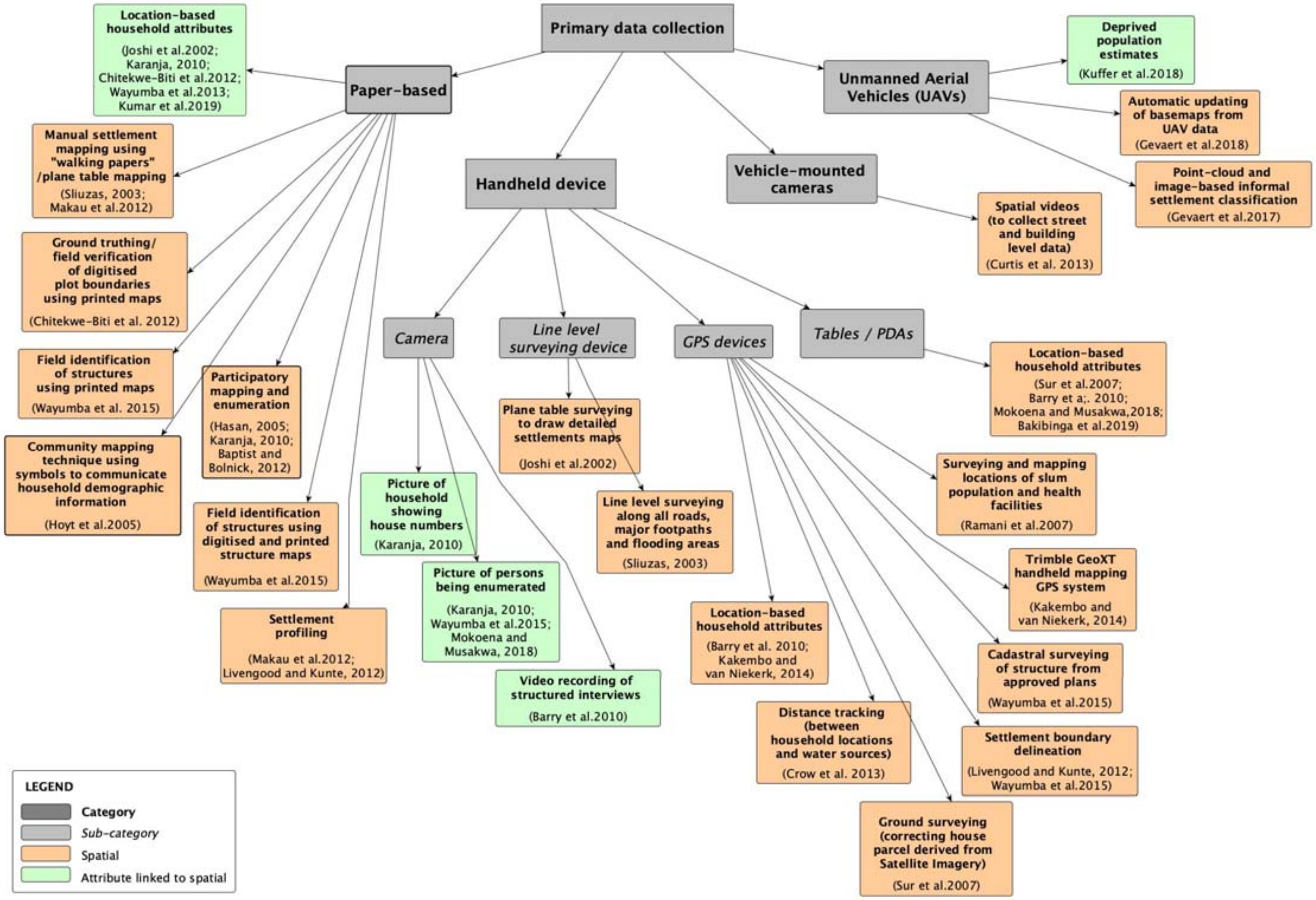

Figure 6. Primary data collection

maps and participatory mapping. These techniques were used to manually map settlements, to ground-truth digitized geospatial information or to identify dwelling structures in the field.

3.2.2. Secondary data sources

Secondary data sources are divided into three categories, depending on how they were collected: spaceborne/satellite-based, airborne/aerial and computer-based. Spaceborne/satellite-based data sources were sub-categorized into different types of sensor platforms, airborne/aerial sources into the kind of data collected (LiDAR or Imagery) and computer-based sources into the kind of platform used (web vs desktop). Figure 7 provides examples of the kind of data that was derived from each of the secondary sources in the diagram. These provide evidence of the usefulness of such secondary data sources for studies in informal settlements. Some features were manually digitized, while others were extracted automatically, e.g., through machine learning techniques and object-based image analysis (OBIA). Phenomena collected from secondary sources or computer-based platforms include building or dwelling footprints, 3D building objects, building roofs, building heights, building counts, parcel/plot boundaries, built-up areas, slum and non-slum areas, land cover, population estimates (requires high resolution imagery), and infrastructure related data, such as roads, footpaths and electricity.

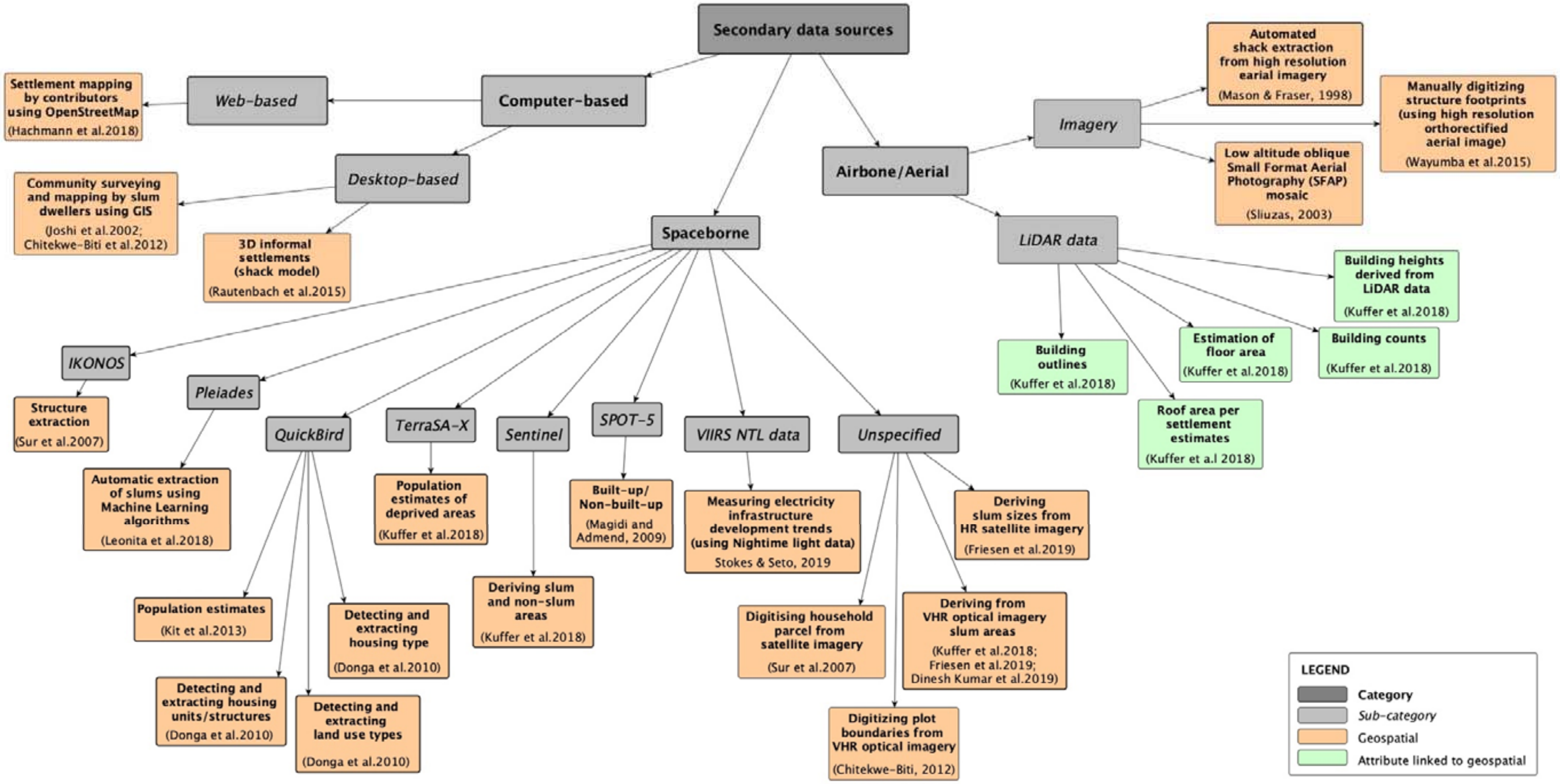

Figure 7. Secondary data sources

3.3 Summary

Table 2 provides a summary of the different kinds of data and how it was collected.

Table 2. How data was collected in the studies

	Primary data collection				Secondary data sources		
	Paper	Handheld	Vehicle	UAV	Computer-based	Spaceborne	Airborne/ Aerial
Physical phenomena							
Structures	X	X	X	X	X	X	X
Land descriptions							
Landmarks	X			X	X		
Land cover				X		X	
Land use				X		X	
Infrastructure							
Services / utilities		X			X		
Mobility network	X	X	X	X	X	X	
Socio-economic phenomena							
Aggregated by area					X	X	
Aggregated by community	X	X					
Household	X	X					
Individual	X	X					
Boundaries							
Demarcated for the study	X	X				X	
Legal demarcation*							

**Legal demarcations were collected from the relevant authority*

Studies reviewed in this article used one or several instruments or platforms to capture geospatial information under the three categories described in 3.1. Under the physical phenomena category, structures were captured using a variety of instruments and platforms followed by mobility network data. For structures, paper-based, handheld devices, vehicle-mounted sensors, UAV, computer-based, spaceborne, and airborne/aerial platforms were used. Building structures were derived from both aerial imagery (e.g., Mason and Fraser, 1998; Wayumba et al., 2015; Kuffer et a., 2018) and spaceborne imagery (e.g., Sur et al., 2007; Donga et al., 2010; Kit et al., 2013). The methods used to derive building footprints in these studies included manual feature delineation (e.g., Wayumba et al., 2015) and automatic feature extraction (e.g., Mason and Fraser, 1998). Studies capturing mobility network infrastructure data used these platforms, except the aerial photography. Services and utility infrastructure data were captured using handheld devices and computer-based platforms. Landmarks data were derived from paper-based, UAVs and computer-based methods. Land use and land cover were captured from UAVs and Spaceborne platforms.

Data about the socio-economic phenomena was captured using paper and handheld devices. Spaceborne data was used to estimate population of deprived areas (Kit et al., 2013; Kuffer et al, 2018). Socio-economic data aggregated to ward level used computer-based methods to create deprivation maps (e.g., Baud et al 2008).

Boundaries data of demarcated study areas were captured using paper (e.g., Sliuzas, 2003; Makau et al., 2012), handheld devices (e.g., Livengood and Kunte, 2012; Wayumba et al., 2015), computer-based (e.g., Joshi et al., 2002; Chitekwe-Biti, 2012; Hachmann et al., 2018), and spaceborne platforms (e.g., Chitekwe-Biti, 2012).

A wide range of methods and tools were used to collect data about physical phenomena while socio-economic data is mostly selected via paper and handheld devices. This can be explained by the fact that physical phenomena can be sensed or observed remotely, while socio-economic data requires contact with the inhabitants. While several studies used a single method of data collection (e.g., Mokoena and Musakwa, 2018c), others use a combination of collection methods (e.g., Barry et al., 2010; Wayumba et al., 2015; Bakinbinga, 2019).

4. Discussion of the results

This study reviewed geospatial information used for informal settlement upgrading and how it was collected. Results confirm that geospatial information and technologies in support of upgrading efforts started about 25 years ago (Mason and Baltsavias, 1997, 1998; Abbott, 2002; Sliuzas, 2003) and that this has grown into a burgeoning body of research in recent years. While authors early on noted the importance of having data about dwellings and their occupants (2003), such as their socio-economic status (Abbott, 2002) and their housing needs (Hardoy and Satterthwaite, 1986), our study reveals that most of the papers from recent years focused on the collection of information about observable physical phenomena.

Any upgrading intervention that focuses merely on physical upgrading does not contribute much to impactful settlement transformation, as Abbott (2003) puts it. Further research is needed about an appropriate mapping context to present concepts such as social interaction, networks or social ties within informal settlements. These are essential to ensure that the quality-of-life of inhabitants is considered and improved by an upgrading intervention. Research could evaluate which information effectively describes the complex social dimensions of informal settlements, and how such information can be collected, also exploring alternatives to time consuming and costly manual questionnaires.

The improvement of land tenure security for residents of the informal settlements is of primary importance for an upgrading initiative. However, this can only be done if information about the current state is available. A significant challenge is that informal settlements are complex and dynamic social systems. Mapping and documentation of rights in the informal settlement should therefore incorporate the complex and dynamic nature of tenure in the settlements. Several methods and instruments have been proposed for the capturing of such information (e.g., Barry et al., 2002, 2010; Barry and Rüther, 2004; Wayumba et al., 2015). The Social Tenure Domain Model (STDM) software has been found to be useful as a pro-poor tool to capture data about tenure in informal settlements that enabled planning the regularisation of tenure in Nairobi (Wayumba et al., 2015).

Our categorisation of the data into physical phenomena, socio-economic phenomena and boundaries (demarcated areas) allowed us to organize the results and to closer examine the nature of the information and how it was collected. Others have classified data about informal settlements differently. For example, the Generic Slum Ontology by Kohli et al., (2012) categorises key features of slums for image-based classification from high resolution imagery. The ontology has three levels: objects, settlements, and environs. Objects relate to buildings (construction materials of buildings) and access network (roads); settlements (shape and density population), and environs (location and neighbourhood characteristics). This classification is useful for image classification but includes only (physical) characteristics observable on imagery; socio-economic information is not included. Lilford et al., (2019) extended this ontology by classifying information into four types that could help to identify slums, namely built environment (construction materials), services (water, sanitation, schools, power), ecology (gradient, altitude, floodplains) and socioeconomic (security, poverty, stigma). This classification is useful for identifying slums, but does not include all information required for upgrades, e.g., boundaries or demarcated areas are not included, and the socio-economic features are only those included in the UN-Habitat definition.

These different kinds of categorizations and classifications are informed by the information requirements, e.g., identifying and monitoring slums or organizing review results. A classification developed specifically for the information requirements related to upgrading projects would also be useful. A limitation of any categorization or classification is that it does not show relationships between the phenomena and the data they describe. For that, a conceptual model would be required.

The data collection methods in the reviewed literature ranged from manual data collection (e.g., through door-to-door questionnaires or digitizing of features from imagery) to semi-automated and automated image-based feature extraction of observable physical objects, such as building structures from very high-resolution imagery. Despite the potential of unmanned aerial vehicles (UAV) as the source of rapid base map updates, we found limited application of this airborne platform in literature, but we expect this to increase in future. Similarly, none of the studies used connected and autonomous vehicles (CAVs) for data capturing, however, CAVs present new and exciting opportunities for geospatial data acquisition in future (Toth et al., 2018), also for informal settlement upgrades. Other emerging data collection approaches involve crowdsourcing via freely available internet mapping platforms for collecting slum data, such as OpenStreetMap, Wikimapia and Google’s MapMaker (Mahabir et al., 2016). In our categorization, we grouped them into the ‘web-based’ sub-category under computer-based secondary sources. Researchers have also highlighted the importance of integrating different data collection approaches in order to improve the geospatial information accuracy, currency and completeness of information about slums and informal settlements, and to effectively manage such integrated information (Mahabir et al., 2016; Thomson et al., 2020). The Integrated Deprived Area Mapping System (IDEAMAPS) aims to do just that.

Accurate, complete and current geospatial information is essential for informed decision-making about upgrading of slums and informal settlements. The results of this review are useful for cities and municipalities who want to understand what kind of geospatial information is useful for upgrading interventions and how it is collected. The results can inform their data collection strategies for upgrading projects.

5. Conclusion

Geospatial information is essential for planning and implementation of informal settlement upgrades. Policymakers, practitioners, and all other stakeholders require information about these settlements to ensure that decisions lead to sustainable improvements. This study reviewed studies involving informal settlement upgrades, the geospatial information used to support them and how it was collected. A categorisation of data and methods of acquisition was developed in order to organize and communicate the research results, included as graphical presentations of the hierarchical categorisations of data and methods. Data was categorized into information about physical phenomena, socio-economic phenomena, and boundaries or demarcated areas, while data collection methods were divided into primary data collection and secondary data sources. Each category was further sub-divided with examples from literature for each sub-category. The information is accessible in the supplementary material.

Our study showed that the collection of information about observable physical phenomena has received much attention in recent years, which can be explained by advances in technologies for collecting remotely sensed information. Studies that made use of information about social interaction, networks or social ties within informal settlements were limited, yet this information is essential for ensuring successful transformation of settlements in the long run. Information about the complex social nature of settlements in need of an upgrade should not be neglected, e.g., by developing and evaluating methods or models to describe the complex social dimensions of informal settlements. Furthermore, alternatives to time consuming and costly manual questionnaires should be explored. Categorizations and classifications of information about informal settlements do not show relationships between the phenomena. A conceptual model can do that and can also assist with communicating the information requirements for upgrades.

Our ongoing research effort is to develop a conceptual model for describing geospatial information required to support informal settlement upgrades. We hope that the results of our study can contribute not only to that effort but also towards addressing problems of informal settlement proliferation more particular in low- and middle-income countries of Asia and Africa where the phenomenon is acute.

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References

Abbott, J. (2002). An analysis of informal settlement upgrading and critique of existing methodological approaches. *Habitat International, 26*(3), 303-315. doi:10.1016/S0197-3975(01)00049-2

Abbott, J. (2003). The use of GIS in informal settlement upgrading: Its role and impact on the community and on local government. *Habitat International, 27*(4), 575-593. doi:10.1016/S0197-3975(03)00006-7

Ahmed, S., Adams, A. M., Islam, R., Hasan, S. M., & Panciera, R. (2019). Impact of traffic variability on geographic accessibility to 24/7 emergency healthcare for the urban poor: A GIS study in dhaka, bangladesh. *PLoS ONE, 14*(9) doi:10.1371/journal.pone.0222488

Bakibinga, P., Kabaria, C., Kyobutungi, C., Manyara, A., Mbaya, N., Mohammed, S., . . . Yeboah, G. (2019). A protocol for a multi-site, spatially-referenced household survey in slum settings: Methods for access, sampling frame construction, sampling, and field data collection. *BMC Medical Research Methodology, 19*(1) doi:10.1186/s12874-019-0732-x

Baptist, C., & Bolnick, J. (2012). Participatory enumerations, in situ upgrading and mega events: The 2009 survey in joe slovo, cape town. *Environment and Urbanization, 24*(1), 59-66. doi:10.1177/0956247811435888

Barry, M., Roux, L., Barodien, G., & Bishop, I. (2002). Video evidencing and palmtop computer technology to support the formalisation of land rights. *Development Southern Africa, 19*(2), 261-271. doi:10.1080/03768350220132477

Baud, I. S. A., Pfeffer, K., Sridharan, N., & Nainan, N. (2009). Matching deprivation mapping to urban governance in three Indian mega-cities. *Habitat International, 33*(4), 365-377. doi:10.1016/j.habitatint.2008.10.024

Baud, I., Sridharan, N., & Pfeffer, K. (2008). Mapping urban poverty for local governance in an Indian mega-city: The case of Delhi. *Urban Studies, 45*(7), 1385-1412. doi:10.1177/0042098008090679

Bossler, J.D (2010). An introduction to geospatial science and technology. In: Bossler, J.D., McMasterm R.B., Rizos, C., and Campbell, J.B. ed. *Manual of geospatial science and technology*. New York, USA: CRC Press, pp.3-8.

Chiodelli, F. (2016). International housing policy for the urban poor and the informal city in the global south: A non-diachronic review. *Journal of International Development, 28*(5), 788-807. doi:10.1002/jid.3204

Chitekwe-Biti, B., Mudimu, P., Nyama, G. M., & Jera, T. (2012). Developing an informal settlement upgrading protocol in Zimbabwe - the Epworth story. *Environment and Urbanization, 24*(1), 131-148. doi:10.1177/0956247812437138

Crow, B., Davies, J., Paterson, S., & Miles, J. (2013). Using GPS and recall to understand water collection in Kenyan informal settlements. *Water International, 38*(1), 43-60. doi:10.1080/02508060.2013.752315

Curtis, A., Blackburn, J. K., Widmer, J. M., & Morris Jr, J. G. (2013). A ubiquitous method for street scale spatial data collection and analysis in challenging urban environments: Mapping health risks using spatial video in haiti. *International Journal of Health Geographics, 12* doi:10.1186/1476-072X-12-21

Dinesh Kumar, K. S. A., Janardhanan, G., & Ravichandiran, R. (2019). Criteria analysis using GIS to priorities the slums. *International Journal of Engineering and Advanced Technology, 9*(1), 7493-7496. doi:10.35940/ijeat.A3125.109119

Dongo, K., Zurbrügg, C., Cissé, G., Obrist, B., Tanner, M., & Biémi, J. (2010). Analysing environmental risks and perceptions of risks to assess health and well-being in poor areas of abidjan. *World Academy of Science, Engineering and Technology, 37*, 961-967. Retrieved from

Dovey, K., & King, R. (2011). Forms of informality: Morphology and visibility of informal settlements. *Built Environment, 37*(1), 11-29. doi:10.2148/benv.37.1.11

Escamilla, V., Calhoun, L., Odero, N., & Speizer, I. S. (2019). Access to public transportation and health facilities offering long-acting reversible contraceptives among residents of formal and informal settlements in two cities in kenya. *Reproductive Health, 16*(1) doi:10.1186/s12978-019-0828-0

Friesen, J., Taubenböck, H., Wurm, M., & Pelz, P. F. (2019). Size distributions of slums across the globe using different data and classification methods. *European Journal of Remote Sensing, 52*(sup2), 99-111. doi:10.1080/22797254.2019.1579617

Gamba, P., Dell'Acqua, F., & Trianni, G. (2007). Satellite SAR and human settlement detection. Paper presented at the *2007 Urban Remote Sensing Joint Event, URS,* doi:10.1109/URS.2007.371872

Gevaert, C. M., Persello, C., Sliuzas, R., & Vosselman, G. (2017). Informal settlement classification using point-cloud and image-based features from UAV data. *ISPRS Journal of Photogrammetry and Remote Sensing, 125*, 225-236. doi:10.1016/j.isprsjprs.2017.01.017

Gevaert, C. M., Persello, C., Elberink, S. O., Vosselman, G., & Sliuzas, R. (2018). Context-based filtering of noisy labels for automatic basemap updating from UAV data. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 11*(8), 2731-2741. doi:10.1109/JSTARS.2017.2762905

Geymen, A. (2010). On the use of terrestrial laser scanners to facilitate project studies of urban transformation in the historic peninsula of the metropolitan area of Istanbul. *Lasers in Engineering, 20*(3-4), 225-239.

E. Hardoy, J., & Satterthwaite, D. (1986). Shelter, infrastructure and services in third world cities. *Habitat International, 10*(3), 245-284. doi:10.1016/0197-3975(86)90054-8

Hachmann, S., Jokar Arsanjani, J., & Vaz, E. (2018). Spatial data for slum upgrading: Volunteered geographic information and the role of citizen science. *Habitat International, 72*, 18-26. doi:10.1016/j.habitatint.2017.04.011

Hofmann, P., & Bekkarnayeva, G. (2017). Object-based change detection of informal settlements. Paper presented at the *2017 Joint Urban Remote Sensing Event, JURSE 2017,* doi:10.1109/JURSE.2017.7924588

Hoyt, L., Khosla, R., & Canepa, C. (2005). Leaves, pebbles, and chalk: Building a public participation GIS in new Delhi, India. *Journal of Urban Technology, 12*(1), 1-19. doi:10.1080/10630730500116479

Jaycox, E. V. K. (1977). Housing the poor: The task ahead in developing countries. *Urban Ecology, 2*(4), 305-325. doi:10.1016/0304-4009(77)90001-8

Joshi, P., Sen, S., & Hobson, J. (2002). Experiences with surveying and mapping Pune and Sangli slums on a geographical information system (GIS). *Environment and Urbanization, 14*(2), 225-240. doi:10.1177/095624780201400218

Jaycox, E. V. K. (1977). Housing the poor: The task ahead in developing countries. *Urban Ecology, 2*(4), 305-325. doi:10.1016/0304-4009(77)90001-8

Kakembo, V., & van Niekerk, S. (2014). The integration of GIS into demographic surveying of informal settlements: The case of Nelson Mandela bay municipality, south africa. *Habitat International, 44*, 451-460. doi:10.1016/j.habitatint.2014.09.004

Karanja, I. (2010). An enumeration and mapping of informal settlements in kisumu, kenya, implemented by their inhabitants. *Environment and Urbanization, 22*(1), 217-239. doi:10.1177/0956247809362642

Khalifa, M. A. (2015). Evolution of informal settlements upgrading strategies in egypt: From negligence to participatory development. *Ain Shams Engineering Journal, 6*(4), 1151-1159. doi:10.1016/j.asej.2015.04.008

Kit, O., Lüdeke, M., & Reckien, D. (2013). Defining the bull's eye: Satellite imagery-assisted slum population assessment in Hyderabad, India. *Urban Geography, 34*(3), 413-424. doi:10.1080/02723638.2013.778665

Kohli, D., Sliuzas, R., Kerle, N., & Stein, A. (2012). An ontology of slums for image-based classification. *Computers, Environment and Urban Systems, 36*(2), 154-163. doi:10.1016/j.compenvurbsys.2011.11.001

Kuffer, M., Pfeffer, K., & Sliuzas, R. (2016). Slums from space-15 years of slum mapping using remote sensing. *Remote Sensing, 8*(6) doi:10.3390/rs8060455

Kuffer, M., Wang, J., Nagenborg, M., Pfeffer, K., Kohli, D., Sliuzas, R., & Persello, C. (2018). The scope of earth-observation to improve the consistency of the SDG slum indicator. *ISPRS International Journal of Geo-Information, 7*(11) doi:10.3390/ijgi7110428

Jaitman, L.J. and Brakarz, J. (2013). *Evaluation of slum upgrading programs : literature review and methodological approaches.* TECHNICAL NOTE No. IDB-TN-604. Inter-American Development Bank.

Leonita, G., Kuffer, M., Sliuzas, R., & Persello, C. (2018). Machine learning-based slum mapping in support of slum upgrading programs: The case of Bandung city, Indonesia. *Remote Sensing, 10*(10) doi:10.3390/rs10101522

Livengood, A., & Kunte, K. (2012). Enabling participatory planning with GIS: A case study of settlement mapping in Cuttack, India. *Environment and Urbanization, 24*(1), 77-97. doi:10.1177/0956247811434360

Lilford, R., Kyobutungi, C., Ndugwa, R., Sartori, J., Watson, S. I., Sliuzas, R., . . . Ezeh, A. (2019). Because space matters: Conceptual framework to help distinguish slum from non-slum urban areas. *BMJ Global Health, 4*(2) doi:10.1136/bmjgh-2018-001267

Livengood, A., & Kunte, K. (2012). Enabling participatory planning with GIS: A case study of settlement mapping in Cuttack, India. *Environment and Urbanization, 24*(1), 77-97. doi:10.1177/0956247811434360

Lucci, P., Bhatkal, T., & Khan, A. (2018). Are we underestimating urban poverty? *World Development, 103*, 297-310. doi:10.1016/j.worlddev.2017.10.022

Magidi, J., & Ahmed, F. (2019). Assessing urban sprawl using remote sensing and landscape metrics: A case study of City of Tshwane, South Africa (1984–2015). *Egyptian Journal of Remote Sensing and Space Science, 22*(3), 335-346. doi:10.1016/j.ejrs.2018.07.003

Mahabir, R., Agouris, P., Stefanidis, A., Croitoru, A., & Crooks, A. T. (2020). Detecting and mapping slums using open data: A case study in Kenya. *International Journal of Digital Earth, 13*(6), 683-707. doi:10.1080/17538947.2018.1554010

Mahabir, R., Crooks, A., Croitoru, A. and Agouris, P. (2016) The study of slums as social and physical constructs: challenges and emerging research opportunities, *Regional Studies, Regional Science*, 3:1, 399-419, DOI: 10.1080/21681376.2016.1229130

Makau, J., Dobson, S., & Samia, E. (2012). The five-city enumeration: The role of participatory enumerations in developing community capacity and partnerships with government in uganda. *Environment and Urbanization, 24*(1), 31-46. doi:10.1177/0956247812438368

Mason, S. O., Baltsavias, E. P., & Bishop, I. (1997). Spatial decision support systems for the management of informal settlements. *Computers, Environment and Urban Systems, 21*(3-4), 189-208. doi:10.1016/S0198-9715(97)10002-3

Mayunga, S. D., Coleman, D. J., & Zhang, Y. (2007). A semi-automated approach for extracting buildings from QuickBird imagery applied to informal settlement mapping. *International Journal of Remote Sensing, 28*(10), 2343-2357. doi:10.1080/01431160600868474

Mokoena, B. T., & Musakwa, W. (2018). Mobile GIS occupancy audit of Ulana informal settlement in Ekurhuleni municipality, South Africa. *Geo-Spatial Information Science, 21*(4), 322-330. doi:10.1080/10095020.2018.1519349

Niebergall, S., Loew, A., & Mauser, W. (2008). Integrative assessment of informal settlements using VHR remote sensing data - the Delhi case study. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 1*(3), 193-205. doi:10.1109/JSTARS.2008.2007513

Nobrega, R. A. A., O'Hara, C. G., & Quintanilha, J. A. (2008). *An object-based approach to detect road features for informal settlements near Sao Paulo, brazil* doi:10.1007/978-3-540-77058-9_32 Retrieved from www.scopus.com

Pedro, A. A., & Queiroz, A. P. (2019). Slum: Comparing municipal and census basemaps. *Habitat International, 83*, 30-40. doi:10.1016/j.habitatint.2018.11.001

Persello, C., & Stein, A. (2017). Deep fully convolutional networks for the detection of informal settlements in VHR images. *IEEE Geoscience and Remote Sensing Letters, 14*(12), 2325-2329. doi:10.1109/LGRS.2017.2763738

Ramani, K. V., Mavalankar, D., Patel, A., & Mehandiratta, S. (2007). A GIS approach to plan and deliver healthcare services to urban poor: A public private partnership model for ahmedabad city, india.*International Journal of Pharmaceutical and Healthcare Marketing, 1*(2), 159-173. doi:10.1108/17506120710763004

Rautenbach, V., Bevis, Y., Coetzee, S. and Rautenbach, V. (2015), "Evaluating procedural modelling for 3D models of informal settlements in urban design activities Study area : Slovo Park settlement", Vol. 111 No. 11, pp. 1–10.

Shabat, A. M., & Tapamo, J. -. (2017). A comparative study of the use of local directional pattern for texture-based informal settlement classification. *Journal of Applied Research and Technology, 15*(3), 250-258. doi:10.1016/j.jart.2016.12.009

Sheuya, S. A. (2008). *Improving the health and lives of people living in slums* doi:10.1196/annals.1425.003

Schotten, M., El Aisati, M., Meester, W.J.N., Steiginga, S. and Ross, C.A. (2017), *A Brief History of Scopus: The World's Largest Abstract and Citation Database of Scientific Literature, Research Analytics: Boosting University Productivity and Competitiveness through Scientometrics*, available at:https://doi.org/10.1201/9781315155890.

Sliuzas, R. (2003). Opportunities for enhancing communication in settlement upgrading with geographic information technology-based support tools. *Habitat International, 27*(4), 613-628. doi:10.1016/S0197-3975(03)00008-0

Stokes, E. C., & Seto, K. C. (2019). Characterizing urban infrastructural transitions for the sustainable development goals using multi-temporal land, population, and nighttime light data. *Remote Sensing of Environment, 234* doi:10.1016/j.rse.2019.111430

Sur, D., Ali, M., Von Seidlein, L., Manna, B., Deen, J. L., Acosta, C. J., Bhattacharya, S. K. (2007). Comparisons of predictors for typhoid and paratyphoid fever in Kolkata, India. *BMC Public Health, 7* doi:10.1186/1471-2458-7-289

Sur, D., von Seidlein, L., Manna, B., Dutta, S., Deb, A. K., Sarkar, B. L., Bhattacharya, S. K. (2006). The malaria and typhoid fever burden in the slums of kolkata, india: Data from a prospective community-based study. *Transactions of the Royal Society of Tropical Medicine and Hygiene, 100*(8), 725-733. doi:10.1016/j.trstmh.2005.10.019

Toth, C. K., Koppanyi, Z., & Lenzano, M. G. (2018). New source of geospatial data: Crowdsensing by assisted and autonomous vehicle technologies. Paper presented at the *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, , 42*(4W8) 211-216. doi:10.5194/isprs-archives-XLII-4-W8-211-2018

Thomson, D. R., Kuffer, M., Boo, G., Hati, B., Grippa, T., Elsey, H.,. Kabaria, C. (2020). Need for an integrated deprived area "slum" mapping system (IDEAMAPS) in low-and middle-income countries (LMICS). *Social Sciences, 9*(5) doi:10.3390/SOCSCI9050080

Ramani, K. V., Mavalankar, D., Patel, A., & Mehandiratta, S. (2007). A GIS approach to plan and deliver healthcare services to urban poor: A public private partnership model for Ahmedabad city, india. *International Journal of Pharmaceutical and Healthcare Marketing, 1*(2), 159-173. doi:10.1108/17506120710763004

Roy, A. (2005). Urban informality: Toward an epistemology of planning. *Journal of the American Planning Association, 71*(2), 147-158. doi:10.1080/01944360508976689

Shabat, A. M., & Tapamo, J. -. (2017). A comparative study of the use of local directional pattern for texture-based informal settlement classification. *Journal of Applied Research and Technology, 15*(3), 250-258. doi:10.1016/j.jart.2016.12.009

Sliuzas, R. (2003). Opportunities for enhancing communication in settlement upgrading with geographic information technology-based support tools. *Habitat International, 27*(4), 613-628. doi:10.1016/S0197-3975(03)00008-0

UN-Habitat (2003), *The Challenge of Slums: Global Report on Human Settlements 2003*, Earthscan: London.

United Nations (2000), 'United Nations Millennium Declaration. Resolution Adopted by the General Assembly' (New York: United Nations).

United Nations. (2015). Sustainable development goals. United Nations Sustainable Development (blog). Accessed 29 June 2020, from https://www.un.org/sustainabledevelop ment/sustainable-development-goals/.

UN-DESA (2019). *World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420)*. New York: United Nations.

UN-Habitat (2016a). *Slum Almanac 2015 2016: Tracking Improvement in the lives of slum dwellers.* Nairobi: UN-Habitat. Accessed 30 June 2020 from https://unhabitat.org/slum-almanac-2015-2016-0

UN-Habitat (2016b). *SDG goal 11 monitoring framework*. Nairobi: UN-Habitat.

UN-Habitat (2020). COVID-19 in African cities: Impacts, Responses and Policies Recommendations. Accessed 29 June 2020, from https://unhabitat.org/sites/default/files/2020/06/covid-19_in_african_cities_impacts_responses_and_policies2.pdf

Wekesa, B.W., Steyn, G.S. and Otieno, F.A.O. (2011), "A review of physical and socio-economic characteristics and intervention approaches of informal settlements", *Habitat International*, Vol. 35 No. 2, pp. 238–2

Wurm, M., Stark, T., Zhu, X. X., Weigand, M., & Taubenböck, H. (2019). Semantic segmentation of slums in satellite images using transfer learning on fully convolutional neural networks. *ISPRS Journal of Photogrammetry and Remote Sensing, 150*, 59-69. doi:10.1016/j.isprsjprs.2019.02.006

Wayumba, G., Tiagi, M., Mumo, T., Matata, P., Odongo, M; Kawira, J. (2015). A Methodology For The Enhancement of tenure security in the informal settlements in Kenya. *International Journal of Scientific Research and Engineering Studies (IJSRES)*, 2(7), 83–88.

Annexure A. Articles included in the review

No	Authors	Title	Year	Source title	DOI
1	Abbott J.	The use of GIS in informal settlement upgrading: Its role and impact on the community and on local government	2003	Habitat International	10.1016/S0197-3975(03)00006-7
2	Ahmed S., Adams A.M., Islam R., Hasan S.M., Panciera R.	Impact of traffic variability on geographic accessibility to 24/7 emergency healthcare for the urban poor: A GIS study in Dhaka, Bangladesh	2019	PLoS ONE	10.1371/journal.pone.0222488
3	Barry M., Roux L., Barodien G., Bishop I.	Video evidencing and palmtop computer technology to support the formalisation of land rights	2002	Development Southern Africa	10.1080/03768350220132477
4	Chitekwe-Biti B., Mudimu P., Nyama G.M., Jera T.	Developing an informal settlement upgrading protocol in Zimbabwe - the Epworth story	2012	Environment and Urbanization	10.1177/0956247812437138
5	Crow B., Davies J., Paterson S., Miles J.	Using GPS and recall to understand water collection in Kenyan informal settlements	2013	Water International	10.1080/02508060.2013.752315
6	Curtis A., Blackburn J.K., Widmer J.M., Morris Jr J.G.	A ubiquitous method for street scale spatial data collection and analysis in challenging urban environments: Mapping health risks using spatial video in Haiti	2013	International Journal of Health Geographics	10.1186/1476-072X-12-21
7	Dinesh Kumar K.S.A., Janardhanan G., Ravichandiran R.	Criteria analysis using GIS to priorities the slums	2019	International Journal of Engineering and Advanced Technology	10.35940/ijeat.A3125.109119
8	Dongo K., Zurbrügg C., Cissé G., Obrist B., Tanner M., Biémi J.	Analysing environmental risks and perceptions of risks to assess health and well-being in poor areas of Abidjan	2010	World Academy of Science, Engineering and Technology	
9	Escamilla V., Calhoun L., Odero N., Speizer I.S.	Access to public transportation and health facilities offering long-acting reversible contraceptives among residents of formal	2019	Reproductive Health	10.1186/s12978-019-0828-0

No	Authors	Title	Year	Source title	DOI
		and informal settlements in two cities in Kenya			
10	Friesen J., Taubenböck H., Wurm M., Pelz P.F.	Size distributions of slums across the globe using different data and classification methods	2019	European Journal of Remote Sensing	10.1080/22797254.2019.1579617
11	Gevaert C.M., Persello C., Elberink S.O., Vosselman G., Sliuzas R.	Context-Based Filtering of Noisy Labels for Automatic Basemap Updating from UAV Data	2018	IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing	10.1109/JSTARS.2017.2762905
12	Gevaert C.M., Sliuzas R., Persello C., Vosselman G.	Evaluating the societal impact of using drones to support urban upgrading projects	2018	ISPRS International Journal of Geo-Information	10.3390/ijgi7030091
13	Hachmann S., Jokar Arsanjani J., Vaz E.	Spatial data for slum upgrading: Volunteered Geographic Information and the role of citizen science	2018	Habitat International	10.1016/j.habitatint.2017.04.011
14	Hofmann P., Strobl J., Blaschke T., Kux H.	Detecting informal settlements from QuickBird data in Rio de Janeiro using an object-based approach	2008	Lecture Notes in Geoinformation and Cartography	10.1007/978-3-540-77058-9_29
15	Hoyt L., Khosla R., Canepa C.	Leaves, pebbles, and chalk: Building a public participation GIS in New Delhi, India	2005	Journal of Urban Technology	10.1080/10630730500116479
16	Kakembo V., van Niekerk S.	The integration of GIS into demographic surveying of informal settlements: The case of Nelson Mandela Bay Municipality, South Africa	2014	Habitat International	10.1016/j.habitatint.2014.09.004
17	Kennedy-Walker R., Holderness T., Alderson D., Evans B., Barr S.	Network modelling for road-based faecal sludge management	2014	Proceedings of the Institution of Civil Engineers: Municipal Engineer	10.1680/muen.13.00021
18	Kuffer M., Pfeffer K., Sliuzas R.	Slums from space-15 years of slum mapping using remote sensing	2016	Remote Sensing	10.3390/rs8060455

No	Authors	Title	Year	Source title	DOI
19	Kuffer M., Wang J., Nagenborg M., Pfeffer K., Kohli D., Sliuzas R., Persello C.	The scope of earth-observation to improve the consistency of the SDG slum indicator	2018	ISPRS International Journal of Geo-Information	10.3390/ijgi7110428
20	Leonita G., Kuffer M., Sliuzas R., Persello C.	Machine learning-based slum mapping in support of slum upgrading programs: The case of Bandung City, Indonesia	2018	Remote Sensing	10.3390/rs10101522
21	Livengood A., Kunte K.	Enabling participatory planning with GIS: A case study of settlement mapping in Cuttack, India	2012	Environment and Urbanization	10.1177/0956247811434360
22	Magidi J., Ahmed F.	Assessing urban sprawl using remote sensing and landscape metrics: A case study of City of Tshwane, South Africa (1984–2015)	2019	Egyptian Journal of Remote Sensing and Space Science	10.1016/j.ejrs.2018.07.003
23	Mahabir R., Agouris P., Stefanidis A., Croitoru A., Crooks A.T.	Detecting and mapping slums using open data: a case study in Kenya	2020	International Journal of Digital Earth	10.1080/17538947.2018.1554010
24	Makau J., Dobson S., Samia E.	The five-city enumeration: The role of participatory enumerations in developing community capacity and partnerships with government in Uganda	2012	Environment and Urbanization	10.1177/0956247812438368
25	Mason S.O., Baltsavias E.P., Bishop I.	Spatial decision support systems for the management of informal settlements	1997	Computers, Environment and Urban Systems	10.1016/S0198-9715(97)10002-3
26	Mason S.O., Fraser C.S.	Image Sources for Informal Settlement Management	1998	Photogrammetric Record	10.1111/0031-868X.00128
27	Mokoena B.T., Musakwa W.	Mobile GIS occupancy audit of Ulana informal settlement in Ekurhuleni municipality, South Africa	2018	Geo-Spatial Information Science	10.1080/10095020.2018.1519349
28	Niebergall S., Loew A., Mauser W.	Integrative assessment of informal settlements using VHR remote sensing data - The Delhi case study	2008	IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing	10.1109/JSTARS.2008.2007513

No	Authors	Title	Year	Source title	DOI
29	Rautenbach V., Coetzee S., Çöltekin A.	Investigating The Use Of 3D geovisualizations for urban design in informal settlement upgrading in South Africa	2016	International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives	10.5194/isprsarchives-XLI-B2-425-2016
30	Ramani K.V., Mavalankar D., Patel A., Mehandiratta S.	A GIS approach to plan and deliver healthcare services to urban poor: A public private partnership model for Ahmedabad City, India	2007	International Journal of Pharmaceutical and Healthcare Marketing	10.1108/17506120710763004
31	Roy D., Bernal D., Lees M.	An exploratory factor analysis model for slum severity index in Mexico City	2020	Urban Studies	10.1177/0042098019869769
32	Shabat A.M., Tapamo J.-R.	A comparative study of the use of local directional pattern for texture-based informal settlement classification	2017	Journal of Applied Research and Technology	10.1016/j.jart.2016.12.009
33	Stokes E.C., Seto K.C.	Characterizing urban infrastructural transitions for the Sustainable Development Goals using multi-temporal land, population, and nighttime light data	2019	Remote Sensing of Environment	10.1016/j.rse.2019.111430
34	Sur D., Ali M., Von Seidlein L., Manna B., Deen J.L., Acosta C.J., Clemens J.D., Bhattacharya S.K.	Comparisons of predictors for typhoid and paratyphoid fever in Kolkata, India	2007	BMC Public Health	10.1186/1471-2458-7-289
35	Bakibinga P., Kabaria C., Kyobutungi C., Manyara A., Mbaya N., Mohammed S., Njeri A., Azam I., Iqbal R., Mazaffar S., Rizvi N., Rizvi T., Ur Rehman H., Shifat Ahmed S.A.K., Alam O., Khan A.Z., Rahman O., Yusuf R., Odubanjo D., Ayobola M., Fayehun F., Omigbodun A.,	A protocol for a multi-site, spatially-referenced household survey in slum settings: Methods for access, sampling frame construction, sampling, and field data collection	2019	BMC Medical Research Methodology	10.1186/s12874-019-0732-x

No	Authors	Title	Year	Source title	DOI
	Owoaje E., Taiwo O., Diggle P., Aujla N., Chen Y.-F., Gill P., Griffiths F., Harris B., Madan J., Lilford R.J., Oyobode O.R., Pitidis V., De Albequerque J.P., Sartori J., Taylor C., Ulbrich P., Uthman O., Watson S.I., Yeboah G.				
36	Karanja I.	An enumeration and mapping of informal settlements in Kisumu, Kenya, implemented by their inhabitants	2010	Environment and Urbanization	10.1177/0956247809362642
37	Geymen A.	On the use of terrestrial laser scanners to facilitate project studies of urban transformation in the historic peninsula of the metropolitan area of Istanbul	2010	Lasers in Engineering	
38	Joshi P., Sen S., Hobson J.	Experiences with surveying and mapping Pune and Sangli slums on a geographical information system (GIS)	2002	Environment and Urbanization	10.1177/095624780201400218
39	Baud I.S.A., Pfeffer K., Sridharan N., Nainan N.	Matching deprivation mapping to urban governance in three Indian mega-cities	2009	Habitat International	10.1016/j.habitatint.2008.10.024
40	Sur D., von Seidlein L., Manna B., Dutta S., Deb A.K., Sarkar B.L., Kanungo S., Deen J.L., Ali M., Kim D.R., Gupta V.K., Ochiai R.L., Tsuzuki A., Acosta C.J., Clemens J.D., Bhattacharya S.K.	The malaria and typhoid fever burden in the slums of Kolkata, India: data from a prospective community-based study	2006	Transactions of the Royal Society of Tropical Medicine and Hygiene	10.1016/j.trstmh.2005.10.019
41	Wayumba, Gordon; Tiagi, Meenashi; Mumo, Tom; Matata, Patrick; Odongo, Malachi; Kawira, J. (2015),	A Methodology For The Enhancement Of Tenure Security In The Informal Settlements In Kenya	2015	International Journal of Scientific Research and Engineering Studies (IJSRES),	

No	Authors	Title	Year	Source title	DOI
42	Baptist and Bolnick, 2012	Participatory enumerations, in situ upgrading and mega events: the 2009 survey in Joe Slovo, Cape Town	2012	Environment & Urbanization	10.1177/0956247811435888
43	Sliuzas R.	Opportunities for enhancing communication in settlement upgrading with geographic information technology-based support tools	2003	Habitat International	10.1016/S0197-3975(03)00008-0
44	Kit O., Lüdeke M., Reckien D.	Defining the bull's eye: Satellite imagery-assisted slum population assessment in Hyderabad, India	2013	Urban Geography	10.1080/02723638.2013.778665